Federal Register Notice: 89 FR 51554, Federal Register :: Networking and Information Technology Research and Development Request for Information on Digital Twins Research and Development, June 18, 2024.

Request for Information on the 2024 National Digital Twins R&D Strategic Plan: Responses

The NITRD NCO seeks public input for the 2024 National Digital Twins R&D Strategic Plan. The Plan will act as an organizing national document, providing guidance for government investments in digital twins related research and offering valuable insights to help guide further federal R&D coordination to advance technology and accelerate the use and early adoption of the digital twin models to address the nation's priorities and fast-track agency missions. This document contains 85 responses received from interested parties.

Table of Contents

Federal Register Notice: 89 FR 51554, Federal Register :: Networking and Information Technology Research and Development Request for Information on Digital Twins Research and Development, June 18, 2024.

Request for Information on the National Digital Twins R&D Strategic Plan

Submission by A. M. Wright and D. J Den Hartog
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By email: [redacted] July 26, 2024

Response to the Request for Information: Digital Twins R&D Plan

Submission by A. M. Wright[1] and D. J Den Hartog[2]
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Digital twins present tremendous – but as yet unrealized – potential as a technology for accelerating innovation in the design of instruments and sensors that monitor the behavior of physical systems. These devices are crucial to modern society affecting everything from critical systems for cyber- and energy security, to commuter vehicles and aircraft, and even household appliances and the Internet of Things. This transformational potential is amplified when coupled with data assimilation, uncertainty quantification and modern machine learning.

Historically, in the physical sciences, digital twins (in conjunction with data assimilation) have been used to *predict* the future behavior of complex systems, most notably in weather forecasting. For ***design***, it is the ability of digital twins to rapidly iterate and optimize the conceptual development and prototyping process that will be transformative.

Impact: Leveraging digital twins to advance scientific measurement capabilities would accelerate scientific discovery and, simultaneously, catalyze translational R&D into sensor innovations with the potential to impact day-to-day life and society more broadly. Increasingly, advancing the frontiers of human knowledge requires probing physical systems in extreme environments and harsh conditions. In Department of Energy priority areas such as fusion energy systems and advanced nuclear reactors, this includes extreme temperatures (150,000,000 °C) and unprecedented neutron-rich environments. Existing electronics and instrumentation for detecting light and other electromagnetic radiation simply cannot survive in these conditions. This necessitates developing new measurement tools. However, the design and prototyping of such tools is a labor and resource intensive endeavor. This creates a bottleneck for innovation, as the design→prototype→test sequence is usually repeated several times during a typical development project. The equipment and materials used for the prototyping process directly affects sustainability, from both a financial and environmental perspective. Using digital twins for design has the potential to substantially reduce the labor and resources needed to develop new sensors and advance measurement capability.

Needs: Harnessing the potential of digital twins for accelerating instrument and sensor design is impossible without a concerted, coordinated effort across disciplines and federal agencies. Inter-agency funding mechanisms that enable interdisciplinary collaboration are needed to simultaneously advance the underpinning science and application-specific computational system modeling needs. A key requirement is that these digital twins must be incorporated into frameworks designed for optimization and rapid iteration, rather than real-time prediction, as is needed in forecasting applications. A key component of what is currently missing is mechanisms that facilitate bridging and translation of research in foundational methods to application domains. **In the public research sector**, this necessarily requires (i) cooperation between funding agencies and, equally, (ii) unambiguous delineation of how funding programs supported by these agencies interact in scope and priorities.

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Request for Information on the National Digital Twins R&D Strategic Plan

Association for Computing Machinery (ACM), US Technology Policy Committee (USTPC)

COMMENTS IN RESPONSE TO
NITRD REQUEST FOR INFORMATION FOR THE CREATION OF A NATIONAL DIGITAL TWINS R&D STRATEGIC PLAN

July 18, 2024

The US Technology Policy Committee of the Association for Computing Machinery (USTPC)[1] is pleased to submit these comments in response to the recent Request for Information for the creation of a National Digital Twins R&D Strategic Plan issued by the Networking and Information Technology Research and Development (NITRD) National Coordination Office.[2] Specifically, USTPC recommends that:

1) A national digital twins strategy should emphasize the importance of developing open interoperability standards for digital twins.

Developing such standards early will benefit the research community, and ultimately the user community, by making it more likely that data will be compatible between multiple digital twins research and production systems. Digital twins interoperability standards should include both application-level interface (API) standards as well as data representation standards. NITRD should consider delegating this activity to the Information Technology Laboratory at the National Institute of Standards and Technology, which should be encouraged to involve other agencies that may have digital twins expertise.[3]

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[1] 1 The Association for Computing Machinery (ACM), with more than 100,000 members worldwide, is the world's largest educational and scientific computing society. ACM's U.S. Technology Policy Committee (USTPC) serves as the focal point for ACM's interaction with all branches of the U.S. government, the computing community, and the public on policy matters related to information technology. This statement's principal authors for USTPC are Digital Government Subcommittee co-chair Simson Garfinkel and subcommittee members Ravi Jain and Arnon Rosenthal.

[2] *Networking and Information Technology Research and Development Request for Information on Digital Twins Research and Development*, 89 FR 51554 (June 18, 2024) https://www.govinfo.gov/content/pkg/FR-2024-06-18/pdf/2024-13379.pdf. This Request for Information, while soliciting alternatives, adopts the definition of "digital twins" specified in the U.S. National Academies' *Foundational Research Gaps and Future Directions for Digital Twins* https://nap.nationalacademies.org/catalog/26894/foundational-research-gaps-and-future-directions-for-digital-twins.

[3] For example, there is currently substantial digital twins expertise within the US Department of Energy and at various national labs as evidenced by the Digital Twin Information Center at the Idaho National Laboratory, as well as specific digital twin initiatives such as the Digital Twin Hydropower Systems Project at the Oak Ridge National Laboratory. https://www.ornl.gov/content/digital-twin-hydropower-systems-project

2) The national strategy should underscore the importance of digital twins models being open source to the maximum extent possible.

The results of government-funded research on digital twins models should be open source so that they can be easily shared within the research community, as well as with government, industry, and the general public. This is especially important in domains with a broad research community given that research software will likely become the basis of production software from multiple sources. This recommendation accords with Federal Source Code Policy M-16-21.[4]

3) NITRD's research strategy should emphasize the importance of federal digital twins researcher adherence to US Government's Open Data Policy M-13-13.

Digital twins research models operated by the US Government should register their datasets with their agency data inventories and with data.gov. Moreover, to support search and discovery, we urge NITRD to work with GSA to expand the Data Catalog Vocabulary (DCAT) standard used by data.gov[5] to include extensions specific for digital twins data. USTPC notes that useful areas of digital twins research are likely to include the development of:

- Digital twins runtime systems that can scale from a single computer to a cluster to a distributed system including many clusters of clusters;[6]

- High-performance digital twins systems that are cloud agnostic, so that they can be run on-site using technology like OpenStack or within cloud systems made available today by existing cloud providers; and

- Portable systems for establishing and implementing data labeling and access controls so that personally identifiable information, protected health information, proprietary data, and even classified data can be appropriately protected within the digital twins framework.[7]

4) Developers of the national digital twins research strategy should reach out broadly to a wide range of researchers whose work could fit a digital twins research agenda, but who may not consider themselves to be engaged in digital twins research.

Today many researchers in many disciplines are involved in efforts that could be described as "digital twins research." It is likely that many of their specific research techniques could be productively shared within this community to inform and advance a national digital twins research strategy. These may include approaches for code and data curation, versioning, validation, replication, citation and distribution.

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[4] https://obamawhitehouse.archives.gov/sites/default/files/omb/memoranda/2016/m_16_21.pdf

[5] https://www.w3.org/TR/2024/PR-vocab-dcat-3-20240613/

[6] The former may be appropriate for monitoring one aircraft engine, for example, the latter for heavy analytic processing or optimization routines that explore the tuning space.

[7] Research could productively develop ways, for example, for enforcing access controls using mechanisms provided by cloud infrastructure providers, as well as through advanced cryptographic approaches, such as secure multiparty computation and homomorphic encryption.

USTPC specifically recommends outreach to social science researchers. For example, DARPA's now completed Ground Truth, SocialSim, and NGS2 programs all could fall within the scope of a digital twins research program. Likewise, programs like the US Department of Veterans Affairs' effort to create the Synthetic Suicide Prevent Dataset with SDoH[8] could be expanded into digital twins research platforms. We also recommend outreach to members of the urban planning research and modeling community, which has experience with simulations such as UrbanSim which can be used, for example, to model and predict the impact of taxation and infrastructure development programs.

5) A digital twins research strategy should include support for funding interdisciplinary workshops and conferences where researchers, advocates and activists can meet, exchange ideas, and plan approaches for maximizing the societal benefits of digital twins technologies.

Specifically, such efforts must include adequate financial allocations for publicity and marketing, as well as support for researchers to attend appropriate conferences either virtually or in-person. Opportunities also should be explored for international collaboration, especially with the United Kingdom, which is a leader in digital twins research. Finally, we encourage NITRD to create broadly available and promoted online digital twins resource centers.

[8] https://www.data.va.gov/dataset/Synthetic-Suicide-Prevention-Dataset-with-SDoH/h5zp-pekf/about_data

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Request for Information on the National Digital Twins R&D Strategic Plan

AiSuNe

Response to Request for Information on Digital Twins Research and Development

Statement

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Response Artificial Intelligence (AI): AI and Digital Twins

Introduction:

The integration of Artificial Intelligence (AI) with digital twins is transforming industries. This response focuses on two key areas: traditional AI/Machine Learning (ML) and Generative AI. It's important to differentiate these areas:

- AI/ML analyzes data, makes predictions, and optimizes operations based on predefined models.
- Generative AI creates new data, models, and solutions, expanding the possibilities of digital twins.

Both significantly enhance digital twin capabilities but in distinct ways. AI/ML excels at pattern recognition and optimization, while Generative AI pushes boundaries in modeling and simulation. Together, they offer powerful tools for prediction, optimization, and decision-making in digital twin applications, revolutionizing system modeling and management across industries.

Details:

1. Integration with AI:

AI algorithms can analyze data from digital twins to predict equipment failures and optimize operations. This can reduce downtime, lower costs, and improve efficiency.

2. Generative AI for Modeling:

Generative AI creates highly accurate models of physical systems by learning from real-time data. These models can adapt based on new inputs, providing precise representations of physical counterparts.

3. Impact on Physical Systems:

AI-enhanced digital twins enable virtual sensors and predictive analytics, improving the monitoring of physical assets. They also increase the accuracy of industrial processes through model-predictive control and optimize operations through advanced simulations and scenario analysis.

4. Enhanced Decision-Making:

The integration provides real-time, data-driven insights, enabling swift responses to changing conditions, minimizing risks, and capitalizing on opportunities across various sectors.

5. Applications Across Industries:

In manufacturing, healthcare, energy, and other sectors, AI-powered digital twins optimize production, predict equipment malfunctions, model patient outcomes, and enhance resource management.

6. Agentic and Autonomous Agency:

AI-driven digital twins increasingly exhibit agentic properties, allowing them to act autonomously within defined parameters. This includes:

- Self-optimization: Digital twins can autonomously adjust parameters to improve system performance.
- Predictive maintenance: They can initiate maintenance requests or actions based on their own analysis.
- Adaptive learning: Digital twins can update their own models based on new data, improving accuracy over time.
- Autonomous decision-making: In some applications, digital twins can make and implement decisions without human intervention, especially in time-critical scenarios.
- Collaborative agency: Multiple digital twins can interact and collaborate to optimize larger, interconnected systems.

These agentic capabilities must be carefully designed and monitored to ensure they align with human-defined goals and ethical considerations.

Conclusion:

Integrating AI, particularly generative AI, with digital twins revolutionizes system management and optimization across industries. It offers more accurate predictions, real-time adaptations, and enhanced decision-making capabilities. The addition of agentic and autonomous properties further expands the potential of digital twins, enabling more responsive, efficient, and intelligent systems. However, this also introduces new challenges in terms of control, accountability, and ethical considerations that must be carefully addressed. As this field evolves, it promises to drive significant improvements in performance, cost savings, and operational efficiency, seamlessly integrating physical and digital realms and driving innovation across sectors.

Response: Business: Business Case Analysis

Introduction:

A comprehensive business case analysis is crucial for justifying investments in advanced technologies like AI and digital twins. It helps secure funding and ensures project alignment with strategic objectives.

Details:

1. Foundational Research Cost:

Initial investments include technology acquisition, software development, and personnel hiring expenses. Ongoing research costs for model enhancement and data integration must also be considered.

2. Value and Return on Investment:

The primary advantages are efficiency gains and increased market competitiveness. Case studies and pilot projects can provide empirical evidence of ROI.

3. Implementation Costs and Timeline:

A detailed roadmap outlining implementation phases, resource allocation, and realistic timeframes is essential. This helps manage expectations and identify potential bottlenecks.

Conclusion:

A thorough business case analysis, including research costs, ROI evaluation, and implementation planning, is vital for successful AI and digital twin projects. It ensures alignment with business objectives and positions the project for successful implementation.

Response: Data

Introduction:

Adopting data management best practices is critical for enhancing data quality, accessibility, and utility across various fields. It forms the foundation for effective digital twin implementation.

Details:

1. Governance Methods:

Standardized protocols for data collection, curation, sharing, and usage ensure consistency and reliability. This includes defining data formats, metadata standards, and quality control measures.

2. Shared Public Datasets:

Encouraging the use of shared public datasets enhances research and innovation. These datasets should be well-documented, easily accessible, and regularly maintained.

3. Real-Time Data Integration:

Implementing advanced technologies for real-time data integration allows seamless merging of data from multiple sources. This is particularly beneficial in IoT, smart cities, and industrial automation applications.

Conclusion:

By focusing on governance methods, promoting shared datasets, and implementing real-time integration, organizations can maximize data value. These practices facilitate better decision-making and innovation while ensuring compliance with ethical and legal standards.

Response: Ecosystem

Introduction:

Creating a National Digital Twin R&D Ecosystem requires coordinated efforts across multiple sectors to address research gaps and leverage opportunities in various fields.

Details:

1. Collaborations Across Agencies:

Developing frameworks for interagency coordination and public-private partnerships is crucial. This enhances innovation and provides additional expertise and funding.

2. Application in Various Fields:

Digital twins have applications in biomedical sciences, environmental ecosystems, smart communities, scientific discovery, agriculture, and military planning. Each field requires specific expertise and collaboration.

3. Foundational Technologies:

Advancing mathematical, statistical, and computational foundations is essential for improving the accuracy and reliability of digital twin technologies.

Conclusion:

Establishing a comprehensive R&D ecosystem involves fostering collaborations, leveraging domain expertise, and advancing foundational technologies. This approach drives progress across multiple sectors and applications.

Response: International

Introduction:

International collaboration on digital twins offers unique opportunities to address global challenges and advance technology across various sectors.

Details:

1. Global Scale Digital Twins:

Developing digital twins on a global scale requires standardized protocols and interoperability across different countries and industries. This ensures seamless integration worldwide.

2. Global Issues and Standards:

Establishing international consensus standards for digital twin technologies is crucial. These standards should cover data formats, communication protocols, and security measures.

3. Collaboration Opportunities:

Programs like EU Horizon 2020 and bilateral partnerships provide funding and networking opportunities for advancing digital twin technologies globally.

Conclusion:

International collaboration on digital twins offers significant potential to address global challenges, standardize technologies, and expand market reach. This collaborative approach ensures that digital twin technology is utilized to its fullest potential globally.

Response: Long Term

Introduction:

Identifying long-term research investments is essential for advancing digital twin technology and ensuring its sustainability.

Details:

1. Novel Modeling Approaches:

Developing crosscutting and fit-for-purpose models that are interactive and data-driven is vital. Advanced algorithms and machine learning techniques can significantly improve accuracy and predictive capabilities.

2. Bidirectional Data Flow:

It is crucial to ensure seamless bidirectional flow between virtual and physical assets. This requires robust data acquisition systems and communication protocols.

3. Test Environments:

Creating test environments with sufficient resources and sustainable high-performance computing solutions is essential for developing and testing digital twins.

Conclusion:

Long-term research investments should focus on novel modeling approaches, bidirectional data flow, and robust test environments. This will drive the advancement of digital twins and unlock their full potential across various industries.

Response: Regulatory

Introduction:

The deployment of digital twins introduces several regulatory challenges that must be addressed to ensure their effective and responsible use.

Details:

1. Data Privacy and Security:

Ensuring secure handling of sensitive data and compliance with existing data protection laws is crucial. Clear guidelines are needed to protect personal and proprietary information.

2. Standardization and Interoperability:

Creating and enforcing standardized protocols and data formats is necessary to ensure interoperability across different platforms and industries.

3. Validation and Ethical Considerations:

Establishing robust validation processes and addressing ethical concerns such as bias and fairness is essential for responsible digital twin implementation.

Conclusion:

Addressing regulatory challenges is crucial for successfully implementing and adopting digital twins. This ensures they are used responsibly and effectively, maximizing benefits while minimizing risks.

Response: Responsible

Introduction:

The responsible development and utilization of digital twins present several ethical challenges that must be addressed to ensure their effective implementation.

Details:

1. Ethical Use:

It is crucial to maintain transparency, accountability, fairness, and inclusivity in the development and use of digital twins. This involves clear communication and regular evaluation of implementations.

2. Identifying Ethical Issues:

Addressing algorithmic bias and broader social and epistemological concerns is essential. This requires interdisciplinary collaboration and stakeholder engagement.

3. Mitigating Biases:

To safeguard all stakeholders' interests, clear guidelines regarding data ownership, intellectual property rights, and privacy protection must be established.

Conclusion:

Promoting responsible development and use of digital twins involves addressing ethical issues, mitigating biases, and ensuring transparency and fairness. This approach fosters public trust and maximizes the technology's potential.

Response: Standards

Introduction:

Developing robust evaluation tools, methodologies, and consensus standards is essential for successfully implementing and utilizing digital twins.

Details:

1. Community of Practice:

Establishing a community for sharing knowledge and best practices is crucial for developing and maintaining standards for digital twin technologies.

2. Standardization Efforts:

Developing standardized ontologies, data exchange protocols, encryption standards, and taxonomies is vital for ensuring interoperability and security.

3. Evaluation and Application:

Creating methodologies for evaluating data-driven components and developing standards for personalized applications derived from digital twins is necessary.

Conclusion:

Addressing these focus areas promotes the development and adoption of digital twin technologies, ensuring they deliver their full potential across diverse industries and applications.

Response: Sustainability

Introduction:

Ensuring the long-term sustainability of digital twins requires focus on several critical areas to maintain their relevance and effectiveness over time.

Details:

1. Adaptation to Evolving Systems:

Digital twins must adapt to evolving operating systems and computational models, requiring continuous updates and maintenance.

2. Organizational Effort:

Developing and sustaining digital twins requires intentional organizational effort and purpose-built modeling ecosystems focused on energy-awareness and resource efficiency.

3. Effective Planning and Interoperability:

Early consideration of computational requirements and establishing effective workflows is crucial. Ensuring interoperability with evolving technology and standards is also essential.

Conclusion:

Focusing on these areas enables the design and development of systems that support the long-term sustainability of digital twins, minimizing environmental impact while ensuring continuous improvement and innovation.

Response: Trustworthy

Introduction:

Developing secure and trustworthy digital twins requires focus on several critical areas to ensure their reliability and resilience against cyber threats.

Details:

1. Security and Cyber Resilience:

Addressing security in all components, including code base, data processing, operational environments, and networking, is crucial for trustworthy digital twins.

2. Secure Development and Operation:

Developing secure code bases, protecting data, securing operational environments, and ensuring networking security are essential aspects of trustworthy digital twins.

3. Enhancing Physical Security:

Through threat analysis and security testing, digital twins can be leveraged to improve the security and cyber resilience of their physical counterparts.

Conclusion:

Focusing on these areas enables the development of secure and trustworthy digital twins that enhance overall cyber resilience, ensuring reliability and security in both digital and physical components.

Response: VVUQ

Introduction:

Developing rigorous methods for Verification, Validation, and Uncertainty Quantification (VVUQ) is essential to ensure the reliability and accuracy of digital twins.

Details:

1. Foundational and Domain-Specific Methods:

Establishing fundamental methodologies applicable across domains and developing tailored approaches for specific applications is crucial for comprehensive VVUQ.

2. Integration and Standards:

Integrating VVUQ into all elements of the digital twin ecosystem and developing standardized protocols ensures interoperability and reliability throughout the lifecycle.

3. Advanced Techniques and Risk Analysis:

Leveraging advanced computational techniques and incorporating risk analysis enhances the efficiency and accuracy of VVUQ processes.

Conclusion:

Developing rigorous VVUQ methods ensures the reliability and trustworthiness of digital twins, enabling organizations to fully leverage their benefits while maintaining high standards of accuracy and reliability.

Response: Workforce

Introduction:

Cultivating a workforce capable of advancing digital twin research and development requires strategic efforts in recruitment, training, and interdisciplinary collaboration.

Details:

1. Diverse Talent Recruitment:

Implementing inclusive hiring practices and expanding global talent acquisition efforts is crucial for building a diverse and skilled workforce.

2. Interdisciplinary Programs:

Encouraging cross-disciplinary STEM research programs and developing collaborative platforms facilitates knowledge sharing and innovation in digital twin technology.

3. Education and Professional Development:

Establishing educational partnerships, developing specialized curricula, and providing continuous learning opportunities ensures a well-trained workforce.

Conclusion:

Focusing on these areas builds a robust pipeline of skilled professionals equipped to drive the future of digital twin technology, ensuring a diverse, well-trained workforce capable of meeting evolving demands.

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Request for Information on the National Digital Twins R&D Strategic Plan

Ala Moradian

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Digital twins are founded based on models, domain knowledge, software, compute, and data infrastructure, as well as sensors and metrology.

The twin would need to be characterized along dimensions such as type of models that re being used, fidelity of the models, connectivity and synchronization, value proposition, as well as type and nature of interaction with the user.

- ***Artificial Intelligence (AI):*** Hybrid twins founded on both physics and data models will be a critical approach in addressing challenging industry problems across domain. The data models include all type of machine learning models such as graph neural nets, physics-informed neural nets (PINN). Other topics could include, AI for system identification and reduce order model development, AI-assisted sensor data screening and clean-up, optimizing approach needed depending on the nature of system and continuous re-training of twins.
  - *"Semiconductor Equipment and Processes Need Digital Twins," 23 Jul. 2023. [Online]. Available: https://www.appliedmaterials.com/us/en/blog/blog-posts/semiconductor-equipment-and-processes-need-digital-twins.html.*
- ***International:*** Opportunities for international collaboration and connecting the focused investments such as Chips for America, i.e., ChipsACT with other international initiatives such as projects funded by European Union like interTwin, TwinGoals, NeuroTwin, Change2Twin, European Union's Horizon
  - *U.S. Department Of Commerce, , "CHIPS for America Announces $285 million Funding Opportunity for a Digital Twin and Semiconductor CHIPS Manufacturing USA Institute," "U.S. Department Of Commerce", 6 May 2024. [Online]. Available: https://www.commerce.gov/news/press-releases/2024/05/chips-america-announces-285-million-funding-opportunity-digital-twin.*
  - *interTwin Project, "interTwin," 2023. [Online]. Available: https://www.intertwin.eu/about-intertwin/.*
  - *TwinGoals, "EIT Manufacturing and 'Digital Twins' improving tomorrow's manufacturing," 28 Oct. 2020. [Online]. Available: https://eit.europa.eu/news-events/news/eit-manufacturing-and-digital-twins-improving-tomorrows-manufacturing.*
  - *NeuroTwin Project Website, "https://www.neurotwin.eu/," 2023. [Online]. Available: https://www.neurotwin.eu/. [Accessed 10 Nov. 2023].*
  - *Change2Twin Project, "Change2Twin - Digital Twin for every manufacturing SME!," 2020. [Online]. Available: https://www.change2twin.eu/.*
- ***Long Term:*** Considering that data would construct the basis of digital twins either for their development or validation, verification, uncertainty quantification, long term investment in improving sensors technology remain critical. Computational hardware advancement fit for use for specific type of twins, hybrid hardware structures, for example, taking advantage of CPU and GPU in a dynamic sense, could be another strategic area to be investigated.

- ***Sustainability:*** digital twins for sustainability optimized operations of manufacturing facilities, entities and tools, e.g., EcoTwin to monitor, improve, and optimize consumptions and operational adjustment, and asset scheduling
  - *Applied Materials inc., "EcoTwin™ Eco-Efficiency Software," 9 Jul. 2023. [Online]. Available: https://www.appliedmaterials.com/us/en/semiconductor/solutions-and-software/ai-x/ecotwin.html.*
  - *SEMICON West, Smart Manufacturing: EcoTwin - An Integrated Solution for Sustainability in Semiconductor Manufacturing, San Francisco, CA, 2023.*
  - *United States Patents US20220334569A1, US20230185268A1, 2021.*
- ***Workforce:*** Use of digital twins to train talents for strategic and national interest like semiconductor manufacturing by developing virtual platforms developed based on actual trends and know-how, e.g., EduTwin™, SemiGuru™
  - *M. da Silva and K. Somani, "Digital Twins in Semiconductor Manufacturing - SEMI Smart Manufacturing Initiative," SEMI, San Jose, CA, 2024.*
  - *Book Chapter: Digital Twins for Sustainable Semiconductor Manufacturing, Volume: Digital Twins, Simulation, and Metaverse, Book Series: Simulation Foundations, Methods and Applications, Editors: Michael Grieves, Edward Hua, Springer, In press (Nov 2024).*

Ala Moradian, Ph.D., P.Eng., ASME Fellow

Biography: Ala Moradian is a director at the Computational Product and Solutions (CPS) Center of Excellence at Applied Materials where he is focused on epitaxy technology and digital twins for semiconductor manufacturing. Over more than a decade at Applied, Ala has worked on different products and business units such as ion implant, rapid-thermal processing, epitaxy, physics-based simulation and led the development of several new technologies and products. His roles included CFD expert, heat transfer subject matter expert, scientist/physicist, program lead and product manager. He is also the intellectual property technologist for Epitaxy business unit at Applied Materials. Ala obtained his PhD in mechanical engineering from University of Toronto, a master's from Sharif University of technology, and a Masters in management from Harvard University. Ala is a Fellow of American Society of Mechanical Engineers (ASME), and an adjunct faculty at UC Berkeley. He has over 20 publications and over8 US patents and applications. Ala have served on NSF SBIR/STTR for the last decade.

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Request for Information on the National Digital Twins R&D Strategic Plan

Lawrence Berkeley National Laboratory

Response to RFI on
Digital Twins Research and Development Plan

Submitted July 28, 2024

Prepared by: Ann Almgren, John Bell, Xiaoye Sherry Li, Daniel F. Martin, James Sethian, Stefan M. Wild (POC,[redacted] Computing Sciences, Lawrence Berkeley National Laboratory

Computing Sciences at Lawrence Berkeley National Laboratory, a U.S. DOE Office of Science National Laboratory, advances computational science in the national interest. This response is based on the extensive experience and expertise of our teams in adaptive modeling of complex physical and biological systems.

The potential of digital twins rests on the ability to intertwine and integrate advances in experimental sensing and measurements, data analysis, real-time feedback and autonomous steering, and advanced computational capabilities to model and simulate highly complex physics and phenomena across a range of time and space scales, changing environments, and dynamic data integration. This will require advances on many crosscutting and discipline-specific fronts.

Leveraging DOE Advances in a National Digital Twin R&D Ecosystem:

The recent emergence of a host of new capabilities within DOE National Laboratories is set to profoundly advance our abilities to intimately couple experiment and simulation to provide a new framework for high-fidelity digital twins.

These new capabilities[1] include:

[1] See, e.g.,
- Hendrickson et al, ASCR@40: Highlights & Impacts of ASCR's Programs, doi:10.2172/1631812
- Heroux et al, ECP Software Technology Capability Assessment Report, doi:10.2172/1888898
- Siegel et al, Map Applications to Target Exascale Architecture with Machine-Specific Performance Analysis, Including Challenges and Projections, doi:10.2172/1838979
- CAMERA: Center for Advanced Mathematics for Energy Research Applications, https://camera.lbl.gov

1. High-order and robust new mathematical and computational methods across fluid mechanics, materials sciences, biological modeling, advanced chemistry, and core physics – including mechanics, quantum effects, and magneto-electric dynamics – that effectively exploit advanced high-performance computing architectures to achieve unprecedented accuracy, resolution, and fidelity;
2. Sophisticated new methods for data analysis, inversion, and edge processing directly at experimental sources to minimize latency between physical and virtual systems;
3. New statistical sampling methodologies to facilitate principled Bayesian model calibration and uncertainty quantification, and provide confidence in understanding; and
4. Powerful new AI/ML techniques to exploit existing data to rapidly interpret results, extract new information, and automatically steer coupled experiments and simulations to achieve unprecedented efficiency and accuracy in new discoveries.

These developments have been concurrent with advances in computing as well as state-of-the-art networking and data transfer to provide close-to-real time processing of information and remote access.

The ability for new methodologies to also take advantage of a DOE computing infrastructure that is second to none provides a unique combination of technical capabilities and the computing capacity to make them transformational components of a national digital twin ecosystem.

Holistic Integration of Verification, Validation, and Uncertainty Quantification (VVUQ):

A key aspect of digital twins is the bi-directional interaction between the physical and virtual system. The physical system provides data to calibrate the virtual system and sets the initial and boundary conditions for the virtual system's predictions. The virtual system provides feedback to the physical system such as control strategies, decision support or requirements for additional measurements. Developing a digital twin for a complex multiphysics system described by partial differential equations, either natural or engineered, poses a number of research challenges. One key challenge is that numerical models (whether traditional, ML-based, or hybrid) for these types of problems involve large numbers of unknown parameters. Uncertainties in the data observed from the physical system can be expressed in terms of a probability distribution. By adopting a Bayesian perspective, one can use data from the physical system to refine the distribution. Feedback from the virtual system to the physical system will be inherently probabilistic, requiring methodology for optimization under uncertainty. Additionally, for risk assessment, specialized methodology for rare-event sampling will also be required. While many of the most advanced numerical models have been developed with rigorous error bounds, advances will be needed to make these models interoperable with such Bayesian and optimization "outer loop processes." Also needed is further theoretical and algorithmic research for error analysis, including in cases where available measurements are sparse or involve reduced-order models or evolving dynamics in latent spaces.

Sustainable Progress in an Evolving Computing Landscape:

Computing hardware – from high-performance systems to edge devices – will continue to evolve rapidly. In developing an ecosystem for digital twins, it is vital to ensure an intentionally sustainable software stack, including the numerical libraries built on top of system software. Sustaining such software often requires whole-of-community efforts[2].

Additional R&D Focus Area: Goal-Oriented and Hierarchical Models for Purpose-Driven Digital Twins:

Another feature of complex multiphysics systems is that there are a wide range of potential uses of a digital twin for the given system. For example, given a digital twin for a wind farm, one might ask: Where should sensors be placed to best improve predictions of system performance? How does the wind farm respond to extreme weather events? What service schedule plan will best keep the complex hierarchy of underlying equipment and materials operational? Answering each of these questions likely requires models of different fidelity in terms of numerical accuracy and/or what physical processes are included in the model, ranging from simple surrogates to detailed physical descriptions of the system. Always using the highest fidelity available is computationally infeasible in most cases. This suggests that an effective digital twin must include a hierarchy of models of different complexity levels. For each model within the hierarchy, one would need to characterize the specific domain of applicability and quantify the uncertainty over that domain.

Effectively exploiting a hierarchy of models of different fidelities and operating at different scales can significantly reduce the (computational, energy, etc.) costs associated with a digital twin. Although emerging HPC architectures have enabled simulations of unprecedented fidelity, directly embedding these types of simulations as part of an optimization algorithm or sampling methodology is not feasible. In addition to understanding the limitations of different models, one also needs to quantify the relationship between models. How can refinement of one model be used to improve other models in the hierarchy? What is the uncertainty associated with mapping between models? Some systems can be characterized by distinct components that can be probed independently. For these types of systems, the relationship between models is fairly straightforward. When the different processes in the system are coupled nonlinearly or when controlled experiments are not feasible, however, the relationship between models can become quite complex. Given a hierarchy of models, one can then bootstrap up from simple, inexpensive models to more models with sufficient complexity to answer a given question, avoiding performing expensive simulations in regions that are not of interest.

Digital twins represent a timely opportunity to advance science and engineering. Realizing their full potential will require taking advantage of recent advances at the DOE National Laboratories; making numerical models and simulations digital-twin-ready, with rigorous error bounds and VVUQ capabilities; developing a sustainable software stack; and addressing their specific goals and downstream uses – each with corresponding fidelity levels – to ensure their effectiveness.

[2] See, e.g., Consortium for the Advancement of Scientific Software, https://cass.community

Federal Register Notice: 89 FR 51554, Federal Register :: Networking and Information Technology Research and Development Request for Information on Digital Twins Research and Development, June 18, 2024.

Request for Information on the National Digital Twins R&D Strategic Plan

Anonymous Ecosystem

Comments on digital twins

Ecosystem: Establish a National Digital Twin R&D Ecosystem: Possible focus areas: collaborations across agencies to identify and address foundational research gaps and opportunities that spans areas such as biomedical sciences, environmental ecosystem, sustainability & climate change, smart and connected communities, scientific discovery, agriculture, military & mission planning, as well as common mathematical, statistical, and computational foundations

The "Ecosystem" topic seeks to establish a national digital twin R&D ecosystem that establishes inter-agency collaborations to address foundational research gaps. I believe this is a critical need, as differences in the challenges and use cases across applications drive methodology development in distinct directions that can be valuable for other communities.

For example, in the mathematical biology / medicine setting, digital twins or mathematical models of living systems have long been used as a tool in the scientific discovery of biological mechanisms (testing/refining mechanistic hypotheses using bidirectional feedback between experimental/clinical data and models), as well as in prediction, e.g. of disease progression and treatment strategy optimization. With exciting current developments and tremendous interest in the space of living biologic therapies, e.g. immune cell therapies, protein replacement using living cell populations, base editing, etc, it is especially critical to develop digital twin models of the complex interactions between living these therapeutic agents and their in vivo, dynamic microenvironment. Such models can aid in therapy design and feasibility analysis (e.g. determining gene editing targets, quantifying achievable protein levels), therapy use recommendations (e.g. understanding optimal/minimum sufficient dose and timing), and trial design (e.g. patient selection, trial endpoint design).

To meet these challenges, I believe it will be very important for researchers in different applications to be able to discuss challenges in development and use of their digital twin models, and to share technologies and best practices. Some of the specific challenges and questions from my perspective of mathematical medicine include:

- **Data limitations and complexity** - specifically, limited longitudinal observations for validating/refining digital twin models, high noise, high variability between samples (patients), highly multi-modal data (e.g. ex vivo sample testing + in vivo clinical follow-up, electronic health records, imaging + genomic + phenotypic profiling) often at a single or limited time points.
- **Need for robust, mechanistically justifiable predictions** - need for treatment design and predictions to meet ethical and regulatory considerations, cost considerations, as well as cultural considerations.

- **Development of mechanistic learning approaches** - need for methods for integrating biological mechanism knowledge (possibly encoded via mathematical models) with ML/data driven methods
- **Multiple models at different scales -** in many cases, data informing digital twin models come from a variety of experimental models at different scales (e.g. mouse models, in vitro 2D culture (plates), in vitro 3D culture (spheroids, organoids, organ on chip) and mathematical models or digital twins are developed at each scale. There is a critical need for a developing an understanding of mapping digital twin models between experimental platforms and the in vivo setting.

While these are a few challenges currently addressed in the mathematical biology/medicine community, I would be quite interested in learning about challenges addressed by other communities (e.g. climate modeling, agriculture, military planning, etc) - and in leveraging different perspectives to solve similar questions. Developing the scientific infrastructure and opportunities to form these connections may include the organization/facilitation of working groups, collaborative research and education funding opportunities, etc.

Federal Register Notice: 89 FR 51554, Federal Register :: Networking and Information Technology Research and Development Request for Information on Digital Twins Research and Development, June 18, 2024.

Request for Information on the National Digital Twins R&D Strategic Plan

Anonymous NAS DT

RFI Response: Digital Twins R&D Plan

We regard Digital Twins to correspond to a virtual environment that encodes an end-to-end physical experiment, incorporating theory/modeling of materials, processes and controls involved in the experiment. Digital twins can constitute a transformative concept in scientific research, offering a powerful approach to understand, model, and optimize materials and processes. They also provide a framework to enhance collaboration and knowledge sharing in the scientific community among different sub-disciplines. Digital twins enable researchers to bridge the gap between the physical and digital worlds, offering numerous benefits such as: (1) providing an in-depth understanding of materials at various scales. When coupled with the growing availably of high-fidelity experimental data, they can be used to create a dynamic, digital representation of materials, allowing for an in-depth analysis of their characteristics; (2) facilitating predictive modeling as they allow researchers to simulate how materials behave under different conditions, such as varying chemical composition, structure, as well as environmental effects like temperature, pressure, or stress; (3) enabling the optimization of materials and processes, by iteratively refining the virtual model based on real-world data and simulations.

Taking large scientific user facilities (SUFs) as an example, experiments can be time-consuming and require carefully planned sequences of steps, including formulating the scientific hypothesis, performing the experiment(s), modeling the results, and theory-experiment matching with data analytics to draw conclusions. Thus, a key challenge is to optimize experimental planning at both the individual and facility levels to reduce time to discovery of scientific knowledge, minimize redundancy, and maximize physics knowledge from each experiment. Examples of planning and optimization challenges include determining optimal synthesis conditions for a new material; selecting the correct set of multimodal experiments to solve a structural inverse problem; optimizing the parameters of specific tools to achieve computational and experimental end goals and generating precise, continuously calibrated models of accelerators for data analysis and interpretation. Key to achieving this objective is the need for a digital twin of each SUF that enables users to design, operate, and optimize experiments in a safe, virtual environment so they can seamlessly transition to the real facility, reducing the time to scientific discovery.

R&D topic areas in which the strategic plan for Digital Twins should focus with respect to SUFs are: *Long Term* investments, *Artificial Intelligence (AI)*, *Sustainability*, *VVUQ*, *Trustworthy*, *Ecosystem*.

Artificial Intelligence (AI): Modern foundational AI architectures are capable for very complex tasks, including the ability to generate new data, but require tuning billions of learnable parameters. Digital Twins provide an efficient platform to train such large foundational AI models that can be deployed in the physical world. End-to-end solutions can be enabled when Digital Twins of physical experiments are coupled with different theoretical and simulation approaches. As an example, in the nanosciences, it is possible to automate nanoscale experiments, such as a scanning tunneling microscope (STM), to perform routine measurements and manipulation. While the human tasks are automated, the speed with which a physical STM can create new complex structures hosting a completely quantum states is still going to be too slow in the real-world. But training such AI models on digital twin data of an STM, comprising an interconnected set of coupled multi-fidelity and multi-scale materials and process modeling, with controls that mimic the input/output to a physical STM chamber, can be extremely efficient. Generative AI models trained on big data coming from such digital twins of the STM can then be deployed on the edge in automated physical STMs to accelerate discovery of new quantum structures and perform measurements confirming the existence of exotic quantum states. In this scenario, few physical measurements come into play mainly to validate and improve the components of the digital twin in an iterative model, and finally to confirm the predictions made by trustworthy generative AI models trained on the digital twin datasets.

VVUQ (relevant for trustworthiness): Digital twins of complex experiments, especially incorporating new materials and new processes is a challenging task. Since discovery always occurs at the fringes of human understanding of matter and energy, theoretical models in digital twins need to be validated and corrected, and uncertainty in predictive models need to be quantified using physical measurements so to increase our trustworthiness of the digital twins. An iterative active learning loop is required that is general purpose to refine multi-fidelity and multi-scale theoretical models using the least possible number of multi-modal physical measurements, to make digital twins trustworthy. In the concrete example of developing digital twins for a scanning tunneling microscope (STM), an active iterative learning loop that validates, verifies the models composing the digital twins, estimates robust uncertainties on outcomes in real physical experiments for new input parameters and incorporate these uncertainties to further refine the digital twins and AI models is a necessity to efficiently utilize the least number of physical experiments to perform new scientific discoveries and breakthroughs.

Long Term (relevant for Ecosystem): Creation and refinement of digital twins is a continuous process, that involves connecting different types of digital twins across different scientific facilities and over different generations of experiments. For nanoscience experiments, digital twins will be deployed on the edge so that it can be actively used by experimentalists to test and validate their ideas on-the-fly, while the digital twin itself learns and improves from the physical measurements. Digital twins will have several layers or components that can be independently validated and verified by experiments across different DOE user-facilities, so that over time the composite digital twin model for specific planned experiments can be actively configured from these improved model components and tested in real-time by an experimenter. The 4 V's of data-science equally hold for digital twins, due to the need for large *V*olumes of experimental datasets, different *V*arieties of data to train the digital twins and subsequent AI models, the *V*eracity of the components composing the digital wins as well as the physical validation and verification data coming from different locations and experimentalists, and *V*elocity of data of data to actively fine tune digital twin models. This requires sustained long-term planning of resources, storage and high bandwidth national network communication, with scientific digital twin end-stations in each facility that can crosstalk continuously based on the latest information. These end-stations can be part of a larger digital twin ecosystem connecting national facilities across different scientific domains and principles.

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Request for Information on the National Digital Twins R&D Strategic Plan

Ansys

Ansys Vision for Empowering the National Digital Twins R&D Strategic Plan

RFI Response: Digital Twins R&D Plan

Walter Schwarz, PhD
Senior Principal Application Engineer
Ansys, Inc.
[redacted]

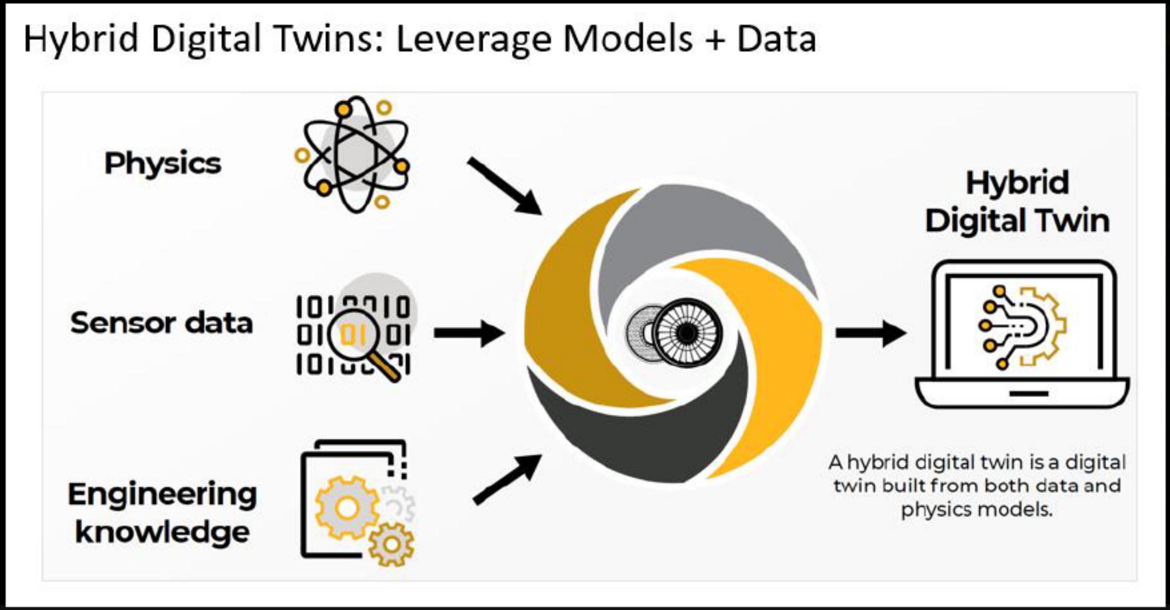
July 26, 2024

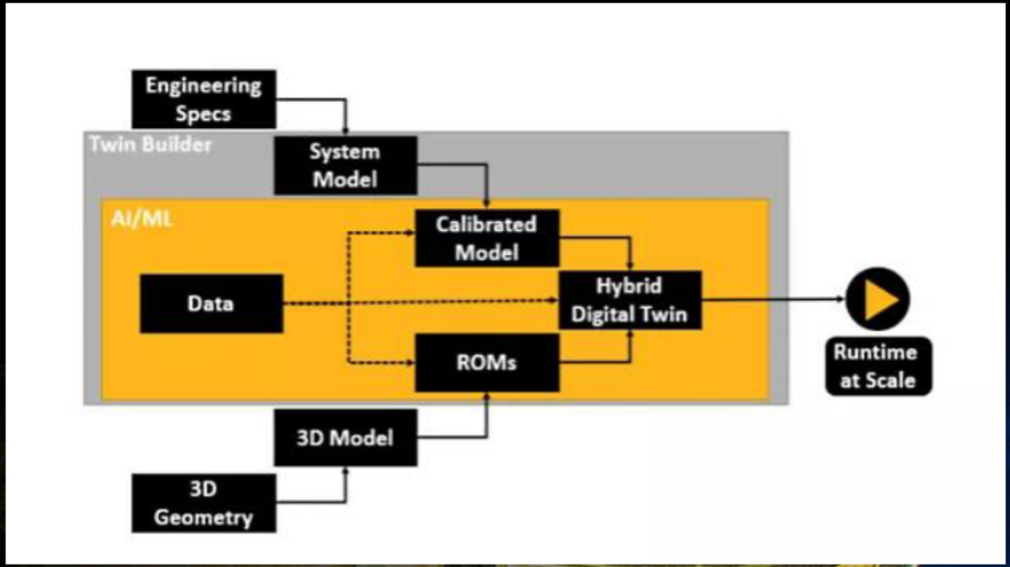
Ansys

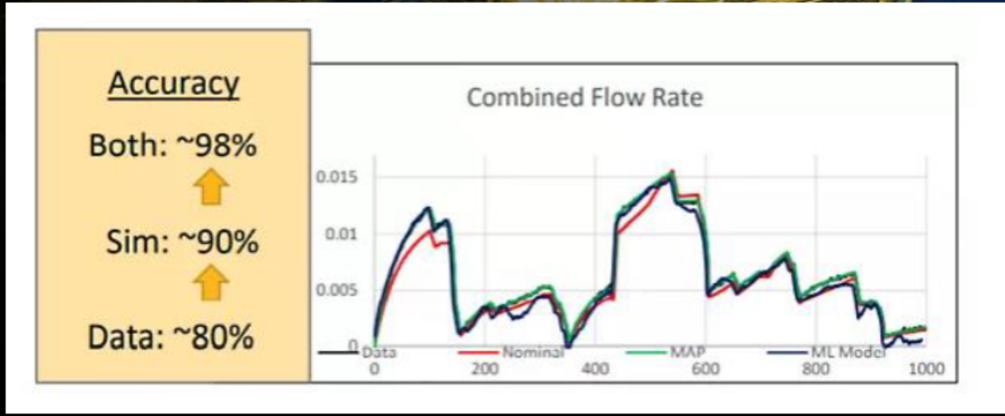
Artificial Intelligence (AI): AI and Digital Twins:

Ansys believes that the AI/ML area is just getting started, there are novel algorithms coming out all the time. Innovators in digital engineering are always watching the latest, newer methods and tracking what is happening in the AI/ML community and applying it to simulation.

Data-driven models alone can provide roughly **80% accuracy**, while **simulation-based models** increase that number to **90%**. But **combining the two methods can produce nearly 98% accuracy results**.







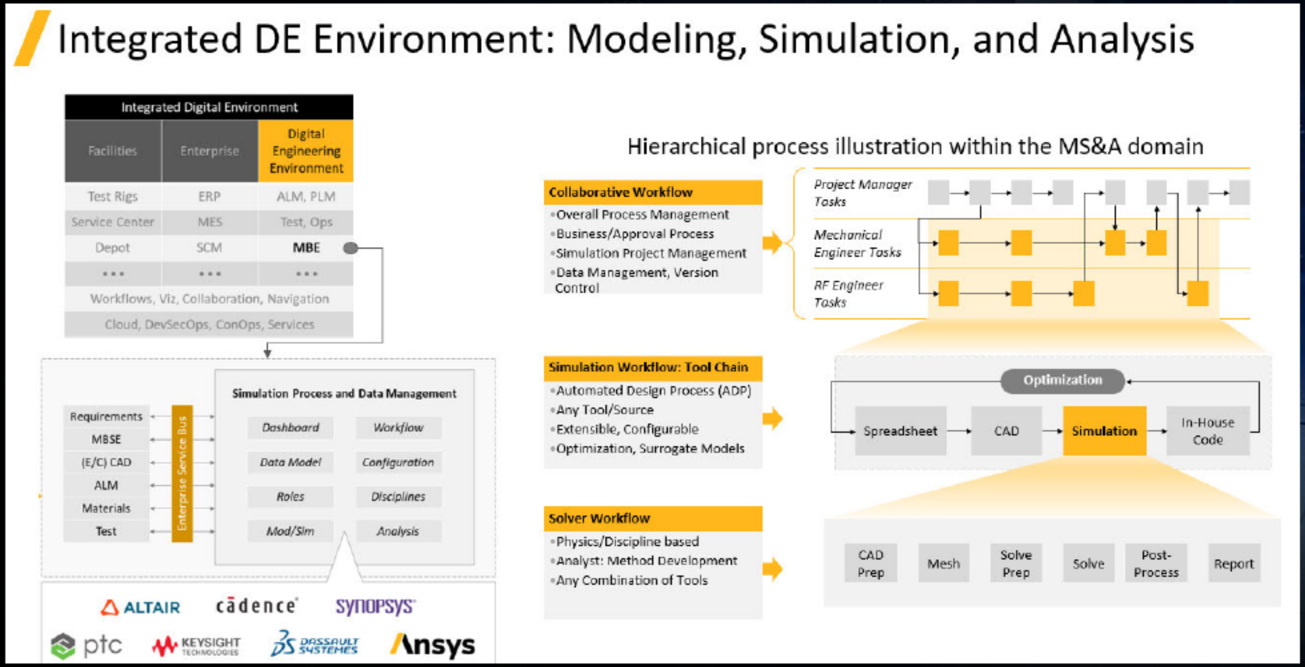
Ansys

Data: Encourage Adoption of Data Management Best Practices:

Ansys believes that it is important to establish **a Digital Engineering Environment (DEE)** that should include a dedicated engineering simulation **authoritative source of truth (ASoT)** in the form of a **Simulation Process and Data Management (SPDM)** system to effectively manage engineering groups and enable simulation data, asset data, and models to be preserved and managed in a structured, traceable, and reusable manner. The SPDM system also allows teams to work effectively as a team using the available **collaboration tools even when the team is not geographically located together.** This environment can also be linked to a more extensive product development ecosystem with other ASoTs, such as **Product Lifecycle Management (PLM)** systems.

A DEE would enable users to harness the benefits of digital twins and take advantage of the synergies that come with a virtual connected system. **Such a system, coupled with the proper methodologies and processes, allows engineering programs to have fine-grained traceability, easy accessibility of tools, managed data and models, and effective information management.**

Commercial Off-the-Shelf (COTS) solutions are available and should be taken advantage of immediately rather than funding and re-inventing the wheel when the **goal is to encourage data collection, curation, expand sharing and usage, and to provide access to shared public datasets and repositories.**

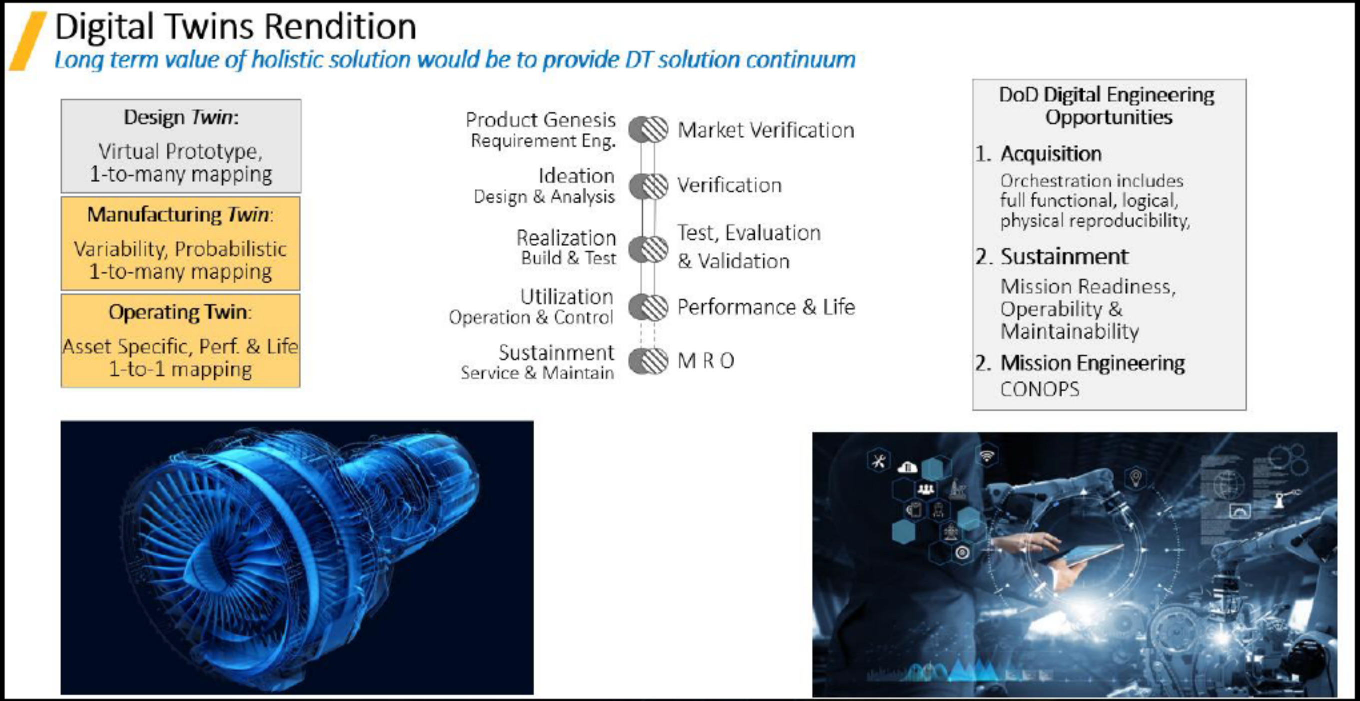


Ansys

Ecosystem: Establish a National Digital Twin R&D Ecosystem:

In 2020, **Ansys** along Microsoft, Dell, Leandlease, and Object Management Group founded the **Digital Twin Consortium** to drive **awareness, adoption, interoperability**, and the **development of digital twin technology**. Members have a **collaborative partnership among industry, academia, and government expertise**. The total number of members is over 100.

Ansys supports the goal to increase collaboration among all who would **plan, perform, and/or benefit from Digital Twin R&D**

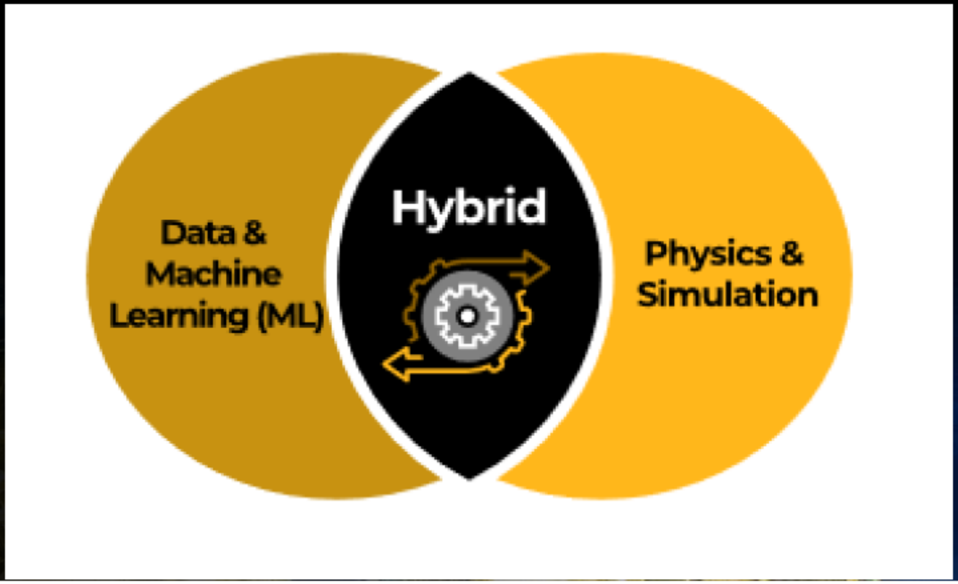


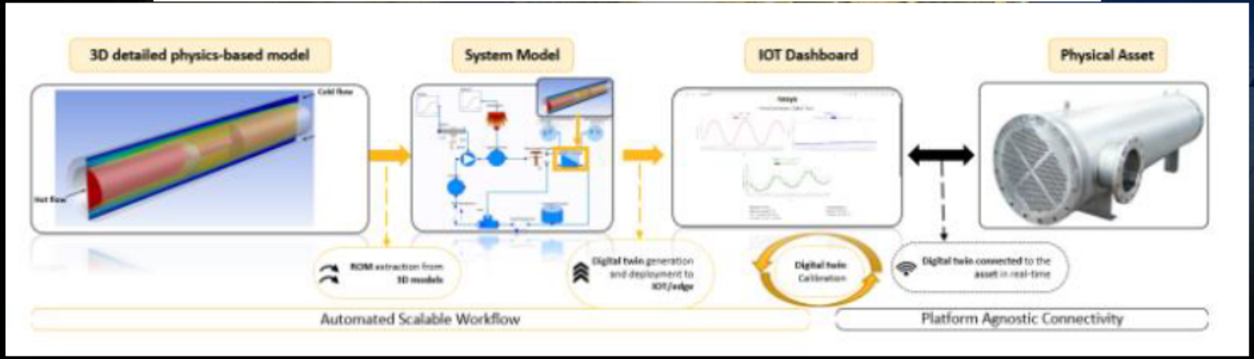
Standards: Promote Development of Evaluation Tools, Methodologies and Consensus Standards for Digital Twin Development and Testing and Interoperability:

Ansys is interested in collaborating to develop Evaluation Tools, Methodologies and Consensus Standards for Digital Twin Development and Testing and Interoperability

In particular, the following areas are important:

- Ontology and data exchange protocols
- Encryption standards
- Taxonomy
- Evaluation of data-driven Digital Twin components
- Hybrid Analytics
- Continuous and multi-modal data sources
- Personalized applications derived from Digital Twins
- Transferability
- IIOT connectivity
- Digital Twin deployment and scalability
- Generalizability and robustness of Digital Twins

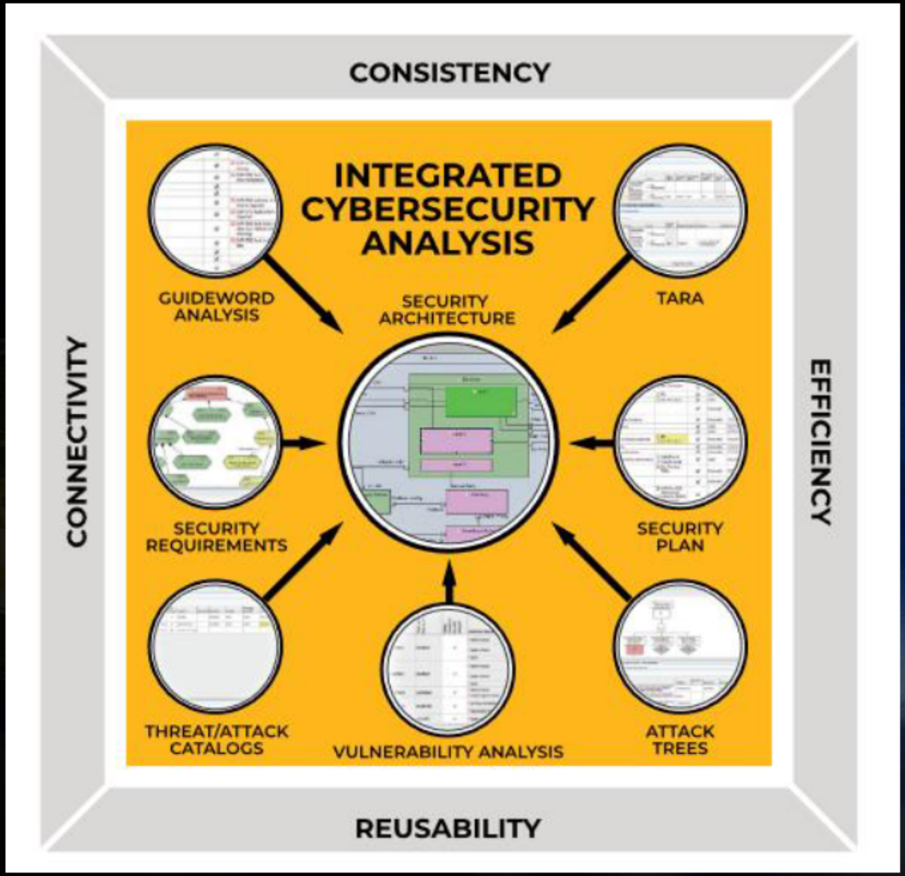




Trustworthy: Realize Secure and Trustworthy Digital Twins:

Ansys considers Cyber Security Analysis to be a critical task to help realize Secure and Trustworthy Digital Twins because it will help to

- Identify the assets in the system and what their important security attributes are
- Systematically identify system vulnerabilities that can be exploited to execute attacks
- Understand the consequences of a potentially successful attack with respect to the assets
- Estimate the potential of an attack (i.e. effort to execute it)
- Associate a risk with each threat
- Plan and execute appropriate security measures based on the identified risk



Ansys

VVUQ: Develop Rigorous Methods for Verification, Validation, and Uncertainty Quantification for Digital Twins:

Ansys sees that Verification, Validation, UQ for Digital Twins is increasingly becoming more important as DTs are being used for a variety applications where **safety is critical & consequences of failure are severe:** Medical, Energy, Industrial, Automotive, Aerospace & Defense

Ansys supports the effort to develop rigorous VVUQ methods

Towards a digital twin for nuclear fusion

UK Atomic Energy Authority

Challenge

Design, monitoring, and maintenance of fusion reactors and equipment cannot rely on extensive testing or in-operation diagnostics due to the prohibitive costs and harsh environments

Solution

A demonstrator is developed to model fusion components subject to combined loads

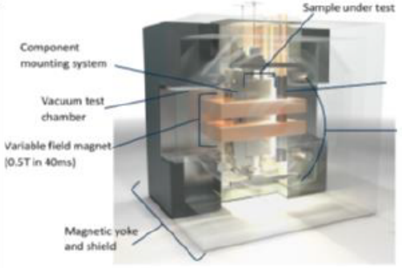
Ansys Maxwell enabled calculating the forces experienced by the equipment due to the magnetic field

Thermomechanical loads were evaluated with **Ansys Mechanical**

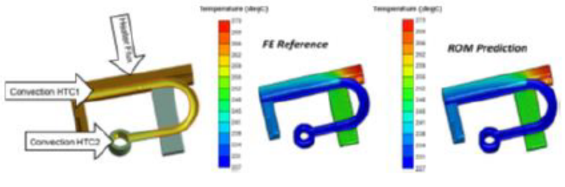
Ansys Twin Builder allowed generating reduced order models and coupling them

Benefits

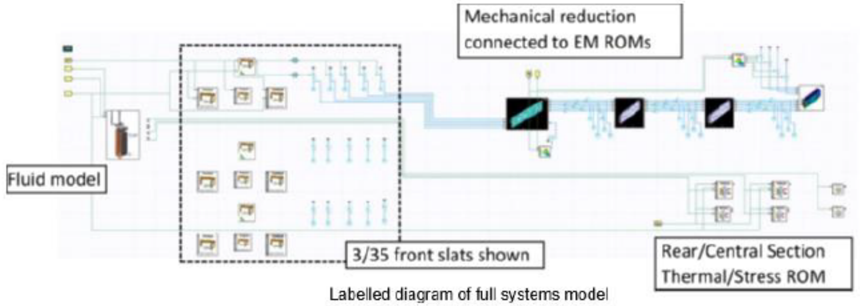
Digital twin is shown to be a key technology to support the design and operation of future nuclear fusion power plants



CHIMERA test rig



From left to right: thermal boundary conditions for the front slat. Temperature profile from FE analysis. Temperature profile from the ROM.



Labelled diagram of full systems model

M. Tindall et al., Towards a fusion component digital twin – virtual test and monitoring of components in CHIMERA by systems simulation, Fusion Engineering and Design, Volume 191, 2023

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Request for Information on the National Digital Twins R&D Strategic Plan

ARA PAWR Rural Wireless Living Lab

Before the
NITRD National Coordination Office
Washington, D.C. 20024

In the Matter of)
)
National Digital Twins R&D Strategic Plan)

Digital Twins for and by Rural Broadband[1]

— Comments by ARA PAWR Rural Wireless Living Lab

Hongwei Zhang
Richardson Professor (ECE), Director (WiCI)
Iowa State University
[redacted]

July 28, 2024

About ARA PAWR Rural Wireless Living Lab

The National Science Foundation Platforms for Advanced Wireless Research (NSF PAWR) program has been supporting the development and operation of the ARA rural wireless living lab to enable research, education, and innovation in agriculture- and rural-focused wireless technologies and applications. ARA is committed to the development and deployment of 5G-and-beyond technologies for rural America, and it is led by the Iowa State University (ISU) Center for Wireless, Communities and Innovation (WiCI). The mission of WiCI is to advance the frontiers of wireless systems and applications while addressing the broadband gap between rural and urban regions at the same time. To this end, WiCI has been collaborating with 65+ public-private partners from industry, academia, government, and communities to drive ARA-enabled wireless and applications technology development, deployment, and adoption, and it serves as a neutral entity in wireless research, education, and innovation. WiCI is a member of the O-RAN Alliance and Next G Alliance, and it has led the establishment of the ARA O-RAN Open Testing and Integration Center (ARA OTIC) to focus on Open RAN for rural America.

ARA deploys advanced wireless, edge, and cloud equipment across the Iowa State University (ISU) campus, City of Ames (where ISU resides), and surrounding research and producer farms as well as rural communities in central Iowa, spanning hundreds of square miles of rural area [1]. Wireless platforms featured by ARA have demonstrated promising performance so far, for instance, up to 3 Gbps

[1] This document is approved for public dissemination. The document contains no business-proprietary or confidential information. Document contents may be reused by the government in the National Digital Twins R&D Strategic Plan and associated documents without attribution.

wireless access throughput, up to 10 km effective cell radius, and close to 10 Gbps throughput across a wireless backhaul link of over 10 km.

Digital twins and AI/ML are two focus areas of ARA and WiCI. WiCI has expertise in developing digital twins for wireless systems as well as connected and automated vehicles, and WiCI is leading activities that use advanced wireless systems for supporting digital twin initiatives such as those for agriculture.

More information about ARA and WiCI can be found at arawireless.org and [redacted] respectively, and inquires can be emailed to [redacted]

Comments on National Digital Twins R&D Strategic Plan: Perspectives from Rural Broadband and Rural Industries

An effective National Digital Twins R&D Strategic Plan is critical to expediting the develop and deployment of digital twins in diverse sectors such as manufacturing, agriculture, renewable energy, transportation, defense, scientific exploration, and education. As we formulate the National Digital Twins R&D Strategic Plan, it is important to pay attention to the unique needs of diverse sectors while addressing the foundational mathematical, statistical, and computational challenges. In particular, ***the rural America presents unique needs for digital twins, and it highlights the urgency of addressing rural broadband both as an application domain and as the virtual-physical communications foundation for rural digital twins in general.*** Specifically, industries such as agriculture and manufacturing can benefit significantly from digital twins, and the realization of these rural industry digital twins relies on real-time communications between sensors and actuators in factories/farms and digital twins at edge/cloud. However, there lacks broadband connectivity to agriculture farms and remote factories. In the meantime, to address the rural broadband challenge, advanced wireless systems are critical [1], and multi-timescale digital twins are critical for the planning and real-time optimization of these wireless systems.

Based on the above observations, it is critical that the Digital Twins R&D Strategic Plan keeps in mind the unique needs and opportunities provided by rural America, with a special focus on rural broadband, rural industries (e.g., agriculture, manufacturing, and renewable energy), as well as workforce development as we explain in more detail below:

- **Data: ARA as source of ground-truth data for rural wireless digital twin.** ARA [1] is the first-of-its-kind wireless living lab for rural wireless systems. It features state-of-the-art wireless access and x-haul wireless platforms (e.g., full-programmable software-defined radios together with open-source 5G/Next-G source platforms at 3.4 – 3.6 GHz band, configurable COTS 5G massive MIMO systems at 3.45 – 3.55 GHz and 28 GHz bands, programmable massive MIMO systems at the TVWS band, as well as configurable 11 GHz, 80 GHz, and 194 THz x-hauls) as well as LEO satellite communications user terminals deployed in real-world agriculture farms and rural community settings [2,3,4]. Therefore, ARA offers unique opportunities of collecting ground-truth data for rural wireless systems, which in turn helps drive digital twin model development and validation. ARA has built-in mechanisms for data storage and sharing, as well as experiment reproducibility, and these mechanisms make ARA an invaluable platform for driving digital twins development for wireless systems.

- **<u>Ecosystem:</u> from rural wireless to rural industries**. Besides wireless platforms, the ARA wireless living lab features real-world agriculture farms for research, education, and production use, and it also includes a bioprocessing plant as well as a mechanical systems design, prototyping, and manufacturing facility, representing bioprocessing and heavy metal industrial settings. Therefore, the ARA wireless living lab can be used to foster cross-sector collaborative digital twins initiatives across wireless and its applications in agriculture and manufacturing.
- **<u>Long Term & Standards:</u>** Given that we are still at the early stage of research and practice in digital twining and that a wide range of policy and technology innovations need to be nurtured and field-tested before their adoption in practice, it will be invaluable to leverage the existing ARA PAWR platform (i.e., both wireless and edge compute resources) to develop sustainable test and evaluation infrastructures for the development of rural-focused digital twins. Besides the hardware and software infrastructures, it is important to engage the diverse stakeholder communities ranging from researchers to application developers, agriculture and rural users, as well as local and state government agencies in developing relevant policies, processes, and standards.
- **<u>Workforce</u>**: Given that digital twining is a new field of innovation and practice, rural-focused technology and policy innovation is critical, which in turn calls for *rural-focused workforce development and innovation capacity building*. To this end, the workforce development aspect of the National Digital Twins R&D Strategic Plan shall have a rural focus and engage rural stakeholders including research and education organizations (e.g., WiCI) and their partners. Specific action areas include *1) developing innovation capacity within the rural regions* so that rural-focused digital twin innovations progress in parallel with urban-focused innovations, and 2) *engaging and empowering rural-regions in digital twin innovations* such as those related to rural broadband, agriculture, manufacturing, and renewable energy.

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[1] H. Zhang *et al.*, "ARA: A Wireless Living Lab Vision for Smart and Connected Rural Communities," in *ACM Workshop on Wireless Network Testbeds, Experimental evaluation and CHaracterization (WiNTECH)*, 2021.

[2] T. Ul Islam *et al.*, "AraMIMO: Programmable TVWS mMIMO Living Lab for Rural Wireless," in *ACM Workshop on Wireless Network Testbeds, Experimental evaluation and CHaracterization (WiNTECH)*, 2023.

[3] G. Zu *et al.*, "AraHaul: Multi-Modal Wireless X-Haul Living Lab for Long-Distance, High-Capacity Communications," in *IEEE Future Networks World Forum (FNWF)*, 2023.

[4] T. Zhang *et al.*, "Exploring Wireless Channels in Rural Areas: A Comprehensive Measurement Study," in *IEEE Future Networks World Forum (FNWF)*, 2023.

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Request for Information on the National Digital Twins R&D Strategic Plan

Argonne National Laboratory

RFI Response: Digital Twins Research and Development

Input from Argonne National Laboratory

July 27, 2024

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Background

Argonne National Laboratory is a multi-purpose Department of Energy (DOE) Laboratory. Argonne is home to five U.S. DOE Office of Science national user facilities, including the Aurora exascale supercomputer and the upgraded Advanced Photon Source, and one DOE Office of Nuclear Energy national user facility. These facilities support nearly 8,000 users annually. Argonne is actively developing and employing digital twins across the laboratory complex, often in a multi-disciplinary environment.

This response summarizes some of Argonne's capabilities and visions for the future of digital twins in science and engineering in seven areas.

1 Artificial Intelligence (AI)

Artificial intelligence (AI) is revolutionizing scientific discovery and engineering innovations throughout Argonne. Here, we highlight how two sample applications combine digital twins and AI, namely nuclear engineering and biomedicine.

Artificial Intelligence (AI) for Nuclear Engineering. AI is revolutionizing nuclear engineering research through the development of digital twins, offering unprecedented advancements in diagnostics, monitoring, and simulation. At Argonne National Laboratory, several digital twin research and development projects are carried out by leveraging AI, and these innovations collectively drive forward the research in nuclear engineering, fostering safer, more efficient, and cost-effective solutions. On-going research projects and future research opportunities and are in (a) Equipment Health Monitoring for Control of At-Power Operation, which focuses on enhancing the diagnostic capabilities of nuclear power systems by integrating AI during the development of digital twins for diagnostics purposes; (b) Real-Time Operating Performance Optimization, which leverages AI-based digital twins to optimize the operational performance of commercial nuclear plants by predicting moisture carryover (MCO) in boiling water reactors (BWRs) due to insufficient liquid phase removal from steam exiting the primary vessel; and (c) Simulation-informed and data-driven Field reconstruction techniques for Monitoring for Control of At-Power Operation, which utilizes AI to develop a digital twin for real-time online monitoring of nuclear reactors and provide a continuous and intelligent oversight of process variables that cannot be experimentally measured during at-power operation, thus addressing the limitations of current data-driven algorithms which often lack diagnostic specificity.

AI and Digital Twins in Biomedicine. Recently, there has been an increased focus at Argonne on AI for biomedicine, and one such ongoing collaborative project is in the area of mathematical oncology aimed at developing digital twins for personalized radiation therapy (RT) strategies. Conventional RT for cancers usually utilizes a single set of imaging acquired prior to the start of treatment and selects a treatment plan that has been shown to work well on an "average patient" However, cancer is a complex, evolving system that exhibits significant inter-patient variations that depend on various factors, including the underlying genomic instability and tumor microenvironment. Physics-informed neural networks (PINNs) are being developed by integrating mechanistic modeling with MRI data to model the spatio-temporal response of tumors to RT, to create therapy plans based on individual tumor biology. Such a PINN model, trained over a broad range of relevant parameters (e.g., diffusion coefficients, tumor proliferation rates, RT dose) and regularized/guided using available MRI data, can be used to carry out near-instantaneous predictions for the tumor trajectory based on parameters corresponding to any new patient, thus streamlining RT planning and precluding the need for a huge number of parameter-specific computer simulations.

2 Data

Research opportunities are in (a) heterogeneous data integration, (b) real-time data transport, and (c) data orchestration workflows. Heterogeneous data integration involves management of multimodal data for physical experiments, numerical simulations, and AI surrogate models. Real-time data transport involves efficient bidirectional data movement between the physical and virtual twins and the analysis of raw data to produce useful high-level knowledge. The orchestration of heterogeneous data in the digital twin ecosystem needs to be automated with workflows capable of managing disparate scales in time and space. Workflows need to designed with intelligence to determine optimal data models, accuracies, and routes.

3 Ecosystem

Digital Twins and the Environment. The use of digital twins in the MOdel Driven EXperiment (MODEX) lifecycle includes active interchange between the digital twin and field observations. Feedback from the observations are used to both improve the digital twin and to assimilate and nudge the state of the digital twin. Edge computing will enable geomorphic computing where digital twins can be run in a resource limited environments that could inclde CPU/GPU limitations, bandwidth limitations or, for off the electrical grid applications, PV limitations.

Digital Twins for Scientific Discovery in X-ray Science. Linking X-ray experiments at synchrotron sources, such as the Advanced Photon Source (APS), with AI-enabled Digital twins is essential to fully realizing the scientific potential of next-generation infrastructure (such as the APS-Upgrade). The potential of AI, high performance, and edge computing (HP-EC) to unlock process secrets by capturing rare events critical to designing and manufacturing advanced materials is truly exciting. Developments such as the high energy X-ray diffraction microscopy digital twin, a part of the Microstructure Identification using Diffraction Analysis Software package (MIDAS-DT, https://github.com/marinerhemant/MIDAS), which operates in real-time, empower scientists to conceptualize, visualize, and drive their experiments. Combining full experiment simulations with material modeling running on remote HPC resources, MIDAS-DT instantly predicts regions of interest in materials. Scientists can use this information to automate experiments adaptively, using multimodal and multiresolution techniques to gain unprecedented insights into material behavior during processes such as deformation and fatigue.

4 Long Term

The two-way coupling between the physical object and its digital twin raises a number of important foundational questions about the stability, accuracy, fidelity, convergence, and correctness of the digital twin. These questions are complex and are connected to uncertainty quantification and validation and verification of digital twins, but are more fundamental in nature, requiting long-term research investments in methodologies, coupling approaches, solution methods, uncertainty quantification, and convergence. For example, the use of a digital twin to control both the data acquisition and manufacturing process in additive manufacturing could in principle be achieved today by simply bolting together data assimilation, simulation, control. However, this simplistic coupling would fail to address the questions about convergence, fidelity, and uncertainty raised above that ultimately determine whether a digital twin can become a truly predictive tool that can be safely used in complex processes. Below, we comment on two fundamental challenges in this area in more detail, namely fidelity and how to develop optimization technology for digital twins that can be used in optimal control or data assimilation.

Fidelity of Digital Twins. With the revolution of AI-driven digital twins, the need to maintain the fidelity of AI models as the underlying data distribution evolves has become crucial. However, naively updating the model with new data can lead to “catastrophic forgetting,” a phenomenon where new data erases prior information stored in the AI model. The paradigm of continual learning seeks to address this issue. There are numerous research opportunities within this context. A fundamental opportunity arises from the heterogeneity in data distribution. For instance, variations in the fidelity of underlying simulations require different AI methods to effectively assimilate such high and low fidelity information into the digital twin. Similarly, the spatio-temporal nature of the data introduces significant complexity, impacting the digital twin in ways that remain opaque. The computational demands of such a structure, coupled with the significant energy requirements, present a research challenge where energy-aware methodologies must be developed. This challenge needs to be analyzed and studied both mathematically and empirically.

Research opportunities include: (a) maintaining the fidelity and time efficiency of digital twins through hybrid modeling approaches that leverage high-fidelity and fast surrogate formulations; and (b) ensuring the computational power required to run complex digital twins in real-time by integrating energy-efficient workload management systems like PBS and Slurm. One example of hybrid modeling is to integrate high-fidelity parallel discrete event simulations (PDES) with statistical or ML based surrogate models to accelerate large-scale simulations (Kronos, https://www.anl.gov/mcs/kronos-hybrid-discrete-event-simulations).

Digital-Twin-Aware Optimization Tools. Optimization plays a fundamental role in digital twins as a tool for optimal control and optimal data acquisition, for example. The development of digital-twin-aware numerical optimization tools is a long-term need, driven by the increasing complexity and scale of digital twins across scientific domains. These optimization tools must be able to handle such dynamic, evolving, data-driven models. Research in methods is needed to ensure that the optimization solutions remain robust and efficient as the underlying digital-twin changes. Addressing this need will require creating novel, sophisticated optimization algorithms that can integrate real-time data and adapt to new environmental conditions, while maintaining previous critical domain knowledge.

5 Sustainability

The design and development of systems and architectures for digital twin sustainability are pivotal for advancing the sector's safety, efficiency, and longevity. By leveraging cutting-edge digital twin technology, researchers can create dynamic, real-time simulations of nuclear systems, providing comprehensive insights into their operations. These digital replicas facilitate predictive maintenance, optimize performance, and enhance decision-making processes. At Argonne National Laboratory, several digital twin research and development projects focus the integration of robust, scalable architectures that ensure the long-term sustainability and adaptability of digital twins, enabling continuous improvement and resilience in nuclear power systems. This approach not only addresses current operational challenges but also sets the foundation for future advancements in nuclear engineering. On-going research projects and future research opportunities and are in (a) Control Strategies Informed by Prediction of Equipment Condition, which focuses on developing control systems that enable semi-autonomous operation, addressing the challenge of ensuring continued safe operation despite component performance degradation, which conventional control systems may struggle to manage; (b) Control for Meeting Equipment Constraints in Integrated Energy Systems, which focuses on the sustainable deployment of digital twins for controlling multiple production assets, addressing the challenge of achieving economically optimal electricity dispatch in integrated energy systems; (c) Control of Advanced Reactors Using Reinforcement Learning, which focuses on the sustainable deployment of digital twins through the development of reinforcement learning-based control algorithms thus addressing the need for self-learning control systems to expand the range of upsetting events that can be managed by the plant control system, and reducing the reliance on protection systems; and (d) Asset management approach through Integrated Online Monitoring and Diagnostics, which aims to enhance the economic competitiveness of advanced reactors by integrating intelligent online monitoring with asset management decision-making methods, thus optimizing the operation and maintenance cost and plant performance through the sustainable deployment of digital twins.

6 Trustworthy

The trustworthiness of digital twins is paramount for their effective implementation and acceptance in nuclear power systems. Digital twins, as virtual replicas of physical systems, offer transformative potential in optimizing operations, enhancing safety, and predicting maintenance needs. At Argonne National Laboratory, multiple research projects focus on enhancing the trustworthiness of digital twins, involving rigorous validation and verification processes by integrating data from physical sensors or high-fidelity simulations, and adherence to regulatory standards. By incorporating advanced algorithms, real-time data analytics, and comprehensive simulations, researchers can build digital twins that accurately reflect the complexities in nuclear systems. Establishing trust in these digital replicas not only bolsters operational efficiency but also strengthens safety protocols and decision-making processes, paving the way for their widespread adoption in the nuclear industry. On-going research projects and future research opportunities and are in (a) Stability and Control in Boiling Water Reactor Feedwater Systems, which focuses on employing a physics-based digital twin specifically developed for the feedwater heater string to enhance the understanding of the underlying phenomena contributing to cycling behavior, and then design an operational control system to address the prevalent issue of oscillatory behavior in the feedwater heater levels of boiling water reactors (BWRs); (b) Dispatch of Electricity for Nuclear Plants with Energy Storage, which focuses on the control of energy storage systems coupled with nuclear plants to match electrical power output with instantaneous fluctuations in net demand; and (c) Control and monitoring for semi-autonomous operation, which focuses on enhancing the economic competitiveness of advanced reactors by optimizing costs and plant performance through the trustworthy deployment of digital twins.

7 Workforce

The inherent complexity of digital twins raises the barrier-for-entry into this critical technology and therefore requires a sustained investment into workforce development. The next-generation of scientists must be competent domain scientists in addition to having fundamental knowledge in AI, numerical simulation, uncertainty quantification, etc. Argonne National Laboratory provides internship opportunities for undergraduate and graduate students that should be expanded to provide training and workforce development opportunities in the area of digital twins. We must extend these opportunities to R2 universities and MSI institutions that may not be sufficiently well-resourced to provide courses and experience with digital twins, in order to democratize access to digital twin technology and development opportunities.

Federal Register Notice: 89 FR 51554, Federal Register :: Networking and Information Technology Research and Development Request for Information on Digital Twins Research and Development, June 18, 2024.

Request for Information on the National Digital Twins R&D Strategic Plan

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Digital Twins for Protecting Agricultural Cyberinfrastructure

RFI Response: Digital Twins R&D Plan

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RFI Response Focus: The U.S. agriculture sector is being infused with various smart technologies and cyber components. However, the cybersecurity of these digital assets is still an afterthought. Digital twins can be useful for analyzing the security posture of applications in precision agriculture and for improving preparation and protection of this sector against cyberattacks. Building effective digital twin frameworks requires concerted, cross-domain research, thoughtful synthesis of ideas and methods, and investment in workforce development.

1. Introduction

Our increased reliance on digital technologies and networked distributed systems across various industrial sectors has made critical infrastructure cybersecurity one of the top priorities for national security. The food and agriculture sector is identified as one of the 16 critical national infrastructures in the U.S., accounting for roughly one-fifth of the nation's economic activity [1], [2]. The adoption of innovative digital technologies -- such as connected sensors, embedded computers, smart tractors, and drones -- and Artificial Intelligence (AI) in agriculture has led to increased production, nutritional value, disease resistance, and, in recent times, maintaining agricultural productivity in the face of climate change. While these technologies have enabled unprecedented gains in innovation and productivity, they expose modern agriculture to various cyber vulnerabilities impacting precision agriculture operations. Due to the high value of agricultural sectors to adversaries, limited or no cybersecurity defense, and lack of domain-specific security understanding of those systems, digital agricultural systems are increasingly becoming targets for cyber breaches. Examples of recent major cyber incidents in the U.S. agricultural sector include ransomware attacks on JBS facilities [3], attacks by Russian hackers targeting an Iowa grain co-op [4], and attacks on a Minnesota grain handler [5]. In fact, the food and agricultural sectors have been increasingly targeted (over 30 major cyber incidents in recent times), leading to significant financial losses. Attacks originating from other critical sectors, such as the utility grid and industrial control systems, could also threaten the food supply chain due to close interdependence, as indicated by the U.S. Department of Energy [6]. Any cyberattack targeting agriculture or closely related critical infrastructure could jeopardize the nation's agricultural production, exports, food security, and ultimately, national security.

A critical gap in our understanding of security vulnerabilities in the agriculture sector is the lack of domain knowledge and misconceptions about adversarial capabilities. As a concrete target for this RFI, we select critical infrastructure associated with agricultural weather and irrigation support. Weather data is a key input attribute needed for agricultural decision-making. Uninterrupted and reliable weather data, obtained at farm scale, is necessary for a variety of real-time tasks, including irrigation, disease and pest management, fruit-growth prediction, and frost mitigation, among others [7]. We envision that **building a "digital twin" framework will be vital for analyzing the security posture of distributed agricultural networks**.

2. Digital Twin for Precision Agriculture Cybersecurity

The correctness, resiliency, and efficiency of smart agriculture systems, especially those that rely on weather and irrigation data, can be improved by using digital twin architectures. The digital twin will be a network representation of active weather and water stations, including associated services for collecting field data, storing data in the cloud or local server, and retrieving data to perform farm decision-making. This digital representation will make it possible to formulate and evaluate various relevant cybersecurity scenarios at the network scale. Some of the benefits of using a digital twin for agriculture cybersecurity include:

a) weather and irrigation data monitoring at different time granularity (e.g., hour, day, month, season) and real-time analysis of misbehaviors or anomalies,
b) early detection of potential vulnerabilities (viz., root cause analysis), and
c) the ability to simulate and test different malicious behaviors and defense measures before implementing them in the production environment.

However, building digital twins for such systems involves many challenges. Some of the key challenges are outlined below.

I. Data Collection and Framework Development Challenges

Data Heterogeneity: Agricultural weather and water networks involve various data sources, including weather stations, satellite imagery, soil sensors, and irrigation systems. How can a digital twin framework be designed to integrate and analyze these heterogeneous data types?

Real-Time Data Acquisition: Ensuring real-time data collection from diverse sources is critical for an accurate digital twin. How do we ensure reliable and continuous data streaming, which can be hindered by connectivity issues, especially in remote agricultural areas?

Data Quality and Consistency: The quality and consistency of data from different sources can vary, impacting the accuracy of the digital twin. Therefore, how can we address issues such as missing data, noise, and inaccuracies due to cyberattacks? Besides, weather and water systems are dynamic and continuously changing. The digital twin must be capable of adapting to these changes in real-time, requiring sophisticated algorithms for dynamic updating and real-time analytics. This is crucial for reliable simulations and predictions.

High-Resolution Modeling: Creating high-resolution models for weather patterns and water distribution systems requires further research. Growers use real-time weather data and associated forecasts tied to crop phenology and cold hardiness models [8], [9] as decision support to actuate resource-intensive active frost damage mitigation methods, i.e., heaters, wind machines, and over- and under-tree sprinkler irrigation. However, what if a *compromised* weather sensing ecosystem and pertinent malicious weather data drive the inversion forecasting and associated wind mixing decision support? For instance, "no actuation" in critical times would result in significant crop loss, and "over actuation" would mean excess use of natural resources and economic burden on the farmer. Hence, how do we develop high-fidelity models to predict misbehaviors? Can a digital twin ecosystem trigger the *early detection* of anomalies?

Scalability and Continuous Integration: The digital twin framework must be scalable to accommodate large agricultural regions with diverse environmental conditions and complex weather and water networks. How do we develop scalable algorithms and leverage high-performance computing resources to handle large data volumes and intricate simulations? In addition, establishing feedback loops between the digital twin and its physical counterpart is crucial for refining and improving the models. Real-time data from the physical system should be used to update and validate the digital twin, ensuring that it remains accurate and relevant. The challenge is: how do we build a continuous feedback mechanism that helps maintain alignment between the digital twin and the physical system?

Dealing With Legacy Systems: Another challenge is that many agricultural operations (as well as other critical cyberinfrastructure such as power grid and control systems) rely on legacy systems and equipment that may not be easily integrated into a modern digital twin framework. Hence, how can solutions be built to bridge the gap between old and new technologies?

Software-defined Digital Twins for Better Resource Management and Resiliency: In current practice, digital agricultural decision-making is often ad-hoc. Further new research is needed to develop a "software-defined" digital twin approach that brings together fault detection, isolation, and system reconfiguration to ensure robust and resilient digital agriculture operations through the identification of servicing needs among potential clients, careful long-term resource management, and cross-checking fidelity of field nodes (e.g., weather stations). For instance, how can software-defined networking (SDN) [10] capabilities be leveraged to provide a "global view" of the distributed infrastructure and use this in the digital twin ecosystem to ease resource management and misbehavior detection?

Another challenge is building *adaptable* digital twin architectures that can be easily transferred and applied to various contexts while preserving their security measures. Furthermore, the end-users (growers and ag-tech companies) can use simulation data from the digital twin and aid in informed decision-making (such as predicting frost mitigations and fruit surface temperatures).

Privacy Concerns: Farmers and stakeholders may have concerns about model and data privacy and the potential misuse of their information. Establishing clear data privacy policies and secure data handling practices is necessary to build trust and encourage participation.

II. Standards and Interoperability Challenges

The need for robust standards and interoperability is paramount. This ensures that digital twins can securely interact with various systems and data sources, maintaining the integrity, confidentiality, and availability of the information they process. Establishing and adhering to standards is crucial for fostering trust and reliability in digital twin technology.

Development of Evaluation Tools: To ensure the cybersecurity of digital twins, comprehensive evaluation tools are essential. These tools should be capable of assessing the entire digital twin ecosystem, including its code base, data handling processes, operational environments, and network connectivity with physical counterparts. Evaluation tools should be designed to identify vulnerabilities, assess risks, and provide actionable insights for enhancing security. Thus, concerted efforts from the research community and ag-tech vendors are required to build open-source tools for better evaluation. Further research is needed to establish guidelines and best practices for conducting threat analysis, risk assessments, and security audits. These should also encompass best incident-response and recovery practices, ensuring that digital twins can effectively withstand and recover from cyber-attacks.

Data Exchange and Encryption Protocols: Establishing standardized data exchange protocols is essential for ensuring interoperability between different digital twin systems. These protocols should define how data is formatted, transmitted, and secured during exchanges between digital twins and their associated physical systems. Secure data exchange protocols help prevent unauthorized access and ensure the integrity of the data being transmitted. In addition, to protect sensitive data within digital twins, common encryption standards must be developed and followed.

Taxonomy and Ontology Development: One challenge in building digital twins for agriculture and other critical infrastructure is the lack of common taxonomy and ontology for ensuring interoperability. Hence, we must define standardized terms and concepts that can be universally understood and applied across different digital twin systems. A common taxonomy facilitates seamless communication and data sharing between digital twins, reducing the risk of misinterpretation and errors.

III. Verification, Validation, and Uncertainty Quantification Challenges

Verification and Validation are critical processes for ensuring the reliability, accuracy, and trustworthiness of digital twins. These processes help establish confidence in the digital twin's ability to accurately represent and predict the behavior of its physical counterpart, thus ensuring its effectiveness in cybersecurity applications.

Code Verification: Code verification ensures that the digital twin's software correctly implements the intended algorithms without errors. This involves rigorous testing to identify and fix bugs, security vulnerabilities, and logic errors within the codebase. How can techniques such as static analysis, formal methods, and automated testing be employed to achieve thorough code verification in this context?

Model Verification and Validation: How do we ensure that the mathematical models and simulations used in digital twins are implemented correctly? We need techniques to check the consistency and correctness of the models against their specifications. Besides, automatic validation tools are required to compare the digital twin's outputs with experimental data and observations from the physical system. We envision further research on statistical validation, benchmark comparisons, and real-world scenario testing, which are essential for validating model accuracy in agricultural digital twins.

Uncertainty Quantification: Another challenge is identifying and quantifying uncertainties in the digital twin's models and predictions, either due to fault or cyberattacks. This includes uncertainties in model parameters, initial conditions, and input data. Can we recontextualize tools such as probabilistic modeling, sensitivity analysis, and Monte Carlo simulations to quantify these uncertainties?

3. Workforce Development and Interdisciplinary Research Environment

Educational Programs: Developing specialized degree programs and certificates focused on digital twin technology and cybersecurity can provide in-depth knowledge and skills to students. These programs should cover areas such as modeling and simulation, data analytics, artificial intelligence, and cybersecurity principles specific to digital twins. We also need to establish innovative programs that provide education opportunities in high school and in undergraduate agricultural programs and hands-on learning experiences for the existing workforce to foster a new generation of professionals equipped with state-of-the-art agriculture and critical infrastructure cybersecurity knowledge and skills related to digital twins.

Cross-Disciplinary Collaboration: Building an end-to-end digital twin ecosystem for protecting crucial cyberinfrastructure requires a coordinated national effort. A tiered "hub and spoke" model could be an effective way to improve communication, adopt new technologies, and mobilize an upskilled workforce [11]. Such models are based on a central hub that collaborates with regional centers that are themselves coordinating hubs for regional or local partners. Establishing a hub and spoke model to address digital twins for critical infrastructure cybersecurity can have significant, lasting impact. A consortium of land-grant universities with strong research and education programs in agriculture, cybersecurity, cyber-physical systems, and extension are ideally suited to act as regional hubs focused on the challenges and diverse needs of a region's agricultural sector. The role of the regional hub will be to engage regional and local partners, develop testbeds, undertake digital twin and cybersecurity research, promote education and workforce development, and be an essential resource to federal agencies like the USDA NIFA, NSF, FBI, and DHS. Leveraging the regional centers, a "national coordinator" can ensure a unified, equitable, and agile response to cybersecurity challenges across the national agricultural landscape. Together, the national coordinator and regional hubs will serve to advance cyber technology to build a strong, informed digital twin architecture.

4. Beyond Agriculture

Considering the diverse agriculture domain (plants, crops, livestock, seafood) and external climatic variabilities (weather, water), understanding cybersecurity issues and building techniques using digital twins to bolster security posture requires concerted, multiyear efforts. Although the majority of this RFI Response document focused on digital twin-centered agricultural cybersecurity, accompanying research is needed to investigate how this agricultural domain knowledge can be transferred to understanding and protecting other critical sectors, such as power grids, transportation systems, biomanufacturing, public health, food supply chain, and wildfire management, using the digital twin technologies.

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Request for Information on the National Digital Twins R&D Strategic Plan

Bentley

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RFI Response: Digital Twins R&D Plan

Prepared for: NITRD, NCO, NSF

National Digital Twins R&D Strategic Plan

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CONTENTS

1. BACKGROUND

Bentley Systems is pleased to offer this response to the Office of Science and Technology Policy ("OSTP") at the Networking and Information Technology Research and Development ("NITRD") National Coordination Office ("NCO"), National Science Foundation ("NSF"), regarding the proposed creation of a National Digital Twins R&D Strategic Plan. Bentley applauds the creation of this plan, and is looking forward to working with NITRD, NCO, and NSF on driving Digital Twin innovation and adoption.

Bentley Systems has been at the forefront of the digital transformation of civil infrastructure for 40 years, and has focused heavily on the creation, management, analysis, and visualization of Digital Twins. These Digital Twins not only encompass the planning and design phases, but transition through the entire asset lifecycle including operations and maintenance. Bentley's multi-discipline, whole life Digital Twins are already making measurable improvements in safety, cost efficiency, construction times, environmental impact, compliance, and reliability for infrastructure in the United States and around the world.

Bentley's solutions encompass the following:

Spatially Enabled Asset Information

View and use information from a graphical perspective for spatially located assets and related information. This asset-centric approach supports enhanced decision-making across different types of assets and information.

Enhanced Decision Support

Combine data from multiple sources with advanced analytics to enable engineers to make more informed decisions relating to maintenance and renewal of infrastructure.

Trusted Information, When and Where it is Needed

Manage information throughout the asset's lifecycle – ensuring the delivery of relevant, trusted information, in context – where and when it is needed.

Connected Data Environment

Leverage existing investments in information by establishing an open framework for collaboration and the management of asset information throughout the full lifecycle of infrastructure.

Reality Models Creation and Visualization

Combine existing point cloud and images to create realistic 3D representations of assets to deliver a baseline for asset condition, provide context to other datasets and support digital inspection.

About Bentley Systems

Bentley Systems (Nasdaq: BSY) is the *infrastructure engineering software* company. Bentley provides innovative software that advances the world's infrastructure – sustaining both the global economy and environment. Bentley's industry leading software solutions are used by engineering professionals, and organizations of every size, for the design, construction, and operations of roads and bridges, rail and transit, water and wastewater, public works and utilities, buildings and campuses, mining, and industrial facilities. Bentley's offerings include applications for modelling and simulation, project delivery, asset and network performance, and sub-surface mapping.

www.bentley.com

Bentley Differentiators

- **Global Reach** – Bentley Systems is a US based, publically traded company with 5,000 colleagues worldwide, offices in over 40 countries and users in over 100.
- **Proven Experience** – Bentley has both local and global experience implementing digital technologies on brownfield and greenfield projects. Bentley has helped deliver civil infrastructure projects in all 50 states and serves as the primary design authoring software for 42 state Departments of Transportation ("DOTs"), the New York Metropolitan Transit Authority ("MTA"), CSX Transportation ("CSX"), Amtrak, Canadian National, and many others.

2. DIGITAL TWIN TOPICS

2.1 Artificial Intelligence (AI)

AI and Digital Twins: Possible focus areas: integration of digital twins with artificial intelligence (AI); leverage generative AI for digital twin modelling & simulation with the consideration of the potential impact on a digital twins' physical counterpart.

Bentley believes Artificial Intelligence ("AI") and Digital Twins are natural partners. AI requires large swaths of data to learn from, and a Digital Twin can provide a rich variety of that required data. Bentley already incorporates AI into its Digital Twin products for a range of different applications. These applications span from concrete crack detection for bridges and dams to intelligent legacy Piping & Instrumentation Diagrams ("P&ID"), and roadway and asset assessment through the use of vehicle dashcams.

Impactful areas of focus could include how AI can better support Digital Twins in automating the assessment of existing infrastructure. Bentley remains deeply focused on helping engineers make better, faster, and safer decisions throughout the entire lifecycle of an asset. These AI capabilities function as a digital co-pilot to support engineers in all facets of their jobs by serving as a repository of information about the current state, history and potential future state of an asset or system. This type of supplemental assistance helps engineers more effectively use their data to make better decisions, leading to improved project delivery.

Additional research could be done to further determine how AI can help train and assist the existing and incoming workforce in transitioning or entering a Digital Twin experience by helping them navigate newly formed tasks, protocols, and procedures. This will help improve performance of job functions that may have changed or adapted from a paper and pdf-based workflow to one that utilizes Digital Twins.

Exploring how building automation into the design process to assist in performing mundane and repeatable tasks could benefit the industry at-large. Developments in task automation often seek to increase efficiency for the designer to achieve the most optimal results when it comes to safety, environmental, ethical, and financial considerations. This research will help the industry get to a point where the cost of Digital Twin implementation pays for itself and drives additional cost-savings for owner-operators.

2.2 *Business: Business Case Analysis*

Possible focus areas: foundational research cost; evaluate value/return on investment; cost and time to implement.

Bentley has been collecting Return on Investment ("ROI") data from its customers' Digital Twin projects for years. Additional analysis could be done to consider user digital maturity, supply chain readiness, contractual relationships, existing IT infrastructure and required process changes to generate an overall roadmap of digital transformation. Digital Twins are a powerful tool, but full value can only be achieved if they are embedded into existing processes and utilized by trained individuals.

Additional research could be done regarding foundational information packs and datasets used to fast-track digital maturity including roadmaps and best practices for pragmatic digital transformation. This would assist in covering roles, accreditations, processes, and impact including security, data volumes, processing power, and compatibility with existing systems. This type of research could result in a better understanding of how to measure ROI during implementation. In the interim, research into extrapolating ROI from multiple siloed instances of existing Digital Twin efforts would help industry leaders more accurately project ROI.

Bentley believes research into short and long-term implementation and expansion of Digital Twins into various agencies and industries would benefit long term, educational, business case, and workforce goals.

2.3 *Data*

Encourage Adoption of Data Management Best Practices: Possible focus areas: governance methods for data collection, curation, sharing and usage; shared public datasets and repositories; real-time data integration.

As an organization helping deliver some of the world's largest civil infrastructure projects, Bentley has users with multi-terabyte sized datasets. These users are federating data from dozens of source systems to provide a "single pane of glass" view into a system. Research regarding open data formats, data validation, Master Data Management ("MDM"), data archiving, data longevity, data management and visualization at scale, and data security should be considered.

Additionally, uncertainty persists around data ownership and its utilization for AI and machine learning ("M/L"). In many instances, data ownership for the use of training AI systems remains unclear; for example, on a government-commissioned project designed by an architecture, engineering, and construction ("AEC") firm using digital design software. Simply put, the clarity surrounding data ownership remains an obstacle to full-scale innovation and adoption. Additional research on these types of data management best-practices, specifically related to improving AI-training data, are going to be paramount in driving Digital Twin innovation forward.

2.4 *Ecosystem*

Establish a National Digital Twin R&D Ecosystem: Possible focus areas: collaborations across agencies to identify and address foundational research gaps and opportunities that spans areas such as biomedical sciences, environmental ecosystem, sustainability & climate change, smart and connected communities, scientific discovery, agriculture, military & mission planning, as well as common mathematical, statistical, and computational foundations.

Through its deep roots in helping deliver government-funded projects, Bentley has continued to build upon its experience working closely with government agencies at the local, state, and federal level. This experience and knowledge are paramount to Bentley's ability to navigate the complexities of working with various levels of government, often on the same project. Bentley knows well that this collaboration is a cornerstone of not only project delivery, but also driving adoption of technology at all levels of government.

Bentley believes that additional research into cross-functional and cross-agency information sharing will help drive the industry forward in a way that accounts for and benefits all levels of government and its citizens. Research into this ecosystem development would ideally include multiple simultaneous coordinated research streams to advance Digital Twin ROI collection and advancement.

Investigating cross functional and cross agency activity sharing in multiple industries would be of great value. Research into this ecosystem development to include multiple simultaneous coordinated research streams to advance digital twin ROI collection and advancement would help foster collaboration at-large.

2.5 *International*

Collaborations on Digital Twins: Possible focus areas: global scale digital twins across foreign markets; global issues and digital twin development consensus standards; opportunities for international collaboration (e.g., European Union's Horizon 2020 program funding digital twin projects).

As a US based, global IT company, Bentley has visibility into cutting-edge digital transformation around the world. Bentley belongs to various international organizations such as buildingSMART and the European Rail Supply Industry Association (“UNIFE”). Researching global supply chain alignment, international standards for file formats, data exchange, and taxonomy would be of great benefit to the Digital Twin industry.

Additionally, as governments around the world continue to invest in building and enhancing existing infrastructure, research regarding technology use within those projects will be paramount in understanding the state of the industry. In cases where a country has a higher adoption rate of Digital Twins, understanding why and what barriers may exist in areas with lower levels of adoption will help organizations and governments more effectively drive adoption and modernization.

2.6 *Long Term*

Identify Long Term Research Investments: Possible focus areas: novel approaches for interactive data-driven modelling and simulation, both crosscutting and fit for purpose; research enabling the bidirectional flow between the virtual and the physical assets; creating test environments for digital twins ensuring sufficient resources and sustainable high-performance computing.

Bentley believes there is immense value in research that will help determine best practices for creation, publication, and maintenance of sample Digital Twins for specific industries that will support innovation and continued long term research opportunities. Research into how to align the rapidly changing world of IT advancements with the relatively static world of civil infrastructure, will help give long term sustainability to the Digital Twins based on today's technologies.

2.7 *Regulatory*

Regulatory Science Challenges associated with the use of Digital Twins.

Bentley has experience in multiple industries globally and is constantly monitoring regulatory developments and requirements. While Bentley does not see any immediate regulatory science concerns when it comes to the use of Digital Twins, ensuring standards, definitions, and requirements are set in close collaboration with industry will be essential to ensure innovation and adoption are encouraged and not stifled. Bentley continues to closely monitor the regulatory landscape as it relates to requirements in cybersecurity, AI, and government data.

2.8 *Responsible*

Promote Responsible Development & Use of Digital Twins: Possible focus areas: ethical use of digital twins; identifying ethical issues, mitigating and biases with respect to data ownership, intellectual property and privacy.

Bentley believes profound care must be taken in determining when and where integrating AI into its Digital Twin technologies makes sense and where its use provides measurable value. Bentley takes seriously concerns about data quality, privacy, data leakage, and the strategic nature of civil infrastructure. Bentley remains steadfast in its view that implementing AI when it doesn't provide additional value could defeat its intrinsic value.

Additional research should be done on managing intellectual property ("IP") in shared Digital Twins, AI respecting data ownership, and AI usage on top of Digital Twins. Further research on access permissions to data derived and data resulted from AI run against sensitive or private data would help mitigate potential privacy issues in the future.

2.9 *Standards*

Promote Development of Evaluation Tools, Methodologies and Consensus Standards for Digital Twin Development and Testing and Interoperability: Possible focus areas: community of practice, ontology and data exchange protocols; encryption standards; taxonomy; address challenges related to evaluation of data-driven Digital Twin components; continuous and multi-modal data sources; personalized applications derived from Digital Twins; transferability, generalizability and robustness of Digital Twins.

Bentley participates in several standards committees and organizations worldwide. Bentley believes that these organizations provide immeasurable value to the greater industry through their approaches on collaboration, information sharing, and standard setting. This collaboration allows the industry to move together in its pursuit of advancement and innovation. Research areas such as standardizing definitions, management and usage of network definitions, and linear referencing systems on top of Digital Twins for civil infrastructure use-cases would be additive to the value of the committees themselves, allowing them to be more effective.

2.10 *Sustainability*

Design and Develop Systems and Architectures for Digital Twin Sustainability: Possible focus areas: sustainment as the operating systems and computational models on which

they are based evolve and the data which they ingest are updated; intentional organizational effort and purpose-built modelling ecosystems energy-awareness; early consideration of computational requirements and effective workflows; develop approaches for the design, development, and deployment of Digital Twins; the ability to create interoperable Digital Twins with evolving technology and standards.

Bentley has been generating open file formats to support Digital Twins for several years. Bentley understands well that longevity of data is critical and works tirelessly to ensure that legacy data can still be accessed in newer products. Bentley sees the immense value in potential exploration of longevity of data, data accessibility, and lossless data migration between Digital Twin technologies. Bentley sees the benefits of researching how to align the rapidly changing world of IT to better provide long term sustainability for Digital Twin products.

2.11 *Trustworthy*

Realize Secure and Trustworthy Digital Twins: Possible focus areas: develop solutions to assure the security, cyber resilience, and trustworthiness of digital twins (taking into account all components of DTs such as their code base, data and data processing, operational environments, networking and connectivity with the physical counterpart); develop capabilities to utilize DTs to improve the security and cyber resilience of the physical counterpart, such as through threat analysis, attack modeling, risk analysis, security testing and similar analyses conducted on the Digital Twins.

Bentley remains committed to security, cyber resilience, and trustworthiness of all its products and data as a standard level of practice. Bentley also takes an additional level of care, when required, by complying with applicable compliance frameworks, which may relate specifically to government data.

Research should encompass not just the resilience of the Digital Twin and its component elements but also the use of Digital Twins to ensure the resilience of the corresponding physical infrastructure. Multiple datasets should be used to cross-reference and validate data currency, completeness, reproducibility, and accuracy to support a self-policing Digital Twin that can raise alerts and alarms when it detects discrepancies or anomalies. Research can also be done to ensure appropriate levels of access and security to Digital Twins are easily obtained, maintained, and verified.

2.12 *VVUQ*

Develop Rigorous Methods for Verification, Validation, and Uncertainty Quantification for Digital Twins: Possible focus areas: foundational and cross-cutting methods as well as domain specific; integration of VVUQ into all elements of the full digital twin ecosystem.

Bentley has created methods for VVUQ on its own digital twins and can provide insight into lessons learned from methods in practice. Researching open source and more transparent VVUQ development through committee creation and practices would also be useful.

2.13 *Workforce*

Cultivate Workforce and Training to Advance Digital Twin Research and Development: Possible focus areas: diverse talent recruitment; incentivize cross-disciplinary STEM research programs across educational institutions.

Over the past decade, Bentley has invested heavily in STEM education spanning from k-12 to higher education. These investments have not only included various levels of education but have also been inclusive of different industries and disciplines of engineering and technology. While Bentley's products may help in addressing workforce shortages, its technologies are not meant to replace human beings. Bentley believes that Digital Twins play a paramount role in helping close existing workforce gaps, all while continuing to support expansion of the STEM workforce.

Bentley sees great value in researching the standardization of workforce and supply chain digital maturity assessment. Providing standard Digital Twin datasets to academic institutions and education organizations as well as the development of short and long-term implementation training strategies will be instrumental in future research and dissemination.

New skillset and role requirements for research, education, and execution of new changes will be required by the workforce to continue the further implementation of Digital Twins. Research into how best to attract the next generation of engineers into asset disciplines will be essential. Additionally, studying how to extract the expertise of experienced engineers to encapsulate within Digital Twins to ensure their knowledge is not lost will be extremely valuable for future generations of engineers.

Federal Register Notice: 89 FR 51554, Federal Register :: Networking and Information Technology Research and Development Request for Information on Digital Twins Research and Development, June 18, 2024.

Request for Information on the National Digital Twins R&D Strategic Plan

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RFI Response: Digital Twins R&D Plan

The Agroecosystem Sustainability Center (ASC, https://asc.illinois.edu) is an interdisciplinary research center at the Institute for Sustainability, Energy, and Environment, University of Illinois at Urbana-Champaign. The ASC is dedicated to advancing agricultural sustainability through cutting-edge research in monitoring and modeling agroecosystems. In alignment with the goals of the National Science Foundation's Networking and Information Technology Research and Development (NITRD) National Coordination Office (NCO), we contribute our insights to the creation of a National Digital Twins R&D Strategic Plan, focusing on **sustaining agricultural production and environmental quality over the broad agricultural landscape**. Our focus is on leveraging digital twin technology to **build resilient agricultural systems and enhance both agricultural productivity and environmental sustainability by empowering adaptive decision-making in managing the broad agricultural landscape**. We envision prototyping and developing the following digital twins will make a profound and transformative impact on U.S. agricultural production and environmental sustainability:

- **Cropland digital twin**: The U.S. croplands are hotspots for human-environment interactions and serve our society by providing food, fiber, fuel, and other ecosystem services. Improving the management of cropland is critical for securing food production, enhancing resource use efficiency, and mitigating climate change. Traditionally, farmers make a series of complex farming decisions mainly based on personal experience and suggestions from peers and trusted advisors to maximize the profitability of crop production. The emerging conservation focus on cropland has the potential to help sustain crop production with less environmental footprints and bring farmers extra revenues from the ecosystem service market, but also further complicates the farming decision-making process due to the complex interactions and tradeoffs among different farming management practices and decisions. Building cropland digital twins can therefore help farmers to streamline and optimize the decision-making process.
- **Pastureland digital twin**: Grazing lands occupy an estimated 3.4 billion hectares (ha; 40%) of the global land surface and provide a suite of ecosystem services including livestock production, wildlife habitat, and many others. Grazing lands function as a key

element in livestock production and support rural and pastoral communities and livelihoods. With a growing population and burgeoning middle class worldwide, the demand for animal-sourced foods is anticipated to increase substantially. Meeting this demand presents several challenges for grazing land ranchers in the US who are already operating under the constraints of natural resource availability, climate change, and the complex demands of ensuring food security and environmental sustainability. Climate change, in particular, imposes substantial challenges for adaptive rangeland management with increased climate variability and frequency of extreme events, such as drought. Ranchers who currently rely on conventional practices and experiential knowledge may not be able to adapt to the changing climate and will require innovative decision-support tools to make their operations more sustainable, resilient, and climate-smart. Building a pastureland digital twin can therefore inform adaptive decisions on pastureland management. We envision a grazing land digital twin can (1) characterize different aspects of grazing land, including forage, animals, economics, and ecosystem services; (2) integrate diverse streams of data as inputs to the digital twin; (3) simulate scenarios and their corresponding impacts to support adaptive decision-making; and (4) generate quantifiable outcomes of different ecosystem services resulting from adaptive decision-making.

- **Watershed digital twin**: Watersheds are complex systems and watershed functions are arguably "emergent processes" – the net outcome from a watershed cannot be well-predicted based on just aggregating information at the sub-watershed scale. Instead, the interactions of hydrological, biogeochemical, and anthropogenic processes across multiple spatial and temporal scales within the watershed must be understood and captured for accurate prediction and interpretation of watershed responses. Climate change and human activities are affecting the quantity, quality, and spatiotemporal distribution of water resources at a watershed scale. Anthropogenic losses of nitrogen and phosphorus from agricultural land not only lower fertilizer nutrient use efficiency, but also lead to eutrophication and harmful algae blooms in streams, rivers, and inland water bodies as well as hypoxia in coastal areas. Building watershed digital twins can help optimize different water resource management scenarios and make more informed decisions related to sustainable water resource management at watershed scales. Watershed-scale digital twins can also help conservationists and landscape resource managers optimize different conservation strategies to improve both water quantity and quality.

Pertaining to the above digital twins, we provide our insights on the following topics:

Artificial Intelligence (AI): Leveraging artificial intelligence in building agricultural digital twins may significantly improve the efficiency and accuracy of prediction. As an example, researchers at the ASC are using knowledge-guided machine learning (KGML) to improve the quantification and prediction of both crop production and environmental footprints (such as greenhouse gas emissions and nitrogen leaching). Researchers at ASC are also coupling existing physical plant models with advanced computer vision techniques to generate 3D crop geometric models for major crops, such as corn and soybean. Given better geometric accuracy produced by these models, physical simulations on aggregated crop canopy digital twins closely mirror real system behaviors.

Data: Proper data collection and management is a cornerstone of digital twin implementation. ASC researchers are building integrated monitoring systems that use a combination of observational techniques to speed up data collection with less cost, including internet of things (IoT) sensor networks and cross-scale sensing (ground, airborne, and satellite remote sensing). We aim to continue and expand these methods to enable comprehensive monitoring and analysis of agroecosystems to inform digital twin models. With proper data quality control, multi-source observational data can serve as a multi-angle lens to depict the dynamics of complex real-world agroecosystems.

Ecosystem: A collaborative ecosystem across agencies and disciplines is crucial to advance the development of agricultural digital twins. Interdisciplinary research including agricultural science, geospatial science, environment science, and computational modeling can bridge potential research gaps. Collaboration across national agencies such as the National Science Foundation (NSF), the United States Department of Agriculture (USDA), or the National Aeronautics and Space Administration (NASA) would create a robust ecosystem for development.

Sustainability: Considerations of sustainability are at the forefront of agricultural digital twin development. Agricultural digital twins may inform humans to adopt sustainable agriculture practices, such as optimizing resource use or adopting smarter farming practices. With a combination of real-time observational data and predictive models, digital twin platforms enable us to make informed decisions to maintain ecosystem productivity while striving for increased sustainability. Enhancing real-time monitoring increases our ability to intervene swiftly. Predictive modeling helps to understand the interactions and trade-offs among different management practices on both ecosystem productivity and environmental sustainability, thus building up the foundation for supporting various decision-making.

VVUQ: To ensure the reliability of agricultural digital twin systems, rigorous methods of verification, validation, and uncertainty quantification should be included in each part of the digital twin architecture. Beginning from collecting and curating data used to empower the system, measurements of observational uncertainty should be collected. Supersites and experimental watersheds should be established to collect gold-standard validation tests. When leveraging artificial intelligence solutions for prediction or simulation, outputs should be associated with accuracies or representations of model confidence. All model predictions, no matter from process-based, AI-based, or hybrid models, should be validated using real-world data to verify model accuracy. Embedding VVUQ into agricultural digital twin architecture improves confidence from a scientific perspective and comforts users who are willing to consider decision-making recommendations from the digital twins.

Workforce: Developing a diversely skilled workforce is particularly important for the advancement of agricultural digital twins. Training programs integrating skills across academic disciplines (agricultural science, environmental science, geospatial science, computer science, engineering, and socioeconomics) would best prepare a workforce to develop agricultural digital twins. Additionally, cross-disciplinary STEM education ensures a broad range of perspectives in R&D efforts related to digital twins.

Concluding Remarks

With the insights above in mind, we currently imagine applications of agricultural digital twins in three broad use cases: cropland, pastureland, and agricultural watersheds. Cropland digital twins focus on complex cropland landscapes, including components such as crops, soil, water resources, climate, and human management to provide insights enhancing productivity and sustainability. Pastureland digital twins focus on the management of grazing lands, monitoring livestock health, and simulating livestock behaviors to predict grazing patterns and optimize productivity and sustainability of grazing land. Watershed digital twins integrate all natural and anthropogenic processes from headwaters to downstreams and from terrestrial to aquatic environments to predict water quantity and quality and also support watershed conservation planning efforts. Across various scales and systems, ASC highlights the potential impact of agricultural digital twins on improving agricultural productivity and environmental sustainability.

In summary, incorporating agricultural digital twins in the National Digital Twins R&D Strategic Plan enables advancement in adopting sustainable agricultural practices and addressing agricultural challenges. The ASC stands ready and excited for the development of a comprehensive strategic plan, including continued collaboration for the future development of agricultural digital twins.

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Request for Information on the National Digital Twins R&D Strategic Plan

BlockScience

Comments Submitted by BlockScience, University of Washington APL Information Risk and Synthetic Intelligence Research Initiative (IRSIRI), Cognitive Security and Education Forum (COGSEC), and the Active Inference Institute (AII) to the Networking and Information Technology Research and Development National Coordination Office's Request for Comment on The Creation of a National Digital Twins R&D Strategic Plan NITRD-2024-13379

Contents

Questions, responses, and requests related to this document may be directed to info@block.science

July 28, 2024

Submitted to:
NITRD/NCO
National Science Foundation | White House Office of Science and Technology Policy
[redacted]

The collaborating representatives applaud the Networking and Information Technology Research and Development National Coordination Office (NITRD/NCO) on its role in facilitating the development of a whole-of-government strategy for research investment on digital twin and model-based systems engineering, and appreciate the opportunity to provide recommendations and perspectives on the topics of (i) **data management infrastructure**, (ii) **trustworthiness and uncertainty quantification**, (iii) **standardization**, (iv) **responsible use**, (v) **professionalization and workforce development**, (vi) **commercial use**, and (vii) **sustainability and provisioning** in the context of digital twin implementation.

The collaborating representatives provide a unique synthesis of perspectives and recommendations on these topics, with consideration for business, operations, legal, technical, and social (BOLTS) use cases and risks, driven by their combined relationships and work within (i) universities, (ii) think-tanks, (iii) standards-setting organizations, (iv) global nonprofits and non-governmental organizations (NGOs), (v) corporations, (vi) military and government agencies, (vii) international policy and standards setting initiatives, and (viii) interdisciplinary academic, professional, and government communities of practice; and background in and prior work on (i) knowledge, information, data, and reference management and library science, (ii) intelligence and sensor fusion, (iii) interorganizational information exchange, (iv) law and legal engineering, (v) data and content verification, (vi) adtech, human factors, cognitive security, and social systems engineering, (vii) red teaming and adversarial use analysis, (viii) data poisoning and information quality control, (ix) sociotechnical systems and digital governance, (x) complexity science and dynamical systems, (xi) cognitive modeling, (xii) artificial intelligence, (xiii) cybernetics, robotics, control theory, and model-based systems engineering, and (xiv) mechanism, market, and institution design.

This response is organized into two sections: (1) background information and basis, and (2) clear, summary recommendations. The collaborating representatives have endeavored to keep this submission concise and policy-oriented, without sacrificing nuance.

Contributing Organizations and Representatives

Dr. Michael Zargham [1] Dr. David Sisson [1] Scott David J.D., LL.M. [2]
Dr. Daniel Ari Friedman [3, 4] R.J. Cordes [1, 3]

1. BlockScience

BlockScience (Block.Science) is a complex systems engineering, research and development, and analytics firm focused on the development and governance of safe, ethical, and resilient socio-technical systems. Sourcing insight and expertise on technology, economics, and governance from a diverse, interdisciplinary, and international community of scientists and engineers, BlockScience provides services to a wide range of clients and contributes to working groups, standards development, communities of practice, open-source projects, and academic literature related to model-based systems engineering, artificial intelligence, operations research, market design, network science, distributed systems, and modeling and simulation.

2. Information Risk and Synthetic Intelligence Research Initiative (IRSIRI)

The Information Risk and Synthetic Intelligence Research Initiative (IRSIRI) at University of Washington's Applied Physics Laboratory is an interdisciplinary program that integrates theory and practice for information risk management across business, operating, legal, technical and social (BOLTS) domains, and engages in research and development of processes to help guide emergent distributed interaction governance structures.

3. The Cognitive Security and Education Forum (COGSEC)

The Cognitive Security and Education Forum (COGSEC.org) was formed to convene experts to contribute to knowledge management and education infrastructure within the context of Cognitive Security - which refers to practices, methodologies, and efforts made to defend against social engineering attempts or intentional and unintentional manipulations of and disruptions to cognition and sensemaking at the scale of individuals, organizations, and societies. It hosts yearly initiatives to facilitate and support interdisciplinary and interorganizational research and engineering within related fields and industries.

4. Active Inference Institute (AII)

The Active Inference Institute (activeinference.institute) is dedicated to learning, researching, and applying Active Inference. AII provides avenues for connection and integration with broad audiences and disciplines and a setting for people to aid each other in pursuit of a better understanding of Active Inference. The Institute organizes education, research, and communications to advance the progress and public awareness of frontier knowledge in Active Inference and closely related topics.

Introduction

Digital Twins are useful enough to be dangerous. US Government Agency interest in funding and facilitating research, development, engineering, and implementation of Digital Twins (alongside factors related to their safe implementation) is therefore both reassuring and urgently necessary. Factors such as trustworthiness, reliability, interoperability, stability, sustainability, and responsible use must be addressed now, as there may not be another opportunity to do so before mass proliferation. If these factors can be adequately addressed, Digital Twins hold the potential to integrate physical and digital space – sparking a renaissance of capability exploration that will expand the horizons of research and commerce. If they are not, Digital Twins will inadvertently – but inevitably – become an evergreen source of threats and frustrations that will continue to challenge future generations. Here we argue that (i) conceptually, Digital Twins are not new – and thus we can learn from the common vulnerabilities, exploits, and remedies developed by prior approaches to closely-related problems in control theory and cybernetics, (ii) stable reference and data management capabilities and provisioning considerations are the underlying (but often-overlooked) prerequisites to building reliable Digital Twins, and (iii) the functional surface of a Digital Twin is roughly identical to its threat surface. We conclude with summary recommendations.

Background

In this section we provide background information and the basis for the summary recommendations offered in the section that follows.

I. Information Twins are a Time-Tested Approach

The notion of a "Digital Twin" gains traction in the early 2000's, but ***the underlying concept of mirroring the properties and state of physical objects, systems, and organizations in information space emerges far earlier***, in areas such as (i) aeronautics, (ii) robotics, (iii) cybernetics, (iv) finance, accounting, and business management, (v) governance, (vi) military science and command and control, (vii) library science, and (viii) logistics. More importantly, both the theory and practice of managing and maintaining information twins has been time tested for decades in spaces with (a) high-reliability conditions (e.g., military and transport aeronautics), (b) interorganizational use cases (e.g., automotive industry), and (c) requirements related to public and environmental hazards (e.g., chemical manufacturing and nuclear power). **Digital Twins are an expansion on prior art related to model reference based forms of control**, with an eye toward inclusion of new affordances, levels of accuracy, computational and forecasting capabilities, interaction affordances, and, most importantly, new areas of implementation. Consequently. **R&D Activity in this domain will include professionals and academics from disciplines that previously did not require an engineering background, or familiarity with control systems and/or model-based systems engineering.**

The depth of prior art in related fields and the breadth of new domains of implementation creates substantial risk of "re-inventing the wheel" and redundant work. For example, best practices, case studies, and toolkits for control, sensor fusion, and requirements engineering related to modeling (and around managing expectations related to modeling) complex systems already exist, but have not necessarily been made generalizable or accessible. If researchers are unfamiliar with the state of the art, they are likely to waste time, money, and effort attempting to advance it.

- **Recommendation 1.1:** R&D Activity should investigate and be complemented by workforce, competency, and professional development related to the art, science, and practice of model-based systems engineering.
- **Recommendation 1.2:** R&D Activity should prioritize professionalization within the context of Digital Twin implementation to ensure engineering capabilities and standards can be generalized or developed as a foundation for setting, communicating, and verifying safety and other requirements.
- **Recommendation 1.3:** R&D Activity should avoid "re-inventing the wheel" by mapping the extant, conceptual terrain. Common Vulnerabilities and Exploits (CVE) and other community pattern-finding and data-basing initiatives may be a functional means of creating a bridge between extant practices, patterns, risks, and remedies, and the interdisciplinary communities necessary to advance Digital Twin methodologies in new domains.

II. Model-Reality-Specification Gap

Even "identical twins" (two human beings with the same DNA) are never *exactly* alike. Although both twins are "generated from the same genetic code," neither twin simply *is* that code; rather, each twin is a distinct *implementation* of a common *specification*, and each will undergo distinct experiences that further differentiate them over the course of their lifetimes. **For the same reasons, a Digital Twin will never be perfectly mapped with its physical counterpart – and the cyber-physical gap between a real-world system and its digital representation will inevitably grow over time. The gap between model and "reality," however, is not the only gap of concern.** Digital Twins will inevitably have to manage not only the reference-referent gap that exists between the model and the *implemented* physical system, but also the reference-referent gaps between (i) the model and the *specifications* of the physical system's subcomponents, (ii) the *specifications* of the model and the *implemented* model, (iii) the systems' sensors and the *specifications* of those sensors, etc. – gaps that all **widen over time** at "power law"-driven rates[1] due to wear-and-tear, replacements, adjustments, modifications, patches, sabotage and malfeasance, perverse incentives, and other entropic factors.

[1] A "power law" describes a functional relationship between two quantities such that a relative change in one quantity leads to a proportional relative change in the other, causing change to occur at exponential rates.

In the fields of hardware security and supply chain engineering, there is already growing concern that these factors are driving **an expanding gap between components and component specifications that has not been properly assessed.** Failure to address specification gaps proactively will substantially increase the likelihood that Digital Twins do more harm than good.

Reference-referent problems are so fundamental that problems of digital "identity" are indistinguishable from classical problems of metaphysical identity and epistemics, such as (i) the "Ship of Theseus" paradox (i.e. *how many parts of an object can be replaced before that object becomes a different object?)*, (ii) the "Sorites Paradox" (e.g., *how many like-objects can be removed from the system before that system should be given a new descriptor?*), (iii) the "River Thames Problem" as posed by Bertrand Russell (i.e. *how does one draw the boundaries of a system or object in cases where those boundaries are subjective?*), (iv) the "Frame Problem" in Artificial Intelligence (i.e. *how do we decide what is relevant or in context without considering all that is not?*), and (v) Heraclitus' "River Paradox" (i.e. *if a continuous system is never the same system, at what point do we define phase transition or assign new identities?*). **These philosophical framings are not merely of academic interest - they are the bases for our legal and commercial framings for identity**. The GDPR-based laws of the EU reflect identity notions based on Hegel and Kant. US privacy and identity laws reflect philosophies of Locke and the Utilitarians. Digital Twins will challenge existing notions of "identity" in myriad ways across business, operations, legal, technical, and social (BOLTS) domains (and their respective performance metrics); thus, the implementation of interacting Digital Twins at scale will require us to update and clarify our understanding of fundamental philosophical concepts.

If and to the extent that existing and historical notions of "identity" (as broadly conceived) can help to stabilize our organization and operation of future Digital Twin systems, it will help us to most effectively direct our attention and resources to those domains and aspects of Digital Twin infrastructure that display less linear behaviors. Digital Twins will require a "neighborhood watch" relationship with humans to maintain stable function in an exponentially-expanding information space. Existing "identity" standards efforts might be usefully and normatively cross referenced to avoid redundancy in research and to increase clarity in approach.

Further, many of the systems of interest require "multiphysics" approaches, in which there is no unified approach to modeling dynamics, but instead a collection of approaches which are fit-for-function for particular areas of the system. This means that the same systems may not only be represented using different boundaries or functions, but also different *collections* of boundaries and functions – resulting in a perceivably infinite number of valid representations and related identities. Therefore, regardless of the consistency or intensity of enforcement functions and standardization, ***Digital Twins can contain multiple overlapping representations of systems or have variable representations of objects contained within them; consequently, their use in a given situation may be ineffective – or even fundamentally misleading.*** It is important that researchers and engineers recognize that **identity, system state, and specifications are intrinsically fuzzy, whether we treat them this way technically or not.**

The intent to design and implement "ecosystems" of Digital Twins – or interaction surfaces among Digital Twins and physical systems – means that **model-reality-specification gaps can generate cascading "telephone-game" errors**. **Furthermore, affordances for digital systems to interact with or command physical counterparts means that these modeling errors can spill into the physical world.** In addition to being able to interact through physical and digital means, **Digital Twins can be represented within one another and process digital objects** (i.e. a product that has both a physical form and digital representation may move through multiple Digital Twin systems, potentially operated by different organizations). ***Lack of common reference architecture for digital objects could create inconsistencies in resulting data outputs which may undermine forecasting, training data pipelines, and intelligence fusion capabilities in ways that are not easily detected until after the damage is already done – and may even be irreversible.***[2] The absence of a common reference architecture may also result in various misuses of data. For example, in cases where Digital Twins are concerned with medical or cognitive systems, there are nontrivial requirements related to the use, storage, and anonymization of data.

Finally, **Digital Twins have maintenance requirements**. As noted, due to wear-and-tear, replacements, adjustments, modifications, and other factors, the gap between a physical system and its digital representation increases over time. Cyber-physical integration thus requires both physical and digital logistics and security considerations. The initial implementation of such systems implies requirements related to **initial provisioning** (i.e. the planning of logistics related requirements for supporting and maintaining a system for its initial period of service), and their use implies requirements related to **assured provisioning** (i.e. the planning of logistics related requirements for rendering the support and maintenance of a system sustainable and reliable for the duration of its expected service/life-cycle).

- **Recommendation 2.1:** Scientific and technical R&D Activity should be complemented by facilitation of the formation of professional and trade associations that can offer continuing professional development, standardization, and certification related to data and reference management and specification assertions and claims (e.g., *has this component been verified as consistent with its digital representation and/or with its reference specification?*). Such organizations can be helpfully cultivated through connection and normative cross reference to the standards, protocols, practices and policies of existing professional and trade associations at the intersection of identity and digital representations of humans across business, operating, legal, technical and social domains.

[2] As an example of irreversible inconsistency, disagreements over the validity of data related to certain kinds of systems (e.g., those which may include a canonical ledger) may result in cases where organizations disagree over overall system identity or state at a particular time-step and must therefore *fork* their representation, from which point the forked paths can never again be reconciled.

- **Recommendation 2.2:** Common data and reference management schemes should be considered critical infrastructure for Digital Twin "ecosystem" implementations. R&D Activity should explore new approaches to interorganizational reference management and data sharing, with a prioritization on use cases where content location, schema, ontology, or underlying data may be unstable or not agreed upon across organizations.
- **Recommendation 2.3:** R&D Activity related to implementations should require consideration of both initial provisioning and assured provisioning related to security, maintenance, and other logistics requirements.

III. Digital Twins are a Threat Surface

The digital representation of the physical system is a threat surface. A cyber-physical system (e.g., a physical system with a Digital Twin) is a distributed system composed of (i) network and authentication protocols, (ii) software, firmware, and hardware components, (iii) APIs and digital asset exchange mechanisms, (iv) sensor arrays, (v) specification- and asset-reference protocols, and (vi) supervisory control and data acquisition (SCADA) interfaces, all of which are points of interaction that represent potential attack vectors. In other words, **the functional surface of a cyber-physical system is essentially indistinguishable from its threat surface.** By creating a reliable, computational digital representation of a physical system, we create a highly efficient targeting apparatus and basis for disruption. ***It is important to repeatedly acknowledge that Digital Twins are useful enough to be dangerous*** – their use in public health, critical infrastructure, and supply chains represent national security risks as much as they represent opportunities for efficiency, stability, and situational awareness. Further, their use in modeling cognition should be approached with extreme caution – the potential intrusions on cognitive liberty and related cognitive security risks created by the use of such models by opportunists and threat-actors should be considered reason for very serious concern. As can be learned from prior work on information-mirroring models in aeronautics, implementation of a sensor array is effectively the implementation of a new attack vector, thus **information warfare and information security are inseparable from the introduction of reliable sensor arrays**. Targeting sensor arrays which are upstream of system action is often cheaper and more accessible than direct, disruptive action.

While the technical risks associated with reliable models and the risks they pose in various domains are reasonably well known, the human factors and cognitive security risks related to perception and use of Digital Twin and supervisory control and data acquisition (SCADA) interfaces are equally important and often overlooked. The kinds of model-reference adaptive control (MRAC), augmentation control, and SCADA control functions that Digital Twin systems promise depend entirely upon the interpretation and reliability of sensor data, which in many cases means requiring agents-in-the-loop to catch and resolve errors (e.g., discovering a broken sensor and turning off adaptive control).

Cognitive security factors related to agent perception and action, such as agents (i.e. humans and digital) engaging with the model as a canonical, unquestionable representation of the state of the system can result in catastrophe. For example, consider the Chernobyl Disaster,[3] Lion Air Flight 610 crash, or Ethiopian Airlines Flight 302 crash,[4] each of which were contributed to by variants of model-specification-reality gaps.

Part of the value of Digital Twins resides in their facilitation of measurement of certain aspects of physical systems *for purposes other than system control*, such as regulation or monitoring of output and certifying estimates of certain aspects of operations (e.g., carbon emissions). **The existence of an extrinsic incentive related to a measurement about a system attribute creates a perverse incentive to target the measurement instead of the attribute** – a phenomenon which is generalized through the lenses of Goodhart's Law[5] and Campbell's Law.[6] **There have already been multiple scandals related to the manipulation of digital representations of physical processes** in the interest of meeting regulatory criteria or qualifying for subsidies, such as targeted parameterization of emission-measuring software to give different results under laboratory conditions as opposed to actual driving conditions.

- **Recommendation 3.1:** R&D Activity should proactively address (i) cognitive security (i.e. human factors and ergonomics problems related to digital and human agent perception of Digital Twins and related interfaces), (ii) cyber- and network-security, and (iii) threats to public safety, liberty, privacy, and general welfare.

- **Recommendation 3.2:** R&D Activity should prioritize exploration of dual-use research of concern, safety standards, and methods of data-sharing and process verification.

- **Recommendation 3.3:** R&D Activity should address mechanism, market, and institutional design factors related to standards and requirements incentives for Digital Twin design and use in industry, commerce, and related regulatory functions.

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[3] The Chernobyl Disaster was caused and exacerbated by a wide variety of issues, among which were lack of clarity in technical specification (expectations of reactor dynamics were based on incomplete information) and a misrepresentation by the on-site supervisory control and data acquisition (SCADA).

[4] Both crashes were related to control, modeling, and sensor errors.

[5] Goodhart's Law can be stated as either (i) *When a measure becomes a target, it ceases to be a good measure* or (ii) *Any observed statistical regularity will tend to collapse once pressure is placed upon it for control purposes.*

[6] Campbell's Law can be stated as: *Quantitative measures used in decision making processes subject those processes to pressures which corrupt and distort the system factors intended to be quantified*.

Summary Recommendations and Overview

Our summary recommendations, based on the background provided in the preceding section and categorized by the areas of interest listed in the request for comment, are as follows:

- **Data Management and Uncertainty Quantification:**
    - Common data and reference management should be addressed as critical infrastructure for Digital Twin ecosystems.
    - R&D Activity should include investigation into new approaches to reference management and data sharing that address instability in data location, schema, ontology, and underlying data; and should prioritize work which does so without requiring centralization, single-sources of truth, or total agreement from all parties in order to interact.
    - R&D Activity should prioritize approaches which treat data values, system state, and system specification as fuzzy or intrinsically uncertain.
- **Workforce, Professionalization, Standardization, and Responsible Use:**
    - Research portfolios should be complemented by convenings, forums, and other forms of multi-sector, interdisciplinary community engagements to facilitate the formation of relevant professional and trade associations.
    - R&D Activity should be complemented by model-based systems engineering education and professionalization activities for researchers and engineers, and should investigate best practices related to education on the topic.
    - R&D Activity should prioritize common vulnerabilities and exploits (CVE) and other community pattern-finding and data-basing initiatives in order to help researchers avoid pitching or performing redundant work.
- **Stability, Sustainability, and Security:**
    - Cognitive security (i.e. human factors and ergonomics) related to perception and use of Digital Twin and related interfaces should be treated as equally important to cyber- and network-security within a broader security and assurance research portfolio.
    - Risks related to dual-use research of concern, public safety, liberty, privacy, and general welfare should be addressed proactively in the research agenda, and potential for perverse incentives in business use-cases related to design and quantification of Digital Twins can be explored through mechanism, market, and institution design.
    - Research related to implementation should require consideration of initial provisioning and assured provisioning related to maintenance requirements.

Federal Register Notice: 89 FR 51554, Federal Register :: Networking and Information Technology Research and Development Request for Information on Digital Twins Research and Development, June 18, 2024.

Request for Information on the National Digital Twins R&D Strategic Plan

Brookhaven National Laboratory

Brookhaven National Laboratory Response to: Networking and Information Technology Research and Development Request for Information on Digital Twins Research and Development

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Date: July 28, 2024
Keywords: Artificial Intelligence, Ecosystem

1 Introduction: Ecosystem – Mathematical, Statistical, and Computational Foundations

The success of modern digital twins is highly dependent on innovations in computational and applied mathematics, jointly with advancements in computer science, high-performance computing (HPC), machine learning (ML), and artificial intelligence (AI), that can enable simulation, prediction, inference, and decision-making for digital twins. While predictive or decision-making capabilities in digital twins may exist, this is currently an active area of research [1, 2, 3]. Hence, continuous data assimilation and model calibration, as well as predictive or decision-making capabilities in digital twins, are not necessarily mature or fully integrated with traditional simulation methods. Thus, at present, digital twins are not utilized at their full potential. Fundamental research needed to achieve the goal of practical development and adoption of such predictive digital twins includes [2, 4, 5]:

- Mathematical methods that allow for unified frameworks for probabilistic modeling, processing, and analysis of data from a wide range of data distributions,
- Scalable and portable high-fidelity simulation algorithms and software libraries,
- Efficient surrogate models to enable fast real-time simulations to support decision making,
- Methods that enable uncertainty quantification (UQ)
- Methods for validation & verification (VV) of software, algorithms, models, and predictions,
- Methods to support processing/fusion of data from diverse sources, e.g., sensor measurements, images, video, and outputs from experiments/simulations,
- Integrated workflows and frameworks to support seamless data ingestion, model calibration, control, and decision making,
- Visualization techniques and other tools to facilitate integration of and support for the human-in-the-loop component of digital twins.

Furthermore, mechanisms that inform a digital twin user (human expert or AI agent) of the expected level of accuracy of the digital twin's simulations or predictive answers, and analogous feedback from the user to the digital twin, are essential to realizing the goal of continuous coupling/integration between the digital and physical twins. Such an ecosystem is depicted in Figure 1. In the next sections we expand upon some of the aforementioned aspects and research needs.

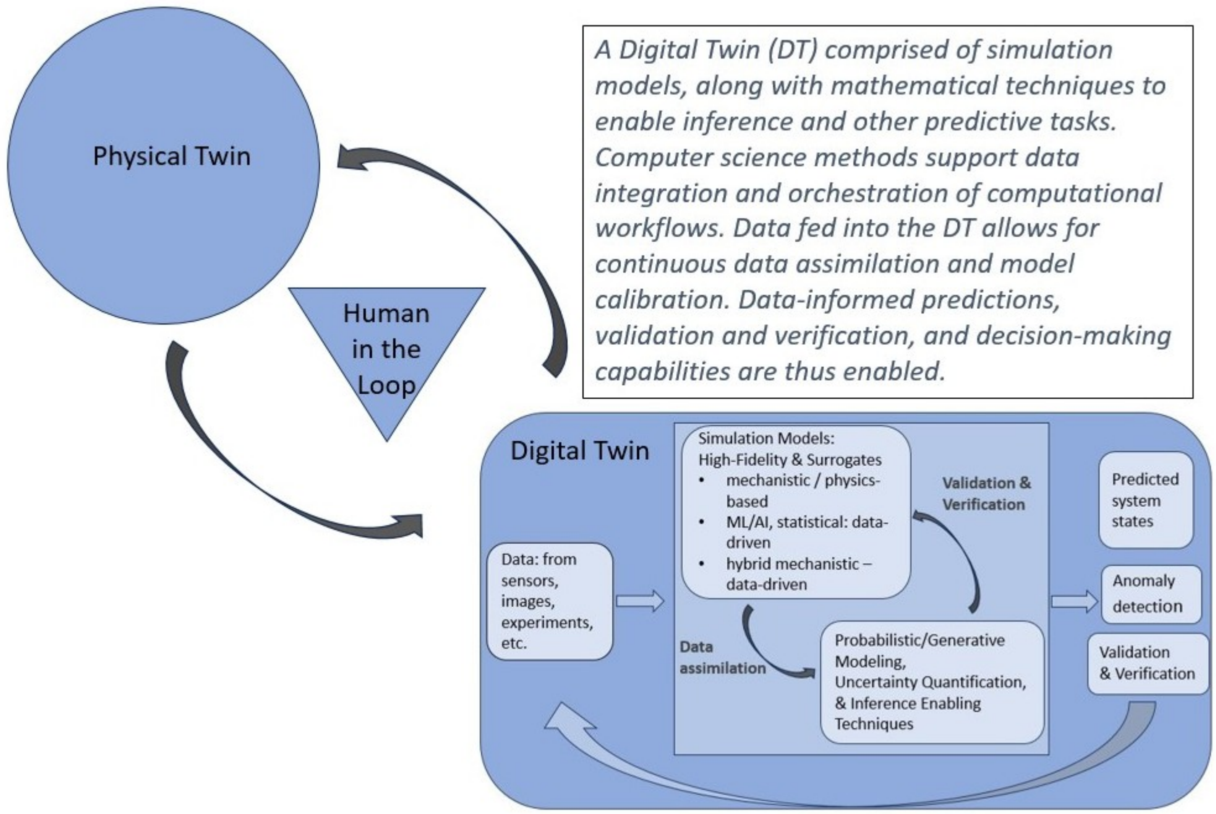

Figure 1: Exemplar digital twin ecosystem

2 Predictive Modeling and Simulation

As illustrated in Figure 1, methods from computational and applied mathematics are central to digital twins (DTs). The success of modern, predictive DTs is thus highly dependent on advancements in computational and applied mathematics that can enable simulation, data assimilation, inverse problem solution, prediction, inference, and decision-making for DTs [2, 4, 5]. Also essential is integration of such methods with computer science techniques for workflow orchestration and frameworks that support seamless processing of data from diverse sources.

A hierarchy of models for simulating phenomena associated with the physical twin is one core component of a DT's mathematical ecosystem. The collection of models may include both deterministic and stochastic models and should offer various degrees of fidelity and levels of required computing resources so as to allow for a range of needs, from real-time or interactive processing to execution of non-real-time simulation workflows. The models can be (a) mechanistic, such as those governed by (systems of) ordinary/differential equations or differential algebraic equations, and should include high-fidelity models and their surrogates of lower levels of fidelity, but which are also less computationally demanding, (b) purely data-driven, such as machine learning (ML), artificial intelligence (AI), or other statistical models, and (c) hybrid mechanistic – ML/AI/statistical models. Via judicious algorithmic choices, surrogate (mechanistic/ML/AI) models can be used together with (or in lieu of) high-fidelity models in order to reduce computing costs, while retaining acceptable levels of accuracy in the results [6, 7].

Probabilistic and statistical methods, modeling frameworks accounting for both additive (i.e., probabilistic) measures of uncertainty as well as for non-additive ones (i.e., imprecise probabilities), and other inference enabling techniques [8, 9, 10, 6, 11, 12, 1, 13, 14, 3, 15, 16] are another class of methods essential for predictive DTs. These include methods that allow for unified frameworks for generative/probabilistic modeling and analysis/assimilation of data from a wide range of distributions, Gaussian and non-Gaussian alike, such as those grounded on the theory and application of optimal measure transport. Equally important are data assimilation techniques as well as methods that enable uncertainty quantification (UQ) and validation & verification (VV) for the assessment of (a) models, (b) simulation of quantities of interest, and (c) predictions resulting from DTs. In conjunction with the aforementioned simulation capabilities, as well as with computer science methods for workflow coordination and data management, they provide core capabilities to enable predictive modeling, simulation, and decision making for DTs.

3 Long-Term Research Needs for Computing

To support digital twins' diverse use scenarios - from real-time monitoring and control, to offline design optimizations of the physical systems - there is a need to provide the computational readiness through the integration and application of modern advanced computing methodologies. The essential components of a responsive digital twin would require the scale-appropriate modeling and simulation approaches and fast, real-time, inference and prediction based on the data streams captured by the digital twin, all of which require considerable computational resources.

However, not all the computational requirements can be met through the large-scale processing at traditional data centers and supercomputing facilities, as the overhead of transferring the data into or out of these centralized facilities may be too large for certain digital twin applications. Edge computing devices and other novel computing architectures may be needed to support digital twins with low-latency requirements. Research and development is needed on the performance, programmability, and energy efficiency of new hardware architectures for compute, storage and data transferring fabrics to support digital twin deployments. In particular, user-friendly and portable programming models need to be developed to ensure the efficient utilization of the new architectures. Software tools, including performance analysis, monitoring and benchmarking, debugging frameworks and workflow middleware will need to be developed or adapted from existing ones to support the unique requirements of digital twin applications.

4 Sustainable and Extensible Software Ecosystem

The advancement and adoption of digital twins in sciences, engineering, and healthcare necessitates the development of a sustainable and extensible software framework. The framework should identify crosscutting creational design patterns and provide base classes for data storage, data refinement, system components, computational models, machine learning methods, and visualization. It should seamlessly combine the aforementioned components with workflow orchestration technologies for efficient execution on HPC machines as well as allow for the bidirectional interaction with a human-in-the-loop.

Thus, a unified software framework encompassing all software needs for a digital twin is an outstanding challenge. This framework must be modular, extensible, portable, and user-friendly to enable widespread adoption by the domain specialists in various applications. Currently, several such frameworks from the industry as well as research labs are undergoing development [17, 18]. The existing tools provide mechanism for asynchronous multi-host execution; however, they lack the interface to workflow scheduling, and execution tools on HPC machines [19, 20, 21]. Moreover, a successful digital twin must scale on the world-class extreme computing platforms which emphasizes performance and energy consideration of each individual component. Such a framework should be built around performance portable programming models [22, 23, 24, 25] to enable utilization of the HPC machines with minimal human effort for software redevelopment.

The digital twins rely on integrating heterogeneous computing components such as AI/ML models with HPC simulations. Currently, most scalable physics-based models are primarily developed in high-performance computing languages like C++. In contrast, the data-driven methods largely rely on Python frameworks such as PyTorch/TensorFlow/JAX. There is also an imperative need of integrating libraries that interface statistical models for uncertainty quantification [26, 27]. Digital twins require load-balancing algorithms to interact with high-performance computing resources, monitoring, logging, and recovery mechanism, and a lightweight 3D rendering for a real-time interactive visualization. The software landscape is complex which makes the integration quite challenging even if several excellent components exist. The adaptation of digital twins into different applications relies on a low entry barrier software framework. This framework should act as a portable and easy-to-use abstraction layer that unifies the various components of a digital twin.

5 Visualization

The development of digital twins (DTs) offers a viable opportunity to leverage human expertise and intuition to guide experimentation design and processes. From the perspective of visualization, such innovative DTs must render realistic physical systems and sensor data, support human interactions with the systems and capture that in real-time, so that generating intervention strategies can be autonomous or via human-in-the-loop. This revolutionary transformation requires orchestrating state-of-the-art visualization, AI, and HPC techniques.

There are three major visualization tasks for DTs [28]: 1) monitor and analyze the data from the physical assets to identify important events and trends in various visualization forms; 2) display simulations that are crucial to identify improvement opportunities and optimize the performance of physical assets and systems, allowing users to explore scenarios in real time, test alternatives, and design more efficient solutions; and 3) generate predictive maintenance alerts, highlighting potential issues before they become critical so that proactive actions can be taken to improve the reliability and efficiency of their equipment.

To realize the digital twin through visualization, there are three different techniques: 1) rendering a virtual 3-D representation (such as using NVIDIA's Omniverse [29]) and allowing users to interactively explore the virtual scenarios that might not be possible with physical systems; 2) situated visualization [30] using augmented reality to overlay 3-D renderings with computer-generated imagery directly in their physical locations; and 3) virtual reality supporting human-physical system interaction with gaze, head, and hand movements with haptic feedback.

The opportunities for enhancing current visualization techniques for DTs include several directions. First, efficient digitization techniques are required to provide high visual fidelity in appearance of the virtual environments with realistic human-system interactions. Even from limited images, it requires to photorealistically digitize complex physical environments. The challenge is to reserve the underlying physical principles or feedback realism of human-environment interaction, which can limit the applications for capturing natural and accurate human activities in scientific experiments. Second, it is essential to develop methods for effectively presenting the data to adapt seamlessly to various experimental conditions. A typical 3D scene visualization system is limited to pre-captured images. Once the experimental conditions vary, the regeneration triggers the need of full-blown experiments, image capture, 3D reconstruction, and rendering. It remains a challenge to bypass the process and result in a significantly faster and more interactive experience. Third, a new approach is needed to understand the rationale behind the decisions made by DT and increase assurance for humans to trust DT's findings [31]. This will facilitate humans-in-the-loop fashion enabled by adding a human cognitive dimension to DT's dynamic data-driven modelling and simulation, by involving human cognition at different simulation stages or in various formats. Finally, capturing human interaction with DTs will be vital for understanding and streamlining the experiment process, allowing us to identify key aspects to observe; improve information synthesis; and, ultimately, optimize decision-making. Currently, the information typically flows from the physical system to the users [32], but the feedback mechanism going the other way remains manual and tedious.

6 Artificial Intelligence (AI) Foundation Models

Foundational models (FMs) have revolutionized AI by providing a unified approach to handling different data modalities and performing a variety of tasks. In the field of digital twin research, FMs have great potential to enhance the development, accuracy, and usefulness of digital twins across multiple scientific fields. For example, in materials science, combining FMs with digital twins enables researchers to simulate and predict material behavior under different conditions, facilitating the design and testing of new materials with desirable properties. This approach can be equally applied to biomedical research, climate science, and nuclear physics, where accurate simulation and predictive capabilities are equally important.

The benefits of combining foundational models with digital twins include:

- **Strong predictive capabilities:** Foundational models trained on broad and diverse datasets demonstrate strong predictive capabilities. In the scientific field, this means more accurate simulations of complex systems under a variety of conditions, facilitating the creation of highly predictive digital twins. These enhanced predictions can inform design, testing, and optimization processes, reducing the need for expensive and time-consuming physical experiments.
- **Multimodal data integration:** Digital twins require the integration of data from a variety of sources, such as sensor data, experimental results, and theoretical models. Foundational models excel at handling multimodal data, allowing for seamless integration and interpretation of diverse data sets. This capability ensures that the digital twin is always updated with the latest data, maintaining its relevance and accuracy.
- **Accelerate scientific discovery:** Foundational models can greatly accelerate the discovery process by providing insights into the complex behavior and properties of the system being studied. By incorporating these insights into the digital twin, researchers can simulate and

predict how new designs or materials will perform under different conditions. This acceleration of discovery is critical to solving pressing challenges in areas such as energy storage, environmental sustainability, and advanced manufacturing.

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Request for Information on the National Digital Twins R&D Strategic Plan

C2SMARTER

C2SMARTER
CONNECTED COMMUNITIES WITH SMART MOBILITY TO EQUITABLY REDUCE CONGESTION

Networking and Information Technology Research and Development Request for Information on Digital Twins Research and Development

This document respondes to ***Artificial Intelligence (AI):* AI and Digital Twins** topic with a focus on **Transportation Digital Twin (TDT).** This response is prepared by Dr. Kaan Ozbay, Director and Professor at ***C2SMARTER Center, New York University (NYU)***, specializing in Intelligent Transportation System, Traffic Safety, Traffic Control, and Dr. Zilin Bian, postdoctoral associate at NYU C2SMARTER center, specializing in AI and systems, and Dr. Jingqin Gao, Assistant Director of Research at C2SMARTER Center, specializing in Intelligent Transportation System, Traffic Management, and Dr. Fan Zuo, postdoctoral associate at NYU C2SMARTER center, specializing in Behavior and Learning theory, Simulation, Cybersecurity.

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Introduction of C2SMARTER

Connected **C**ommunities for **S**mart **M**obility towards **A**ccessible and **R**esilient **T**ransportation for **E**quitably **R**educing *Congestion* (C2SMARTER), is a multi-university U.S. DOT Tier 1 University Transportation Center, uses **cities as living laboratories** to study challenging transportation problems and **find solutions from the unprecedented recent advances** in communication and smart technologies. C2SMARTER is led by New York University (NYU) and is a consortium of seven universities working across fields and geographies. We focus on emerging technologies, operational policies, and their interactions with and impact on transportation and urban systems — including using evidence-based decision making to turn research into transformative solutions that take advantage of recent advances such as artificial intelligence (AI) and digital twins.

C2SMARTER has coordinated and collaborated with other universities and agencies to develop multiple digital twins testbeds, especially transportation digital twins (TDT) for emergency vehicle operations, flooding management, connected and automated vehicles (Figure 1). Leveraging Digital Twins in the transportation sector, significant energy savings can be achieved. Digital Twins enable more efficient traffic management, reducing congestion and optimizing vehicle routing, directly lowering fuel consumption and emissions. In the event of accidents or major catastrophes requiring evacuation, Digital Twins provides real-time data and predictive insights to streamline operations, minimize delays, and ensure energy-efficient responses. This integration not only improves operational efficiency but also supports sustainable urban mobility. Furthermore, Digital Twins are essential for planning and managing multi-modal transportation systems, enhancing the efficiency and coordination of various transport modes such as buses, trains, bikes, and ride-sharing services.

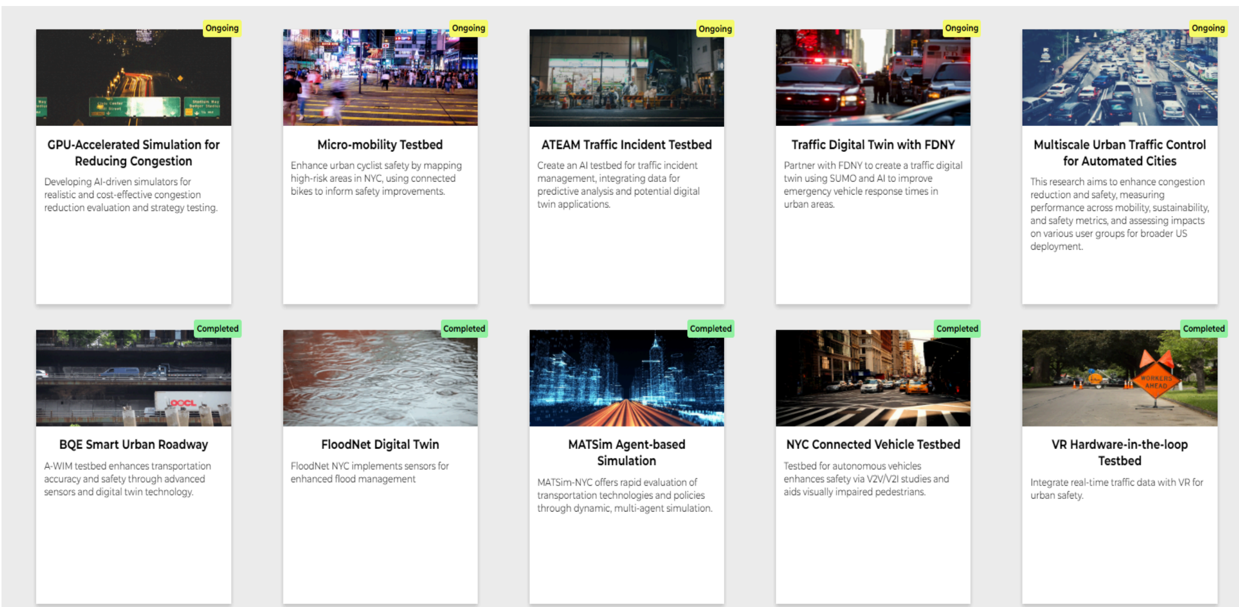

Figure 1. C2SMARTER Digital Twins Testbeds.

Transportation Digital Twin (TDT)

This document adheres to the definition of Digital Twins (DT) as provided by the DOE's Office of Science and Technology Policy (OSTP) and the National Coordination Office for Networking and Information Technology Research and Development (NITRD). According to this definition, a DT is a set of virtual information constructs that mimics the structure, context, and behavior of a natural, engineered, or social system (or system-of-systems). It is dynamically updated with data from its physical twin, possesses predictive capabilities, and informs decisions to realize value. The bidirectional interaction between the virtual and the physical is central to the DT concept.

Applying this concept to the transportation domain, a TDT includes three primary stages:

1. **Physical Space**: This includes human beings, vehicles, and transportation infrastructure.
2. **Digital Space**: This involves the creation of digital replicas of the aforementioned physical entities and assets.
3. **Bidirectional Communication**: This stage facilitates continuous, dynamic interaction between the physical and digital spaces, ensuring that the digital twin is consistently updated with real-time data and can influence the physical world.

Transitioning from this foundational understanding, the effectiveness of a TDT is realized through three integral processes: Sensing, Modeling, and Intervening.

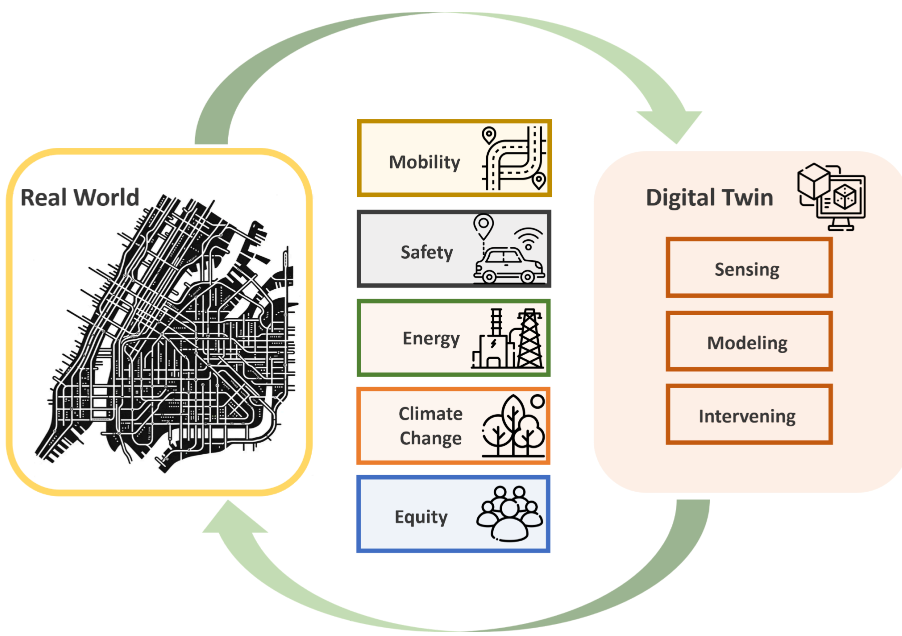

Figure 2. Concept of Transportation Digital Twins.

Sensing

Sensing involves the process of collecting data from the physical world through various sensors and monitoring devices. This data encompasses traffic flow, vehicle speeds, road conditions, and environmental factors. Accurate sensing information ensures that the virtual space remains synchronized and accurately represents the physical space.

Various sensing infrastructures, such as connected vehicles, infrastructure-based surveillance cameras, loop detectors, and probe vehicles, provide varied data types and levels, from individual human or vehicle data to route/network-level information.

Computer vision technology has significantly improved traffic sensing infrastructure, enabling the capture of real-time traffic information through dash-cameras in vehicles and surveillance cameras along roadsides. AI methods such as object detection, sorting/tracking, and re-identification can track trajectories of traffic objects, generating continuous captures across multiple sensing infrastructures. Additionally, AI can facilitate the coordination and cooperation of multiple sensing infrastructures, capturing a broader scale of traffic information through cooperative perception methods that fuse data from vehicle-onboard and roadside devices.

Moreover, augmented reality (AR) and virtual reality (VR) technologies can enhance information capture for DTs. For instance, VR has been used to study work zone workers' interactions with roadside units and connected vehicles, improving their safety and reducing conflicts.

Recent advancements in generative AI (GenAI) present further opportunities for the sensing stage. Technologies such as visual foundation models (VFMs) can accelerate and automate the processing of vast amounts of traffic scene videos, reducing the need for human labor in extracting useful information like congestion and incident data, thereby aiding in the construction of the virtual space in DTs.

Modeling

At the modeling stage, DTs perform two primary tasks: representing and reconstructing the current physical space, and estimating and forecasting the future physical space. Representation and reconstruction ensure that DTs create accurate replicas, while forecasting provides predictive insights and guidance for intervening in the physical space.

Representation/Reconstruction: With data from sensing infrastructures, the virtual space must accurately reconstruct the physical space. This requires robust representation capabilities, whether from the vehicle-end or system-end. For advanced vehicles, such as automated vehicles, real-time environmental reconstruction is crucial. AI methods, such as 3D modeling and occupancy neural networks, convert captured data into digital objects. At the system-end, DTs must calibrate and fine-tune agents in the virtual space to replicate behaviors observed in the physical space, using methods like simultaneous perturbation stochastic approximation (SPSA) to calibrate traffic agents within simulation environments.

Forecasting: Forecasting within DT leverages AI to predict future traffic conditions, enabling proactive interventions and strategic planning. Machine learning models, such as neural networks and gradient boosting machines, analyze historical and real-time traffic data to predict congestion patterns, incident likelihood, and travel demand. AI techniques like graph neural networks combined with temporal methods, such as transformers, can process complex datasets to forecast traffic flow and potential disruptions. GenAI can enhance these predictive capabilities by generating synthetic datasets for training, simulating rare events, and providing advanced analytics to improve model accuracy. These predictive capabilities allow for dynamic adjustments in traffic signal timings, ramp metering rates, and real-time routing suggestions, optimizing traffic flow and minimizing congestion.

Furthermore, modeling within a TDT includes energy consumption simulations, allowing for assessing and optimizing fuel use and emissions. By predicting and managing traffic conditions, TDTs can recommend energy-efficient routes and speeds, reducing fuel consumption and lowering emissions. This aspect is crucial for planning sustainable urban transportation systems and mitigating the environmental impact of vehicular traffic. Additionally, TDTs are crucial in planning and managing multi-modal transportation systems and integrating emerging connected and autonomous vehicles. They also support the development of Mobility as a Service (MaaS) by providing real-time data and predictive analytics to optimize the use of various transport modes, enhancing the efficiency and convenience of urban mobility solutions.

AI-driven forecasting integrates weather data, demographic trends, and economic indicators to enhance the accuracy of predictions. By simulating various scenarios, AI can predict the impact of adverse weather conditions on traffic and the efficiency of public transportation systems. These advanced forecasting methods support long-term infrastructure planning, emergency preparedness, and the integration of emerging technologies like autonomous and electric vehicles, ensuring the resilience and sustainability of transportation networks.

Intervening

Intervening leverages insights from the digital twin model to make informed decisions and take proactive actions in the physical world. This stage includes real-time decision-making, automated control systems, and strategic planning, based on data and simulations provided by the digital twin.

Vehicle-End Intervention: Vehicle-end interventions within DT can leverage AI to enhance the functionality and safety of individual vehicles. AI algorithms, such as those used in adaptive cruise control and automated driving, process real-time data from sensors to optimize trajectory planning, routing, and navigation. Reinforcement learning and spatial-temporal modeling techniques enable vehicles to dynamically adjust their paths, avoid obstacles, and respond to incidents, improving overall traffic flow and safety. Additionally, Vehicle-to-Everything (V2X) communication, powered by AI, facilitates real-time data exchange between vehicles and infrastructure, enhancing situational awareness and coordination.

GenAI can further improve autonomous driving by better identifying and reacting to road risks. Visual Foundation Models (VFMs) and Large Language Models (LLMs) can convert visual information into descriptive contexts, interacting with human-knowledge databases to inform vehicle motion and risk responses. For example, GenAI can enhance trajectory prediction through chain-of-thought reasoning processes tailored to specific traffic scenarios. By leveraging the power of LLMs, semantic annotations can be generated to significantly improve the understanding of complex traffic environments, thereby boosting prediction accuracy and robustness.

System-End Intervention: System-end interventions in DT can utilize AI to optimize and manage complex transportation networks. AI-driven traffic signal control employs reinforcement learning algorithms to dynamically adjust signal timings based on real-time traffic conditions, reducing congestion and improving flow. Traffic camera control systems use computer vision to detect incidents and monitor road conditions, automating responses and maintenance. AI enhances ramp metering by analyzing real-time data to regulate vehicle entry onto highways, balancing demand and capacity to prevent congestion. AI-driven demand management strategies predict travel patterns and suggest optimal routes, influencing travel behavior to reduce congestion. Integrated Transportation Management Systems (ITMS) leverage AI for real-time data analysis and automated control, ensuring coordinated responses to traffic conditions.

Additionally, system-end interventions can significantly contribute to energy savings by optimizing traffic signals to minimize idle times and stop-and-go waves, which are major causes of fuel wastage. AI-driven traffic management can smooth traffic flow, reduce delays, and lower overall fuel consumption, promoting a more sustainable transportation system. Furthermore, TDTs are essential for implementing Mobility as a Service (MaaS), providing a comprehensive platform for decision-makers in both public and private sectors to manage and optimize multi-modal transportation networks, enhancing the user experience and operational efficiency.

Conclusion

This document explores foundational research gaps and opportunities for digital twins in the transportation domain by following the processes of sensing, modeling, and intervening. The integration of AI at each stage enhances the capabilities of DTs, providing accurate representations, predictive insights, and effective interventions to improve transportation systems.

The application of Digital Twins in the transportation sector presents a transformative opportunity to enhance energy efficiency and sustainability. By optimizing traffic management and reducing congestion through real-time data and predictive analytics, DTs can significantly lower fuel consumption and emissions. Furthermore, Digital Twins facilitate more effective responses to accidents and major catastrophes, ensuring efficient evacuation and minimizing delays, which are crucial for saving energy during emergency operations. Incorporating energy consumption simulations within the TDT framework allows for continuous fuel use assessment and optimization, reinforcing the commitment to sustainable urban mobility.

In summary, the strategic deployment of Digital Twins in transportation improves system efficiency and safety. It plays a vital role in reducing the environmental impact and supporting the transition to sustainable urban mobility. Integrating AI and DTs positions us to meet future transportation challenges while advancing energy-saving and sustainability objectives. Additionally, Digital Twins support the planning and operation of multi-modal transportation systems and the integration of connected and autonomous vehicles. They are essential for implementing Mobility as a Service (MaaS), providing a comprehensive tool for decision-makers in both the public and private sectors to enhance the efficiency and user experience of urban mobility solutions.

Federal Register Notice: 89 FR 51554, Federal Register :: Networking and Information Technology Research and Development Request for Information on Digital Twins Research and Development, June 18, 2024.

Request for Information on the National Digital Twins R&D Strategic Plan

Center for Virtual Imaging Trials, Duke University

Future of Digital Twins and *In Silico* Trials in Medicine

Response to the National Academies report: National Digital Twins R&D Strategic Plan

Comments from Center for Virtual Imaging Trials, Duke University[1]

We have reviewed the National Academies report on Digital Twins with great interest and commend the committee for developing this comprehensive and invaluable document. The report effectively outlines foundational research gaps and future directions for digital twins across various domains, addresses practical concerns, and provides recommendations for program development and cross-agency collaboration. We believe that this document offers a thorough roadmap for advancing digital twin technology, enhancing scientific research, and industrial applications. We would like to share some complementary thoughts that may be considered for the Research & Development Strategic Plan in the context of biomedical sciences.

Moonshot for the future of digital twins and *in silico* trials in medicine

We believe that a strategic plan needs a "moonshot" goal, with identified gaps and prioritized areas. In April 2024, the Virtual Imaging Trials in Medicine (VITM) Summit at Duke University hosted a roundtable where thought leaders, developers, and regulators from academia, industry, government, and funding agencies gathered to chart a path forward for use of digital twins and *in silico* trials in medicine. The roundtable included leaders from the NIH, FDA, congressional offices, and leading experts of *in silico* methods. A white paper reflection of this roundtable is currently under peer review. The roundtable participants reached a consensus on an ambitious goal to drive the future of digital twins in medicine:

> ***Form and foster a digital twin of every individual, integrated into their medical record, owned by them, and continuously updated with new data. This twin will be used to deliver optimized personal care and, with the individual's permission, for technology assessment, real-world evidence, and population aggregate analysis.***

This moonshot envisions a future where every person has a digital twin that evolves over time, becoming more personalized with the integration of new data. This approach promises to revolutionize personal care across various medical priorities and conditions, including cancer, cardiovascular disease, diabetes, geriatrics, and obesity.

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Achieving this moonshot requires overcoming several critical gaps and obstacles identified during the discussions:

- Data access and privacy: Ensuring data accessibility while maintaining privacy and security, establishing an economical framework for data access and sharing, and emphasizing patient engagement in data sharing.
- Harmonization and standardization: Creating standardized resources and protocols.
- Educational and training gaps: Addressing educational deficits and skilled expertise in digital twin technologies, ensuring physicians have access to necessary technology, and providing more training to understand and use resources.
- Clarity of scope: Clarifying the complementary roles of regulators, industry, and academia.

These gaps are well articulated in the current National Academies report. Additionally, our roundtable discussions recognized two critical gaps when digital twins are used in biomedical applications:

- Individualized patient access and health equity: Tailoring access to technology for individual patients and ensuring equitable access for all, recognizing the willingness of individuals to share information if managed well.
- Regulation and reimbursement: Securing reimbursement from insurance companies, overcoming regulatory hurdles, and ensuring strong engagement of biomedical engineers at the Food and Drug Administration.

As rightfully mentioned in the National Academy report, "publicity around digital twins and digital twin solutions currently outweighs the evidence base of success." We agree with this sentiment and believe that priorities are needed to ensure credible advancement. Towards this, the VITM roundtable emphasized the need for national and global collaboration. Establishing a digital Contract Research Organization (CRO) framework is suggested to foster systematic trial development and build trust and awareness through transparent communication and early discussions. Additional advancement might be energized by

- Advocating with funding agencies
- Forming multi-disciplinary teams and initiating a regulatory science collaborative community
- Identifying and engaging standards communities for interoperability
- Harmonizing efforts across regulators and academics to devise good simulation practices
- Engaging the industry through regulatory affairs

We are pleased to see that the National Academy report has highlighted several of these priorities. An additional key priority recognized by us is:

- Engaging with patients and patient advocacy communities

We believe that patient engagement is crucial to ensure trust and their benefits since patient benefit and care is the ultimate goal in medicine. Advocacy communities are also needed to ensure that patients have proper ownership of their digital twins, integrating them into their medical records, and updating them continuously with new data.

Four key priority area

In advancing the cause and potential of digital twins in medicine, the VITM summit further discussed and details four specific priority areas that we suggest to be incorporated in the deliberations of the National Digital Twins R&D Strategic Plans:

Real plus Virtual: Maximizing the complementary role of clinical and in-silico methods in medical evaluation

Proficient and efficient evaluation of medical products is a crucial need in medicine. The requisite proficiency and efficiency can be enabled by integration of diverse clinical trial methodologies, focusing on optimizing the complementary aspects of real and virtual methods. Common among all types of trials is the need and challenge of ensuring the diversity of studied population, addressing the needs of rare diseases focus, complexity of the research design and avoidance of bias, managing the open-source vs. proprietary nature of some tools, and lack of broad standards for trial design and execution. Within this landscape, real, virtual, and hybrid clinical trials, offer comparable advantages and disadvantages:

Real Clinical Studies:

- Advantages are well-detailed, reflecting standard clinical practices and educational alignment, and definitive clinical endpoints.
- Disadvantages accurately highlight the slow, costly nature and large sample size requirements.

Virtual/In-silico Clinical Studies:

- Advantages include subject safety (e.g., no radiation exposure), long-term monitoring, rare disease study capabilities, testing of new concepts, reduction in animal testing, and providing quantitative endpoints.
- Disadvantages include needed validation for realism and credibility, as well as ease of implementation by users.

Hybrid Studies:

- Advantages includes potential balance between efficiency (of virtual) and accuracy (of clinical) methods.
- Disadvantages include certainty re the best integration strategy.

A key consideration for incorporating a virtual approach as a trial tool is its level of reliability and trustworthiness. These can be enhanced by combining the virtual approach with complementary physics experiments. This aligns with the need for quality metrics that closely reflect clinical outcomes, and in the same vein, clinical outcomes that should be expected and meaningful for virtual trials. Such goals, while worthwhile, are not absolute: striving for perfection can be counterproductive, as perfect is often the enemy of good.

Towards that goal, the FDA has recognized virtual diagnostic imaging tools as Medical Device Development Tools (MDDTs) in the Non-clinical Assessment Model category, indicating their acceptance for non-clinical evaluations of medical devices [1]. Future strategies should facilitate uniform testing across imaging modalities and realistically optimize associated parameters through simulations followed by clinical validation. In that effort, the focus should extend from specific parameters to quantitative biomarkers to understand how simulation processes and accuracy impact imaging endpoints. Imaging and clinical and endpoints are certainly not necessarily identical either. They are distinct measures in medical research, each providing different information about treatment efficacy and patient outcomes. Understanding these distinctions is crucial for ensuring that research findings are relevant and applicable to broad patient populations.

Physics plus Biology: The intersection of physical and biological simulations impacts our understanding of metabolism, treatment, and disease progression

Real trials involve the entire complexity of reality, but they can only reveal a part of it due to practical limitations. Simulations focus on a limited aspect of reality, but within that scope, they can offer complete and detailed insights. These distinctions are important for understanding the strengths and limitations of different research approaches and methodologies.

Physics and biology take different approaches to simulation, each of which with their own assets and limits. Physical models tend to be more straightforward as physical approaches often involves well-defined laws and equations that can predict outcomes with high precision. In contrast, modeling biological systems is much more complex due to their high variability, numerous interacting components (genes, proteins, cells, etc.), and the influence of countless internal and external factors. This complexity makes it challenging to create simple models in biology such that they are accurate and predictive. However, this task can be a bit more manageable when the variabilities are captured for individual patients, as opposed to aggregates across patients which introduce additional sources of variability.

Utilizing digital twins to tailor treatments to the unique characteristics and requirements of an individual is an additional consideration. While clinical trials typically address the general population, evaluating utility across a population might disregard individual experiences. An “average” patient represents no single individual within a cohort of individuals. Consequently, although trials provide insights into broader trends for a given technology or intervention across a population, they naturally fall short of fully capturing what might be optimum for an individual patient.

Looking ahead, therapy and healthcare are becoming more personalized and responsive. Concepts like prospective adaptive therapy and response prediction are driving this shift. Additionally, individualized surveillance decisions are seeking to ensure monitoring strategies are customized for each person. These advancements promise more effective and precise care, better meeting the diverse needs of patients in the future. Towards that goal, there is need for the integration of physics- and biology-based models, as they not only invoke complementary mindsets, but together cover a broader swat of physical reality and offer different dimensions of phenotypes that are instrumental to personalized care.

Of course, as in any modeling effort, isolated or integrated, there is a need for a structured approach to validation of the models and processes. As integrated models are particularly complex, validation should begin with simpler, more fundamental aspects and progressively move to more complex and advanced components. This progressive approach ensures that each level of complexity is thoroughly tested and verified before moving on to the next, more advanced level. This approach helps ensure that each stage is solidly built upon a verified foundation, reducing the risk of overlooking critical issues as complexity increases.

Virtual meets Diversity: Strategies to generate digital patient representations with enhanced diversity

Representing diversity is a key requirement of any clinical trial – recognizing that evaluation, claims, or solutions are only valid if generalized across a population. This need for diversity is also applicable to practitioners of medical interventions including image interpreters. While current imaging practice often assumes an "average" interpreter or observer, no single observer represents such a hypothetical average interpreter. Thus, there is a need to include diverse observers and incorporating their variability, which can be dataset-dependent, to assure generalizability.

This highlights the significance of virtual trials incorporating diversity in their constructs. In representing diversity, virtual trials provide unique opportunities. Virtual trials offer the capacity to represent a diverse patient population with fewer virtual patients compared to physical clinical trials. Instead of replicating the sampling of the data of clinical trials, the virtual trial can deploy differing distribution of configurations, including both uniform and skewed sampling towards "edge" cases, thus enabling a simpler and targeted trial design. An illustrative application of diversity in virtual trials involves simulating rare diseases across diverse patient cohorts to clarify disease responses and evaluate simulation boundaries. In the trial design for rare diseases where large-scale trials are impractical, Bayesian approaches are particularly beneficial. Such designs can provide evidence of efficacy and safety by integrating virtual and real data.

Recognizing the importance of diversity in trials highlights the need to create a "science of diversity" to understand the complex factors that influence imaging examinations and trial outcomes. Often diversity is targeted by using large datasets, assuming that higher numbers translate to higher diversity. Typically, diversity is characterized by generic attributes such as age, sex, race, etc. However, these broad representations rarely capture all attributes that influence the outcome. There is a need for a systematic of diversity at multiple scales. Virtual trials offer a controlled way to do so, with its inherent unique advantage of defining and controlling for the ground truth of the subjects and the interventions. Such a control also offers an opportunity to consider matching the data and interpretations so as to optimize or fine-tune the intervention for specific subpopulations. This is a unique asset to balance generalizability (ensured by population statistics) with personalized care, recognizing that while models must account for diverse populations, individual patient needs should not be overlooked.

Addressing diversity gaps in clinical trials requires a multi-layered approach. Options include generating numerous digital phantoms based on real data, manual modifications using 3D modeling, leveraging deep learning methods such as generative AI, and exploring other strategies. While digital phantoms offer flexibility in simulating diverse scenarios, they may still follow a distribution, limiting their effectiveness in truly addressing diversity. However, incorporating interpolation techniques can mitigate this limitation. Diversity in virtual trials is also crucial when dealing with underrepresented groups or when real data collection is challenging. It is essential to recognize biases and actively pursue inclusivity in trial design and data representation, ensuring that virtual trials reflect the diverse global population accurately.

Virtual meets Reality: Overcoming barriers to accessibility and widespread implementation

To take advantage of what virtual trials can offer, we need to have reliable and easy to use tools and resources. These resources are currently not where they need to be. There are various challenges and opportunities towards such readiness and confidence. Those includes factors related to the validation and realism of simulation methods, as well as transparency associated with 'black box' AI systems. There is a significant need for openness, transparency, and collaboration to address these challenges and fully capitalize on the opportunities within medical imaging research to synergistically integrate experimental and modeling aspects to enhance healthcare outcomes.

This level of confidence is essential, especially when virtual trials are planned to address the needs in regulatory science. The regulatory evidence has a pivotal role as the cornerstone of scientific validation, going towards controlled trials, prioritizing simulation to adhere to the principle of "first do no harm". In that regard, we emphasize the distinctions and interconnections between basic science, regulatory science, and translational science in the development and evaluation of products, post-market surveillance, and public health preparedness through multiple programs include the Centers of Excellence in Regulatory Science and Innovation (CERSI) program [2]. Pertinent to virtual trials is the establishment of Good Simulation Practices (GSP), which build upon other established Good Practices, setting the level of needed details and credibility assessment guidelines [3].

In terms of availability of tools and resources, current offerings range from independently developed tools to FDA-provided and FDA-approved programs [4-7]. Those include Monte Carlo packages like PENELOPE [8] and GEANT4 [9], demonstrating a balance between open-source software and self-developed technologies. Key factors to consider include accessibility, quality, and regulatory compliance. There is a dynamic tension between making open-source software widely accessible, ensuring high quality, and meeting regulatory requirements. Balancing these factors is challenging because increasing one aspect (e.g., accessibility) might impact the others (e.g., quality or regulatory compliance).

Currently, there exists a prevalent uncertainty within the community regarding the reliability of virtual imaging trials which underscores the need for improvement in robust validation of simulation technologies. Further, there is a deficiency in the lack of crucial biological data which hinders the accuracy and reliability of virtual trials, contributing to widespread skepticism regarding their predictive capabilities. To build trustworthiness encompassing credibility, reproducibility, and accessibility, it is essential to address these data gaps, thereby enhancing the validity of virtual trials and fostering greater confidence in their outcomes. Towards that goal, several actions may be considered:

- Developing a quality for the quality of simulation studies, similar to the AAPM Task Group 268 report [10].
- Consider establishing certification standards or good simulation practices to increase trust in *in silico* results submitted for regulatory review.
- Explore a neutral third-party validation mechanism to validate proprietary simulation aspects from manufacturers, ensuring protection of intellectual property while encouraging collaboration.
- Requiring manufacturers to provide research access to reconstruction algorithms and data through contractual agreements or incentives from regulators.

- Continuously monitor clinical reports for changes in disease detection correlated with imaging protocols to help validate virtual results.
- Establish a community of stakeholders (e.g., The Regulatory Science In-Silico X Collaborator Community – ISXCC) to coordinate and facilitate efforts across stakeholders.
- Clarify designations and terminology within this space, which can offer consistent and clear definition of terms such as digital twins, in-silico, and virtual.
- Develop stages for granularity and quality of digital data.
- Ensure the context of use for an in-silico tool is always noted to ensure relevance to regulatory practices and beyond.

By implementing these action items, the medical imaging community can improve the credibility, reproducibility, and accessibility of virtual trials, thereby enhancing their overall trustworthiness and effectiveness. Equally important is the need to effectively incorporate patient perspectives into the prospects of using virtual trials for evidence generation including AI-driven medical research. Patients are the ultimate recipient of the "good" that virtual trials would offer and thus their voice and agency should be respected.

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Request for Information on the National Digital Twins R&D Strategic Plan

Charalampos Markakis

Via FDMS

Charalampos Markakis, 7/28/2024

[redacted]

Subject: RFI Response: Digital Twins R&D Plan Attention: Melissa Cornelius, [redacted]. Include a phone number for reference: [redacted] Approval Statement: This document is approved for public dissemination. The document contains no business-proprietary or confidential information. Document contents may be reused by the government in the National Digital Twins R&D Strategic Plan and associated documents without attribution. [redacted]. Include a phone number for reference: [redacted]. Dear Fast-Track Action Committee, Thank you for the opportunity to provide input on the National Digital Twins Research and Development (R&D) Strategic Plan. I am a scientist and university professor supervising transdisciplinary teams working on supercomputing applications. I would like to suggest expanding the definition of digital twins to encompass their diverse applications across important strategic areas in computational fields. This will ensure a comprehensive and effective strategy for digital twins research and development. Definition of Digital Twins in computational sciences To effectively guide R&D priorities of federal agencies, it is important that the definitions of digital twins encompass their diverse applications across various fields. In particular, it is important to include the concepts of numerical modelling, numerical simulation, and development of numerical algorithms, in various fields. For example: Computational fluid dynamics, numerical mathematics and computational physics: Digital twins can involve numerical simulations solving the hydrodynamic or magnetohydrodynamic equations numerically to model fluid flow. Numerical simulations in fluid dynamics are essential for studying complex flow phenomena across various scales, from atmospheric flows and turbulence modelling, to neutron stars and black hole accretion rings. These simulations of the digital twins can help increase our understanding of their physical counterparts, to detect such systems and estimate their physical parameters from observations, and predict their behaviors. For example, this can include: -Computational atmospherical sciences: simulation and prediction of hurricanes and weather forecasting -Computational astrophysics: simulation of binary black holes or neutron stars, and their gravitational wave extraction from simulations, used for their eventual observation by detectors such as LIGO or LISA. -Shock formation in hydrodynamic and other partial differential equations The above methods can be enhanced with AI (i.e. with numerical simulations used to calibrate AI algorithms, or AI algorithms used to complement and improve numerical methods). Computational finance, forecasting and risk modeling: Digital twins, enhanced by AI and advanced metrics like Value-at-Risk (cVaR) or Conditional Value-at-Risk (cVaR), offer significant improvements in managing market risk - the risk of losses due to extreme market price fluctuations, which can impact the wider economy. We might propose a focus on two areas: Market Scenario Simulation - Implement digital twins to simulate market conditions and their reaction to extreme scenarios - Leverage AI to enhance simulation accuracy, learning from historical data - Capture tail risks and extreme market movements underestimated by traditional models Advanced Risk Metrics - Use digital twins for dynamic VaR assessments based on real-time data, and incorporate cVaR to estimate potential extreme losses - Employ AI to refine these models by analyzing large datasets and identifying subtle risk factors Such approaches would provide a better assessment of credit and market risks, allowing financial and government bodies to better anticipate or mitigate them. This line of research can use AI to build upon established methods of improving risk management through advanced computational techniques and robust statistical models. This can help predict and minimize "fat tail" risk (i.e. black swan events) and make the US economy stronger and more robust in the event of extreme (black swan) phenomena, such as pandemic outbreaks, wars, and other financial shocks. The National Digital Twins R&D Strategic Plan can maximize its impact by encompassing transdisciplinary computational topics. This approach will drive innovation, improve predictions, and enhance decision-making across domains. By integrating AI with numerical methods and investing in cross-disciplinary research, we can advance science, strengthen technological leadership, and transform complex system management. Strategic investment in digital twins will yield both scientific progress and practical societal benefits.

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Request for Information on the National Digital Twins R&D Strategic Plan

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Response to RFI on the Digital Twins Research and Development[1]: Digital Twin to Improve Access to Services - the Case of the U.S. Federal Court System

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Abstract

We wish to highlight the potential benefit and high feasibility of employing the digital twin approach in services, including public and government service providers. To illustrate these advantages, we focus on the complex set of processes and services embodied by the U.S. federal court system. The court system, pivotal for administration of justice, is often characterized by congestion which affects social welfare, economic development, and access to justice. This highly important system possesses multiple operational complexities, such as constrained resources, uncertain demand, long in-process waiting time, "impatient" clients, and service times measured in years. Nevertheless, empirical research on court operations remains limited, and designing and implementing improvement interventions is extremely complex. For these reasons, we suggest leveraging the digital twin approach to improve access to administration of justice, with a focus on the U.S. federal courts. Our approach employs Natural Language Processing (NLP) and Artificial Intelligence (AI) tools to transform U.S. federal district court case dockets into a detailed "event log," to which process- and queue-mining techniques can be applied to explore judicial congestion and highlight ways to ameliorate it. By scraping, labeling, and analyzing millions of docket entries through an operation management lens, we are able to observe the case flow in the system and assess congestion impacts on case processing. After illuminating the judicial workflow, it is possible to create a

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digital twin of this complex service system, not only to predict changes in the state of the system but also to estimate the effect of various interventions to improve access to justice.

1. Background

The court system is a unique environment, aimed to produce justice. However, it suffers severe congestion worldwide. Drawing an analogy to the healthcare system, another social service system characterized by the "Iron Triangle" of access, quality, and cost containment (Kissick, 1994), congestion in court systems poses a significant threat not only to quality and cost, but also to access to justice. Timely and efficient resolution of disputes is a vital aspect of ensuring access to justice (Vitkauskas and Dikov, 2017).

Unfortunately, the demand for judicial services continues to grow worldwide, resulting in severe congestion and delays (Church et al., 1978; Dakolias, 1999; Decker et al., 2011; CEPEJ, 2015; CEPEJ, 2016; Voigt, 2016). Moreover, evidence from various countries indicates that court congestion is not solely driven by exogenous supply and demand trends but also by other endogenous factors such as inefficient processes, judicial passivity, and mismanagement (Mitsopoulos and Pelagidis, 2010; Dalton and Singer, 2014; Castro and Guccio, 2015; Moffett et al., 2016; Peyrache and Zago, 2016).

The complexity of the court system, as discussed by Azaria and Shamir (2023), can be described on three levels: operational, organizational and incentives. As for the operational complexity, first and foremost, the court system is usually a geographically decentralized system with numerous employees in various positions, serving a wide range of individuals. Secondly, this system is characterized by a high degree of process and procedural variety, with high uncertainty regarding case flow and timing of events within each case.

Moreover, the court system possesses distinctive attributes that set it apart from other complex service systems. Court systems endure limited managerial flexibility, as major changes to processes and procedures must be authorized through legislation or regulation and, in the U.S., may implicate litigants' Constitutional and statutory rights. Within their jurisdiction, judges and court administrators have limited authority to introduce operational changes to the established local routines.

As for the organizational complexity of the court system, it arises from one of the fundamental principles of democracy, which necessitates the independence and autonomy of judges (Tacha, 1995). This independence relates not only to external influences such as government, media, and public opinion, but also to influences within the judicial system. Moreover, interference with case management could even be viewed as a threat to judicial independence (Agmon-Gonnen, 2005). In addition, as in many other organizations in the social sphere, the efficiency of the system relies mainly on the expertise of judges (Christensen and Szmer, 2012), who are traditionally evaluated and rewarded based on judicial quality rather than efficiency (Posner, 2004).

As for the complexities due to incentives, the nature of the court system is its conflicting views and that these views are represented by different parties. The plaintiff and the defendant have completely different incentives and objectives, the lawyers have complex laws they need to adhere to and often need to explain these to their client, and the court's objective is different altogether. Moreover, the complexities of the process implies that even when incentives are aligned- finding this alignment may be extraordinarily difficult if not impossible.

For the reasons stated above, the management, improvements and optimization of court systems is not only immensely important, but also complex and expensive. For example, when the U.S. federal courts experiment with operational change, they often do so via pilot programs that test various interventions, though pilots can be slow, expensive, and limited in scope (one example of such pilot program can be found in https://www.fjc.gov/content/321837/mandatory-initial-discovery-pilot-project-overview).

In order to address some of these complexities, costs and uncertainty, we propose to employ the digital twin approach to mimic the structure, context, and behavior of the judicial system, based on reliable and accessible data. This unique application will enable multiple channels of improving access to justice: (1) advancing scientific research in law as well as operations management; (2) enhancing operational efficiency by allowing better monitoring of performance and assessing effects of interventions; (3) enabling predictive analytics and effective optimization, and (4) allowing the analysis of impacts of different interventions on the digital twin with less costs and less complexity than a pilot program; this will allow the system to focus pilots on interventions with a high potential benefit.

2. Digital Twin of a Federal District Court

Digital twins are designed to mimic "a natural, engineered, or social system (or system-of-systems)." Similar to its application in manufacturing, where a digital twin mirrors the physical production processes to enhance efficiency, predict failures, and optimize performance, a digital twin in a service system can simulate various scenarios, predict outcomes, and improve decision-making. The uniqueness of applying a digital twin to a service system lies, amongst other things, in the complexity and variability of human interactions, customer behavior, and service delivery processes. Unlike manufacturing, where processes are often more standardized and predictable, service systems require the digital twin to account for dynamic and often unpredictable human and exogenous factors. This necessitates more sophisticated modeling and real-time data integration to capture the nuances of service operations.

The first step in creating a federal court digital twin is data generation. This data must be in the form of an event log, as described below, and should be very granular, reflecting every important event in the system. The Federal Judicial Center produces a database of all cases filed and terminated in the federal district courts. But granular detail on each case's progression through a pathway of litigation events is not recorded. To transform the available data into the case-level event log format required for the approach described here, it is necessary to mine the text of each case's docket sheet. (Docket sheets are the chronological record of a case's litigation activity, available from the federal courts' Public Access to Court Electronic Records (PACER) system.)

The National Science Foundation's Convergence Accelerator program funded the SCALES Open Knowledge Network project (see https://scales-okn.org/), a multidisciplinary, multi-university research group. This group created a public repository of U.S. district court docket sheets along with standardized per-case litigation event labels. In total, the SCALES project holds approximately 1.3 million docket sheets and court documents from criminal and civil cases filed in the 94 U.S. district courts. The SCALES project used an English-based Large Language Model (Microsoft's large DeBERTaV3) trained also on 11 million docket entries and fine-tuned for classification tasks with manually annotated docket entries. This trained model allowed the SCALES team to generate standardized event labels from the unstructured docket text. For example, in one civil case, a docket entry might read, "The plaintiff and defendant have agreed to settle," whereas a docket entry in another case might read, "The parties reached a mutual resolution of all claims." Both entries are reporting the parties' settlement; the SCALES labeling workflow identifies both as 'settlement,' despite the substantial difference in wording.

Leveraging SCALES' standardized litigation event labels, along with event dates and judge information from the docket sheets, enables the creation of event logs that serve as the foundation for generating a digital twin of the court system. For this purpose, we define an "event" as a timestamped occurrence in a case that impacts the flow, with respect to either the routing (meaning, what would be the next occurrence) or the timing of the next occurrence.

An important component of the efficacy of digital twins in the service industry is better planning and design of the data collected, e.g., to make the creation of an event log straight-forward. Modern information systems typically gather transactional data on every customer, event, and activity that is being processed by that system. Such data includes at least a case identifier (unique customer or visit id), the event or activity name, and the event or activity timestamp; a set of additional attributes, such as customer type, resources required, or activity capacity, may also exist. This granular event data is collected by the system and may be stored in various system databases and be dispersed along numerous tables. Event data allows the inference of the process structure and dynamics. Moreover, enriched event data can be transformed into event log data. A high level of data granularity that facilitates the creation of an event log is maintained by many service providers. An example of an event log for the court system is given in Table 1.

Table 1: One case event log (partial)

Case ID	Date	Event	Attribute	Judge	Number of Plaintiffs	Number of Defendants
01-cv-0XXX6	4/12/2017	complaint	opening	SJID0125	7	3
01-cv-0XXX6	4/12/2017	case assigned		SJID0125	7	3
01-cv-0XXX6	4/14/2017	summons issued	scheduling	SJID0125	7	3
01-cv-0XXX6	4/28/2017	summons returned		SJID0125	7	3
01-cv-0XXX6	5/2/2017	status hearing reset	scheduling	SJID0125	7	3
01-cv-0XXX6	5/8/2017	motion for time extension	unopposed	SJID0125	7	3
01-cv-0XXX6	5/8/2017	motion granted	hearing held	SJID0125	7	3
01-cv-0XXX6	5/11/2017	order		SJID1007	7	3
01-cv-0XXX6	6/27/2017	settlement	dispositive	SJID1007	7	3
01-cv-0XXX6	6/28/2017	dismiss without prejudice	dispositive	SJID1007	7	3
01-cv-0XXX6	6/28/2017	case dismissed	dispositive	SJID1007	7	3

The path from the SCALES data to the creation of an event log that can be used for process mining, and later for the creation of a digital twin is not trivial. It requires a panel of multidisciplinary experts from law, data science, operations research and computer science. By interlacing these disciplines, we can construct a toolkit which will eventually transform the natural language html dockets to comprehensive workable even logs. These event logs are the building block of understanding this complex process. These event logs can bridge the gap between the designed process, the process observed by domain experts, the process captured in the raw data, and the real process. After bridging these gaps, a digital twin can be generated and transform the process into the optimal process.

To demonstrate how process mining helps to close these gaps, we created event logs for a complete set of all civil and criminal cases filed in the U.S. District Court for the Northern District of Illinois. (This is the federal district court that encompasses Chicago and the surrounding areas.) In all, our data set covers all cases filed in 2002-2018 and consists of events harvested from the docket sheets of 178,523 cases. The process map of a sample of 1,000 civil cases from one of the courts in our data, created using SiMLQ (see Section 3), is shown in Figure 1. This map demonstrates the complexity of the flow of cases.

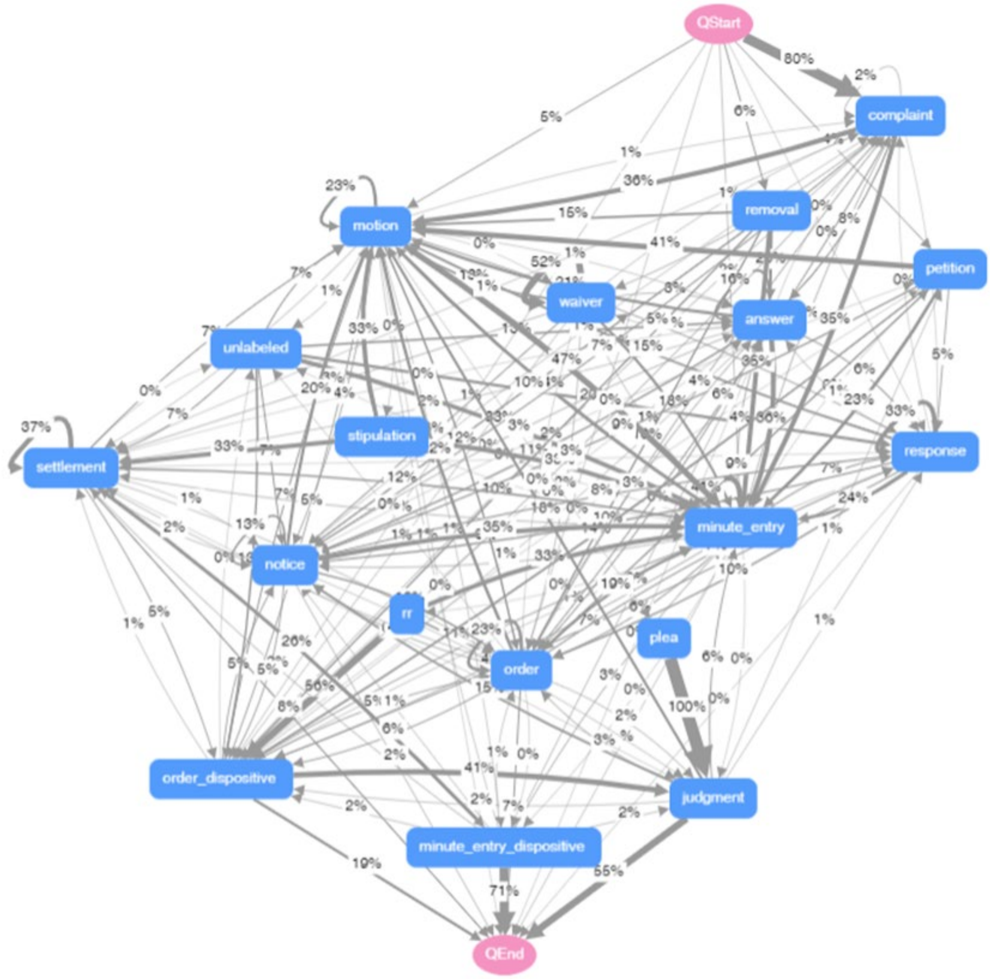

Figure 1: Process map of civil cases sample

In this map, each arrow signifies transition of cases from each event to all the relevant subsequent events. It also shows the portion of cases transitioning to each of the possibilities, which is also demonstrated by the width of the arrow. For example, 80% of the cases in this sample started by a complaint and 2% of them were followed by another complaint.

Now that the service process is mapped, we can combine it with queueing theory models to shed light on some of the interdependencies of this complex system. For example, customers (cases) compete for resources (judges) and not activities, waiting times are generated by the process, not exogenously, and so on. In operations management, the most fundamental method to analyze such complex service networks is simulation. So, we employ queue-mining and machine learning (ML) to create data-driven simulation that can automatically produce a digital twin of the system.

To conclude, using a digital twin in the Federal Court system could improve access to justice and overcome the unique complexities of the system in several aspects:

- A key part of the problem is when decisions at both micro and macro levels are made, the downstream impacts of these decisions on system delays are not visible. Thus parties making these decisions are either completely unaware of these impacts, or are, at best, guessing at what these might be.

- The main advantage of developing a digital twin is that it can make such impacts visible. Thus, a judge deciding whether to grant a party's motion for a time extension on a filing deadline (for example) can check the impact of this decision on the current and other cases. Similarly, when evaluating a system intervention (e.g., changing certain filing procedures) the impacts can be made visible to all affected parties.
- Once the impacts are quantified, an educated decision can be made on whether the expected additional delays are offset by the usefulness of the proposed action (or vice versa – whether the extra costs imposed on the parties in the present case and other cases in the judge's caseload are sufficiently offset by the improvements in Key Performance Indicators (KPIs).
- Experimentation in the U.S. courts often happens through various pilot programs that test different kinds of interventions. Those are expensive, slow, and limited in scope. The digital twin approach promises a much more nimble, real-time alternative to pilot programs.

3. SiMLQ

SiMLQ (see www.SiMLQ.com) is a recently-developed leading edge software that uses ML and AI to quickly generate data-driven simulation models of congested systems, where queueing plays an important role. The court systems example, as well as many other services, such as healthcare, license renewals, contact center, and insurance, are prime examples of such congested systems. The SiMLQ software (patent pending) automatically creates data-driven simulation models of congested systems. SiMLQ uses machine learning to quickly process event logs and generate a high fidelity simulation model of the process that generated this data. Creation of digital twins of congested processes can build upon SiMLQ's capabilities. SiMLQ's initial set-up and training would lead to a well calibrated simulation model of the system. Then, there are two main steps required to enable SiMLQ as a digital twin.

The first step is on the input side. An API should support the continuous upload of recent events into SiMLQ. This upload will update the current system status, allowing the system to depict the current process map and to initiate the simulation run of the current state of the system. Once the simulation model is calibrated and validated, various interventions designed to enhance system performance can be specified and their effect simulated. Then, comparing the impact of different interventions on KPIs in view of the cost of these interventions, would be used to prescribe optimal actions. The newly created data (after implementation of actions) would be immediately uploaded to the digital twin created by SiMLQ allowing it to stay up to date.

The second step is retraining. The continuous data input would keep the digital twin updated by supporting the retraining of the simulation model. SiMLQ's quick training allows it to be retrained much more often than standard MLOPS principles consider. Depending on the actions taken and the speed in which the process changes, different retraining periods, such as daily, can be implemented. Such training, with data generated after actions are implemented, is required to provide full functionality of a digital twin model.

This two-step process would allow SiMLQ to keep its digital twin up-to-date in terms of both capturing and describing the current situation as well as maintaining a current, well trained, digital twin to capture the impact of additional actions on the updated system.

4. Summary

As our discussion on the implementation of digital twins in the U.S. federal court system demonstrates, implementing digital twins in services, including public and governmental services, holds substantial promise for improving access and efficiency. In the court system, digital twins can improve justice by addressing congestion and inefficiencies inherent to the judicial process. This approach leverages AI, ML and NLP to transform court case data into detailed event logs. These logs enable advanced process- and queue-mining techniques, as used in SiMLQ, that can illuminate the flow of cases in the system and highlight issues and ways to address them.

The unique complexity of the court system, characterized by its operational, organizational, and incentive-based challenges, necessitates sophisticated solutions like the digital twin approach. By creating a virtual replica of the court system, stakeholders can simulate different scenarios and make data-driven decisions to enhance efficiency and reduce delays.

Key benefits of the digital twin approach include:

- Operational Efficiency: The ability to simulate interventions before implementing them can lead to more cost-efficient operational changes, as well as improve the efficiency of existing resources.
- Predictive Analytics: The digital twin enables predictive modeling, helping to foresee and mitigate potential issues before they escalate. In many services predicting longer than allowed delays for some customers can support an intervention that expedites their service.
- Cost Reduction: Both direct and indirect costs associated with delays can be minimized, benefiting the broader economy.
- Improved Access to Service: Supporting the delivery of services, such as justice, in a timely fashion improves not only the efficiency of the system but also the efficacy of the service (resolutions in the court system).

The collaborative effort involving legal experts, data scientists, and operations researchers underscores the interdisciplinary nature required to successfully implement digital twins in services. Moreover, the digital twin model offers scalability and adaptability, potentially benefiting public services, such as court systems, worldwide by providing a framework to address similar challenges of congestion and inefficiency. Overall, the adoption of digital twins in services is a forward-thinking strategy that is aimed to drive significant improvements in service delivery. In the judicial system this would be a better administration, ultimately contributing to a more efficient, equitable, and accessible legal system. In the healthcare services this would be an improvement of quality of life and longevity.

Finally, below we briefly address the following topics outlined in the RFI:

- Artificial Intelligence (AI): Machine learning(ML) and AI would support the creation of digital twins for service systems. The ability to use this twin to simulate the impact of different actions on the system and optimize such actions may be an important and effective avenue for using ML&AI in practice. ML&AI would be used in different phases of the creation of the digital twin- from making existing data accessible to the twin, see, e.g., the SCALES project, via the algorithms used to provide data driven representation of the process, and to the algorithms that generate, train, maintain, and analyze the digital twin.
- Business: The “return on investment” in improving access to justice can be observed on two levels - internal and external. First, the direct cost of the justice system can be affected, as improving efficiency can deal with expenditures which are now dedicated to dealing with system inefficiencies. Second, there are indirect costs to lengthy litigation which burden the economy. This means that improving access to justice has the potential to reduce the cost of doing business. Generally, digital twins of a service system can (1) improve access to these services, e.g., in access to healthcare where delays have very high costs, (2) improve equitability of service offerings to different populations, e.g., between rural areas and suburbs, and (3) reduce the cost of providing an adequate service level, e.g., by expediting the implementation of process improvements.
- Data: Our approach requires a well constructed event log which traces the path of every task (i.e. each customer, patient, or litigant, depending on the setting), with the activities and resources involved in each activity. Such data often exists in service systems. Therefore, the data gathering, governance, and planning methodology that would allow for the creation of digital twins in services may be cheaper than those required for the creation of digital twins for physical systems, as the latter often requires additional investments, e.g., in sensors or other recording devices, to collect real time data.
- Ecosystem: Creating a valuable digital twin to a complex system, as the court system, requires the collaboration of researchers and practitioners from several disciplines: legal subject-matter experts, queueing theorists, data scientists, ML & AI experts, and others. The combination of knowledge and complimenting perspectives can push forward this initiative, as well as develop knowledge relevant to other environments.
- International: While court systems worldwide are somewhat different in structure and in nature, they are very similar in dealing with the challenge of congestion. To that extent, comparing court systems and enriching the understanding of the common dynamics has significant potential for mutual benefits. The digital twin approach allows for testing different models based on other systems, without changing the actual system. This benefit of the scalability of digital twins in the service industry may increase their economic value.
- Long Term: Creating digital twins in the service industry is a challenging task that has a very high potential reward. A long term vision where managers of service processes can easily manipulate a digital twin to test the impact of different actions on Key Performance Indicators (KPI) and optimize their process faces several challenges that can only be addressed by combining resources of the government, private companies, and academia. This vision requires appropriate data management and governance, at the personal, interorganizational, country, and global levels (e.g., to support using data from a digital twin in one court system to the one in a different country); adequate computational power

to generate, maintain, and use the digital twins; and an improved understanding of the impact of managerial actions on people (both service providers and consumers) and the data generated by the system (that is than fed into the digital twin).

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Federal Register Notice: 89 FR 51554, Federal Register :: Networking and Information Technology Research and Development Request for Information on Digital Twins Research and Development, June 18, 2024.

Request for Information on the National Digital Twins R&D Strategic Plan

Computing Community Consortium

CCC's Response to the Networking and Information Technology Research and Development Request for Information on Digital Twins Research and Development

This response is prepared by the Computing Research Association (CRA)'s Computing Community Consortium (CCC) by inviting CCC Council members with interest and knowledge of the use of digital twins to a roundtable discussion. The participants discussed the RFI and contributed to this written response document. CRA is an association of over 270 North American computing research organizations, both academic and industrial, and partners from six professional computing societies.

The mission of the CCC, a subcommittee of CRA, is to enable the pursuit of innovative, high-impact computing research that aligns with pressing national and global challenges. Please note any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the authors' affiliations, or of the National Science Foundation, which funds the CCC.

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July 28th, 2024

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Digital twin models have the potential to revolutionize the ways we conduct R&D and to evaluate and measure the performance of systems and physical entities across research sectors. Digital twins can significantly reduce the costs and risks associated with conducting testing, speeding the rate of development and improving overall product design and safety considerations. Digital twins can also be programmed to offer personalized solutions which can be tailored to specific projects or individuals, and the application areas are nearly limitless. However, these models can also cause harm when they are poorly designed and/or implemented, or when we assume the results from these simulated environments seamlessly translate to real world outcomes. Below, we enumerate several critical considerations when developing and implementing digital twins.

To begin with, the term “digital twin” can be misleading for a number of reasons. “Digital” implies that these models live online, only in the digital sphere. However, this implication is incorrect, as seen by the definition used by this Request for Information. Digital twins utilize sensors in the real world to more accurately mimic their physical counterparts. In addition, the term “twin” is misleading as well, because though incredible advances have allowed digital models to progress, we should not be under the assumption that these models are perfect mimics. Digital twins may overvalue data received by certain sensors and conversely may not have enough sensors to perfectly reflect their physical counterparts. Furthermore, there are many varieties of digital twins, such as digital human twins versus twins of environments (e.g., virtual reality). A well-defined taxonomy of the different forms of digital twins should be established to create a shared language between different communities.

Digital twins could potentially be created for almost any physical entity, from modeled organs to digital twins of entire cities. Specific constraints of these systems, however, should be taken into account. Data limitations especially are something to consider. Digital twins cannot take into account every single piece of data in some instances, as this would overload the model. A digital twin meant to measure erosion, for example, could not take into account the minute movements of every individual grain of sand on a beach - this volume of data would overload the system. Instead, a model meant to measure erosion of a certain beach would have to approximate or group together thousands of grains of sand, meaning a certain amount of precision will be lost by the model. The same goes for climate models and models of ocean currents. Learned history by a digital twin can practically only be stored for a certain amount of time or at a certain granularity, leading to a degree of precision loss over time. Digital twins are closed systems, which are constrained to underlying assumptions (i.e. assuming a certain climate model or scenarios under which the model will operate), so we cannot hold all values at a constant and assume the model is robust and will always give accurate results when physical models exist in complex systems that may affect actual results.

Alternatively, expecting too many specific requirements and capabilities of a single digital twin may overload the model or lead to inaccurate results. For example, a single digital twin meant to mimic the world's climate may perform very well, but if it is asked also to begin accurately modeling the weather patterns of specific locales, this may confuse the model, leading to inaccurate results across all of its approximations. This is also a concern with digital twins for cities, which attempt to model a variety of diverse processes at once (i.e., traffic flow, energy consumption, weather patterns, impacts of recent policy measures, etc.).

We also advise caution on using digital twins which rely heavily on surveillance data, such as CCTV footage. Video footage of individuals, while important to the efficacy of many digital twin models, especially digital twins of cities, can capture and store sensitive personal information without individuals' consent.

We believe the **Trustworthy** topic area identified in the RFI will be a critical component of any Digital Twins R&D Strategic Plan, and we recommend expanding and renaming this topic area to "**Security, Integrity, and Trust"** of digital twins. As the NASEM report points out on p. 36, the tight integration between a physical system and its digital twin creates a new attack surface for the physical system. Digital twins, especially those that store sensitive data or are coupled to physical critical infrastructure, will be prime targets for adversarial attacks[1]. In instances such as these, digital twins can act as massive security vulnerabilities, allowing attackers unfettered access to both the digital twin and physical entity. To prevent this kind of unauthorized access, developers must secure all endpoints, which can be tricky, especially when digital twins may be receiving data from outside systems operating on outdated legacy code. Digital twins must also be developed with security considerations in mind, not as an afterthought, and every aspect of the system, from where the data is coming from to the actual digital twin model itself must be secured.

Similarly, the coupling between a digital twin and its physical system counterpart also creates a new attack surface for the digital twin, because it may be possible to maliciously manipulate or corrupt the digital twin via the physical system. In the digital domain, cryptographic algorithms and protocols may be used to ensure the integrity, authenticity, and confidentiality of all the components of a digital twin; similar security guarantees will have to exist for coupled physical systems.

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[1] For example, a digital twin of a power plant that has access to the control mechanisms of the physical power plant.

We also note that there will need to be close coordination between the **Security, Integrity, and Trust** and the **Standards** portions of the Strategic Plan. Creating secure and interoperable digital twins will require agreement on standards for data encryption, digital signatures, authentication protocols, authorization models, and policy language. New standards and language for constrained delegation models (e.g., the ability for the owner of a digital twin to delegate a portion of their access to other entities for legitimate purposes) will need to be developed, coded, and standardized. Standardizing security considerations alone will be very complex given a lack of interoperability standards.

Additionally, digital twins cannot be developed in siloed environments. Though only a small team may be necessary to write the code for a digital model, experts across disciplines need to be consulted to make sure the models are implemented accurately. Engineers can inform developers of optimal sensor placements and can verify that the digital representation accurately matches the physical one. Security experts and data privacy officers can help prevent adversarial attacks and data leaks. Depending on the application area of a digital twin (i.e., agriculture, economics, social sciences, etc.) experts from those domains must also be consulted. The NASEM report on digital twins enumerates several recommendations for federal agencies to improve cross-agency and cross-community collaborations.

Co-design of these systems is also incredibly important. When we use the term "co-design", we are referring to the conceptualization of the key features of a digital twin as well as the end user or primary stakeholders who will be using the model. Co-design cannot focus solely on design of the model without considering who will use the model and how it will be deployed. Users must be informed of the system constraints, possible edge cases where the model may not deliver reliable results, and unacceptable use cases that the system was not designed for. Developing key features while keeping end users in mind can ensure the models are accurate, comprehensible to those outside of the development team, and most importantly, useful to the organization.

While digital twin models offer transformative potential across numerous research sectors by reducing costs, minimizing risks, and enhancing the precision of product designs, their implementation demands careful consideration. The CCC strongly advises that digital twins be viewed as what they are: tools for prediction and approximation, not prophetic devices that should replace decision makers. These tools should also not be viewed as being so important that they are deserving of funding without robust methodologies or evaluation plans. A nuanced understanding of these models' constraints, such as data overload and the necessity of approximations, is critical to their effective deployment. Furthermore, the security and privacy concerns associated with digital twins necessitate robust safeguards to protect sensitive information and prevent adversarial attacks. Again, digital twins are not novel, they are an existing technology that has recently been bolstered through recent innovations, including the development of real time sensors, AI, and virtual reality. For digital twins to be truly valuable resources, we need to assess their value and what affordances are needed before implementing them widely across sectors.

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Request for Information on the National Digital Twins R&D Strategic Plan

David Elbert

Response to Networking and Information Technology Research and Development **RFI on Digital Twins Research and Development,** posted in Federal Register vol. 89, no 118, June 18, 2024, for NITRD, NCO, and the National Science Foundation (NSF).

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Response Text Organized by RFI Sections

Overview: Digital twins offer a variety of high value returns but, to date, have been most effective in industrial settings where process optimization requires interaction between tools and supply flows that are well defined. More complex systems stretching from fundamental research to deployment of findings remain largely out-of-reach of current twin concepts and technologies. This difference is due to details outlined in the references included in the RFI, but primarily centers on gaps in accurate physics-based models, data-driven models, appropriate datasets, and lack of accessible infrastructure to produce accurate results or meet the high-rate needs of these systems. Recent advances in data infrastructure and AI/ML availability, however, make investment in digital twins of complex system timely as well as critical given investment by other nations.

In planning investments in digital twins, it is worth noting that the highest value digital twins will be in spaces undergoing rapid evolution in component modeling and data. This means that a central tenet of digital twin development must be a forward looking, composable approach that can absorb new ideas and tools that we cannot even anticipate. The rapid turnover in AI epitomized by LLM applications in just the last two years makes it clear that a digital twin plan must be ready to embrace transformative tools as they arise. This also argues to prioritize creation of conceptual frameworks that can adopt developments from outside the digital twin work itself. Indeed, it shoud be expected that most fundamental advances in physical asset development and characterization; and most advances in data and computing systems will come from researchers working in non-aligned areas without regard for digital twins. This reality means that a successful digital twins program needs composable pluggability and will fail if locked into early technical choices or intransigent investigators. In this sense, digital twins should be conceptualized as “living systems” and may always be in a state of evolution. An important implication of this realization is that a central gap in creation of digital twins reflecting the science enterprise is the current dependence on stateless precepts (e.g. RESTful or GraphQL-based web services) and lack of recognition that a digital twin is most functional when conceived as stateful. The most powerful strategies to build a digital twin ecosystem and tool set will require significant advances in how the scientific community understands their own work. Complex systems, including research and development, are neither linear not stateless. Digital twins and eventual autonomous digital twins will require transformative change in perspective by many investigators creating critical pieces of the ecosystem. To compete globally and provide leadership across a digital twin ecosystem will require leadership-level investment in digital twin research and development that embraces and confronts the challenges of stateful architectures.

The following information on specific gaps and challenges is provided in the topical outline suggested in the RFI.

Artificial Intelligence (AI): AI has quickly emerged as a powerful tool for understanding complex systems and providing opportunity for transformative change in the practice of science and the control of autonomous systems. AI will clearly be a critical technology across the hierarchy of digital twins from virtual twins through truly autonomous twins. While many gaps exist, the central challenge for AI applications in digital twins is the rapid pace with which AI concepts and tools are evolving. Planning the digital twin ecosystem must focus less on specific types of AI tools and most critically on nimble integration of the breadth of AI tools and the inevitable emergence of new, transformative tools. To do this will require careful attention to AI/ML advancement that integrates with domain problems and that creates composable tools with clear protocols for advancement and deployment. Interoperability of AI/ML tools will require high-level incentives and sustained community collaboration to avoid creation of new barriers as we move to overcome those inherent in the current ecosystem.

A central challenge for AI components of digital twins is realistic understanding and mitigation of risks related to uncertainty in decisions and their implementations. This challenge is well known in autonomous systems where misinterpretation of new data or blind spots in models can cause deadly mistakes in systems such as autonomous vehicles and laboratories. In the same way, digital twins provide systematic decisions, deployment and guided production of materials and parts that may be used in mission-critical applications. The mismatch in risk profile between traditional manufacturing, where a person routinely takes for granted the competence of a part in a care or plane, and the risk profile of a part validated by a digital twin that may be vulnerable to model or system deficiencies that have never been experienced before, makes focus on safety a priority that must temper the speed at which advances can be made using AI.

In a rapidly evolving, high-value space such as AI, there are also strong incentives to compete against other concept and tool developers. Digital twins leveraging AI will need to develop protocols to use AI as a service or share AI technologies in ways unseen in other research. Ultimately, top-down support for grassroots community efforts will be necessary to encourage community participation and to sustain efforts. The NSF has built a foundation for such effort with the inaugural cohort of 10 FAIR and Open Science Research Coordination Networks (https://new.nsf.gov/funding/opportunities/findable-accessible-interoperable-reusable-open/nsf22-553/solicitation). These FAIROS-RCNs have established a strong community base around data-centric work including many AI/ML and model-centric topics driven by shared data resources. These efforts should be sustained and coordinated resources provided to facilitate coordination that embraces AI development and tools across communities.

Business Case Analysis: Digital Twins that span the data lifecycle and technological readiness levels will facilitate high value return on data produced from basic research. The Materials Science domain is inherently interdisciplinary with ultimate drivers focused on delivery of products that need new materials capabilities. The Materials Genome Initiative (MGI) provides a natural partner for digital twin efforts focused on business cases with its focus on leveraging data-centric acceleration of new material discovery, design, *and deployment* critical to every societal Grand Challenge. MGI Challenges center on providing materials that play a central role in areas as broad as:

- Protecting and Improving Human Health
- Delivering Sustainable and Resilient Energy
- Thriving in Extreme Environments
- Enhancing Structural Performance
- Protecting the Environment
- Propelling the Information and Communications Technologies Revolution
- Advancing Critical and Emerging Technologies

Recently, MGI efforts have expanded in the realm of building success at higher technical readiness levels (TRL) meaning using data-driven techniques near the testing and deployment end of the materials development continuum. Research partners within the defense sphere (AFRL, ONR, and ARL) have inherent need to provide research outcomes that deliver outcomes that can be deployed in the field on compressed time scales. The new NASA Space Technology Research Institute for Model-based Qualification & Certification of Additive Manufacturing (IMQCAM; https://techport.nasa.gov/view/156318) specifically embraces a digital twin approach to product delivery. IMQCAM spans university, research-institute, and industry partners to develop a digital twin provided certified and validated aerospace parts created by metal additive manufacturing. This effort combines multiple important digital twin themes with direct economic value aimed to leverage data and models to allow manufacturing of flyable parts without need for expensive physical testing and verification on Earth. The IMQCAM digital twin conception is an important touchstone, and may be unique in the world, for creating a truly deployable, autonomous twin spanning from fundamental research to manufacturing methods. IMQCAM leverages decades of NASA experience with twins and would be an ideal partner to lead broader efforts to ideate business case analyses.

Data: A central challenge for digital twins remains machine operable discovery, sharing, and interoperability of data. FAIR data principles are gaining traction in many fields but continue to need high-level motivation, advanced efforts, and sustained support. In the Materials Domain, the Materials Research Data Alliance (MaRDA) is a US National Materials Data Network as envisioned in Goal 1, Objective 2 of the MGI Strategic Plan (https://www.mgi.gov/sites/default/files/documents/MGI-2021-Strategic-Plan.pdf). MaRDA drives US and international efforts through a community-led network focused on connecting and integrating materials research data and data infrastructure to realize the promise of open, accessible, and interoperable materials data. Each of these elements are aligned with the goals of the Materials Genome Initiative (MGI) but a broadly congruent with concepts of FAIR data across disciplines and addresses a central gap to realization of broad application of digital twins. Without community data and without broad adherence to data sharing in interoperable, reusable ways, digital twins cannot be implemented for the types of big, complex problems that makes them valuable. Recent reports make it clear that a computational model is not a digital twin and that twins require actionable data across the domain of fundamental parameters encompassed by the twin. As a network that promotes the convergence of ideas, people, data, and tools to accelerate discovery, MaRDA provides an exemplar for other domains as well as a contact point to link efforts that are interdisciplinary. Such alliances are required to enable new insights into materials mechanisms and lay the foundation for both human-centered and artificial intelligence-assisted approaches to materials and product design. The structure of MaRDA includes governance by an elected council that facilitates a broad base of stakeholder interaction. This structure emphasizes that community work must be done at the community level, with mission-driven priorities, yet supported with top-down efforts to link the community with policymakers and high-level priorities. In many ways, the complexity of data infrastructure and community interaction mirrors the complexity of a functional digital twin; success of twins will require interoperability of the human infrastructure needed to develop the hardware, software, and protocols that will ultimately comprise digital twin environments. MaRDA and international partners are central to creation of interoperable data formats and semantic context required for functional reuse. A successful campaign to develop digital twins must include expanded work on data, metadata, and focused creation of foundational, sustainable data resources that serve digital twin development and not rely on current focus on absorbing data created for unaligned research directions.

Ecosystem: A persistent gap in development and deployment of digital twins centers on cost and lack of access to high-performance, managed data center resources. While compute resources are addressed in digital twin reports, data infrastructure is rarely recognized as a separate and critical realm. Few researchers understand that secure data infrastructure performant at the level of petabytes (and beyond) is well beyond the realm of university IT staffs or even traditional HPC centers. Digital twins will mirror the distributed nature of research itself and will need high performance network and storage backbones with secure, yet seamless access from researchers. Current high-performance data infrastructure is concentrated in commercial cloud options; some national laboratories (the planned DOE High Performance Data Hub is particularly notable); and rare university facilities such as the Bloomberg Data Center in the Institute for Data Intensive Engineering and Science at Johns Hopkins which already hosts multiple community datasets and will expand capacity to nearly 100 PB by the end of 2024. Such facilities will need to be sustained and should serve as guides to substantial growth in data infrastructure resources that are accessible to research budgets and require minimal advancement in expertise within the research teams themselves. A summit to convene expertise in data IT and infrastructure including these leading lights is recommended to develop realistic mission options and a roadmap for delivering consistent with the imminent needs of digital twin development.

International: All projects I participate in endorse international collaboration. This is important not only to accelerate progress, but to create compatibility between the entrepreneurial approach of US research with the centralized, hierarchical approach of many international projects. Data and models are without geographic boundaries and digital twin projects will benefit by sharing resources and concepts with international allies.

Long Term: The scale and ambitiousness of digital twins provide opportunity for the long-term, sustained investment needed to address three central challenges and related gaps.

First is the need to build sustained community efforts in data interoperability and reusability that leverage FAIR data principles to create a ecosystem of high-value, foundational data with a specific focus on experimental data and linked data semantics. These efforts can be interwoven by creating community inspired and defined datasets that are then instantiated using the advanced research infrastructure available at National Laboratories, the NSF MIPs, centralized user facilities at federally funded laboratories (such as the Cornell High Energy Synchrotron Source, CHESS, and the National High Field Strength Laboratory, MagLab), the Advanced Cyberinfrastructure Coordination Ecosystem: Services & Support (ACCESS), and US investments in high-speed networking through Internet2. With digital twin leadership at the table, planning and realizing these community dataset can be coordinated and accelerated.

Second is the need to create the high-speed, high-availability data centers and versatile data-stack tools required to provide the data resources required for instantiation of digital twins. Centralizing these resources will provide opportunities for economies of scale in the data center while also avoiding unmeetable costs and incongruent approaches in the diverse efforts working across the digital twin ecosystem. Data resources are complex and should be constructed to avoid concept and technology lock-in. Twin advances should be able to find willing and resourced infrastructure partners that will accelerate their efforts rather than provide the all-too-common barriers found today. One suggestion would be to create an ecosystem of providers with most resources being high availability, high speed data stacks and clusters using modern object storage and economical storage such as that pioneered and deployed by the Open Storage Network (OSN) (https://www.openstoragenetwork.org/), while other resources provide nimble sandboxes to try new technologies as they emerge and meet the needs of research applications creating new challenges.

The third critical long-term need is development of bidirectional data flows that mirror the conceptual framework of a research enterprise comprising physical assets, synthesis of materials, modeling of structure-property relationships, physics-based modeling, data-driven modeling, automated data analysis, automated data curation, and AI/ML decision makers. The vision and foundation for such a framework is well known in computer science and autonomous systems research, but rarely appreciated in physical, chemical, and biological sciences. Digital twins require flexible, fast interaction between changing systems. An appropriate framework should be stateful with decoupling of resources though use of asynchronous subscription modes. Current science automation focuses on use of stateless, RESTful systems that are easy to implement and rely on local, modest performance computing. Alternatives are already arising in the Materials Domain and include the creation of nascent autonomy in the Open Materials Semantic Infrastructure (OpenMSI) project that has created tools to provide routine access to the Apache Kafka streaming infrastructure as a backbone for event-driven, loosely coupled infrastructure. OpenMSIStream (https://doi.org/10.21105/joss.04896) provides a robust adaptation of a standard streaming ecosystem to address challenges in laboratories producing large, diverse data volumes. Such efforts should be bolstered by reducing the barrier to stateful approaches by providing sustainable, economical brokering for mediation of data transfer between physical and virtual parts of the digital twin. New tools will arise and be adopted only when barriers such as these and seamless use are solved.

Regulatory: A valuable by-product of providing data infrastructure and streaming data tools is the ability to apply data governance. This will include the ability to assess and control data quality but will also provide ways to automate regulatory compliance. There remain challenges to establish a global regulatory framework that respects intellectual property in data, but we should not wait for clarity on governance before adopting an infrastructure that allows measurement and deployment of that governance.

Responsible: Responsible and ethical use of the data resources and models of a digital twin will be enhanced by the transparency created through contextual metadata and data streaming.

Standards: Standards and protocols are clearly critical, but the field is moving too quickly to wait for years of community agreement and mediation. The focus should be on transparency and function so research may move quickly, and interoperability can be assured. It is clear that AI/ML methods will provide new ways to create ontologies far faster than humans have proven able. Visibility of data and methods across disciplines and endeavors will be the rate determining step in development of tools to create standards or obviate their need in specific cases.

Sustainability: The persistent challenge of all great data and infrastructure advances is sustainability. The strong potential for commercialization of digital twins suggest that there are opportunities for partnerships with industry partners, but resources that are of fundamental importance to the national interest should receive support to be sustained. The framework for sustainability of data resources is well established in the community authored TRUST principles for digital repositories. These are identified as Transparency, Responsibility, User focus, Sustainability, and Technology and were reported in an article in Nature in 2020 (https://doi.org/10.1038/s41597-020-0486-7). These have been instantiated in detail for repositories and US research should adopt them through the Core, Trust, Seal digital repository certification (https://www.coretrustseal.org/). The community cannot be expected to share data and models if the hosts are not trustworthy.

VVUQ: Digital twins provide a unique opportunity to leverage data across the research lifecycle and prevent the need to recreate data for validation of deployed assets. To do this, VVUQ methods should be expanded to encompass datasets and be deployable across the instantiated digital twin.

Workforce: Workforce development will need continual attention but there are two central challenges. First will be training advanced computing and data techniques across the curriculum in domain fields. Second will be meeting salary competitiveness to bring skilled computer and data engineers into the digital twin enterprise within domain science. It currently is virtually impossible to recruit a postdoc or transition a masters student to the PhD at university, academic salary rates. A good engineering Postdoctoral Fellow earns $65-80,000 per year. My recent MS graduates in Data Science and Engineering receive offers at $120-150,000 per year. It is reasonable to think that the intellectual draw of a good project might induce someone to defer some income, but it is unrealistic to think that strong candidates will accept significant differences in pay.

Summary: In summary, digital twins create significant opportunities but are restrained by significant gaps and challenges. Recent workshops provide an excellent advance in understanding these gaps. With appropriate resources that meet the directions I have tried to highlight here, the US can lead digital twin development and application through the next decade.

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Request for Information on the National Digital Twins R&D Strategic Plan

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Digital Twins and Game Technology

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1 Terminology

This RFI (https://www.federalregister.gov/documents/2024/06/18/2024-13379/networking-and-information-technology-research-and-development-request-for-information-on-digital) defines via The National Academies report, "Foundational Research Gaps and Future Directions for Digital Twins:"

> *A digital twin is a set of virtual information constructs that mimics the structure, context, and behavior of a natural, engineered, or social system (or system-of-systems), is dynamically updated with data from its physical twin, has a predictive capability, and informs decisions that realize value. The bidirectional interaction between the virtual and the physical is central to the digital twin.*

We refer readers to a recent explanation via RIT faculty: https://theconversation.com/what-are-digital-twins-a-pair-of-computer-modeling-experts-explain-181829.

Given that the RFI welcomes alternate definitions from various fields, we suggest supplementing (not replacing) the definition of a digital twin via https://www.unrealengine.com/en-US/digital-twins:

> *A digital twin is a 3D model of a physical entity like a building or city, but with live, continuous data updating its functions and processes in real-time, providing a means for analyzing and optimizing a structure. When live data from the physical system is fed to the digital replica, it moves and functions just like the real thing, giving you instant visual feedback on your processes. The collected data can be used to calculate metrics like speed, trajectory, and energy usage, and to analyze and predict efficiencies.*

2 Game Engines

Please refer to resources like Schwartz's Game Design Primer for those unfamiliar with games and game design.

Game Engines are a cohesive collection of software development environments for creating interactive multimedia experiences that incorporate digital models, audio, user interaction, display (or rendering), physics (simulated or imaginary), parallelism, AI, and other critical aspects of games. The Unreal Engine (Section 1) is especially popular, e.g., the "power" behind Fortnite.

Readers may need to realize that popular game engines like Unreal and Unity have expanded multimedia and enterprise divisions. When we meet prospective students at RIT and ask if they've enjoyed *The Mandalorian* or *Star Trek*, we note that they've also witnessed Unreal. A search on Google Scholar for *Virtual Production* will show research from various sectors.

The enterprise divisions of Unreal and Unity offer opportunities in simulation, architecture, construction, and more:

- https://unity.com/industry
- https://www.unrealengine.com/en-US/uses/automotive
- https://www.unrealengine.com/en-US/uses/simulation

The authors research and teach in games, animation, and multimedia development, especially in applications extending beyond the entertainment industry:

- https://theivytree.com/category/portfolio/current-projects/
- https://www.rit.edu/news/rit-researchers-create-serious-video-game-infrastructure-resilience-cyberattacks

We note that *serious games*, *gamification*, *game-based learning*, and related concepts rename simulation and attempt to distill how games, interactive development and design, and multimedia applications have developed over time. Digital twins allow games to impact scientific research and educational processes.

A quick search for "game design" via NSF and NIH yields multiple projects and results:

- https://search.nsf.gov/search?query=game+design&affiliate=nsf&search=
- https://search.nih.gov/search?utf8=%E2%9C%93&affiliate=nih&query=game+design&commit=Search

We refer readers to additional resources for recent research:

- https://seriousplayconf.com

- https://www.iitsec.org
- https://chiplay.acm.org/2024
- https://www.gamesforchange.org

Despite the role, popularity, and success of games in STEAM (STEM with the Arts), we note the lack of a top-level division in NSF and NIH that is devoted to the study of game design and development. This issue will significantly affect the advancement of digital twins research, as discussed in Sections 3 and 4.

3 Connecting Digital Twins and Game Technology

Even without our supplements to the supplied definition of digital twins, we suggest that readers search for the terms *interaction*, *visualization(s)*, and *game* (or *game engine*) in the National Academies report.

Among the 18 references to the visualization of digital twin data, this passage is significant:

> *Effective visualization and communication of digital twin data, assumptions, and uncertainty are critical to ensure that the human user understands the content, context, and limitations that need to be considered in the resulting decisions. While opportunities for data visualization have expanded considerably over recent years, including the integration of GUIs and virtual reality capabilities, the understanding and visualization of the content in context, including the related uncertainties, remains difficult to capture; effective methods for communicating uncertainties necessitate further exploration.*

"Interaction(s)" appears 109 times, further stressing connecting components. We highlight the report's involvement of people in the connectivity via Figure S-1. While graphics, interaction, and visualization tend to combine conceptually regarding virtual reality, a search for the primary technology for doing this work—game engines—has zero mentions in this report. When searching for just "game," we also find no mention.

As discussed in Section 1, game engines have already proliferated and have several industry examples. When we expand to industries that support game engines, modeling, and related technologies, we can generate a significant and critical list of companies already providing digital twin capabilities:

- https://www.unrealengine.com/en-US/digital-twins
- https://www.esri.com/en-us/digital-twin/overview
- https://www.nvidia.com/en-us/omniverse/solutions/digital-twins
- https://unity.com/topics/digital-twin-definition
- https://www.autodesk.com/solutions/digital-twin/architecture-engineering-construction

For those curious about NVIDIA's approach to digital twins, readers from outside of art and animation domains might be surprised about the reliance on Pixar's open-source *Universal Scene Descriptor* (USD) data format:

- https://docs.omniverse.nvidia.com/digital-twins/latest/building-full-fidelity-viz/usd.html
- https://openusd.org/release/index.html

At RIT, we have recent and current grants leveraging game engines, e.g.,

- https://www.rit.edu/news/hanif-rahbari-earns-nsf-career-award-enhance-connected-vehicle-security (Unreal)
- https://www.rit.edu/imagine/exhibits/integration-gamification-and-ideis-enable-crew-health-and-performance-mars (Unity)

And many other academic game programs are doing similar work.

4 Workforce Development and Broader Impacts

In 2022, Game Career Guide (https://www.gamedeveloper.com/gcg-status-update; no longer functional) listed almost 500 academic programs listing games as degrees, minors, or other. For now, we refer readers to https://hevga.org, US News & World, The Princeton Review, and The Animation Career Review for examples of academic programs.

Say 500 schools generate an average of 25 students annually. If we consider the thousands of computer science and art students also applying for the game industry, the estimated 12,500 graduates balloon to potentially tens of thousands more. When narrowed down to a non-enterprise, purely entertainment-based game industry, we cannot place everyone into "just games" jobs. A simple Internet search for "how to break into the game industry" will demonstrate many editorials, advice columns, and more.

However, simply telling prospective students "no" will not work—witness the proliferation of entertainment-based academic programs. Based on a multitude of outreach components in NSF grants, we ask what we believe are critical and related questions to resolve:

- **If we suggest attracting STEM majors and graduates via games, shouldn't we provide more career opportunities, especially if the fields have applications beyond entertainment?**
- **Learning how to make games can be very intense and competitive. Wouldn't we want potential students to apply their skills to interactive, 3-D, real-time applications?**

Solving these questions involves including games, game technology, and faculty in these domains. These driven, talented, multidisciplinary students can forge future generations of skilled problem solvers, especially in real-world applications.

Throughout this RFI, we note the representation and advertising of digital twins via Unreal, Unity, and NVIDIA. We strongly recommend NSF and other funding agencies ensure we incorporate games, game design and development processes, and artists as top-level, critical partners in future digital twins research and development.

5 Potential Research Areas

The Foundation Research Gaps report makes a critical distinction between simulation and digital twin on Page 3, also with Figure S-1:

> *Finding 2-1: A digital twin is more than just simulation and modeling.*
>
> *Conclusion 2-1: The key elements that comprise a digital twin include (1) modeling and simulation to create a virtual representation of a physical counterpart, and (2) a bidirectional interaction between the virtual and the physical. This bidirectional interaction forms a feedback loop that comprises dynamic data-driven model updating (e.g., sensor fusion, inversion, data assimilation) and optimal decision-making (e.g., control, sensor steering).*

We anticipate that modern AI will be essential to processing large amounts of data flowing between twins and their real-world counterparts, but we will still need people in some capacity. From the perspectives of games, art, animation, and related fields, we stress the critical importance of including such researchers in any digital twins project that includes humans-in-the-loop, e.g., **data visualization and communication, significantly to help people understand and operate this technology**.

Considering the visual fidelity and interaction of and with a digital twin, game engines are especially adept at representing large digital models in real-time at varying levels of detail. Every functional, real-time game runs on limited hardware—a typical game developer already works in this capacity. **We must continue studying how to increase simulation and visual fidelity at varying levels, leveraging fields connecting game programming, computer engineering, and interactive computer graphics.**

As game programs tend to focus on entertainment or serious games, many have options for simulations but not digital twins. With the incorporation of real-time interactions between digital and real objects, we need pedagogical research to understand how students can combine and possibly converge engineering, games, and art.

Finally, we suggest a further extension of a digital twin from emergency management and disaster response, especially when considering anthropogenic disasters. For example, say we wish to study the real-time impact of a hurricane. A real-time digital twin of the environment will improve training environments and mitigation plans, save more lives, and deepen the connection between designers and the designed environment. We suggest **asynchronous digital twins—we seek to understand how a simulated virtual environment can be trained and twinned.**

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Deborah Duran

Although digital twins have their place in R&D, we must be careful to assess the efficacy and the limits of that efficacy before applying it to human research. Digital Twins and all synthetic data is contrived or cloned. It is not the original data. In human research, this is critical to distinguish as humans have many complexities not captured by cloning one aspect.   In clinical trial research, cloning small sample sizes to extrapolate about the efficacy of the treatment to all populations remains problematic without additional testing. Model Autophagy Disorder also has to be considered. Not only, does the efficacy of using a digital twin needs to be assessed, but also how many iterations can that model be used before it collapses. R&D needs to determine exactly when does AI models repeatedly trained on AI generated data actually collapse. This occurs because models forget the true data distribution. This occurs because digital twins/synthetic data is not real data.

Please include

- the need to test the efficacy of the digital twin to represent the original source (this may fit in the VVUQ section)….this needs to be called out for humans especially
- the need to test the model for the tipping points that it shifts from valuable to harmful
- the need to test the fidelity or the degree to which the digital twin is delivered as intended by its developers. It's crucial to measure this variable to understand how and why the digital twin works and to assess its impact on outcomes.

Please do no harm to humans using digital twins

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Request for Information on the National Digital Twins R&D Strategic Plan

Digital Twins for Health (DT4H) Consortium

A Strategic Plan for Research and Development of Human Digital Twins

Digital Twins for Health (DT4H) Consortium

I. Introduction

Although the concept of a Digital Twin and virtual simulation dates back to early work in aerospace vehicles by NASA in the 1960's, the DT concept has been gaining increasing popularity in a variety of industries and areas of science as a promising platform for integrating data-driven and mechanistic modeling with artificial intelligence (AI) [1-3]. In early 2023, the National Academies of Sciences, Engineering, and Medicine appointed an ad-hoc committee to identify the needs and opportunities to advance the mathematical, statistical, and computational foundations of digital twins in applications across science, medicine, engineering, and society [4].

Among a wide range of applications, the concept of digital twin can play a particularly important role in modeling and simulation of the human body and its intricate subsystems. Known as a Human Digital Twin (HDT), this branch of digital twin research holds the potential to profoundly impact human society and enhance lives by enabling personalized health monitoring, improving the detection, screening, and prevention of adverse health conditions, and facilitating virtual testing and clinical trials. It is acknowledged, however, that significant research and development efforts are still needed to fully realize the potential of digital twins in healthcare. In this response, we present our vision for advancing the emerging field of HDT and propose strategies, discuss challenges, and make recommendations for its future applications in the scientific community.

II. Definition of a Human Digital Twin (HDT)

In its most general form, a human digital twin (HDT) is a virtual representation of an individual human, that can encompass real-time simulations of multiple sub-systems operating at multiple length scales ranging from microscopic cells and molecules to tissues, organs, organ systems, and ultimately the entire human body. In general, the biological class of digital twins share the following basic properties [5]:

- **Individualized** - An HDT is highly personalized, at the level of an individual human, or a specific genotype or phenotype.
- **Interconnected** - An HDT is informed by a real-time connection to a living biological system.
- **Interactive** - An HDT enables a real-time closed loop feedback between the physical and virtual systems.
- **Informative** - In addition to the physical and virtual components, an HDT platform must also provide a means for third-party observers to view, control, test, and interpret the behavior and response of the virtual system.
- **Impactful** - An HDT can contribute significantly to better health and well-being through continuous monitoring and analysis, early detection of potential health issues, and improved treatment strategy.

III. Strategies for Advancing Human Digital Twins for Better Health

In March 2022, the Digital Twins for Health (DT4H) Consortium was established, comprising a global network of professionals and researchers with diverse domain expertise who share a common goal of advancing HDTs [6]. Since its inception, the DT4H Consortium has conceptualized a research cyberinfrastructure, i.e., a DT4H Gateway, to advance R&D for HDTs by addressing the challenges faced by researchers, developers, and users and facilitating their navigation of the HDT landscape across multiple disciplines for the first time. As shown in **Figure 1**, the DT4H Gateway includes five infrastructure modules: (1) computing; (2) standardizing; (3) learning; (4) modeling; and (5) training, operating under four guiding principles: (i) collaborative scientific teamwork; (ii) ethical and trustworthy digital twins; (iii) commitment to diversity, equity, and inclusion; and (iv) active community involvement and partnership.

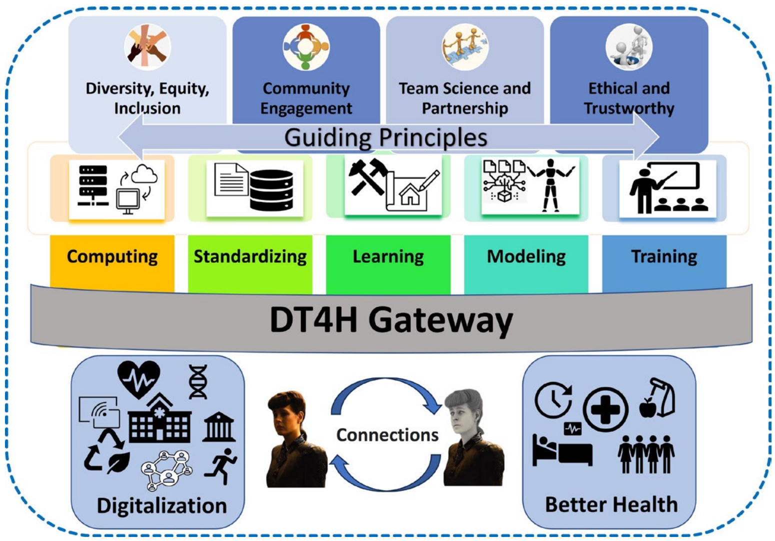

Figure 1. Our overarching vision of advancing HDTs for better health via a DT4H Gateway.

As a consortium, we have identified several fundamental strategies for advancing the field of human Digital Twin research. A basic summary of the strategic areas is listed below.

III.1 Concerted Research Experience Integrated through Computing

The vision of the computing module is to provide a concerted research experience by orchestrating a seamless integration of diverse datasets, tools, models, and computing resources to provide researchers with an efficient and cohesive workflow management environment [7-9]. Providing interfaces between data and AI algorithms allowing continuous model enhancements and interfaces for comparing user data to existing models is a significant technical undertaking and a necessity for data and model standardization. Consistent well-documented and well-preforming application programming interfaces (APIs) will allow reproducible HDT workflows which include a mixture of data, algorithm, model, sharing, and visualization components.

Specifically, the environment needs to manage user accounts with precision and foster a collaborative spirit by enabling users to work effectively in groups. Tools and datasets need to be managed efficiently to facilitate team science. Users should be able to write and execute code remotely, and user interfaces should be intuitive for users to design, track, and manage virtual experiments. Additionally, the computing environment must support collaborative scientific inquiries through metadata-rich virtual experiments. Adherence to metadata standards can ensure those experiments are FAIR (findable, accessible, interoperable, and reusable), enhancing collaborative scientific inquiries. Adopting industry standards on task and workflow execution, data management, privacy and security management is necessary to foster translation of user research environments with diverse backend resources.

III.2 Enhancing HDT Data Standardization and Integration under an Ethical Framework

The standardizing module focuses on providing resources, best practices, and tooling to facilitate data standardization and integration for HDTs, as summarized in **Table 1** above. This will ensure the HDT data are accurate, reliable, and interoperable across different systems and platforms.

Table 1. The multimodal data types used in HDTs and the potential standardization strategies.

Multimodal data types	**Standardization strategies**
Electronic Health Record (EHR) data	Observational Medical Outcomes Partnership (OMOP) Common Data Model [10] and HL7 FHIR (Fast Healthcare Interoperability Resources) [11]
Mobile health data	HL7 consumer mobile health application function framework guideline [12]; Open mHealth tools [13]
Physiological and biomedical imaging data	Digital Imaging and Communications in Medicine (DICOM) [14]; Hierarchical Data Format version 5 (HDF5) [15]
Genetic testing data (-omics)	Variation Representation Specification (VRS) [16]; MIGS-MIMS for genomics [17]; MIAPE for proteomics [18]; CIMR for metabolomics [19]; MIAME for transcriptomics [20]
Social Determinants of Health data	Social Determinants of Health Ontology (SDoHO) [21]

III.3 Establishing Advanced Machine Learning Framework for Building HDTs

The vision of the learning module is to provide a comprehensive and advanced framework for building HDTs, encompassing a range of tools and methodologies to extract, augment, integrate, and interpret data effectively, as summarized in **Table 2** below.

Table 2. Various approaches to extract, augment, integrate, and interpret multimodal datasets.

Multimodal data types	**Learning strategies**
Genetic/genomic data	Pararead [2], COCOA [23], AIList [24], GATK's FilterIntervals [25], LOLAWeb [26], DeepChrome [27]
Imaging data and textual feature	AALIM [28], large language models (LLM) [29]
Behavior and health data	Machine learning tools [30]
Social media data	Natural language processing (NLP) tools [31]

Moreover, tensor fusion networks [32] and multiplexed graph neural networks [33] can be used for modality integration. For data visualization and interpretability, a variety of methods can be applied, such as AI Explainability 360 [34], Boolean Decision Rules [35], Generalized Linear Rule Models [36], LIME [37], SHAP [38], TED [39], t-SNE [40], PCA [41], and UMAP [42].

III.4 Developing HDT Capabilities through Modeling and Simulation

The modeling and simulation module, integral to building specific HDTs, is responsible for developing retrospective restructuring, monitoring, analytical, and predictive capabilities of HDTs by integrating data-driven and mechanistic approaches with advanced AI technologies and data science methods. The type of modeling employed can depend on the specific type of data being used. **Table 3** lists various data types and the corresponding modeling and simulation strategies.

Table 3. Modeling and simulation strategies for various data types and scenarios.

Multimodal data types and scenarios	**Modeling and simulation strategies**
Longitudinal Data modeling and forecasting	Various dynamical system models [43], including neural dynamical systems, neural integral-differential equation models, RNN models, transformers, GNNs, diffusion models, and latent variable approaches
Omics data	Gene regulatory networks [44] and functional protein network models
Single-cell, cell aggregates	Multiphase materials models, level-set models, phase field models, and Cellular Potts Model (CPM) for modeling single-cell and cell aggregates [45]
Organs and tissues	Spatial-temporal dynamical models based on non-equilibrium thermodynamics and network models, including level-set models, phase-field models, etc. [46]
Multimodality data fusion	Graph-based toolkits and graph neural networks [47]
Environmental particulates and drug interactions	Pharmacokinetics/Pharmacodynamics modeling tools [48]
Human behavior, mental health	Various temporal models for simulating norms in online social networks and cross-platform prediction and simulation [49]
Human-environment interactions	Agent-Based Models [50]
Integration of physics-based, agent-based, and statistical models with generative AI such as ChatGPT, GPT-4, Claude 3, and DALL-E	Large language models (GPT-4, Claude 3, etc.), multimodal generative AI model based on stable diffusion models [51-52]

III.5 Building a Sustainable Community Through Training and Workforce Development

Our vision for the training module is to facilitate the training of the next generation of leaders in engineering, science, and technology to become HDT creators, builders, and users. As listed in **Table 4** above, it is imperative to build a sustainable program focusing on career development support and mentoring across all career stages, emphasizing underrepresented and minority groups.

Table 4. Various programs to enhance training and workforce development for HDTs.

Programs	**Training and workforce development strategies**
Interdisciplinary Mentoring	Dual mentorship in biomedical science and AI/ML, leveraging online forms, PubMed knowledge graph [53], and mentorship databases [54] for diverse pairing and flipped mentorship

Recruitment and Diversity	Utilizing various channels for recruitment and focusing on increasing diversity through lectures and mentorships by experts from academic partners and government organizations [55]
Outreach and Partnership	Forming partnerships with communities, industries, and advocate groups, offering internships, practicum opportunities, and HDT data and tool challenges
Ethical and Trustworthy DT	Emphasizing ethical AI algorithm and model development, data privacy, and security technologies

IV. Specific Challenges for Human Digital Twins

While HDTs represent a groundbreaking advancement in personalized healthcare and offer immense potential for improving health outcomes, realizing the full potential of HDTs in healthcare requires addressing several formidable challenges that span across various domains.

Challenges of inherent complexities and uncertainties in human bodies: Human bodies exhibit significant heterogeneities at the molecular, cellular, and organ levels, resulting in substantial differences in biological responses among individuals. Biological processes can change over time. The dynamic nature of biological systems often exhibits non-linear behaviors and emergent properties, making it difficult to predict responses accurately. Incorporating the temporal aspect into an HDT is complicated, especially considering the various factors that influence human health over a person's lifetime, the incomplete understanding of underlying mechanisms, and often incomplete or limited available biological data from various sources.

Challenges in advanced algorithms, computational resources, and validation: The current state of knowledge regarding human physiology, disease mechanisms, and treatment responses remains incomplete and continuously evolving. Integrating this fragmented understanding and theoretical frameworks into HDT models, while simultaneously accounting for inherent uncertainties and facilitating seamless model updates as novel insights emerge, poses a critical challenge that demands innovative solutions. Furthermore, HDT simulations and analyses often involve processing massive volumes of data and performing computationally intensive operations, necessitating the development of highly efficient computational algorithms and the strategic harnessing of high-performance computing resources to enable real-time simulations and analyses. Moreover, ensuring the accuracy, reliability, and robustness of HDT models and simulations is of paramount importance for their practical applications in healthcare settings. Developing rigorous validation and verification frameworks, encompassing virtual clinical trials and comparative studies with real-world data represents a significant challenge that requires focused efforts and interdisciplinary collaborations.

Privacy and regulatory challenges: The wealth of personal and sensitive healthcare data embedded in HDTs raises significant privacy concerns, necessitating stringent measures to safeguard individuals' information. HDT data collection and sharing must also adhere to existing regulations and standards related to health data protection. This includes compliance with frameworks like the Health Insurance Portability and Accountability Act (HIPAA) in the United States or the General Data Protection Regulation (GDPR) in Europe to ensure the lawful and ethical use of digital twin technology in healthcare. Informed consent in the HDT context, particularly with continuous data collection and updates, necessitates a nuanced approach that prioritizes ongoing communication, transparency, and respect for individuals' autonomy over their health data. Informed consent in HDT involves providing individuals with comprehensive information regarding the purpose, risks, benefits, and potential uses of creating a dynamic digital representation of their health based on personal data. Challenges arise due to the complexity of HDT technology, requiring efforts to ensure individuals fully grasp the implications of this technology.

Security and safety challenges: The reliability of an HDT hinges on the accuracy and fidelity of its digital representation, which, if compromised, can lead to erroneous conclusions and potentially harmful consequences in fields such as healthcare and engineering. Ensuring the reliability of data inputs, calibration processes, and the overall model becomes crucial to maintaining the integrity of the HDT's predictions. Simultaneously, security-related issues pose significant ethical challenges, as the vast amount of personal and sensitive data incorporated into HDTs requires robust protection mechanisms. Unauthorized access or malicious tampering with HDT data could not only jeopardize individual privacy but also result in inaccurate representations and recommendations, potentially impacting real-world entities connected to the HDT.

Data heterogeneity and quality challenges: One of the primary challenges of healthcare data is its inherent heterogeneity and varied quality. Health-related information frequently exists in disparate systems and diverse formats, making integration a complex task. This data, sourced from EHRs, wearable devices, and other digital health tools, often varies significantly in accuracy, completeness, and reliability. The technical intricacies involved in harmonizing this data are considerable, as it necessitates sophisticated methods to ensure consistent and accurate interpretation across different platforms and data types. Moreover, the reliability of HDT models in healthcare heavily relies on the quality of the underlying data. Therefore, establishing robust protocols for data quality assurance is crucial. These protocols must address the nuances of health data, ensuring that the integrated data is not only interoperable but also maintains a high standard of precision and validity. Such meticulous attention to data quality is essential for the successful implementation and effectiveness of HDT models in healthcare.

Data representation and bias challenges: The potential for bias in healthcare data, often reflective of historical disparities and systemic inequities, can be perpetuated in HDTs, leading to unequal outcomes. If not meticulously addressed, this bias may result in disparities in healthcare recommendations and interventions. Furthermore, the development and utilization of AI predictive models within the HDT context carries the risk of encoding and amplifying existing biases present in the training data. Equitable access to HDT technology is another critical concern, as disparities in access may exacerbate existing healthcare inequalities. Ensuring that the benefits of HDTs are accessible across diverse populations becomes imperative to prevent the technology from inadvertently reinforcing societal disparities.

V. Recommendations for Human Digital Twin Research

Addressing these challenges requires a combination of advanced computational techniques, interdisciplinary collaboration, improved data standards, and ongoing refinement of biological models as our understanding of human biology advances. Collaboration with relevant stakeholders, adherence to ethical guidelines, establishment of standards for data integration, model development, and system benchmarking, and a commitment to data privacy are crucial.

Regulatory framework for data security and privacy: The regulatory framework for data security and privacy must evolve to address the unique considerations of HDT in healthcare. It involves collecting diverse and relevant information about individuals to create accurate and representative models. Potential sources include EHRs, wearable devices, genetic data, surveys, mobile apps, and more. It is critical to implement robust data privacy and security measures to protect sensitive health information and adhere to relevant regulations, such as HIPAA or GDPR, and obtain informed consent from individuals. Meanwhile, longitudinal data collection is necessary to capture changes over time. This is particularly important for understanding health trends, monitoring interventions, and predicting future health states.

Standardization: By offering personalized insights, early disease detection, and treatment optimization, HDTs are capable of revolutionizing healthcare. However, there is a lack of standards and guidelines for modeling humans as part of the system, and data standardization is set to become an issue. Thus, it is important to architect data standards that can provide robust information to support human modeling. Additionally, a global perspective should be considered to allow advances in HDTs to have a worldwide impact.

Ethical implications of human digital twins: The HDT technology for personalized medicine may not be accessible to each individual or community, highlighting the unequal distribution of technology. This can cause an additional form of 'digital divide' among persons and populations. It is therefore important to ensure digital equality to advance HDTs for better health. Moreover, unacceptable segmentation and discrimination/injustice may be triggered by patterns identified across a population of HDTs. Thus, there is a need for governance mechanisms to safeguard the rights of individuals who own HDTs, ensure data security and privacy, and foster transparency and fairness of data usage, health equity, and all derived benefits at both individual and wider societal levels.

Increase community engagement: Efforts should ensure community input in the development and implementation of HDTs. HDT research should promote ongoing bi-directional engagement, ensuring the inclusive involvement of diverse community perspectives. Some of these strategies include focus groups, town hall meetings, dissemination forums, and interactive digital platforms tailored to the different community stakeholders. Further, these forms of engagement should endure cultural sensitivity and inclusivity to avoid biases and ensure relevance across different communities and stakeholders.

Funding implications of human digital twins: Funding agencies would have a significant amount of impact on advancing HDTs. Specifically, they can offer financial support, promote research prioritization, interdisciplinary collaboration, data sharing, and standards, ethical and regulatory frameworks, invest in educational programs and public outreach efforts, invest in the development of enabling technologies such as HPC and ancillary resources, help ensure that there is sustainable support for maintaining and updating HDTs, continuously monitor the progress and impact of HDT, and encourage collaboration and information sharing on a global scale.

Specifically, a substantial initial investment is required to develop the necessary cyberinfrastructure. This includes hardware, software, and network capabilities to support complex data processing and simulation tasks. Leveraging collaborative funding from various sources, such as government grants, private sector investments, the healthcare industry and academic institutions, can provide a more robust financial foundation. Ongoing operational costs, including maintenance of technology infrastructure, data storage, and security, require sustainable funding sources. This might involve subscription models, partnerships with healthcare providers, or government support. Investing in training programs to develop a skilled workforce capable of building, maintaining, and utilizing DT technology is essential. This includes funding for educational programs, workshops, and certification courses. Such goals can be embedded in the request for proposals (RFP) and broad agency announcements (BAA) as the NSF and NIH routinely do in their portfolio.

VI. Conclusions

The emerging HDT technology offers tremendous opportunities for personalized healthcare, predictive interventions, remote monitoring, and medical research advancements. It has the potential to revolutionize healthcare by integrating with the healthcare sector, information technology, AI industries, the government and private sector stakeholders. While there are still many obstacles and challenges in implementing human digital twins for healthcare, we envision a bright future for HDT with cross-disciplinary collaborations and efforts by all the stakeholders including the government, industry, academia, and private sectors.

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Federal Register Notice: 89 FR 51554, Federal Register :: Networking and Information Technology Research and Development Request for Information on Digital Twins Research and Development, June 18, 2024.

Request for Information on the National Digital Twins R&D Strategic Plan

DoD Blast Injury Research Coordinating Office (BIRCO)

Department of Defense Blast Injury Research Coordinating Office response to:

The National Science Foundation Networking and Information Technology Research and Development Request for Information on Digital Twins Research and Development

We greatly appreciate the opportunity to reply to the Networking and Information Technology Research and Development Request for Information (RFI) on Digital Twins Research and Development Request for Information. Since 2014, the Blast Injury Research Coordinating and Development Office (BIRCO) has been working toward the development of human digital twins to understand and mitigate lethality, injury, and impairment from blast hazards. We have been leading cross-organizational Working Groups to achieve this goal both within the US Government and with our NATO partners. These engagements have resulted in the development of many research and development (R&D) topics that have relevance to the RFI that are discussed below.

Data: Two significant challenges faced by the biomedical community in establishing human digital twins are a) access to industrial, academic, and Government data sources and 2) robust understanding of the quality of these data. Providing appropriate access, minimizing burden on the host site, and maintaining intellectual property controls were challenges discussed across our domestic and international engagements. Data quality varies widely and methods for effective methodological reporting are inconsistent. A more robust and consistent way to provide end-users of the data with an understanding of its limitations is necessary.

VVUQ: The ability for models to effectively and correctly communicate is necessary in the development of a human digital twin due to the complexities of different body systems and spatial and temporal changes biological responses. Conceptual alignment of the models and associated simulations is necessary to support the creation of the integrated system of simulations with correctly aligned data and orchestrated processes. Trust in the model between modelers and stakeholders, which can be built on effective validation, is critical for credibility and acceptance of outputs from a Digital Twin. Unfortunately, human body computational models are not generally designed to be integrated within a digital twin or even exchange data. Concepts that are explicitly defined or assumed within one model may be absent or assumed incapable with another model challenging the ability to use these models within the same simulation environment. Model validation is complex and varied and models of interest are likely not to be validated in all relevant environments or for all injuries of interest. Research into appropriate model extrapolation as part of VVUQ beyond its original intended use would be of significant interest within the Strategic Plan.

Ecosystem and International: The DoD Working Group on Computational Modeling of Human Lethality, Injury, and Impairment from Blast-Related Threats (CMWG) established by BIRCO garnered support from 26 DoD organizations and 7 other federal agencies including NSF. The NATO Human Factors and Medicine (HFM) Research Technical Groups (RTGs) chaired by BIRCO were supported by 13 NATO nations. Establishing and sustaining these communities required appropriate alignment of interests and consensus building to give all parties a voice.

Extending from these engagements, development of a human digital twin requires successful coordination and resourcing from across the federal Government as well as international partners. An appropriate governance structure that gives all parties a stake in the results will help to establish a lasting eco-system. A collaborative governance structure promotes collective decision-making in situations where one or more public agencies directly engage non-governmental stakeholders in a formal, consensus-oriented, and deliberative decision-making process aimed at making or implementing public policy and/or managing public programs or assets. Research into understanding how to establish and sustain a collaborative governance structure would greatly enhance the Strategic Plan. Lessons learned from the BIRCO domestic and international engagements may prove beneficial in the Strategic Plan's development.

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Request for Information on the National Digital Twins R&D Strategic Plan

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To whom it may concern,

We are submitting a joint comment on the Networking and Information Technology Research and Development Request for Information on Digital Twins Research and Development Request for Information Document Citation: 89 FR 51554, Page 51554-51555 (2 pages), Document Number: 2024-13379. Below are the authors of this document:

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We come from a wide swath of the federal government, academia, and industry. We believe diverse viewpoints and stakeholders are necessary to develop the National Digital Twins R&D Strategic Plan and to see the Strategic Plan through to fruition. This comment outlines our vision for 13 core topics identified in the RFI, and how they can be integrated into a national strategy. The Strategic Plan can be realized only through significant and close collaboration, and we are positioned to undertake the endeavor through a future National Digital Twin Center.

Artificial Intelligence (AI):

Although the role of **Artificial Intelligence** (AI) in the context of Digital Twins (DTs) has been recognized[1], there has been limited focus on how DTs can generate sufficiently large **training datasets** to enhance AI training and testing. Specifically in military and mission scenarios, DT models can impact **mission scenarios** by accelerating the development process and reducing the time and cost required for AI training[2].

The past few years have seen the advancement of generative models (a part of the larger **artificial intelligence** domain) and their success in many domains. Although past work has shown that generative models can be leveraged in DTs to, for example, extract features from high-dimensional data[3] and predict future states[4], the integration of **generative models** to DTs is still understudied. The most important capability of generative models involves learning data distributions, which can be exploited to learn the (potentially high-dimensional) uncertainties of the physical twin's state based on sensor data (e.g., the geometric uncertainties of fabricated part[5] or uncertainties of the physical twin's future state given its current state). This will allow more robust control of the physical twin's outcomes. The challenges will be two-fold: 1) the lack of data to train a high-fidelity generative model and to update the model in real-time and 2) the model's generalization ability to unusual or extreme conditions.

One of the challenges of integrating different models into a **Digital Ecosystem** is real-time information retrieval from heterogeneous sources. **Artificial intelligence** agents (a.k.a. cognitive assistants) can assist the user to seamlessly and quickly retrieve information from different sources, which can be applied throughout the system's lifecycle, from design[6] to operations[7]. **Question Answering (QA) systems** allow for information retrieval from multiple data sources in natural language. However, traditional QA systems based on question intent classification, parameter extraction, and predefined queries and answer templates, lacks scalability and flexibility. **Large language models** (LLMs) have been recently used to significantly expand the capabilities of information retrieval and QA systems. LLM-based systems can now be integrated into AI agents to interpret natural language questions, retrieve the relevant information from an information space, and generate natural language answers, without the need for pre-specifying a set of known question types[8]. However, the use of LLMs has brought new challenges. First, LLM-based QA is slower than traditional QA systems, in part because of the latency of the request to the application programming interface (API). Second, organizations have expressed concerns about the **security** of their data; if any dialogues between users of the QA system and the tool go through the servers of the organization providing that API service, that undermines the confidential nature of the data, especially if the API service provider uses that data to train their models. Finally, for some applications there are challenges related to computing infrastructure requirements. Many of the more powerful LLMs are based on APIs that require an internet connection. Some models exist that can be hosted locally but they are less powerful. One can also train smaller language models for a particular task, but that may require access to significant computing infrastructure.

An interesting new approach that DT enables is based on **Artificial Intelligence** and machine learning harnessing the power of plasma chemistry as a programmable intelligent material with a new concept of a chemical-based algorithm[9]. The focus of some future research will be on integration of DTs with AIto allow development of predictive capabilities by DTs.

Business: Business Case Analysis:

Despite the advantages of DT and Industry 4.0, **small and medium manufacturers (SMMs)** face low **Industry 4.0** readiness[10] due to challenges in understanding how DTs optimize operations, enhance product development, and improve maintenance processes. This is compounded by a lack of **business case analysis** studies demonstrating return on investment, difficulties in identifying suitable applications, and issues with compatible software solutions. Furthermore, SMMs often lack clarity on where to begin, what steps are involved, and what resources are needed, which stalls progress and deters manufacturers from pursuing DT initiatives. A higher understanding of business cases for using Industry 4.0 solutions is essential to prepare SMMs for investing in such capabilities[11]. Because they are purpose-driven, a given DT must match the fidelity and scope of the model to the type of problem being solved. Excessive detail (fidelity), high-bandwidth updates (frequency), and broad boundaries (scope) add unnecessary cost and complexity, delaying value realization. This challenge is compounded by a lack of common definitions of DTs, their components, and capabilities. The DT Consortium and other bodies have invested in creating common definitions and reference frameworks for DT use cases. These **standards** must now be widely utilized, revised based on real-world implementations, and enhanced with complimentary tools that accelerate DT adoption. Research should be done to help SMMs deciding upon system boundaries, curating minimum-viable datasets, and making efficient choices to focus system development on the problem statement. Manufacturing executives need tools to evaluate whether DT is a good fit for their problem, challenge, or business need, while system architects need guidance on scope, frequency, and fidelity to maximize business value. IT/OT professionals require estimates of the labor needed before a DT system produces outputs to allocate resources and set expectations effectively.

Traditional **simulation and DT models** share the same capability to replicate physical systems in virtual environments[12], but they are fundamentally different[13]. Simulation is in the core of DTs leading to confusion and the mislabeling of simulation models as DTs and vice versa[14]. Unlike simulations, DTs feature continuous bilateral communication, sensor-based monitoring of physical system changes, and real-time decision-making support. Research has found that a significant portion of literature claiming to present DT case studies fails to achieve true DT capabilities, instead presenting simulations as DTs[15]. Even among correctly built DTs, many underutilize their potential. This highlights a persistent gap between the conceptual understanding of DTs and their **practical application**. Research is needed to develop business decision-making tools, such as decision trees, to help determine when a DT is viable for a problem or if a simulation model will suffice. These tools would guide the selection of the appropriate technology based on the specific scope and requirements of each problem.

The **Department of Defense** (DOD) is transitioning the **acquisition community** for the development of new military systems to a digital engineering environment in which computer models and formal representations of the system are used to inform decisions throughout the entire life cycle of the system. One goal is to have a **digital thread** connecting all the disparate models of the system. Ideally, a DT would be a part of the **digital engineering** infrastructure. Specifically, research is needed in how conceptual and detailed design models can be used to generate some or all of a DT. Such an approach of integrating the development of the DT with the development of the system would greatly reduce costs of DT development and support **verification** that the DT represents the physical system. Also, each additional ship, plane, tank, etc. produced by a DOD program tends to incorporate many engineering changes and technology upgrades which make it significantly different from previous systems in its class. Research is necessary in processes and technologies to generate and manage serialized DTs corresponding to individual fielded systems.

<u>Data:</u>

Research has shown that within enterprises, over 90% of data exchanges are not governed and around 90% of data element exchanges lack digital connectivity[16,17]. Additionally, key vessels of data such as models and documents are often spread across dozens or hundreds of disparate storage locations for stand-alone efforts. Therefore, a primary hurdle that must be overcome for successful DT development and implementation is the adoption of **data management best practices** that enable the realization of the **digital thread**. When determining what data will be used to create the DT, it may be helpful to categorize the data as being related to four different phases of DT implementation: Representation, Replication, Reality, and Relational[18]. Prior to realization of the DT, it is advisable to deploy a methodology to identify disparate and ungoverned elements of data within the system of interest. Once the elements of data are identified, they can be systematically categorized as relating to the Representation, Replication, Reality, and Relational phases of the DT, and consequently, the **digital thread** will be enabled alongside the DT.

Ecosystem:

For **military and mission planning** to make significant advances, a **national Digital Twin R&D ecosystem** must be established both of military and defense systems, and of the industrial and commercial systems that support them. **Mission engineering**[19], planning, operations and maintenance, and many other activities will be enhanced with better DT development and implementation[20]. Already, some work has pointed towards the effectiveness of DTs in improving outcomes for route planning[21], maintenance, and etc. Further, having better access to data through DTs will allow for rapid fielding of new capabilities that can be achieved by integrating existing systems into systems of systems, and identification of capabilities gaps.

The complexity of adapting to existing and future **climate change** impacts and reducing emissions to try to mitigate future effects requires a diverse R&D ecosystem to facilitate the flow of ideas and expertise toward relevant research and technologies. **Artificial Intelligence** and DTs can add to the R&D ecosystem through identifying and quantifying the sources and amount of emissions along with advancing environmental monitoring and efficient data collection and analysis[22]. A DT of the **climate system** allows for better models that simultaneously produce interactive information for **climate adaptation**, emissions reductions and streamlining carbon capture processes[23].

DT **behavior** is a key element in understanding the **functionality** and **operability** of the physical system with the digital model. The modeling of system behavior involves the identification and use of system state variables in the construct and execution of the DT. **State Analysis Modeling** (SAM) is an emerging system state variable modeling approach that provides a digital representation of the system behavior in an interactive simulation[24]. SAM includes the software algorithm, hardware state machines, and mission/flight timelines representing the integrated system behavior in an accurate representation of the physical system. Operator/user input can be supported in the execution of this DT model providing interaction with the user input as well as software to fully encompass DT behavior of the system. This DT of the system behavior has been applied in a few examples and the development of the SAM DT representation is needed in multiple technical domains within the US industrial base. Identification of system state variables and construction of accurate hardware state machines is essential in the model achieving DT behavior representation. Operator/user interaction also requires investigation in providing both live and simulated human behavior interacting with the SAM. The development of this modeling concept provides a system simulation that encompasses a DT of the physical system behavior.

International:

Historically, military systems have struggled to balance security, standards, and proprietary equipment. As a result, military equipment often does not fully leverage **international integration standards**. The result of this coupled with different international languages, units of measure, and other factors can result in **interoperability** issues. The end result can drive increased costs and complexity of development, test and evaluation, training, and failure to maintain a shared operational picture and full transparency across international partners[25].

During system architecture, design, and initial synthesis, the development of early virtualization **DT frameworks** can provide a readily available testable solution for **verifying interoperability** throughout early phases of a system's lifecycle. This will significantly reduce the risk that once fielded, systems will face integration hurdles that become more costly later. Once a system approaches low-rate production and begins being used to test the many diverse use cases required by international partners, the DT can offer significant value to low-cost early test and evaluation to allow stakeholders the ability to defer many requirements to later test phases resulting in significantly more **risk reduction** data collection and reduced overall total ownership costs.

The utility DTs offer for **operations support** is widely described throughout this document, but from an **international partners** perspective there is significant need for **shared operational picture** and **maintaining transparency** across stakeholders. When considering the operational picture, different stakeholders may have different assets and resources available to create international solutions to local problems. DTs that monitor the use of assets in the field and provide contextual awareness of functionality to those partners will significantly speed up response times and improve efficiencies of those operations by eliminating the need to regularly communicate status and request supports. In effect, a DT – Physical Asset pair allows people on the periphery of direct operations to act autonomously in their support to the activity. From a **transparency** perspective, there is significant value in objective quality evidence of what assets are doing. The maintenance of DTs and distribution of their data sets can allow international stakeholders (both allied and others) to have **higher confidence** in activities and **validate assumptions**. The result is allies will know that they are being given accurate information, and adversaries can eliminate suspicion of nefarious activities.

Long Term:

Since its inception, DT has always been intended to exist in all four phases of the **product lifecycle**: create, build, operate and sustain, and dispose. However, there is a common misconception that DTs can only be created once a physical product exists. This belief is understandable, given that most discussions and applications of DTs occur when there's a tangible product to work with. However, a DT exists from the beginning of a product's development and, in fact, precedes the physical product and it is a false notion to claim otherwise. The essence of a true DT lies in its ability to represent something that is intended to exist physically. A DT starts as a foundational model early in development, capturing the product concept for further refinement. As the project progresses, the DT incorporates design specifications and performance data. During operation and sustainment, it serves as a tool for real-time monitoring and optimization of the ongoing performance of the product. When considering the journey of a DT throughout a product's lifecycle, it is essential to understand its evolution and adaptability. Research is needed to show how DTs **evolve** with the product throughout its **lifecycle**, highlighting their **adaptability** and utility f**rom conception to disposal**. Furthermore, the value of having a DT before the physical entity exists should be illustrated.

Regulatory:

The more complex a DT, the more information it requires or produces, and the longer a DT is in operation, the more potential regulatory and legal challenges may exist. Developers and users of DTs must be aware of a variety of such issues including **data ownership**, **causation** and **liability**. In particular, a **regulatory framework** must consider **cybersecurity**, protocols for **modelling risk**, **intellectual property**, allocation of risk and external requirements such as responsibility for data quality and effective function[26]. The risks posed by DTs differ depending on the nature of the DT; a **regulatory** regime will need to take such differences into account, while also facilitating the growth of sustainable DTs[27].

Responsible:

The US Navy's Smart Ship Systems Design (S3D) platform using Formal Object Classification for Understanding Ships (FOCUS) requires **compliant data** relative to a ship design such as properties and geometry for ship components, interconnects (i.e. shafts, piping and cables) and structures (i.e. hulls and bulkheads), behaviors, and simulation results with their Leading-Edge Architecture for Prototyping Ships (LEAPS) repository[28] is an example of a **responsible** approach to DTs. Nothing is released into LEAPS that is not FOCUS-compliant. FOCUS compliance includes **time stamps** and pointers to relevant **measured data** from which parameters are derived. Building on the FOCUS **compliance concep**t of including identifiers on ownership and **intellectual property/data ownership** to the already existing (or in process) **traceability** to data sources and Technical Readiness level of data is critical to having responsible, **ethical** DTs.

Standards:

The sudden proliferation of publications on DTs could be counterproductive to the advancement of the state of the art in any field of application for DTs due to the lack of **standardization**. The term "DT" is sometime used to replace the terms "modeling and simulation" and the objectives and functionalities of the published DTs are often unclear. The recently published DoDI 5000.97[29] clearly places DTs within the larger **digital engineering ecosystem**, providing the first, basic DOD standard on this topic. Future **standards** should focus on the **interoperability** of DTs, with clear definitions of inputs and outputs, connections, communication, data exchange, etc. Within a system, each subsystem or component could have a DT developed by different manufacturers. Clear and detailed standards will ensure that all DTs can be connected together to form a larger system. This concept is similar to what happens with power electronics-based power distribution systems, such as microgrid or transportation power systems, where power converters from different manufacturers work together to form the power system.

Sustainability:

The manufacturing industry consumes significant energy and raw materials globally. Often, locally inefficient decisions, such as using excess packing material, are made to simplify the overall distribution system. Logistics chains, material usage, and product design processes are optimized for business needs rather than **sustainability**, with little focus on end-of-life considerations, re-use, recycling, or circularity during the initial design and business model development stages. DTs can integrate cross-domain information to support more informed local decisions. For example, using less packing material for a product shipped locally versus across the country. Research should highlight how the holistic system view provided by DTs can reduce waste, increase efficiency, and support **circular economies**.

The development of DTs – and any **Artificial Intelligence** technology that is developed to address **climate change** – must consider the **life cycle emissions** of the DT. Without that, the tool that is expected to help model, monitor or reduce impacts is adding to emissions and exacerbating climate change in the process. It is critical that DT prioritizes energy demand reduction first and energy-efficiency second. Reducing energy demand over the life of the DT not only reduces future climate impacts but also models such opportunities for other technologies. Simultaneously, a DT can be used to model improvements in future technologies and extend the life cycle of products through predictive maintenance thus driving **sustainability**[30].

DTs can be designed with **energy efficiency** as a design objective; the virtual twin continuously collects and processes data from the physical twin and can provide feedback to the user about energy consumption and potential energy savings, thus influencing user habits. Further, the DT could take action to reduce energy consumption, for example during the time in which the physical twin is on standby.

Additional energy savings could be obtained with DT to reduce maintenance events, as previously stated, through prognostics and predictive maintenance, to replace scheduled maintenance. However, DTs inherently increase energy consumption, due to the parallel operation of control systems, particularly if **Artificial Intelligence** is implemented. **Guidelines and standards** for use of AI should be provided to avoid abuse, which could drive energy consumption with no obvious return on investment. In other words, not all DTs must have extraordinary processing capabilities to be able to run AI algorithms which are energy-hungry. Designing DTs with **sustainability** in mind is imperative from the start.

Trustworthy:

Security in the context of DTs applies to (1) modeling of the physical system components in the DT so as to elucidate **cybersecurity** issues, (2) security of the DT system infrastructure, and (3) security of the interaction between the DT and physical system and other external components including other DTs as a system of systems of DTs (SoSDT), covering information, updates, controls, and changes that are transmitted among these systems. The authenticity of data and reliability of the DT or SoSDT are thus contingent on networking security. Bitencourt et al.[31] have identified two primary perspectives of **trustworthiness** for the DT: 1) trust in the DT's information and that information has not been tampered with[32] and 2) trust from the user that the DT's information is correct to support decision-making[33].

Developing **secure and trustworthy** DTs presents some unique challenges and opportunities. As DTs grow in complexity, it is essential to ensure all the interactions across different components within the DT, as well as between the DT and the modeled physical systems, are **secure**. Furthermore, if the DT enables a real-time, accurate modeling of the relationships within the physical system, this can unveil hidden **vulnerabilities** and **attacks** that would otherwise go undetected. Therefore, it is imperative for the DT to capture and understand these important relationships for a better **situational awareness** of the complex, dynamic, and highly interconnected environments that the DT represents. A promising solution to meet these demands is the adoption of a knowledge graph approach, which offers a robust and efficient **security** strategy for DTs[34]. This approach employs graph data structures that are made up of nodes (entities) and edges (relationships) and can utilize a variety of techniques, from conventional graph algorithms to cutting-edge machine learning and **Artificial Intelligence** models, such as graph neural networks. In the event of a security incident, the graph methods can help analyze the dependency within the system, trace the steps of an attacker, and mitigate the risks and damages.

Developing a **secure and trustworthy** DTs system infrastructure could be substantially enhanced by adopting **threat modeling** approaches. Threat modeling is a critical component throughout a software product development process and plays an important role in ensuring software security. The analytical process of threat modeling examines the system's architecture and design to identify and mitigate security vulnerabilities[35]. The analysis of threat modeling not only helps in crafting robust security measures specifically designed for the system's needs but also ensures a security-focused mindset throughout the DT system design, leading to a more secure and resilient DT system infrastructure.

The implementation and operation of DT system infrastructure require seamless integration with multiple system components and coordination across various operational platforms. Such integration of diverse systems can introduce numerous vulnerabilities, posing significant challenges for timely mitigation in such an interconnected environment. Adopting **risk-based vulnerability management**[36] approaches can enhance the secure implementation and operation of DT system infrastructure by providing effective and efficient vulnerability management across the integrated DT system. Risk-based vulnerability management approaches patch vulnerabilities more efficiently than the traditional one-for-all approach, especially when remediation resources are limited and may provide a more comprehensive understanding of vulnerabilities and associated risks for DT system infrastructure in the interconnected environment.

Given the vulnerabilities of networked-focused **cybersecurity** and the benefits of data-centric security, focusing on application layer security requirements is essential in this regard. Namely, it may not be within scope to ensure full and adequate network protections suitable to DT and SoSDT needs, but it is possible to institute standards for **cryptographic controls** on application layer protocol protections that are uniquely suited to the needs of the DT and SoSDT environment. Promising approaches in this area include continuous key agreement protocols such as the Messaging Layer Security (MLS) protocol[37] that offers asynchronous application layer security support with end-to-end encryption[38].

Additionally, adequate control and management of key infrastructure for DT and SoSDT use is essential. Given historical issues, vulnerabilities, and exploit with standard certificate use in Internet of Things, work on development and widespread actualization of DTs should look at **Certificate Transparency** and **Key Transparency** as promising solution areas for long-term protections against DT system and component impersonation (both internally and externally). Such approaches support a **zero-trust** approach and can offer solutions for complex systems[39].

Verification, Validation, and Uncertainty Quantification (VVUQ):

As the use of DTs becomes more widespread across the product life-cycle there is a need for formal methods to support **Verification, Validation, Uncertainty Quantification** and **Calibration** and **Certification**. A recent systematic literature review on the verification and validation of DTs in manufacturing found a lack clear definition for the **verification and validation** of DTs[31]. Additionally, very few academic works claiming to create DTs reported that the DTs had been verified and validated[31]. Moreover, there is a need to track the changes and life-cycle of the DT through a digital ecosystem. DTs may be used in the early stage of design to support design decisions of future systems, often denoted as simulation-based design. Conversely, DTs may be used during deployment and usage to monitor the operation and health of the systems. This range of use cases provides a unique opportunity to develop a digital ecosystem of DT development and usage.

An example of DT usage throughout the life of a system is the design and development of an autonomous tracked vehicle. A simulation model of a tracked vehicle was developed to support early-stage **conceptual design exploration**. The models were developed based on existing models of wheeled vehicle and first principles. This digital asset was developed and subsequently used to make certain decisions about the design and related physical asset. A physical representation of the system was developed as a test rig that was closely mapped to the simulation model. The physical system was exercised through a series of planned experiments and data was synchronized across the digital and physical assets. Based on the DT, a deeper understanding of the physics, the use-case, and modeling assumptions was developed, and the simulation models was refined resulting in a **validated** DT. Subsequently, the designed system, as vetted in the test rig and the associated simulation model, were integrated to the full-scale vehicle and used for autonomous driving. The full-scale vehicle was then tested and synchronized with a full-scale DT. The example highlights several key challenges in DT development including the **lifespan** of the digital and physical asset, linking the DT to increasingly detailed design decisions, capturing the stream of data between the digital and the physical world.

There are challenges associated with DT **validation** and a conceptual framework is needed that addresses modeling realism, data uncertainty, system dynamics, use case alignment, and reporting of invalid models. Dahmen and colleagues[40] proposed a testbed for **validation and verification** of DTs through three components: 1) DT representations, 2) simulation approach, and 3) the virtual testbed. The testbed must be structured to capture a modular architecture of the physical system and the associated simulation models. Key areas of interest that represent significant research and educational challenges within DT include: 1) characterizing simulation model **fidelity**, 2) **coordinating and synchronizing** physical system data with predictive simulation models, 3) developing formal approaches for capturing **uncertainty quantification** and mathematical models of fidelity, 4) creating threads that capture the **traceability** of the virtual and physical assets, 5) guidance on level of model fidelity and the mapping to a lower fidelity physical asset, 6) creation of approaches for generalizing DT relationships and extending them to yet-realized systems, and 7) identify approaches for simulation model development, text and data **formalization**, and the thread between the digital and the physical representation, essentially creating a formal approach for capture the devolutionary development of DTs. DT must be **useful and trustworthy** to support the lifecycle of complex systems.

Workforce:

Digital twin **workforce** development has implications across several national interests including defense, energy, manufacturing, and infrastructure. There is an opportunity to enhance existing engineering programs at individual institutions through a national testbed and training resource set. Significant challenges associated with DT development often exist because of limited access to models and data across the lifecycle of the systems and the limited complexity of systems commonly found in traditional academic institutions. To address these challenges, a testbed is needed that consists of digital representations and data that capture both the simulation and physical space. These assets will be curated for complex systems that may include such systems as autonomous ground vehicles, wind turbines, electric vehicle powertrains, microgrids, manufacturing plants, and industrial HVAC systems. The curated DTs will enable **training and education** modules to be developed at scale and complexity of real systems while not impacting the operation of the physical systems. The **future workforce** prepared for DTs will span several domains, thus it is imperative to create opportunities for workforce development that targets deep expertise as well as **systems-thinking** and **integration** skills.

In addition to curated sets of data, the testbed must be highly dependent on working with software providers within the CAD, product life-cycle management (PLM), and **digital thread** space. Universities often lack the infrastructure to deploy complex software systems so mutually beneficial relationships with software solutions providers must be leveraged and established to enable the **future workforce** to access and use tools that are often accessible within industry and government. Such examples include the use of systems modeling approaches (i.e., SysML) and PLM tools to support digital assets associated with DTs[41]. There are numerous opportunities to establish a **shared resource** across institutions to scale learning and research opportunities across partner institutions and companies.

Additionally, integrating **cybersecurity training** into the DT workforce development program will equip system developers and operators with the necessary skills to manage cyber incidents related to network and data-centric security. This training includes hands-on cybersecurity laboratory exercises that replicate real-world attack and defense scenarios. By participating in such training, the DT workforce will enhance their proactive thinking about cyber risks and improve their ability to apply effective mitigation techniques during DT system operations, thereby bolstering their capacity to protect digital twin environments.
Training is a pervasive critical component in the fielding and sustainment of any system, and training pipeline establishment is costly. Leveraging or modifying DTs that are designed to emulate physical system behavior allows a low-cost, scalable, and geographically dispersed training system. If disconnected from physical assets then the operational concept is a virtual twin or a simulation environment for training, but if live streams from assets undergoing test and evaluation, demonstrations, or low-rate fielding will enable classroom environments to participate in dynamic live events, increasing the variability and depth offered over traditional training environments.

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Request for Information on the National Digital Twins R&D Strategic Plan

DTE-FS

A Model Based System Specification for Use in Construction of an

Interoperable Digital Twin Earth Framework

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Version 1.0.1

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Table of Contents

Abstract

The earth science community has long been motivated in achieving harmonization of the ways it represents its domain in order to achieve a comprehensive, confident, current, and shared understanding of the earth system that is broadly available for democratic decisional use. Countless efforts across data, semantic, technology, and governance disciplines have been

undertaken toward furthering this goal, and the dream seems closer to being realized than ever. It is believed that with a proper synthesis of available efforts, a widely accessible and evolutionary digital twin earth may now be defined, constructed, and managed.

In this work we describe a specification useful in guiding construction of a model-based framework that enables implementation of a multi-viewpoint, evolutionary, and communally managed digital twin earth that is represented as a syntactically, schematically, semantically, and legally interoperable system of systems. A framework implementing this specification is capable of supporting the management of a contextually rich, user driven, readily accessible, easily manageable, and entirely flexible model of the earth system that spans its lifecycle, updates from real-time data of wide variety and source, and supports making, storing, justifying, and publishing fully traceable decisions made using machine learning, simulation, reasoning, and other process techniques.

Along with contextual grounding, this work provides a technical validation of the framework specification through description of a practical reference implementation framework - the virtual Archival Information Package (vAIP) - that is core to NOAA's upcoming Next Generation Archive and Access service. A variety of use cases of the digital twin earth framework, both in general and as implemented in the vAIP, are provided throughout this work to further refine understanding of specification configuration, utility, and implementation.

Introduction

Represented as a physical system, the earth is incomprehensibly complex, and the scope of efforts undertaken to measure it, understand it, and explain it, together with the effort-relevant context questions of who, where, when, what, why, and how, are incredibly rich in character, utility, and provenance. These humanity-spanning endeavors toward earth-system-based understandings and actions are fundamentally data-dealing, and in theory, the data they produce and consume should be readily understandable and widely reusable across various viewpoints and contexts, thanks to the tireless history of scientific effort expended in careful development and stewardship of specialized formalisms, vocabularies, lexicons, ontologies, formats, tools, and techniques that comprise the basis of holistic earth science.

However, while data related to a holistic representation of the earth system may be interoperable in theory, most implementation efforts made to take advantage of the interoperability potential toward formation of some shared system have proven to be expensive, incomplete, rigid, unsustainable, and generally unsuccessful as measured through a holistic lens. Practically unlocking the promise of universal interoperability for full data access, use, and dissemination in order to answer or better support queries through data fusion, while maintaining stable access to that interoperability through chaotic system change, has long been an end-goal of many in the earth science community, and there have been a number of approaches to its fulfillment. Some of these efforts have suited some localized domains and use cases very well under specific conditions and through particular considerations, but a general achievement of interoperability in earth science, one that allows open access and reuse of data across disciplines, catalogs, viewpoints, and motivations, that maintains stability through evolution in character and composition, that enables natural evolution in data governance, and that scales to meet the enormous process and storage requirements of such an undertaking, has proven elusive.

While the reasons for lack of success in achieving a more universal interoperability for purposes of improving decision making based on a shared understanding of the earth system may be extremely nuanced and contextual, a reading of Conway's law, which states that "any organization that designs a system (defined broadly) will produce a design whose structure is a copy of the organization's communication structure" - gives a reasonable basis of explanation. Under Conway's law, if the data produced by an organization through its systems is tightly process bound to that organization's communication structure, then the type of interoperability offered between organizations (or between internal parts of an individual organization) is limited to the types of mutually shared support in terms of both intercommunication and intracommunication.

In other words, for multiple organizations - or even multiple divisions within a given organization - to support a basic level of data exchange, they must share an understanding of syntactic interoperability; if they further want to support data integration between each other, they must share understanding of schematic interoperability; if they want to further support the ability to derive meaning from each other's data in order to enable wisdom-tier decision making, they must share an understanding of semantic interoperability; and if they want to be able to discover and reuse each others data at all, they must share understanding of legal interoperability.

This multi-faceted view of interoperability, formalized in the Group on Earth Observations (GEO) data management principles and guidelines, illustrates why general interoperability has proven to be so difficult in a scientific domain that is strongly characterized by the variety of independent efforts; at every interface boundary between organizations, defined by communication structure, there are multiple hurdles to negotiate and manage in terms of communication structure normalization between systems.

To help ground the communications issue and the value proposition of overcoming it, a quick examination of practical users and uses within the broader earth science organization produces an unsurprisingly complex panorama of scenarios. Financial institutions making investment decisions, retailers optimizing logistics, NOAA setting fisheries limits, state DEQs issuing environmental permits, USDA predicting crop yields, US Census forecasting population migrations, NASA planning satellite launches, archaeologists looking for dig sites, environmentalists coordinating pollution cleanups, utilties predicting drought, insurers providing hazard insurance, oil companies looking for drill sites, developers looking for build sites, biologists looking for new species, governments deciding on national policies, and individuals planning a camping trip, are all completely valid and significant executive-focused use cases of a physical representation of the earth system, and each represents a traditional organizational stovepipe (or collection of stovepipes) in terms of interoperable accessibility. Each also represents its own rich set of insights, ideas, tools, techniques, and collected data that, if available for shared use, would at the least enable synthesis of a much more complete physical representation of the earth system in terms of, among other metrics, resolution, performance, and accuracy.

Under Conway's law, then, the ground truth domain complexity in terms of practical communication structures makes it clear that while earth science is fundamentally interoperable in terms of its physically described foundations, making practical use of that interoperability is limited by the practical communication-related incongruities assumed by its many implementers.The significance in overcoming these incongruities is in eliminating them as the primary limiting factor of how good any practical physical representation of the earth can be, toward an ultimate purpose of allowing all users of the representation to improve their decision making.

Based on this view, with respect to our interest, we can define our problem boundary as a set of axioms. We propose that

- **Axiom A -** Organizations and individuals (defined broadly as 'users') contribute to and study the earth system to answer questions and make decisions for reasons that are meaningful to certain other users.
- **Axiom B -** The users, questions, decisions and reasons are all infinitely variable.
- **Axiom C -** Users may greatly improve their own decision-making confidence, capacity, and capability due to improved model capability via shared representation.
- **Axiom D** - Achieving a shared representation of users is limited by the communication interfaces they share.
- **Axiom E -** Issues with communication interfaces may be defined and addressed in terms of classified interoperability.

Using these axioms, a restatement of the thesis of this work in terms of relevant context questions is possible. In these terms, our thesis may be defined as

- **What** we want to achieve (a digital representation of the physical earth that is complete, efficient, and accurate)
- For **who** we want to achieve it (users of the representation)
- The reason **why** we want to achieve it (to improve user decision making about the physical earth based on the representation)
- **When** we want to achieve it (for the length of use of the representation)
- **Where** we want to achieve it (on user infrastructure)
- **How** we can achieve it (by enabling interoperability between users)

The primary focus of this work will be in deriving and describing specification for the how, by determining requirements given defining the what, why, when, and where.

Concept Mapping

What we have defined as our primary concern may be readily understood as an attempt to support application of the concept of a ‘digital twin’ to the earth system. A **digital twin** is commonly defined as

“a virtual representation of an object or system that spans its lifecycle, is updated from real-time data, and uses simulation, machine learning and reasoning to help decision-making.” It is usually considered implicit that in this definition, ‘decision-making’ refers to decisions about improvement of the object or system itself.

The concept of a digital twin is not new, having a long history of use in industrial settings including automotives, automation, manufacturing, energy, logistics, and utilities. Any system that uses remote sensing data to represent and make decisions about itself may benefit by being modeled as a digital twin. Functionally, digital twins are primarily defined by providing a system with capabilities that include

- **Operations optimization** via simulation and monitoring
- **Predictive maintenance** recommendations based on holistic or targeted analysis of system properties
- **Anomaly detection** based on historical trend reliant models
- Fault isolation via reasoned **root cause analysis**

Applying our boundary value axioms to the basic definition of a digital twin, we might specify a **digital twin earth** (DTE) as

“a virtual, dynamic, up-to-date, physical representation of a multi-user earth system of systems that enables making decisions about the earth through the use of process techniques including simulation, machine learning, and reasoning.”

We know through Axiom D that communication structure is the defining feature of coherence in a system, and through Axiom E, that communication structures can be defined in terms of distinct interoperability focus. Our DTE may then be defined by the syntactic, schematic, semantic, and legal communications structures that it relies on. Given the existing entrenched communications structures of intended DTE users, it is not practically feasible to construct a coherent and fully user supportive system from the top down. Our DTE must therefore be supported by a set of portable communications structures that exist independently of any user system. This leads to construction of a statement on framework methodology.

- **Framework Methodology** - *In order to support a holistic DTE, we must construct and provide a portable interoperability-model framework (DTE-F) that supports all required DTE functionalities in a manner compatible with existing communication structures of the* *systems owned by all intended DTE users through implementation of a Digital Twin Earth Framework Model Specification (DTE-FS).*

Framework Specification

Syntactic Interoperability

Under our methodology constraints, if we imagine our user systems as a set of independent, uniquely identifiable nodes in global DTE space, our DTE-F may be conceptually modeled as a set of bi-directional connective edges between them. If we then apply our understanding of user systems as collections of earth-related decisional processes (Axioms A and B), we can improve the correctness of the initial model by requiring DTE-FS to model connections between user processes directly rather than their parent systems. This leads to the first specification requirement:

- **DTE-FS Requirement 1**: A DTE-F implementing DTE-FS shall provide model-based, schema-standardized, machine-readable access and control interfaces to DTE processes for the purpose of enabling universal syntactic interoperability.

Stated another way, this requirement says that by holding process as a space-spanning concept, DTE-FS fundamentally supports the construction and management of process-oriented frameworks, and DTEs constructed through a DTE-F will rely on process as the fundamental representation dimension supporting each aspect of interoperability. By enforcing exposure of all control and access of processes through schema-standardized machine readable interfaces, this requirement provides the foundation for a capability that enables a general process-to-process syntactic interoperability, while simultaneously supporting the non-functional architectural goals of general scalability through distributed ownership and a flexible (i.e., asynchronous-capable) communication protocol.

Practically, we may understand this requirement as addressing the aspect of communication structure concerned with making requests and returning responses, in a way that uses a standard vocabulary and structure, so that we may construct and pass information between distributed nodes completely, asynchronously, and contextually.

To illustrate how this may look, we can refer to the MessageAPI process specification, which uses the concept of a top-level session container, similar to a **document object model** (DOM), to structure and organize requests, which in turn consist of declarative and structured records and flow conditions. Content-complete sessions are delivered to remote processors, where they are parsed, initialized, runtime processed, and returned to the original caller as a packet of records, rejections, and original request reference.

The DOM foundation of this pattern allows for **query, construction, evaluation, validation, and execution of sessions at-a-distance** by humans or machines through a standard API and also provides an easy basis for persistent storage of the workflow for full provenance and reuse.

Further, this syntactic interoperability approach is reliant on complete encapsulation of whole immutable requests and enables a concurrent processing model for achieving horizontal scalability across DTE system users. This type of concurrent processing has been described and leveraged in Communicating Sequential Processes (CSP), as well as various process calculii, including the Actor Model, to support, among other things, full linear traces of intra-process vocabulary changes as well as process-side request throttling.

Technologies covering syntactic support in this way are widely available, generally being classified as workflow management system (WMS) related tools. While not strictly required, WMS tools which implement fully declarative information model based systems that pass full instruction sets via text may be best suited for fully meeting the syntactic requirement in the long term. The Onyx Platform, TaskAPI, MessageAPI, Argo, Amazon Web Services (AWS) Step Functions, by being fully declarative and model based, provide the ability to self-describe and be constructed at-a-distance, while enabling full replay and providing static, well known bounds on their control interfaces. Systems that rely on deeply ingrained, non-model-based coded instructions and rules, such as NiFi, Metaflow, Airflow, and Flyte, may not continue to meet the syntactic interoperability requirement in the long term.

Schematic Interoperability

While our first requirement is sufficient for ensuring support of foundational syntactic interoperability across our DTE representation, it does not address how to achieve interoperability in terms of schema, and we must address this in our framework model. Toward this end, we can first refer to the definition of process as “a series or sequence of operations, tasks, and/or procedures performed on something in order to change or preserve it”.

This definition says that every one of the DTE processes that we must support are made up of smaller, purpose-oriented tasks (subprocesses), linked together in specific ways. Specifically, process tasks are classifiable in terms of their contextual process purpose - either input, identity, transformation, or output - and each is constrained in terms of allowable types of downstream connections. Taken together, these facts lead to the DTE-FS requirements two, three, four, and five.

- **DTE-FS Requirement 2**: A DTE-F implementing DTE-FS shall provide model-exposed process structure in terms of DTE subprocess tasks.
- **DTE-FS Requirement 3**: A DTE-F implementing DTE-FS shall provide model-based, schema-standardized, machine-readable access and control interfaces for DTE tasks.

- **DTE-FS Requirement 4**: A DTE-F implementing DTE-FS shall declaratively classify the purpose of every DTE process task as one of acquisition, identity, transformation (considered to include classification), or delivery.
- **DTE-FS Requirement 5**: A DTE-F implementing DTE-FS shall enforce constraints on allowable downstream DTE task connections based on type.
    - 5a. Input tasks must connect downstream to identity tasks
    - 5b. Identity tasks must connect downstream to transformation tasks or output tasks
    - 5c. Transformation tasks may connect downstream to transformation tasks or output tasks

While these specified requirements do not on their own appear to support a general schematic interoperability of processes represented within the DTE, they do lay a needed foundation. To complete the picture, we must combine them with a functional understanding of tasks. In a functional view, a task takes some schema-structured input, does some arbitrary processing, and produces some schema-structured output. In this view, for any given process task, the computational workflow that produces some output is coupled with output structure, and both must be available together for complete contextual understanding of a given process definition or execution. Additionally, in order for a machine to automatically connect a given task to one downstream, the output structure of the first task must be known to the second so that it, or parts of it, may be used to drive the workflow of the downstream task automatically. This reasoning leads to the final requirement set related to content structure.

- **DTE-FS Requirement 6**: A DTE-F implementing DTE-FS shall provide standard, machine-readable access and control interfaces for all DTE processes and tasks in terms of coupled workflow and persistence structure.
- **DTE-FS Requirement 7**: A DTE-F implementing DTE-FS shall structure all DTE processes so that a given process may be executed to completion by syntactically interoperable submission of a complete declarative, schema-standardized machine-readable map of valued fields and conditions.
- **DTE-FS Requirement 8**: A DTE-F implementing DTE-FS shall structure all DTE tasks so that a given task may be completely machine-executed toward populating a known output storage structure.

Taken together, Requirements 2 through 8 provide the ability for complete automation of process construction, process execution, task composition and validation, task execution, and provenance analysis, and this ‘single-pane-of-glass’ approach reduces schematic interoperability to a problem of providing up front values of known key-value pair fields and conditions through a uniform interface.

To illustrate this concept in practice, returning to the MessageAPI process specification, the previously described session requests provide a standard schema pattern for a request record, so that it may be composed purely in data and submitted completely for processing.

The record pattern requires provision of a flat set of fields, each needing specification of field id, type, value, required status, and optional metadata; as well as a similar flat set of conditions used for data flow routing. The record then requires each field to be containerized in some custom pattern or patterns, which is referred to as a contextual identity container, allowing conditions to make determination of inclusion. Each container is then potentially referenced in some arbitrarily nested and/or branched pattern of transformations and/or classified labels, each stage of which specifies its own output field set. All computational paths are ultimately referred to within a connection to a defined endpoint that defines what its output records are.

When a session is initialized by a processor, any construction time logic for individual tasks, including transformation context or endpoint connection, are executed to create the session context; field and condition values are then applied as a set to create and submit a request of one or more records; and endpoint connections drive processing in a lazy way, first through up front validation of task-output-to-task-input schemas, and then while during each computation iteration. At each stage of its processing, if a task fails, it is added as a rejection for return and explanation to the original caller that lists specific fields and reasons for failure.

Through this method of coupling task workflow and output in a schema-normalized way through record-based sets of fields and conditions, defined generally by DTE-FS requirements 2 through 8, schematic interoperability across processes is enabled generally for any classifiable task. Driving a process becomes a matter of valuing known fields and conditions, and driving individual tasks becomes a matter of mapping fields needed to drive a task workflow with generated and potentially persisted output of upstream tasks. Readers should note that this section, particularly in light of requirement 6, provides the described level of schematic interoperability both inter-process and intra-process.

As a final illustration of the use of schematic interoperability in the terms laid out in this section, imagine a DTE process that receives raw station temperature measurements for some given location over an hour time, does a time-interval average of them, validates the average against known seasonal expectations based on historical measurements, and then packages validated ones as a NetCDF file for reporting.

In our defined framework, this process may be modeled as consisting of five distinct tasks - An input task, which takes station measurements; a first transformation task, which does some aggregation based time-interval average; a second transformation task, which does some validation; a third transformation task, which converts file type into NetCDF format; and a final output task, which sends knowledge of the process execution to some endpoint. Each of these tasks in the process has its own functional workflow and output schema. By requirement, the process itself defines an acyclic digraph of process order, and a final output schema. In order to construct the process within the framework, the tasks must first be linked together.

Assuming a known workflow and output structure is already known for each, they can be linked together automatically, matching input requirements for a given task workflow to output from the previous task, and applying general constraints of the system in terms of classified task type. As an example of this, the precipitation task might get raw measurements as strings, in which case there might be a workflow key called ‘precip value’, and one called ‘precip units’. This task might specify as its output structure a single JSON map of precip value and structure, called ‘precip object’.

The next task, the aggregation transformer, might take as a workflow input value a list of ‘precip objects’ and a ‘historical file location’. Since this ‘historical file location’ is not provided by the output of its upstream task, it will be required to be provided in the flat field set as a model parameter to begin execution of the overall process, and the machine can inform its caller about this fact. The NetCDF transformation task might use a ‘NetCDF template’ field, and a ‘normalized precip set’ in its workflow. Again, if the NetCDF template field isn’t provided as output from the upstream task, it will be called out as a flat-map input requirement for use at session initialization.

Careful reading of this process approach may glean that while it provides a generalized strategy for schematic interoperability, there are some shortcomings - i.e. other than key to key matching for field values, how would a machine know that one key’s content actually matches with its target? This leads us to the derivation of semantic interoperability related requirements for our DTE-FS.

Semantic Interoperability

While the DTE-FS as described thus far covers support of both generalized syntactic and schematic interoperability, it has not addressed the critical capability of semantic interoperability. Semantic interoperability between two nodes with respect to some topic is broadly defined as a shared understanding of meaning of that topic. To enable interoperability in this way, we must be able to provide the ability to understand the context of a thing, what kind of contexts a thing might belong to, reason about whether two things are the same, if they are different, if they are compatible, in what ways they are compatible, in what ways they are different, if they are related, if they are completely different, and so on.

The study of knowledge graphs has been concerned with this type of interoperability for many years, and has made great strides in its enablement, in terms of formalisms, tools, and techniques. The concepts of vocabularies, lexicons, thesaurus, knowledge organization systems, and ontologies in particular are well fleshed out systems for addressing semantic interoperability. Ontologies are patterns of understanding about some topic, using hierarchical classification of concepts and relationships between them to allow patterned storage of data and inference based on new data.

It may seem, then, that an ontology or defined vocabulary is the best way to approach providing interoperability support within the DTE-FS, and this is the approach that is taken. However, when talking about generalizing semantic interoperability between arbitrary DTE users, in order to support semantic interoperability across an enormous variety of highly specialized use cases, it also becomes obvious that a single ontology by itself is not enough - because, to support semantic interoperability across unbounded and unknown use case, an ontology by itself would grow unbounded - thus rendering the system essentially unstable and unsustainable. So, while the concepts of ontology are indeed foundational to addressing semantic interoperability, they must be augmented with further ceremony in order to meet the requirement in letter and spirit.

To do this, we combine a number of complementary concepts to ontology. First we introduce the concept of **'fuzzy semantic interoperability'** via prototype patterned archetypes. In this approach, a bounded and flexible reference model (i.e., one that has some support for recursion and composition) that spans the desired domain is selected and converted into ontology. This reference model derived ontology then forms the foundation for allowing DTE users to build user-specific archetypes, also referred to as empty human-labeled structures. These structures are unvalued instances that derive from the small class set of the reference model ontology, providing intrinsic interoperability, but they are also human readable and easily composable, thanks to their open ended human labeling.

A quick understanding of the utility in this may be understood by this short example - if two DTE users both use the concept of a 'granule', but use their own properties to define the structure of the granule (i.e., one requires a DOI, the other requires a UUID and a DOI, one requires a checksum, the other requires two checksums, one holds the file directly, one holds a link to the file, and so on), each user may define the concept of granule in a very specific and highly customized way, but do it based on the same semantic ontology - so that either user, or another DTE user entirely, may discover both types of 'granule' together.

In order to support the requirements of the storage structures described for use in the schematic interoperability toolset, archetypes defined within the DTE-FS must support one of the distinct task types of input, identity, transformation (including classification), or output.

- **DTE-FS Requirement 9**: A DTE-F implementing DTE-FS shall provide a small, static, space-complete, and flexible classification-oriented reference model derived ontology for use in defining DTE process task produced structures.
- **DTE-FS Requirement 10**: A DTE-F implementing DTE-FS shall enforce that all DTE process tasks define their process output in terms of partially valued archetypes, known as process-specific templates, that derive directly from 'fuzzily interoperable' archetypes, also known as unvalued human labeled structures, which in turn derive from classes in the implemented DTE-F reference model ontology.
- **DTE-FS Requirement 11**: A DTE-F implementing DTE-FS shall enforce that all DTE process tasks define their output archetype in terms of the relevant supporting archetype class, either input, identity, transformation, or output.

Furthermore, as transformations likely involve field set modifications for their output, the generic archetype for transformation must support use of arbitrary ontology to contextualize identified task outputs. To accommodate this need we introduce the second concept needed to augment ontology in support of generalized semantic interoperability, which is contextualized knowledge of data. To do this, we must require that our reference model ontology support rich contextualization of the data it holds - it must be able to describe data in terms of its relationships to potentially rich networks of structural, semantic, and other representation, it also must be able to describe data in terms of its packaging and preservation information.

- **DTE-FS Requirement 12**: A DTE-F implementing DTE-FS shall provide accommodation for process transformation tasks in supporting ontological restructuring of upstream task output within arbitrary and machine-accessible context in terms of content and character.

What this means practically is best illustrated through example. Going back to the previous section and our discussion on schematic interoperability, we have a task in our sample process that produces NetCDF files. This is a transformation task, so it must be supported by an archetype related to transformation. If the transformation output archetype has a structure of two fields, one the key label of 'netCDF file', and one with label of 'netCDF template' the archetype must include links to or direct text that describes that this is a known ontology; what URI to load the ontology namespace from; where to find the schema; potentially what fields in the netCDF file schema mean; etc. Through this approach, we might support any known ontology, within our reference model ontology, and also, through the use of modern tools like NLP, enable machine access to understanding and parsing of arbitrary context.

Another common use of this approach to semantic interoperability within the DTE is in a contextual assessment, or qualified quality control, of given identified entities. As a distributed framework supporting arbitrary users, there can be no guarantee of the quality of something that is produced, other than through the lens of contextual certification. For example, there may be 100 DTE users that produce rainfall data of varying qualities. If another user needs to use the output from each, but weight each output differently, they may first run each through an assessment transformation characterized by an evaluative metric space structure - e.g. confidence score, accuracy, precision, etc. alternatively, a model or simulation transformation may be run with and without each data in order to determine these scores and then use them in a weighted or considered way depending on context.

In any case, the result is the ability for multiple users in multiple contexts to provide a 'goodness' type score, in a specific metric, and make that score context available to other users for discovery and use along with the originally identified data. Imagine if NOAA or another authoritative agency were to use crowd sourced data in a product, they might certify it first through some quality score, and then other users could use semantic contextualization for search during data mining.

This approach also provides a mechanism for constructing and feeding multiple semantically discoverable and interoperable viewpoints to monitor the system health of the DTE itself, in terms of security viewpoints, integrity viewpoints, performance viewpoints, and others. Viewpoints may represent parameter sets and machine-accessible usability context to feed graphical user interface (GUI) analysis tools, multi-layered inference ontologies for inference based reasoning, and others.

There are several generic ontologies that may meet the requirements laid out in this section, including OAI-ORE, PROV-ES, OAIS-VAIP, and OpenEHR. This is not an exhaustive list of base level ontologies that may support the requirements, and there are several existing standards and ones in development that may be provided by a DTE-F to meet the needs of a given DTE. It is strongly recommended, but not required, that any DTE-F implementing DTE-FS use existing ontologies based on standard, self-contained, and space complete reference models. While a DTE-F backing ontology may be constructed ad-hoc from various reference models or on a case by case basis, this strategy may result in violation of requirement and invalidation of the DTE over time, if the ontology is found to be unbounded, space-incomplete, or otherwise incongruous with evolutionary growth of the specified domain.

Legal Interoperability

The last interoperability toolset targeted for support by the DTE-FS framework is that of legal interoperability, which in our context deals with whether and/or what level of access a given DTE user process has to another DTE user process, its tasks, and/or its data. This is particularly important to address in the holistic DTE that is envisioned for support, as not every user of the system might want to make its processes and process related data available to every other user in the same ways. There are two aspects of legal interoperability control that are considered by DTE-FS - first, the ability to discover rights, and second, the ability to enforce access rights.

The ability to discover and assess access rights, including the method of requesting accommodation via those access rights, should be handled through use of archetype augmentation within the semantic framework, and thus we have a new requirement for the semantic framework to be able to handle management of attached access rights information on both processes themselves and all of their content. This seemingly small modification to our reference model requirements has rather broad implications for our system, as it now places an additional constraint on the choice of reference model, as well as a less obvious constraint on processes themselves - as with this additional requirement, processes can now be inferred to need their own archetype that fits within the reference model.

- **DTE-FS Requirement 13**: A DTE-F implementing DTE-FS shall require that all DTE assets described by an archetype-derived storage structure include easily accessible access rights.
- **DTE-FS Requirement 14**: A DTE-F implementing DTE-FS shall require that DTE processes be described through an archetype derived from the implemented DTE-F reference model ontology that includes access rights information.
- **DTE-FS Requirement 15**: A DTE-F implementing DTE-FS shall require that DTE processes described by an archetype derived template be provided standard, machine-readable access and control interfaces.

The access rights that describe the asset they are attached to should provide a machine-readable representation of the specific access rights policy, in terms of whether or not a particular hopeful accessor can retrieve them, and then if allowed, provide machine-readable instructions to what ways the accessor should go about requesting the retrieval. This may involve, for example, a link to a token-request process that takes a user id and some password, generates a time-sensitive token, and then enables this token for use in running the process.

- **DTE-FS Requirement 16**: A DTE-F implementing DTE-FS shall require that access rights attached to a given DTE asset provide machine-readable capability for automatically using assets in the ways they are allowed.

Requirements Verification

With the basic framework derivation complete, it is important to first return to the DTE functional definitions to assess whether or not all of the functionality that defines a DTE is supported by the specified requirements model. We do this now by first describing the functional requirement, then assessing if and how it is supported in turn, adding new DTE-FS requirements as needed.

- **Functional Support Requirement:** Operations optimization via simulation and monitoring.
    - Simulation usually involves running a known model many times with ensembles of input data, according to some distribution of one or more model parameters, in order to determine a range of outputs. Important for simulation are the ability to trigger the same process model with different input; the ability to store output alongside given input conditions; the ability to deliver model output to multiple visualization tools; and the ability to deploy a new version of a model for simultaneous testing in the case that operations is changed as a result of simulation.
    - Monitoring usually involves analysis of many user-consumable insights that live fairly close access to raw data. Important for monitoring support are the ability to handle data availability in real-time; the ability to transform data for use by analysis and visualization tools; and the ability to send alerts in the case of issue.

Based on these descriptions, our specification may be missing requirements related to guarantee of streaming data acceptance, support for online models, versioning of models and associated process and task control context, and the ability to feed visual and other analysis tools within the model.

To guarantee streaming data support, we should add more stringent constraints to our existing requirements of asynchronous data passing to ensure that DTE users are always available to take requests and serve responses to other users of the DTE, and in the case of brief unavailability, must recover and catch up quickly in processing requests and serving responses exactly.

- **DTE-FS Requirement 17**: A DTE-F implementing DTE-FS shall require that all DTE users accept and process all syntactically complete and legally acceptable process requests in a timely way.
- **DTE-FS Requirement 18**: A DTE-F implementing DTE-FS shall require that all DTE users immediately return a response to requesting users that contains tracking information about the request and status of the request.
- **DTE-FS Requirement 19**: A DTE-F implementing DTE-FS shall require that all DTE users recover quickly in the case of brief unavailability.

To guarantee support for online models, we should add a requirement that online models be declared as such within their task context and that online models persist information about state change.

- **DTE-FS Requirement 20**: A DTE-F implementing DTE-FS shall require that all DTE process tasks containing malleable models declare the model as malleable as part of the archetype based task context container derived from the DTE-F reference model onlology.
- **DTE-FS Requirement 21**: A DTE-F implementing DTE-FS shall require that all DTE process tasks containing mutable models persist any state changes made to them within an archetype derived task context in a way that makes them completely machine recoverable.
- **DTE-FS Requirement 22**: A DTE-F implementing DTE-FS shall require that all DTE process tasks containing mutable models make any previous state changes discoverable, accessible, and completely recoverable to any legally authorized user of the DTE.

To guarantee support for versioning of models and their context control structures, we should require that all task and process deployments persist and provide ready access to their state history.

- **DTE-FS Requirement 23**: A DTE-F implementing DTE-FS shall require that all DTE processes and DTE process tasks persist all deployments as versions within an archetype derived task context in a way that makes them completely machine recoverable.
- **DTE-FS Requirement 24**: A DTE-F implementing DTE-FS shall require that all DTE processes and DTE process tasks make all versions of themselves discoverable, accessible, and completely recoverable to any legally authorized user of the DTE.

To guarantee interoperability and support for visual tools, opinionated catalogs, and other analytical tools, we should require that visual tools and other DTE-aiding endpoints be represented through archetype by the DTE-F provided reference model derived ontology.

- **DTE-FS Requirement 25**: A DTE-F implementing DTE-FS shall require that all DTE and DTE-adjacent tools related to or assisting in DTE decisions, including visual tools, access tools, opinionated catalogs, and other analytical tools, be persisted as DTE-F archetype structured entities.

- **DTE-FS Requirement 26**: A DTE-F implementing DTE-FS shall require that all DTE-persisted archetype structured entities be complete and available for complete machine configuration.
- **DTE-FS Requirement 27**: A DTE-F implementing DTE-FS shall require that all DTE-persisted archetype structured entities be machine findable, accessible, and controllable in all ways they are used.

- **Functional Support Requirement:** Predictive maintenance recommendations based on holistic or targeted analysis of system properties
    - In an earth system, properties may be user-specific parameters that include things like pollution levels, water levels, drought indeces, and others. Holistic analysis requires synthesis of various sources, which in turn requires identification and aggregate transformation. Targeted analysis may or may not require synthesis or splitting data apart, also requiring identification and split or join transformation. Both analyses rely on historical information and searching across data persistence. Predictive maintenance recommendations based on either of these analyses requires further transformation and delivery of results and recommendations.

Existing DTE-FS requirements cover basic machine-readable semantically interoperable information discovery, synthesis and splitting via transformation. Existing requirements also cover preservation of historical information about transformation models via versioning. However, new requirements must be added in order to cover historical analysis completely, as well as to ensure delivery of machine-readable and semantically interoperable results and recommendations.

- **DTE-FS Requirement 28**: A DTE-F implementing DTE-FS shall require that all system properties of interest be persisted as DTE-F archetype structured identified entities so they may be machine or human discovered, accessed, and contextually linked to other DTE entities through DTE processes.
- **DTE-FS Requirement 29**: A DTE-F implementing DTE-FS shall require that all DTE-produced archetype structured process output that relates to any system properties of interest be persisted and contextually linked to the system property of interest in a machine discoverable and accessible way.

- **Functional Support Requirement:** Anomaly detection based on historical trend reliant models
    - Modern anomaly detection generally relies on the use of machine learning transformation models to assess new real-time data against historical trend and expectation data. The model may require online updates through the integration of new data into the model. When anomalies are detected, notice may need to be sent as alerts to one or more recipients.

Existing DTE-FS requirements cover machine interoperable model contextualization, online model handling, historical versioning and version recovery, historical persistence of output data for retrieval, and version replay. Alerting behaviors are notionally covered, however existing requirements may be augmented to support complete knowledge of alert targets.

- **DTE-FS Requirement 30**: A DTE-F implementing DTE-FS shall require that all targets of DTE outputs for use in decisions be constructed and persisted as archetype structured identity entities so that they may be machine or human discovered, accessed, and contextually linked to other DTE entities through DTE processes.

- **Functional Support Requirement**: Fault isolation via reasoned root cause analysis
    - Root cause analysis requires full provenance tracing in terms of process workflow. In an earth system context, fault isolation might deal with attempting to determine the reason why some parameter or metric was affecting the earth in some way, which requires holistic system searching, process synthesis, and semantic inference.

Existing DTE-FS requirements cover most requirements for fault isolation capability, including historical tracking of process and task, contextualized semantic discovery for inference, and process synthesis tracking. Requirements may be augmented to more specifically support holistic system searching.

- **DTE-FS Requirement 31**: A DTE-F implementing DTE-FS shall require that all DTE archetypes be readily human or machine discoverable, accessible, and usable in a fast and efficient way.
- **DTE-FS Requirement 32**: A DTE-F implementing DTE-FS shall require that all DTE templates, derived from DTE archetypes, be readily human or machine discoverable, accessible, and usable in a fast and efficient way.
- **DTE-FS Requirement 33**: A DTE-F implementing DTE-FS shall require that all DTE entity individuals, derived from DTE templates, be readily human or machine discoverable, accessible, and usable in a fast and efficient way.

Practically, this may mean that federated archetypes, templates, and entity individuals be hierarchicaly catalogued by a DTE user, potentially in many layers, within their own archetype derived template or entity individual so that search may quickly find and drill down areas of interest in a concurrent and parallel way.

With these final derivations, the DTE functional requirements are verified, and the basic DTE-FS requirements set is functionally complete. However, it is understood that practically meeting so many requirements may be difficult during implementation, and so we introduce to DTE-FS two additional requirements, coherent with the core set, that serve to guide architectural and design implementation.

- **DTE-FS Requirement 34**: A DTE-F implementing DTE-FS shall require that all DTE users implement a small, static, DTE-F interoperability-model-complete and fully DTE-FS requirement-compatible API, in whatever language or technology required for that user.
- **DTE-FS Requirement 35**: A DTE-F implementing DTE-FS shall require that all DTE users interact with the DTE solely through the user-specifed and implemented API, building any additional interactive tools on top of the API itself.

By enforcing this API requirement, DTE-F will assure that users enable better understanding of the data model and compliance with the specified requirements in a sustainable way.

Illustrative Case Study

To better illustrate the goals, use, and utility of what we are proposing, it is useful to walk through practical examples. Toward this end, we may first consider the Virginia Department of Mines, Minerals, and Energy (DMME) as a user of our DTE. Through Surface Mining Control and Reclamation Act (SMCRA), Clean Air Act (CAA), and Clean Water Act (CWA) authorities, with oversight by the EPA and OSM, DMME owns a system (process set) responsible for making decisions about whether or not to issue, revoke, or modify energy permits, including natural gas and coal mining permits, in the state of Virginia.

Permitting decisions made by DMME are composites of multiple smaller analyses and predictions (tasks) about water quality, benthic health, hydrologic impacts to wetlands, and land use management, among others. Each of these individual analyses may be based on any number of complex and highly customized algorithms reliant on synthesis of voluminous and diverse real-time and historical experimental data. Much of this data is collected by DMME directly, by hand or automated sensor, stored and managed within a database according to some custom structure.

In the water quality process alone, there are multiple instream, non-point, groundwater, precipitation, cumulative hydrologic, and total maximum analyses across dozens of parameters done based on data from multiple real-time input data flows. The fundamental output of these analyses, a singular decision on whether or not to allow or enable some wide-scale change to the earth, is determined by the quality of the analyses which are ultimately dependent on the models and raw data they have access to. Improving the decision, therefore, is reliant on improving the analyses, in turn reliant on improving the models, in turn reliant on the availability and quality of raw data. Discovery, construction, and/or management of these decisions and associated analyses, models, and data is also heavily dependent on the subject matter experts (SMEs) in staying abreast of current implementation and new developments; this is generally a slow, expensive, and uncontrolled process.

Let us now consider a second user of our DTE, NOAA, which may be thought of as a large and multi-system (process) owning DTE user. One of the systems (processes) NOAA owns is real-time collection, quality control, product synthesis, and analysis of a remote sensing pipeline (process) for creating and serving authoritatively certified precipitation data. This pipeline (process) relies on one and five minute report output collected by individual sensors that are multi-agency (multi-DTE-user) owned and operated as part of a national in-situ sensor network. Sensor data are collected and combined with other data to perform internal quality control, and the products that are produced are ultimately published for use by other DTE users through several types of interfaces in various formats to make decisions with broad international legal and regulatory ramifications. Similar to DMME, NOAA relies on multiple algorithms of various nature to maintain the precipitation pipeline, including multi-tier quality control algorithms that use historical data and machine learning based anomaly detection. Like DMME, the QC algorithms, and those important to other parts of the pipeline, depend on access to supplementary data for analysis and improvement, ultimately resulting in support of downstream decisions that have broad implications for the health of the earth system itself.

Both of the DTE users described in this example do related yet obviously different work in very different contexts, and both have different viewpoints in terms of decision support, but it is fairly obvious that each may benefit to their own ends from automated access to each other's data for improving their own models, quality control, predictions, products, and reasoning.

To enable this data sharing, we provide a DTE-FS compliant DTE-F to both users, and they thus become full participants of the resultant user-driven DTE. Each user selects or constructs a DTE-F compliant API to interact with the system. When initializing as users of the DTE, they are loaded as known entities, choosing their defaults about access rights and methods of acquiring access tokens. Once users of the system, they each describe their individual process through the API as a set of tasks based on the traditional pipeline, where each task is described in terms of its workflow and output structure.

The output structures for each task are constructed according to each user's own unique understanding of their own data, but with each backed by the DTE-F implemented reference model, the output from each task is semantically interoperable and discoverable by both themselves and other users, both preserving lineage analysis and promoting process, method, and/or ontological reuse. Every output is intrinsically described in terms of schematic and semantic representation, preservation information, potentially customized access rights over the default values, and packaging, and each gets a searchable and findable description. Tasks are purpose specific and linked in order, with input tasks describing the process of retrieving or accepting data, identity tasks describing individual entities, transformation tasks describing what shape the transformation produced data in, and how to understand it.

When tasks are linked to the process, the process is similarly given a description on accessibility and packaging, and when complete, it is deployed. The deployment validates the process in terms of task linkages, and if valid, makes the process, process tasks, and archetypes used to define process task outputs available for search as structure. This is accomplished by other automated DTE users that listen for new process deployments. One of these users looks for new archetypes, one of them looks for new processes, and both run NLP driven processes that store and maintain a hierarchical knowledge of methods for drilling down and accessing a particular federated DTE user's data.

Upon deployment, both user processes are active, able to handle event driven data from sources specified by individual processes, or alternatively they may begin to go out and retrieve data in an input task with custom configuration. As the processes work, they begin executing computational logic according to workflow, and persisting archetype-derived data entities, which are now available for interoperable search and discovery.

One or both users might then decide to augment their own process, and to that end, search the DTE-F API for archetypes with labeled fields they are interested in, processes that might have description they are interested in, or templates that might have context they are interested in. In the NOAA user's case, once it discovers the output template from a given data producing task owned and performed by DMME contains rainfall data for a specific area, in a specific format, it can understand how to acquire this data, and creates a new version of its own existing process that listens for triggers on completion of the DMME rainfall data task, assesses it in terms of its own online historical accuracy score model of that metric, and if it is satisfactory, integrates it into its own precipitation QC model, which it now generates and delivers multiple versions of, for selection and use by other external DTE users based on reference to the DMME identified rainfall system property.

Reference Implementation

The NOAA National Centers for Environmental Information (NCEI), part of the National Environmental Satellite, Data, and Information Service (NESDIS), is responsible for archival of all of NOAA funded data in a way that is consistent with National Archives and Records Administration (NARA) guidelines, and NOAA access to research results (PARR) guidelines. This means that NCEI must provide timely archive and broad access to data that comes from, among other sources, nationally scoped in situ networks, polar and geosynchronous satellites, focused research studies, ocean dives, autonomous vehicles, hurricane trackers, and more, and deliver this data in many specified ways to internal users, national and international partners, and the general public.

Efforts to fulfill this mission have taken on a large number of forms as the mission boundary conditions - the technologies, standards, agencies, people, and systems - have evolved over time. With the maturation of the cloud computing era, the method of mission fulfillment of NCEI has changed direction yet again, and the agency is currently building NOAA's Next Generation Cloud Archive (NAAS) service to meet the new implementation requirements and opportunities afforded by this development.

Eventually, NAAS is intended to function as part of the NESDIS Common Cloud Framework (NCCF), a holistic model based cloud computing system that is intended to function as a single unit toward fulfilling NESDIS goals. To that end, the NCCF includes aspects of data onboarding, product generation, ingest, and the NAAS. As the Archive and Access component, NAAS is in a unique position relative to the NCCF in two ways.

First, it must handle all NOAA funded data. This includes, but is not limited to, satellite data, which is historically the primary focus of NESDIS by a large amount. This necessarily means that NAAS sees and must support, in terms of content and character, an enormous amount and variety of data. Second, as the outgoing interface, NAAS must serve this data, to all intended users, in all expected ways. In the modern age, this involves knowing about and supporting all of the historically expected and held heritage formats, proprietary data repositories, custom schemas, and narrowly understood and used products that NOAA has accrued over the life of its mission and even the life of historical earth data record keeping, while simultaneously supporting things like distributed format transformations, on-the-fly aggregations, and targeted catalog platforms, including NASA's Common Metadata Repository (CMR), to keep up pace with and stay compatible with and useful to modern machines and users.

Based on these boundary conditions, it is clear that goals of the NAAS readily fit into the DTE model as described above in the DTE-FS. While 'only' the Access and Archive part of the NCCF, as both a consumer and disseminator of all NOAA product data, the NAAS is clearly an ideal user of a DTE, both for its own benefit and that of its intended consumers. To this end, the design of the NCCF Archive and Access service essentially 'trained' the DTE-FS model against specific NOAA user community requirements and boundary conditions, including reference model ideals, NCCF cloud architecture guidance related to implementation on Amazon Web Services, and governance structure.

The DTE-F developed for NCEI's use in building the NAAS is designated at the virtual Archival Information Package (vAIP). The name itself belies one of the core choices of DTE-FS implementation, which is the reference model used in defining the ontology to be used for defining all system concepts through archetype, thus enabling intrinsic semantic interoperability through a small, static, space-complete, searchable model. This reference model, the Open Archival Information System (OAIS), is an ISO standard and stalwart pillar of archival thought, and a space systems recommendation. While extraordinarily large if taken on the whole, the only parts of the OAIS that were found to be needed for implementation to support a full DTE-FS implementation were a rather small collection. In fact, the NAAS took only the OAIS concepts of the information object, the information package, and the access aid, to construct its core ontology.

This ontology was then built and validated in OWL and RDF using visual tools including Protege, WebProtege, and VocBench. Figures 1 and 2 provide a WebProtege visualization of the primary concepts of concern on which all other concepts may be implemented as archetypes.

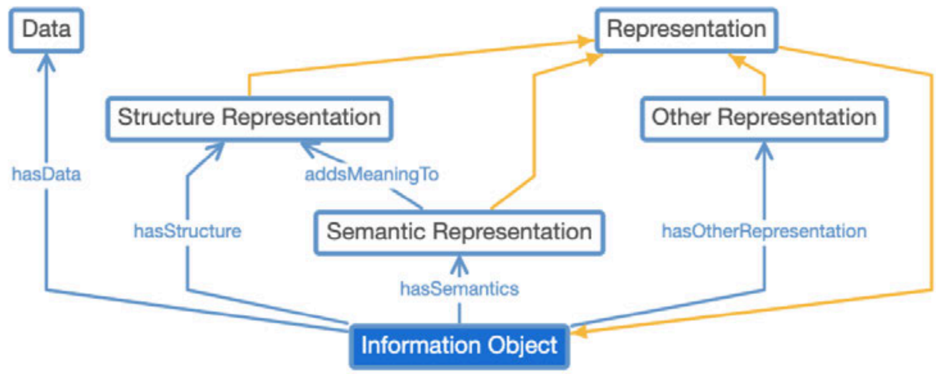

Figure 1*: the primary vAIP building block, the Information Object. Important to understanding this concept is that the data in an information object is the primary focus, held as 'just bits', and must be entirely qualified through its representation network, which is similarly made of information objects. This allows construction of rich semantic networks that are made easily machine-readable through SPARQL and easily machine-validatable through SHACL.*

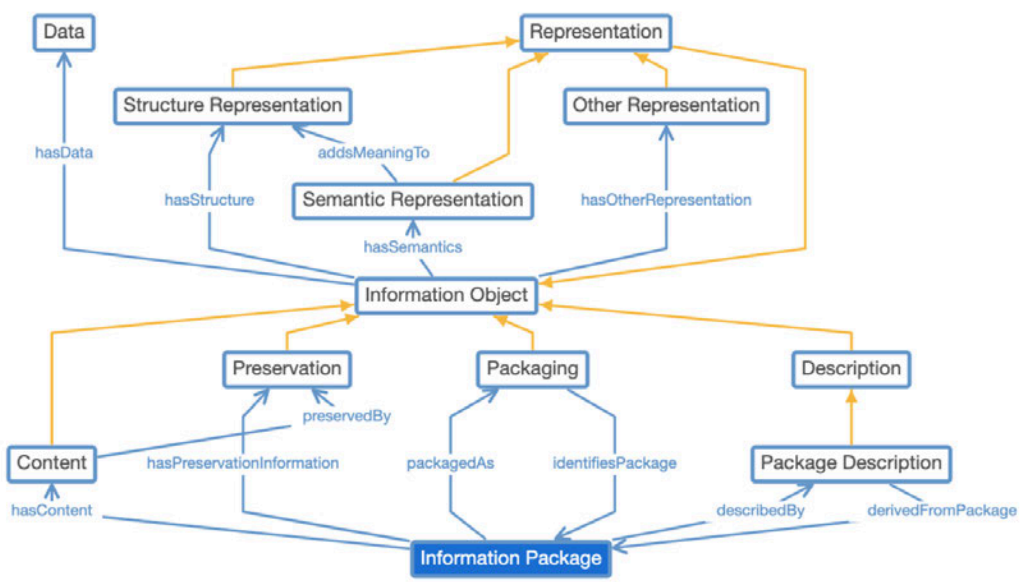

Figure 2 *- the secondary vAIP building block, the Information Package. Note that this ontological layer constructs a specific pattern of information objects, requiring storage of any unit to include its content, preservation (of which there are multiple types), packaging, and description information.*

Using these core concepts, following DTE-FS requirements, other fundamental aspects of vAIP DTE-F were implemented as archetypes. Figure 3 illustrates what vAIP implemented to fulfill the DTE-FS specification for a process task archetype (called step function archetype in the vAIP).

This archetype defines tasks that may be linked together in a DTE-FS Process, and it holds reference to its workflow configuration, output structure template, and the process flow policy (PFP).

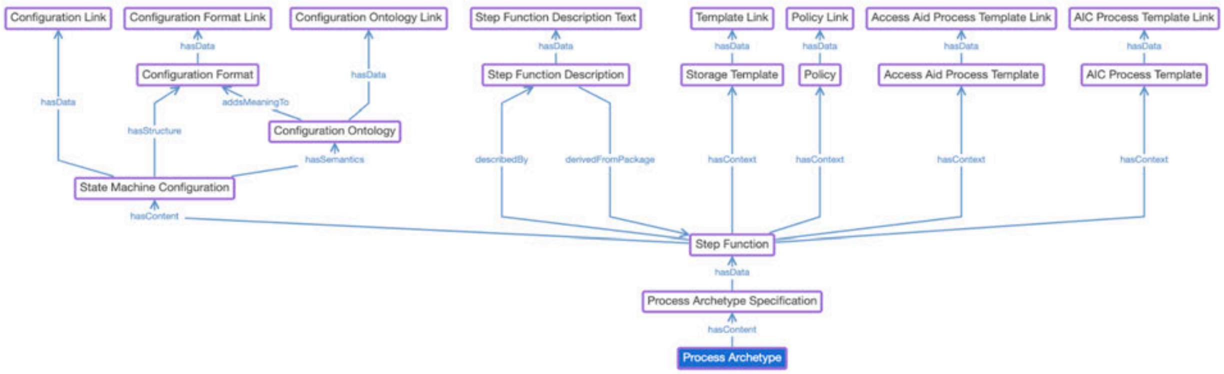

Figure 3: *A DTE-F task archetype, implemented in vAIP as a step function archetype, following the implementation choices of AWS step functions for workflow management.*

Each of the task types was also implemented in terms of structure in the vAIP ontology as a purpose-formed pattern. Figure 4 provides an example of an identity task storage archetype of a ‘granule’ implemented in terms of the OAIS concept of an identity focused archival information unit (only a cropped part of the archetype is displayed for compactness); Figure 5 provides an example of a transformation archetype, implemented using the OAIS concept of a membership-focused Archival Information Collection; and Figure 6 provides an example of an output archetype, implemented in OAIS as a Dissemination information Package (DIP) to an Access Aid (AA).

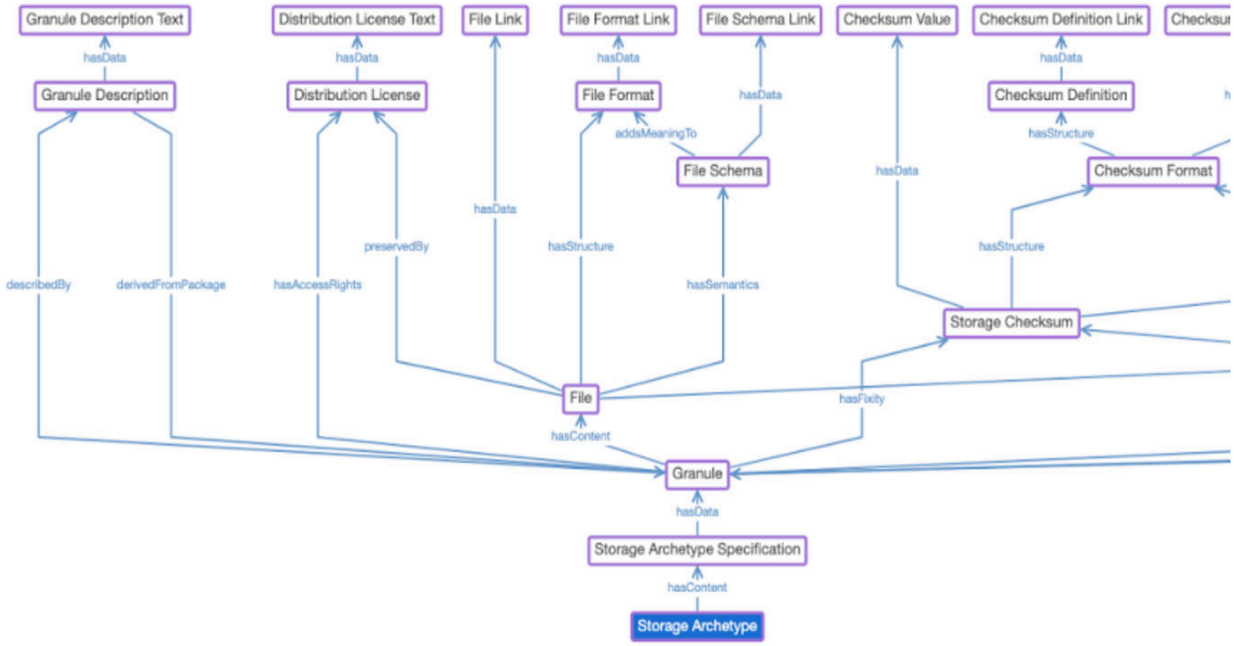

Figure 4: *An example of a DTE-FS identity archetype, modeled in the vAIP as an identity focused AIU.*

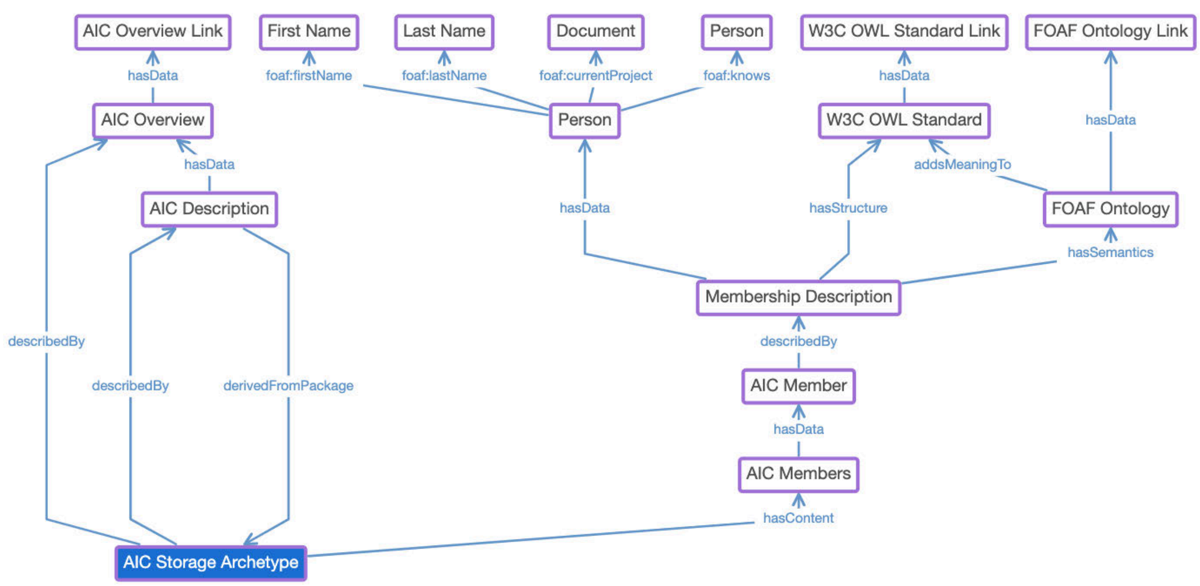

Figure 5: A DTE-F transformation archetype structure, implemented in the vAIP as a membership-focused AIC.

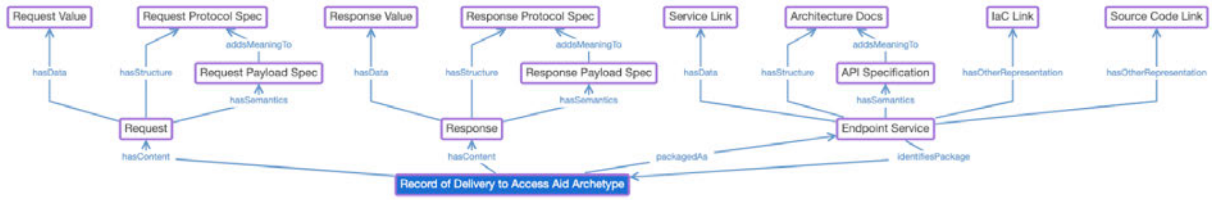

***Figure 6**: A DTE-F output archetype structure, implemented in the vAIP as a delivery focused DIP.*

Importantly, these archetypes are only examples. The vAIP API both satisfies and allows other DTE-FS requirements to be satisfied in terms of user-specific, human and machine readable, findable and accessible, semantically interoperable, configurable, reusable, and versionable archetypes.

In the vAIP, syntactic interoperability requirements and goals including those related to submission of entire requests, retries, provenance, and model-based syntax, were met by implementation of several ‘workflow’ archetypes in the AWS step functions WMS, and functional requirements surrounding real-time data and submission were handled through their connection to the AWS eventbridge event bus utility. The workflow archetypes themselves were stereotyped according to the task types, and each includes automatic wrapping utility around custom user-task code to handle automated schema matching. Figure 7 represents the input, identity, transformation, and output workflow archetypes. As they are built in AWS Step Functions, their modeled design exactly matches the structure of implementation itself. Note the hidden model layer of the DTE-FS implementation used to trigger the overall process from real-time messages about data events.

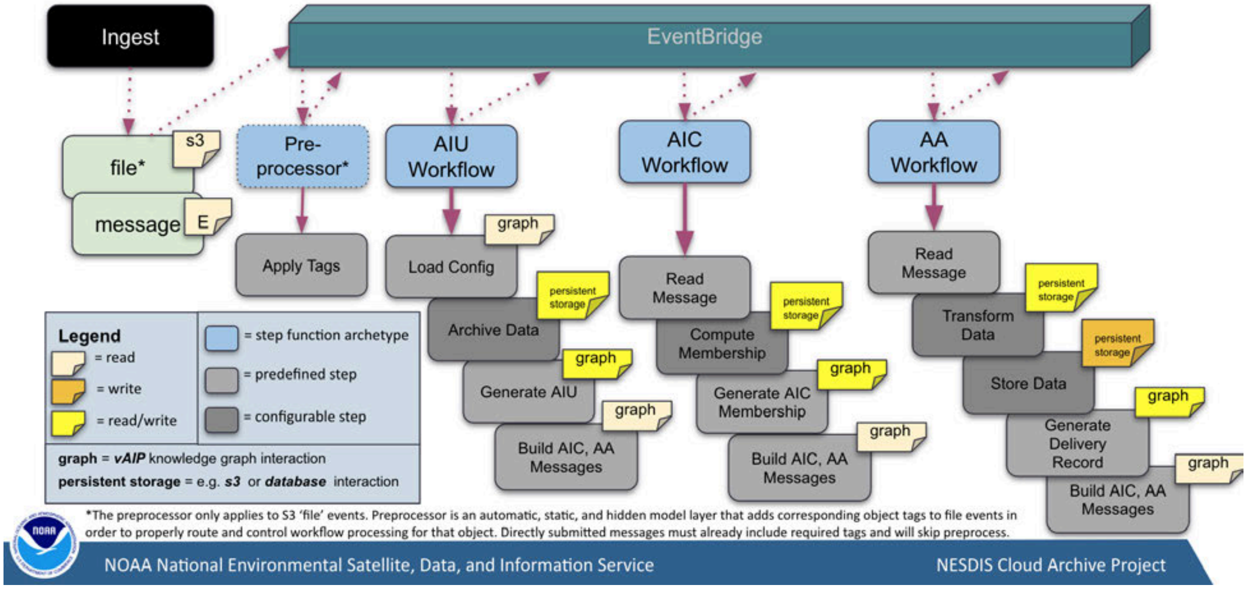

Figure 7: *Workflow archetypes implemented in the vAIP to satisfy, from left to right (ignoring the preprocessor), DTE-F task types of identity, transformation, and output, respectively.*

Further note that functional requirements of a DTE related to syntactic interoperability and non-functional requirements related to concurrency and composability are satisfied through the use of the EventBridge event bus as an intermediary between each workflow. As stated previously, validation of tasks is handled automatically based on key-value pair matching, and may eventually be improved further through the use of Natural Language Processing (NLP) reasoning to support semantic evaluation of workflow output to persistence input, and persistence output to downstream task input.

Task composition in vAIP is handled through implementation of the DTE-FS concept of process as a Data Stream Configuration, or Process Flow Policy. These policies further meet requirements of archetype description and versioning through their use of the process flow policy to store themselves as units within the system itself. Figure 8 illustrates composition of the policy, while figure 9 illustrates deployment of the policy itself within the vAIP framework.

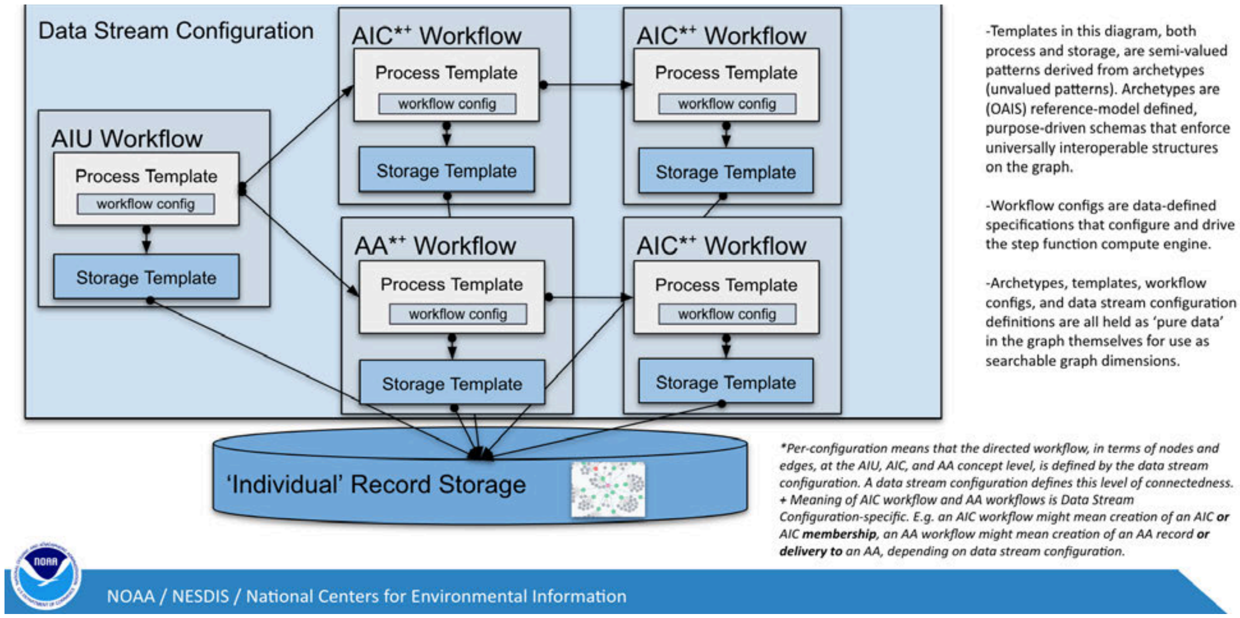

Figure 8: *The DTE-FS concept of process, along with notion of versioning and access requirements, as implemented in the vAIP as a 'Data Stream Configuration'.*

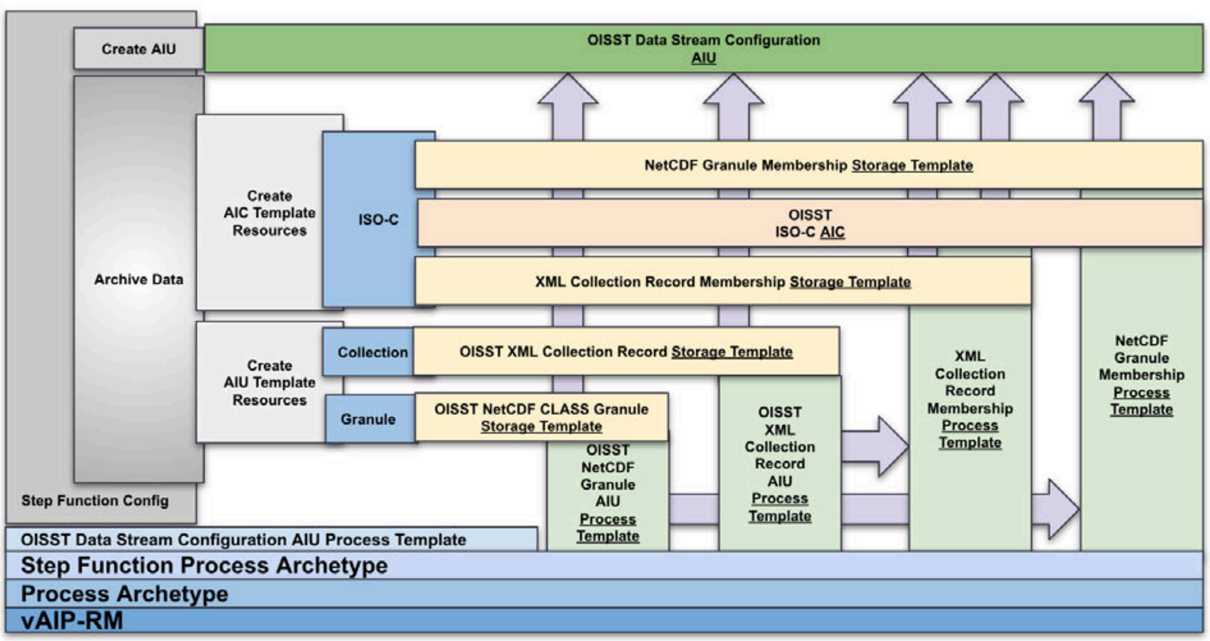

Figure 9: *Satisfaction of the DTE-FS requirements related to machine and human accessibility and versioning of processes within the archetype system as implemented in the vAIP.*

DTE-FS schematic interoperability requirements were demonstrated as partially satisfied through vAIP implementation of process triggering and task execution, while schematic interoperability between task output structures is further illustrated in figure 10, which also illustrates how identified entities within the system, defined in terms of rich contextual networks of their own, may be made semantically available in transformation contexts.

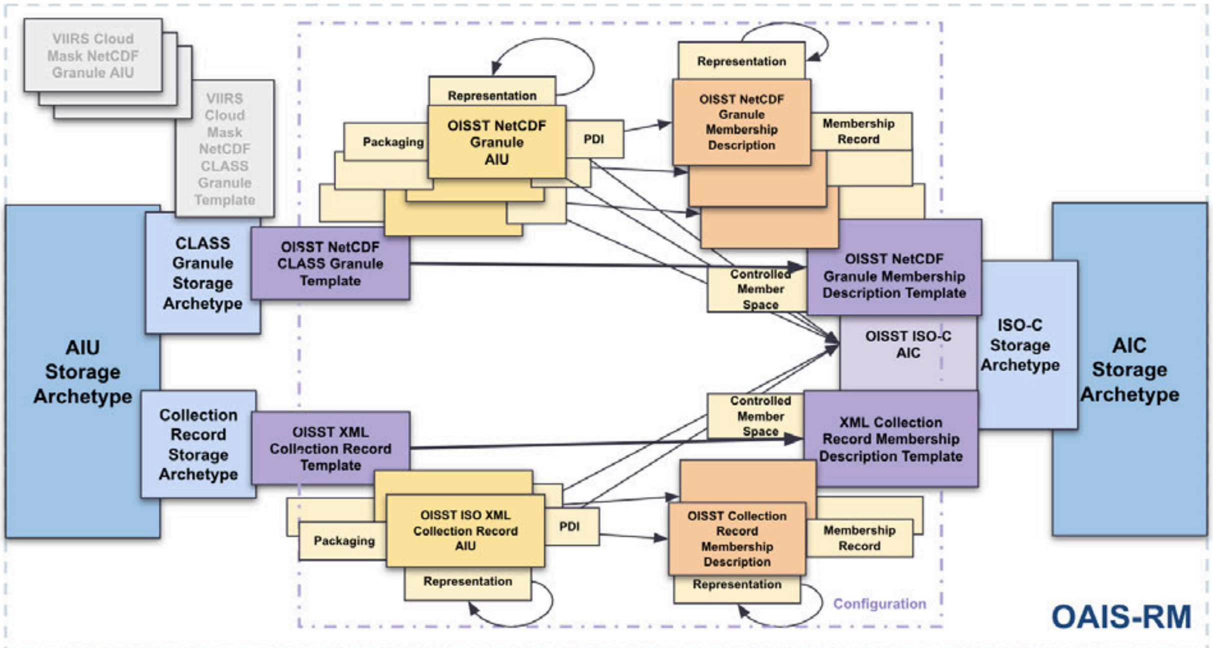

Figure 10: *Visual illustration of task to task structure in terms of schematic and semantic interoperability.*

As a DTE-F based on DTE-FS, the vAIP is intended to satisfy a broader DTE. The workflow for how this should look is illustrated in figure 11. Figures 12 and 13 illustrate how vAIP satisfies DTE-FS requirements of the API, in terms of provision and use as a building block.

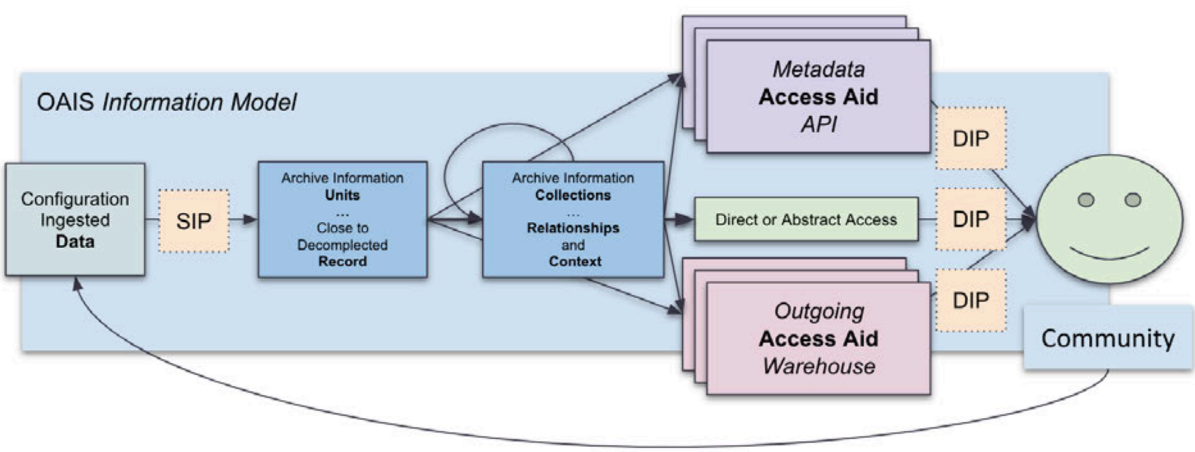

Figure 11: *Concept of Operations of the vAIP as an enabler of NOAA as a DTE user.*

```python
import vaip

#Create a new NEXRAD configuration
my_nexrad_configuration = vaip.create_configuration()

#Create AIU workflows for each data type in the configuration
tarball_aiu_workflow = my_nexrad_configuration.create_aiu_workflow()
xml_file_aiu_workflow = my_nexrad_configuration.create_aiu_workflow()

#Note that in the future, we can support manual workflows with 'human-in-the-middle' activities.
my_human_workflow = my_nexrad_configuration.create_manual_aiu_workflow()

#See if we have any available AIU archetypes that might match our criteria

matching_aius = vaip.find_aius(
    filters={"name": ["NEXRAD", "Granule"], "representation": ["File Link"]})

# zero, there are no matching AIUs in our system with these filters
print(len(matching_aius))

#We now need to create AIU storage for each of our workflows
tarball_aiu = vaip.create_aiu()
xml_file_aiu = vaip.create_aiu()

#Let's get a validation report to see what's required for our model
# returns a SHACL validated map and overall status (FAIL)
validation_report = vaip.validate_aiu(tarball_aiu)

#Now let's fill in our tarball archetype with some values
packaging_info = tarball_aiu.add_packaging_info(
    name="object_prefix", type=vaip.LINK)
structure_rep = packaging_info.add_structure_representation(
    name="object_prefix_format", type=vaip.LINK)
semantic_rep = packaging_info.add_semantic_representation(
    name="object_prefix_layout", type=vaip.LINK, structure_representation=structure_rep)
```

Figure 12: *Screenshot of use of a space-complete API for encapsulation of DTE interoperability for the purposes of security, usability, and sustainability.*

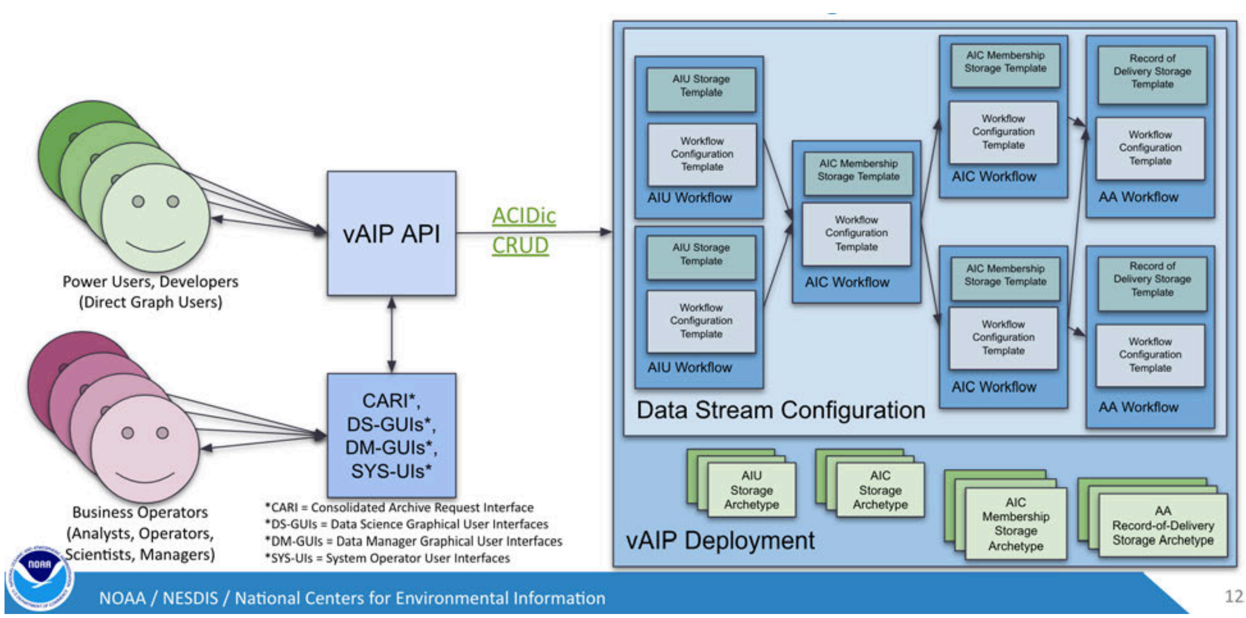

Figure 13: *Notional expansive use of the vAIP API to support broader user needs in terms of visualization tools and interfaces.*

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Federal Register Notice: 89 FR 51554, Federal Register :: Networking and Information Technology Research and Development Request for Information on Digital Twins Research and Development, June 18, 2024.

Request for Information on the National Digital Twins R&D Strategic Plan

eLife

eLife RESEARCH ARTICLE

Predicting ventricular tachycardia circuits in patients with arrhythmogenic right ventricular cardiomyopathy using genotype-specific heart digital twins

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Abstract Arrhythmogenic right ventricular cardiomyopathy (ARVC) is a genetic cardiac disease that leads to ventricular tachycardia (VT), a life-threatening heart rhythm disorder. Treating ARVC remains challenging due to the complex underlying arrhythmogenic mechanisms, which involve structural and electrophysiological (EP) remodeling. Here, we developed a novel genotype-specific heart digital twin (Geno-DT) approach to investigate the role of pathophysiological remodeling in sustaining VT reentrant circuits and to predict the VT circuits in ARVC patients of different genotypes. This approach integrates the patient's disease-induced structural remodeling reconstructed from contrast-enhanced magnetic-resonance imaging and genotype-specific cellular EP properties. In our retrospective study of 16 ARVC patients with two genotypes: plakophilin-2 (*PKP2*, $n = 8$) and gene-elusive (GE, $n = 8$), we found that Geno-DT accurately and non-invasively predicted the VT circuit locations for both genotypes (with 100%, 94%, 96% sensitivity, specificity, and accuracy for GE patient group, and 86%, 90%, 89% sensitivity, specificity, and accuracy for *PKP2* patient group), when compared to VT circuit locations identified during clinical EP studies. Moreover, our results revealed that the underlying VT mechanisms differ among ARVC genotypes. We determined that in GE patients, fibrotic remodeling is the primary contributor to VT circuits, while in *PKP2* patients, slowed conduction velocity and altered restitution properties of cardiac tissue, in addition to the structural substrate, are directly responsible for the formation of VT circuits. Our novel Geno-DT approach has the potential to augment therapeutic precision in the clinical setting and lead to more personalized treatment strategies in ARVC.

eLife assessment

This **important** study brings together a clear application of the digital twin approach to make predictions using patient specific models with different genotypes. The data are **compelling** and go beyond the current state-of-the-art to support proof-of-principle evidence. Given the low subject numbers, further studies will be required going forward to support the veracity of the data and its translational utility.

Introduction

Arrhythmogenic right ventricular cardiomyopathy (ARVC) is an inherited cardiac disease that affects young adults and has a prevalence estimated as high as 1 in 1000 (**Sen-Chowdhry et al., 2010**). ARVC is a major cause of ventricular tachycardia (VT), a life-threatening fast heart rhythm that can lead to sudden cardiac death (SCD) and accounts for up to 10% of unexplained SCD cases in people younger than 65 years old (**Calkins et al., 2017**; **Thiene et al., 2007**). Catheter ablation, which delivers energy to disrupt abnormal electrical conduction, is a mainstay in treating sustained VT in ARVC, but the success rate of ablation in ARVC patients is only 50–80% (**Mathew et al., 2019**; **Arbelo and Josephson, 2010**) and there is a high rate of VT recurrence (**Waintraub and Gandjbakhch, 2020**). Determining all the locations that could sustain VTs is always challenging in treating ARVC and requires extensive mapping. Difficulty in identifying and targeting all VT circuits could lead to VT recurrence as early as a few months after the initial procedure (**Souissi et al., 2018**; **Mathew et al., 2019**). If all VT circuits could be localized and defined prior to ablation, procedural duration could be potentially shortened, and the effectiveness of the procedure in ARVC patients could be significantly enhanced.

Most ARVC cases are associated with mutations in desmosomal genes, including plakophilin-2 (*PKP2*), desmoglein-2 (*DSG2*), desmocollin-2 (*DSC2*), plakoglobin (*JUP*), and desmoplakin (*DSP*) (**Dalal et al., 2005**). Among these, *PKP2* is the most common genotype, observed in 60% to 78% of ARVC patients with known pathogenic variants (**Mahdieh et al., 2018**; **Protonotarios et al., 2022**; **Corrado et al., 2020**). The PKP2 protein plays a significant role in maintaining the structural integrity of the ventricular myocardium and in facilitating signal transduction pathways, thus *PKP2* pathogenic variants lead to fibrotic remodeling and subsequently to distorted electrical conduction (**Vimalanathan et al., 2018**). Interestingly, around one-third of all ARVC patients do not have known causal pathogenic variants (**Protonotarios et al., 2022**; **Corrado et al., 2020**; **James et al., 2021**). The pathogenesis of these gene-elusive (GE) patients is highly associated with frequent high-intensity exercises that lead to fibrosis formation on the RV (**Benito et al., 2011**; **Breuckmann et al., 2009**; **Sawant et al., 2014**). Overall, both structural and genotype-modulated electrical abnormalities serve as essential VT substrates in ARVC (**El-Battrawy et al., 2018**); however, their specific roles in VT circuit formation remain unexplored.

Previous studies from our group have successfully employed patient-specific heart digital twins in investigating VT mechanisms and in predicting VT locations and morphologies to support ablation targeting in ischemic heart diseases (**Prakosa et al., 2018**; **Deng et al., 2019**; **Sung et al., 2020**; **Sung et al., 2021**). Here, we develop a new personalized genotype-specific heart digital twin approach, Geno-DT, which combines image-based structural information with genotype-specific EP properties at the cell and organ levels. We use the approach to investigate the role of pathophysiological remodeling in ARVC in sustaining VT reentrant circuits and to predict the VT circuits in ARVC patients of the two main genotypes, *PKP2* and GE. The results of this study advance the understanding of arrhythmogenesis in ARVC and offer a pathway to improving VT targeting by ablation.

Results

The Geno-DT approach involves creating three-dimensional (3D) patient-specific electrophysiological (EP) ventricular models incorporating both personalized structural remodeling (diffuse fibrosis and dense scar) constructed from late gadolinium enhancement cardiac magnetic resonance (LGE-CMR) and genotype-specific (GE and *PKP2*) cellular-level membrane kinetics developed here based on the patient's genetic testing results. For 16 ARVC patients of the two genotypes, *PKP2* and GE, we analyzed VT induction in each personalized heart model to understand the arrhythmogenic mechanisms, and specifically, the contributions of structural remodeling and genotype-modulated EP alterations to sustaining VT reentrant circuits in ARVC. The Geno-DT approach was used to predict rapid-pacing induced VT circuit locations in these patients, which would constitute the ideal targets for ablation. The accuracy of the predictions was demonstrated by comparison to the VT circuits induced in clinical EP studies (EPS). An overview of our study is presented in **Figure 1**.

Patient characteristics

This retrospective study was approved by the institutional review board and included 16 patients with ARVC. **Table 1** provides demographic information for this cohort. All patients were adults with

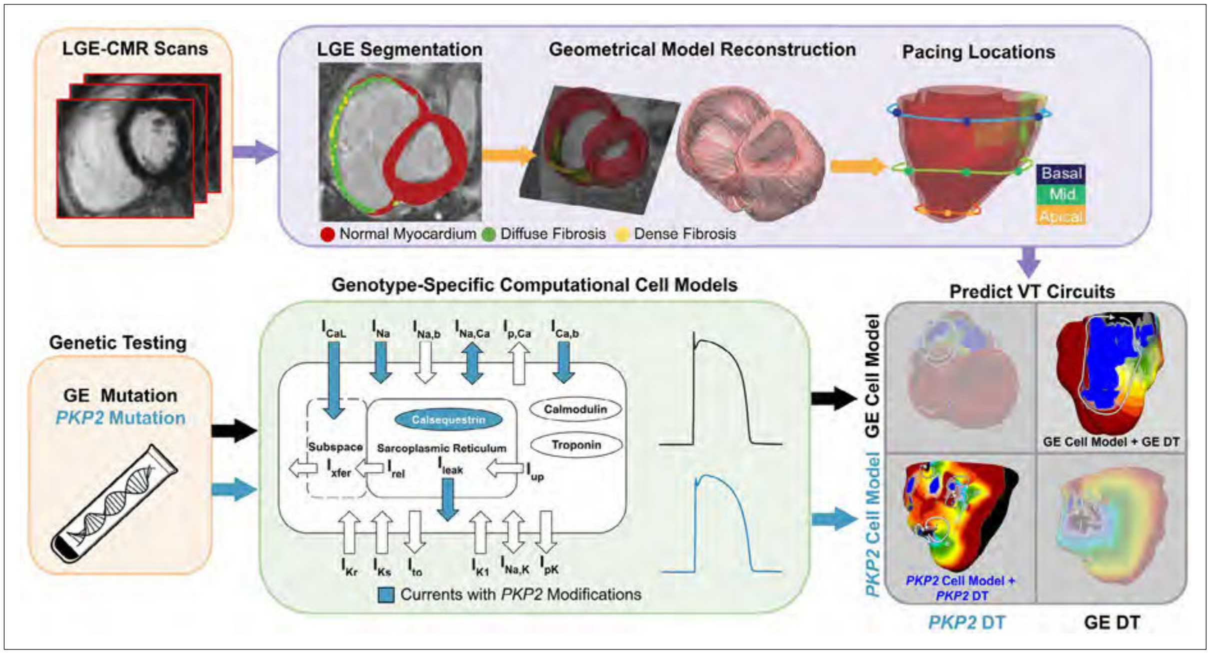

Figure 1. Overview of the study. The flowchart summarizes the workflow of using Geno-DT to understand ARVC arrhythmogenesis and to predict VTs in ARVC patients of the two genotype groups, *PKP2* and GE. Geno-DT integrates genotype-specific cell models (green) and patient-specific clinical-image-based heart digital twin modeling. Orange blocks refer to clinical data, which include genetic testing results and LGE-MRI images for each patient in the cohort. Patient-specific geometrical heart models were reconstructed from the LGE-CMR (top, purple, left and middle images). Genotype-specific cell models (green) developed here were incorporated into each heart model based on the patient's genetic testing result. The integrated multi-scale (from the subcellular to the organ), patient-specific Geno-DT models were subjected to rapid pacing from multiple sites on the RV (top purple, rightmost image) to understand the role of remodeling in ARVC arrhythmogenesis and to predict VT circuits (bottom gray).

a median age of 31 years, and 75% of them were female. All had VTs induced during clinical EPS, where information about the patients' VTs were recorded. Genetic testing for ARVC risk variants was performed for the entire cohort. Eight patients were found to have *PKP2* loss-of-function variants, while the remaining eight did not test positive for variants in any of the known causal genes and were thus considered gene-elusive (GE; ***James et al., 2021***).

All 16 patients had RV enhancement on LGE-CMR; none of them exhibited enhancement on the left ventricle (LV). The clinical parameters previously found to be associated with VT in ARVC (RV ejection fraction and RV end-diastolic volume index [RVEDVI]) (***te Riele et al., 2014***) did not differ significantly between the GE and *PKP2* groups. There was also no statistically significant difference in any of the other common clinical features between the two genotype groups.

EP properties of the *PKP2* cell model

Our Geno-DT approach incorporates, in the patient-specific computational models, cellular EP that is distinct between the two genotypes, *PKP2* and GE. The cell-level electrical behavior for the GE genotype was modeled based on the ***ten Tusscher and Panfilov, 2006*** (TT2) human ventricular model (see Methods). Since there is currently no cell model representation of *PKP2* pathogenic variant that can be used in organ-level simulation in terms of computational tractability, we developed one here, by modifying the GE cell model to represent remodeling in the sodium currents and calcium-handling as reported in experimental studies (***Sato et al., 2009***; ***Kim et al., 2019***; ***Lyon et al., 2021***). Details on the *PKP2* cell model implementation can be found in Materials and methods.

The new *PKP2* model includes a downscaled maximum conductance for the sodium current (I_{Na}), resulting in a peak inward sodium current at a membrane potential of –36 mV that is truncated from –502.71 pA/pF in the GE model to –171.56 pA/pF in the *PKP2* model (***Figure 2A***). Additionally, the *PKP2* cell model includes various calcium currents, each modified from the baseline GE model (see Methods). These changes collectively produce an altered calcium transient (CaT) with a larger area under the curve and a faster decay, giving it a more acute shape (***Figure 2B***). The CaT in the *PKP2* cell

Table 1. Patient characteristics (*n* = 16).

Clinical characteristics	ARVC GE patients (*n* = 8)	ARVC *PKP2* patients (*n* = 8)	p value
Male	2 {25}	2 {25}	-
Age at CMR, years	31.0 [22-45]	35.3 [18-55]	0.55
Age at first clinical VT, years	34.0 [22-45]	31.0 [17-55]	0.94
ICD implantation	7 {88}	7 {88}	-
Beta blocker	8 {100}	5 {63}	0.056
Sodium channel blocker	2 {25}	3 {38}	0.59
Syncope	2 {25}	2 {25}	-
Cardiac function			
RV hypokinesis	4 {50}	6 {75}	0.15
RVEF (%)	37.6±5.5	36.1±9.7	0.76
RVCO (L/min)	4.7±1.2	4.9±0.9	0.72
RVEDVI (ml/m^2)	131.8±31.2	144.5±63.3	0.66
LVEF (%)	57.2±6.5	55.7±10.0	0.74
LVEDVI (ml/m^2)	89.3±9.2	89.7±23.0	0.97
LVCO (L/min)	5.1±0.8	5.0±0.9	0.86

Values are given as *n* {%}, mean [range], or mean ± standard deviation. p Values were calculated using Student's *t*-test and z-test with $p \leq 0.05$ as statistically significant. CMR = cardiac magnetic resonance; VT = ventricular tachycardia; ICD = implantable cardiac defibrillator; RV = right ventricle; LV = left ventricle; RVEF = right ventricular ejection fraction; RVCO = right ventricular cardiac output; RVEDVI = right ventricular end-diastolic volume index; LVEF = left ventricular ejection fraction; LVCO = left ventricular cardiac output; LVEDVI = left ventricular end-diastolic volume index. The cardiac function parameters were obtained from CMR reports.

model has a longer time to peak (32 vs 27 ms), a significantly higher peak (0.0023 vs 0.00084 mM), and a shorter time to 90% return from peak (319 vs 379 ms).

The resulting action potential (AP) shape of the *PKP2* cell is distinct from that of the GE cell, as depicted in ***Figure 2C***. The downregulation of I_{Na} results in a lower upstroke peak and slower maximum upstroke velocity (V_{max}). The changes to calcium handling led to an elevated resting membrane potential and longer AP duration at 90% depolarization (APD_{90}). These differences in AP behavior between the two cells underlie the organ-level EP differences between *PKP2* and GE genotypes.

Since in this study we used a rapid pacing protocol to induce VTs in the personalized ARVC models, cell-level restitution properties, and specifically the difference in restitution properties between the *PKP2* and GE cell models, have important consequences for ARVC arrhythmogenesis. ***Figure 3*** examines these restitution properties. The GE cell model exhibited a decrease in APD_{90} with diastolic interval (DI) shortening (***Figure 3A***), consistent with normal calcium-handling behavior (***Franz, 2003***). In contrast, the *PKP2* cell model's AP showed some shortening of phase two duration but with very little reduction in plateau amplitude, resulting in more triangular APs at fast pacing without much change in total duration.

Figure 3B highlights the differences in restitution curves for the *PKP2* and GE cell models. Notably, at the fast-pacing intervals of the steep initial phase (25–160 ms), the two restitution curves diverge significantly. While the GE cell APD_{90} continued to decrease to 148ms before loss-of-capture, the *PKP2* cell APD_{90} only decreased to 208 ms. The maximum slopes of the restitution curves were measured to be 1.16 and 0.59 for the GE and *PKP2* cell models, respectively. The substantially lower slope for the *PKP2* cell's restitution curve indicated a reduced ability of its AP to adapt to fast pacing rates.

The GE and *PKP2* cell models described above were incorporated in LGE-based geometrical models of the patients' ventricles from the respective patient groups. In addition to EP remodeling, ARVC is also characterized by structural remodeling, i.e the presence of dense scar and diffuse fibrosis. While replacement scar is non-conductive, myocardium in the diffuse fibrosis regions exhibits altered EP properties, which were represented in the personalized ventricular models by additional alterations in

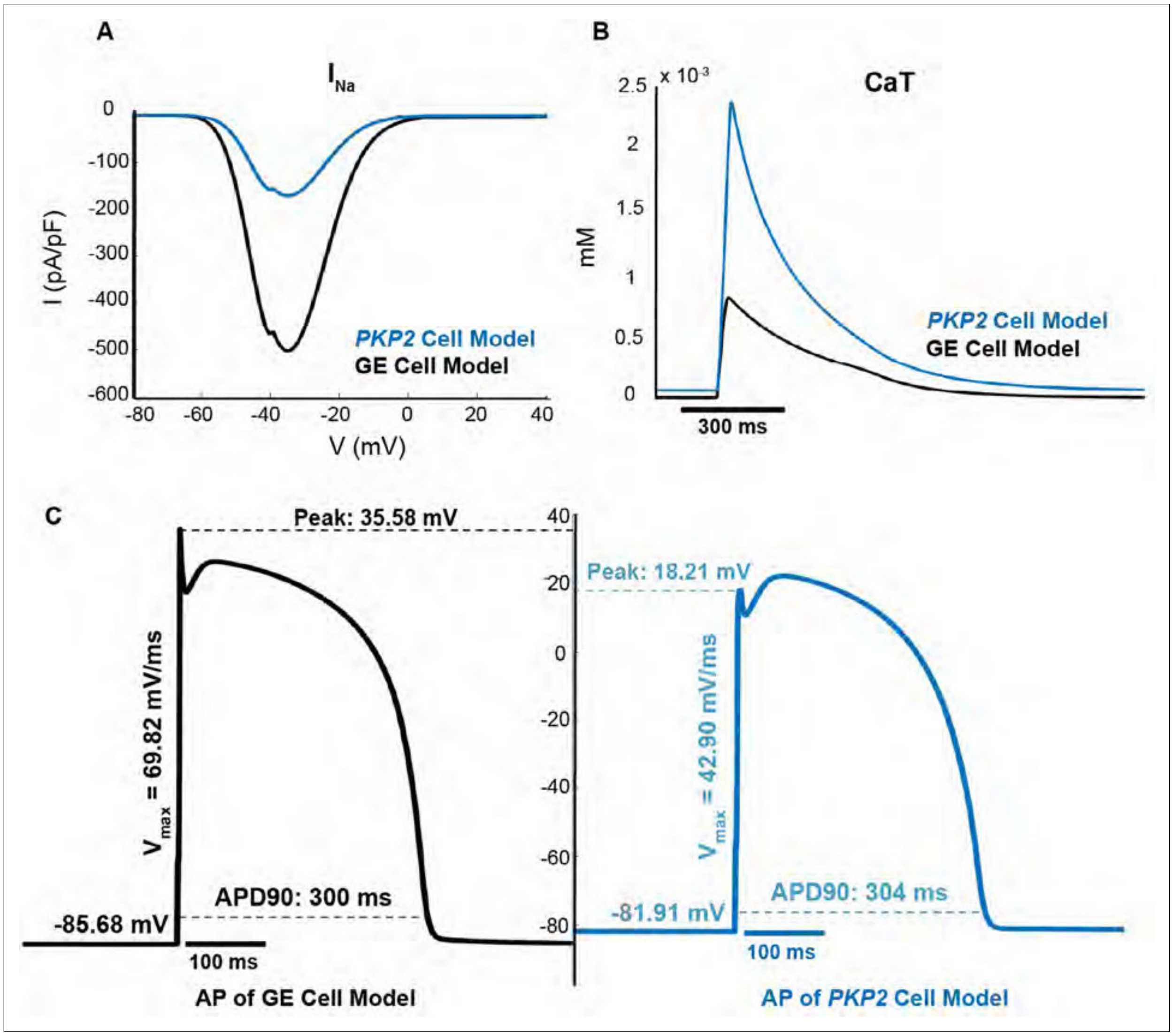

Figure 2. The *PKP2* cell model has lower excitability and altered calcium-cycling as compared to the GE model. (**A**) Current-voltage curves for I_{Na}; (**B**) Calcium transient curves; (**C**) Action potentials at steady state at 1 Hz pacing.

cell-level properties in these regions, as we have done previously (***Shade et al., 2020***; ***O'Hara et al., 2022***); see Materials and methods for detail. The resulting heart models of ARVC patients thus represented both EP and structural remodeling in ARVC.

Analysis of structural remodeling distribution and its relationship with VT inducibility for different genotype patient groups

Here, we first utilized the LGE-reconstructed ventricular geometrical models to examine the distribution of structural remodeling in various regions of the RV and its relationship to VT. We found that across the entire ARVC cohort, the diffuse fibrosis was most abundant at the base of the RV and least abundant at the RV apex (***Figure 4A***). There were significant differences in the amount of diffuse fibrosis between the basal, mid, and apical regions (14.01 ± 4.37% for basal RV vs 5.41 ± 2.61% for mid RV vs 1.13 ± 1.71% for apical RV, $p < 0.0001$ for pairwise comparisons). A similar trend was observed for dense scar amounts with significant differences between the basal, mid, and apical regions (5.51 ± 2.71% vs 1.74 ± 1.99% vs 0.42 ± 0.90%, $p < 0.05$ for pairwise comparisons; ***Figure 4B***). There was no significant difference when comparing the amounts of structural remodeling between anterior, lateral, and posterior regions.

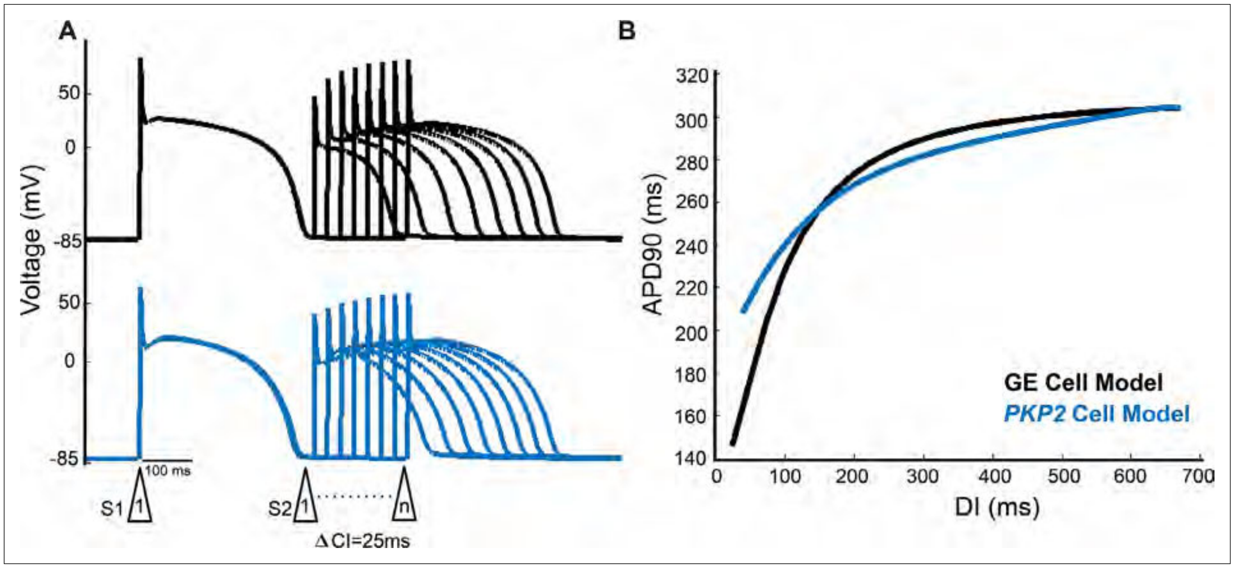

Figure 3. The *PKP2* cell model exhibits poorer rate adaptation and a flatter electrical restitution curve as compared to the GE model. (**A**) Representative premature APs at DIs decrementing to just before loss of one-to-one capture of GE cell model (top) and *PKP2* cell model (bottom). (**B**) APD restitution curves of GE and *PKP2* cell models.

We found that the distribution of diffuse fibrosis was different in the two patient groups, with GE patients having a significantly higher amount of diffuse fibrosis burden than *PKP2* patients in the basal anterior wall (6.07 ± 3.18% vs 1.85 ± 0.017%, $p < 0.01$ for pairwise comparisons) and basal lateral wall (5.77 ± 2.34% vs 3.24 ± 1.40%, $p < 0.05$ for pairwise comparisons), and a significantly lower amount in the basal posterior wall (3.36 ± 2.92% vs 7.73 ± 4.38%, $p < 0.05$ for pairwise comparisons; ***Figure 4C***). There was no statistical significance in the dense scar distribution between the two genotype groups.

Next, we performed simulations, with the personalized Geno-DT heart models, of VT induction following rapid pacing (see Materials and methods) and evaluated the induced VT circuits in the entire cohort. We performed a total of 144 ventricular simulations (16 patients × 9 pacing locations) to determine the induced VT circuit morphologies. We examined the correlations between the structural remodeling features (diffuse fibrosis volume [DF], dense scar volume [DS], total fibrotic remodeling volume (both scar and diffuse fibrosis) [TFV]) and the number of unique VT morphologies induced during EPS across the different RV AHA segments. ***Figure 5*** summarizes pairwise correlations between these variables for both GE and *PKP2* patient groups. Our analysis revealed a highly positive correlation between the number of VTs induced during EPS and the volume of each type of structural remodeling (both DF and DS) and total fibrotic volume (TFV) in the GE patient group ($r = 0.91$, 0.91, 0.92 for DF, DS and TFV respectively), while in the *PKP2* group, we observed only moderate correlation ($r = 0.65$, 0.7, 0.7 for DF, DS and TFV respectively).

Importantly, we found a strong correlation between VTs induced during EPS and those induced in simulations within the different RV regions in both patient groups ($r = 0.99$ for both groups), indicating that our heart digital twins effectively capture the occurrence pattern of EPS-induced VTs. Notably, although the structural remodeling in the *PKP2* group was less correlated with EPS VTs as compared to the GE group, the VTs induced in the *PKP2* models still exhibited high correlation with the VTs recorded during EPS.

These findings suggest that structural remodeling plays a more important role in VT arrhythmogenesis in GE patients than in *PKP2* patients. The moderate correlation in the *PKP2* group indicates that additional factors contribute to VT, specifically the EP remodeling associated with the *PKP2* pathogenic variants.

Predicting VT circuits using Geno-DT

We next assessed the predictive capability of the Geno-DT approach in determining accurately the VT circuit numbers and locations in the two ARVC genotype groups. In ***Figure 6***, the bullseye plots summarize the number of unique VT morphologies induced during EPS and those induced in Geno-DTs

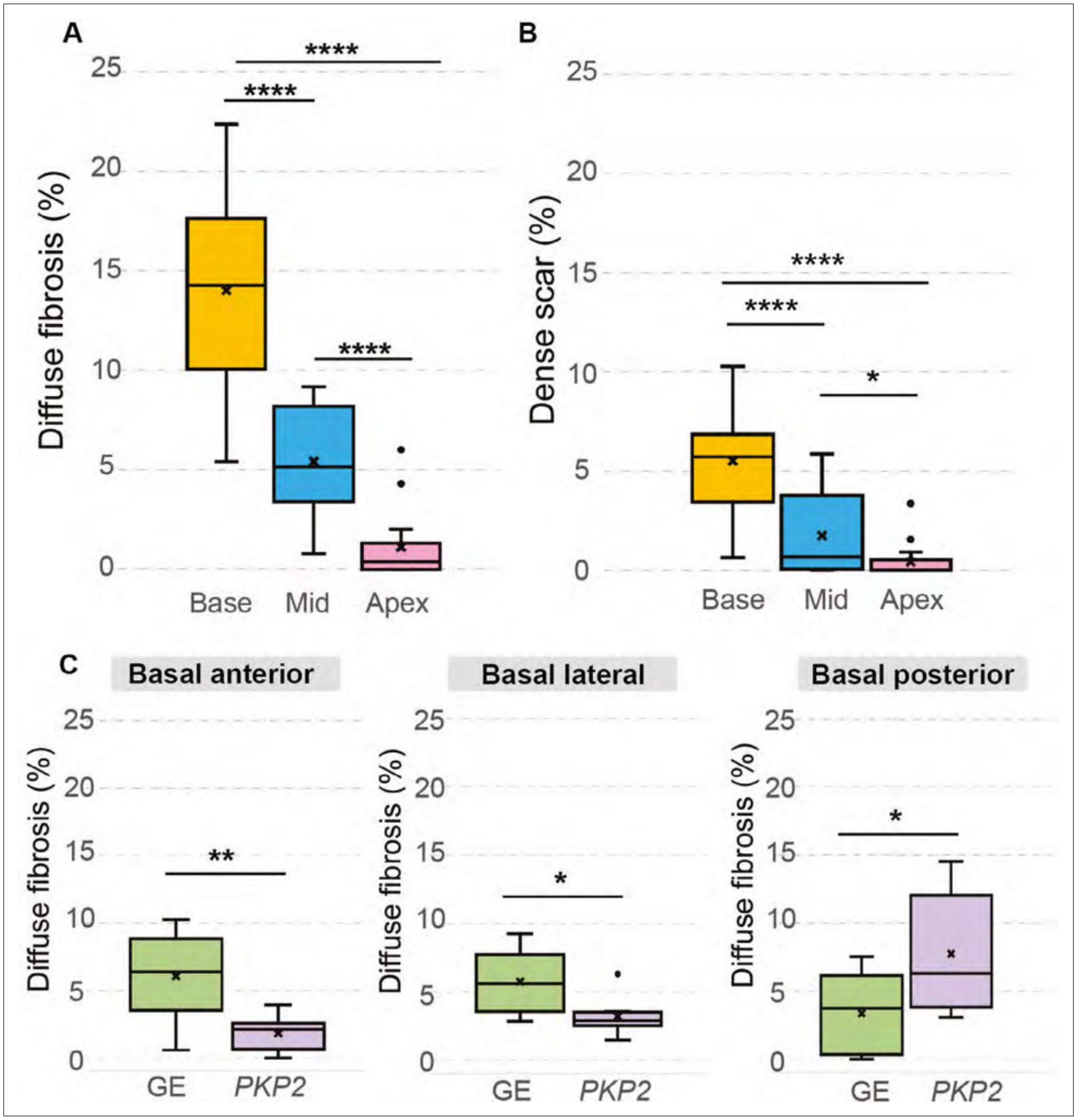

Figure 4. Amounts of diffuse fibrosis and dense scar in different regions of the RV and in the two patient groups. (**A, B**) Boxplots showing the amount of diffuse fibrosis (**A**, Base: $n = 16$, interquartile range [IQR] = 7.43; Mid: $n = 16$, IQR = 4.65; Apex: $n = 16$, IQR = 1.18; ****$p < 0.0001$) and dense scar (**B**, Base: $n = 16$, IQR = 2.73; Mid: $n = 16$, IQR = 3.14; Apex: $n = 16$, IQR = 0.36; *$p < 0.05$, ****$p < 0.0001$) in the entire ARVC cohort in different regions of the RV. (**C**) Boxplots comparing diffuse fibrosis amounts in different RV AHA segments between the two genotype groups. Significance was found in the following basal segments: basal anterior (GE: $n = 8$, IQR = 2.91; *PKP2*: $n = 8$, IQR = 1.78; **$p < 0.01$), basal lateral (GE: $n = 8$, IQR = 3.21; *PKP2*: $n = 8$, IQR = 0.75; *$p < 0.05$), and basal posterior (GE: $n = 8$, IQR = 4.74; *PKP2*: $n = 8$, IQR = 7.25; *$p < 0.05$). Amounts of diffuse fibrosis/dense scar are normalized with respect to the patient's total RV tissue volume. Median and interquartile range were represented in each boxplot, where dots indicate outliers. Paired Student's *t*-tests were applied to assess statistical significance.

for each RV AHA segment in all 16 ARVC patients. In the GE patient group, Geno-DT resulted in 28 distinct VTs being induced, 25 of which were observed during EPS. The *PKP2* group showed comparable results, with 25 VT morphologies induced in *PKP2* ARVC models and 25 reported in the EPS record. In terms of VT circuit locations, Geno-DT captured all VT locations that were observed during EPS except for one VT on the mid lateral RV wall in the GE group. In the *PKP2* group, Geno-DT predicted all the VT locations recorded during EPS, except for one VT on the basal anterior RV wall

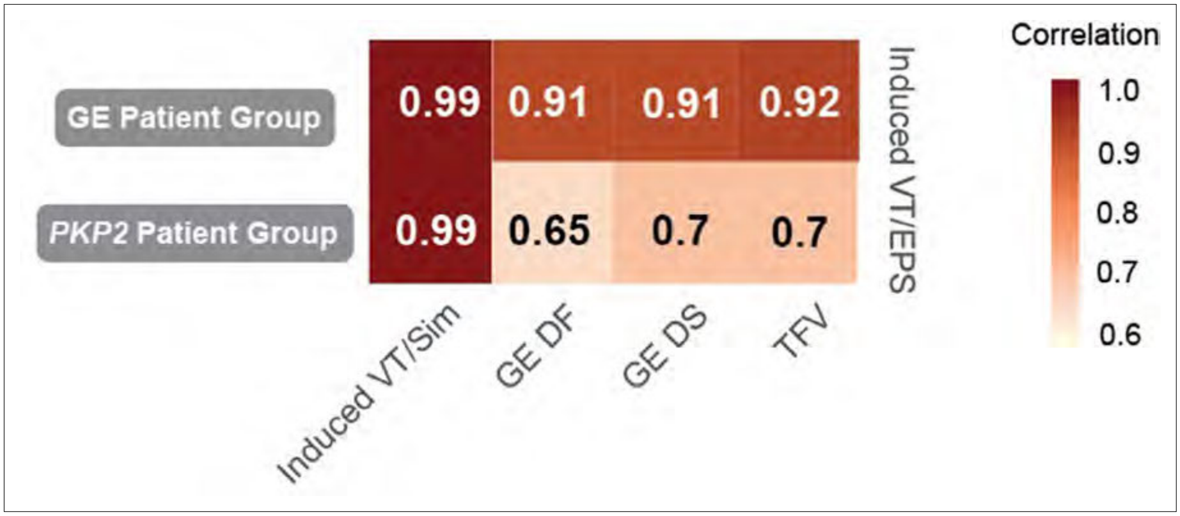

Figure 5. Correlation between the number of VTs induced during the EPS and structural remodeling features across different RV anatomical locations in ARVC patients. The number of VT episodes induced during EPS is highly correlated with the volume of structural remodeling (DF, DS, TFV) in GE patient group (top row), while correlated less in *PKP2* patient group (bottom row). The VT episodes induced during EPS and by Geno-DT are highly correlated in both patient groups (first column). Numbers in the block stand for the correlation coefficient (**r**) between the two corresponding variables. $r > 0.7$ stands for high correlation; $0.5 < r \leq 0.7$ stands for moderate correlation. Induced VT/EPS: VTs induced during the clinical EPS; Induced VT/Sim: VTs induced in Geno-DTs; DF: diffuse fibrosis; DS: dense scar; VT: ventricular tachycardia, TFV: total fibrotic volume = DF + DS.

and two on the basal posterior wall. Hence, in both cases, Geno-DT accurately predicted the locations of nearly all the VTs induced during EPS.

Additionally, for each individual ARVC patient, we compared the AHA segment of every VT circuit induced in each Geno-DT to the patient's EPS VT record obtained from EPS. In ***Table 2***, we summarized the capability of Geno-DT in predicting VT locations. The results showed outstanding accuracy, sensitivity, and specificity in both GE and *PKP2* patient groups.

Figure 7A and B illustrate the above findings with two examples, one from GE and one from *PKP2* group. For the GE patient (***Figure 7A***), the genotype-matched model induced three VT morphologies: two figure-of-eights on the anterolateral and posterolateral RV wall and a single-reentry VT on the posterior RV wall. This GE patient had two VT circuits observed during the clinical EPS, each one on the basal and mid lateral wall of the patient's RV. Although the clinical EPS report did not mention VT induced on the posterior RV wall, it did mention that fractionated potentials, which are considered as VT circuit indicators, were observed in the posterior RV, and thus, clinical ablation was done there. Therefore, we consider all our predicted VTs in this patient in agreement with the clinical findings. Similarly, for the *PKP2* patient, the genotype-matched model induced five VTs: a figure-of-eight reentry on the anterolateral wall, a single-reentry VT and two figure-of-eight VTs on the lateral RV wall, as well a single-reentry VT on the posterior RV wall (***Figure 7B***). This *PKP2* patient underwent two clinical ablation procedures within one year. The first ablation identified three VTs, one in the mid lateral region, one in the basal posterolateral region and one in the basal posterior region. The EPS procedure during the second ablation identified two sustained VTs on the anterolateral and lateral wall. These examples showcase the excellent correspondence between Geno-DT VT circuit predictions and clinical observations.

The role of genotype-specific EP remodeling in VT propensity

Once we ascertained the ability of Geno-DT to correctly predict VT circuits in ARVC patients, we investigated the contribution of pathogenic variants (via the corresponding genotype-specific EP properties) in creating propensity to VT. To do so, we switched the cellular models between GE and *PKP2* patient groups to introduce a mismatch between personalized structural remodeling and genotype-specific EP properties. We then repeated the simulations under these mismatched conditions. ***Figure 8C*** provides a summary of the findings. We also present examples in ***Figure 8A and B***, which are the same two patients' ventricular models included in ***Figure 7*** but simulated under genotype-mismatched conditions. Evident from the figure is that VT reentrant circuits were also

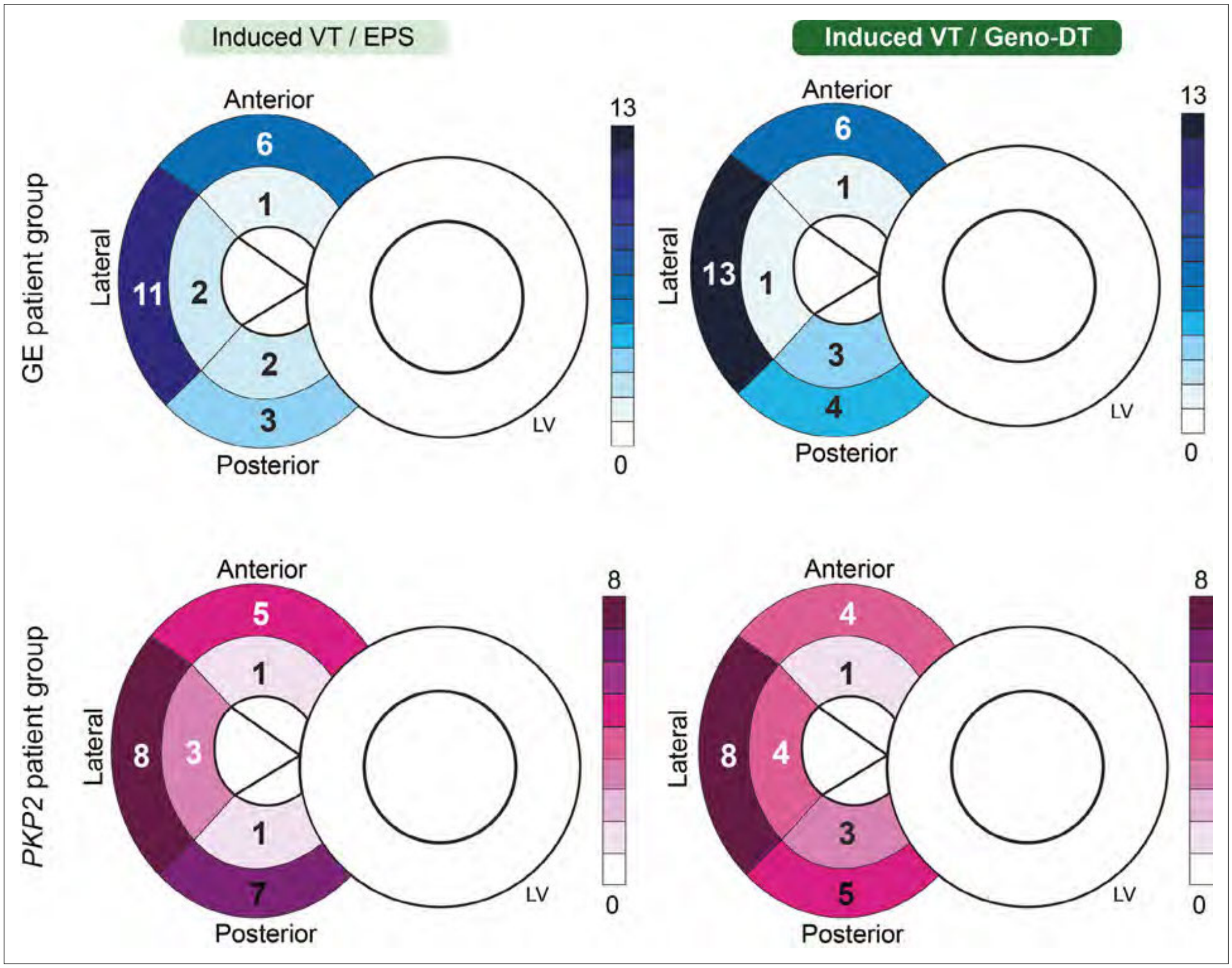

Figure 6. Comparison of the number of unique VT morphologies induced in Geno-DTs to VTs induced during EPS in each RV region. Schematics of the heart were labeled with the numbers of unique VT morphologies at different AHA segments on the RV induced during clinical EPS (left) and induced in Geno-DTs (right) of the two ARVC genotypes (GE: blue, *PKP2*: pink).

induced under genotype-mismatched conditions, however, they are distinctly different from those in the genotype-matched models, and very different from the VTs induced during EPS. In ***Figure 8A***, the mismatched GE DT had only one VT circuit induced on the posterolateral RV wall, and in ***Figure 8B*** the mismatched *PKP2* DT presented only one VT in the anterolateral RV wall. For both the GE and *PKP2* examples, the genotype-mismatched DTs missed many VT circuits induced during EPS. The bullseye plots in ***Figure 8C*** emphasize the underprediction of the genotype-mismatched Geno-DTs, in comparison to those in ***Figure 6***.

Table 2. Capability of Geno-DTs to predict VT locations.

	GE patient group (n = 8)	*PKP2* patient group ($\mathbf{n}$ **= 8**)
Sensitivity	1.00	0.86
Specificity	0.94	0.90
Accuracy	0.96	0.89
Error rate	0.042	0.11
F1 score	0.89	0.83
MCC	0.90	0.76

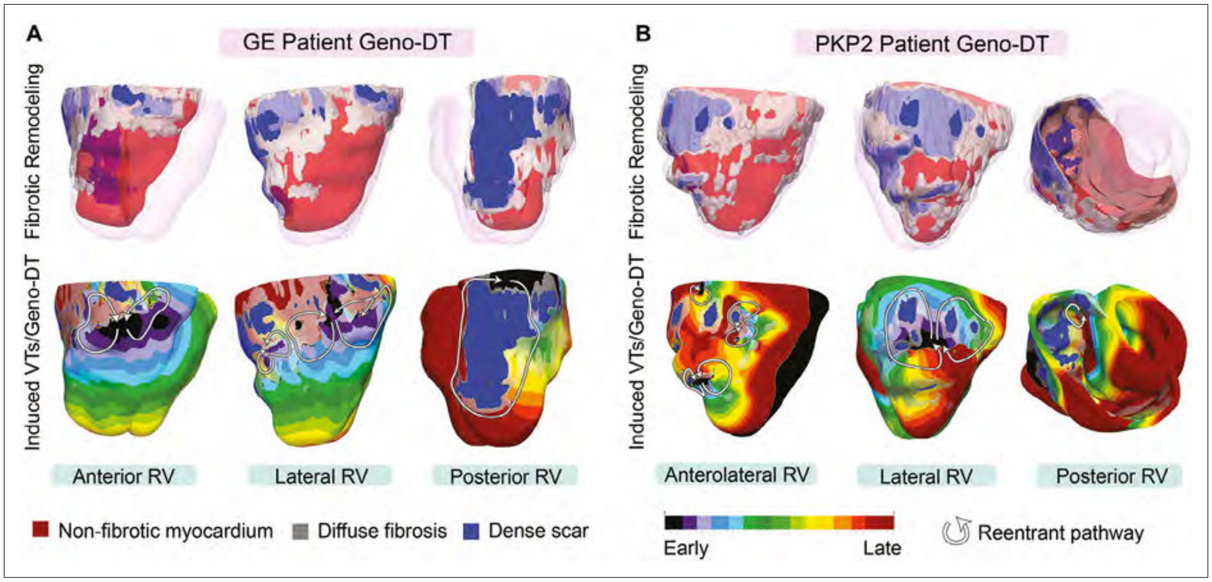

Figure 7. VTs induced by Geno-DT in two ARVC patients each from the GE and *PKP2* genotype groups. (**A, B**) The top row shows three different views of reconstructed geometrical models of GE and *PKP2* patient hearts with personalized diffuse fibrosis (gray) and dense scar (blue). The bottom row shows the activation patterns of the VT reentrant circuits induced by Geno-DT rapid pacing.

Mechanisms by which genotype-specific EP remodeling alters VT circuits

To gain a better understanding of the mechanisms underlying the induction of different reentrant circuits resulting from EP remodeling, we analyzed in detail the VT circuits simulated under genotype-matched and genotype-mismatched conditions. Two examples of this analysis are presented in ***Figure 9*** for the *PKP2* ventricular model from ***Figure 7B***. Animation of the VT circuits propagation is available in ***Figure 9—video 1***.

Reentrant circuit 1 is the VT induced in the lateral RV wall of the *PKP2* (genotype-matched) DT (***Figure 9A***). This circuit involved two dense scar islands surrounded by diffuse fibrosis, creating an isthmus of low conductivity in between. The initial wavefront elicited from a basal posterior pacing site propagated around the dense scar and through the isthmus. As the exiting wavefront encountered non-fibrotic myocardium, it had a slow conduction due to the lowered upstroke velocity and elevated resting membrane potential resulting from *PKP2* EP remodeling. Consequently, downstream tissue failed to be excited due to source-sink mismatch. Two other wavefronts propagated from either side of the dense scar islands into this unexcited myocardium and collided. In the time it took for the two opposing wavefronts to meet, the non-fibrotic myocardium at the entrance of the isthmus remained refractory (*PKP2* cell model has extended refractoriness), thereby allowing the collided wavefront to travel back up the isthmus, meet refractory tissue and ultimately form the figure-of-eight reentry. In contrast, no reentry was induced at this same location with the incorporation of GE EP properties (***Figure 9B***). Specifically, as the wavefront left the isthmus and encountered non-fibrotic myocardium, its propagation speed was higher due to the GE cell model's rapid upstroke velocity and unchanged resting membrane potential. Because of the fast conduction velocity, the isthmus did not have time to recover, thereby excitation occurred only of tissue ahead of the wavefront.

Reentrant circuit 2 was induced in the posterior RV wall of the *PKP2* genotype-matched DT (***Figure 9C***). The wavefront elicited from the same basal posterior pacing site had slowed down significantly while traveling through a band of diffuse fibrosis. In areas where the band was wide, the conduction velocity decreased to the point where the wavefront was unable to excite non-fibrotic myocardium due to source-sink mismatch. This was a result of the fact that the *PKP2* cells have slowed upstroke velocity and elevated resting membrane potential. An adjacent wavefront was thereby able to turn into this unexcited region and initiate reentry. In contrast, no reentry occurred at this location in the GE DT (***Figure 9D***). The GE cell's rapid upstroke velocity allowed the wavefront to excite the

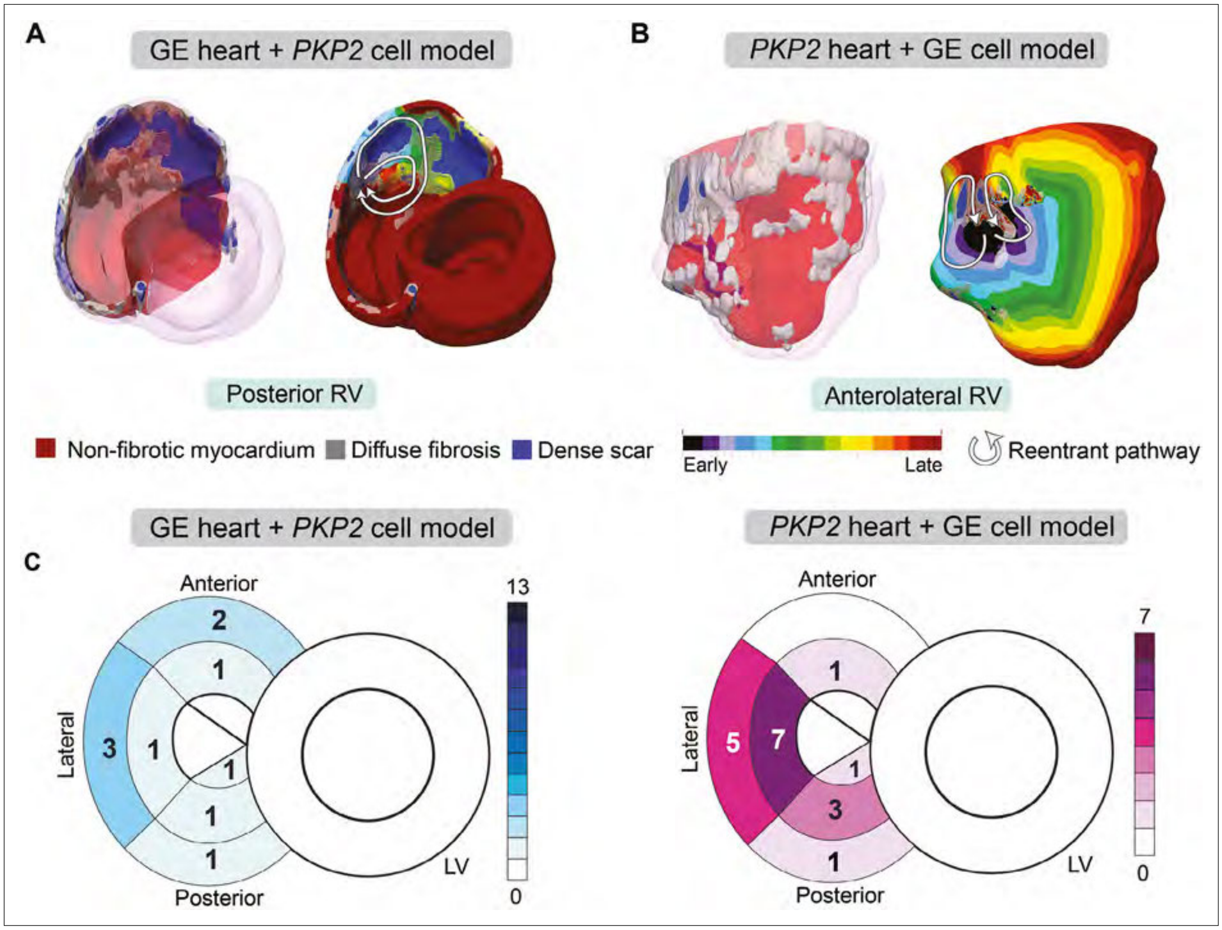

Figure 8. Genotype-mismatched DTs significantly underpredicted VTs in ARVC patients. (**A, B**) Geometrical ventricular models with structural substrates visualized (left); VT circuits induced in genotype-mismatched DTs (right). (**C**) Bullseye plots labeled with the number of unique VT morphologies in different RV AHA segments induced in Geno-DTs under genotype-mismatched conditions.

non-fibrotic myocardium after exiting the wide diffuse fibrosis band. Consequently, the wavefront leaving the diffuse fibrosis was more planar, avoiding source-sink mismatch, and did not result in reentry.

Together, these results help illustrate the contribution of genotype-based EP differences to the variability of organ-level wavefront propagation patterns.

Discussion

This study presents a novel heart digital-twin approach called Geno-DT, tailored to predict VT reentrant circuits in patients with different ARVC genotypes. We demonstrated that Geno-DT has excellent capability in predicting VT reentrant circuits non-invasively for patients with both gene-elusive and *PKP2* positive genotypes. In predicting VT circuits, the study also reveals new mechanistic insights regarding VT arrhythmogenesis in ARVC. By comparing the VT circuits predicted by Geno-DT to the clinical EPS observations, we demonstrated that Geno-DT has high sensitivity, specificity, and accuracy in predicting non-invasively VT circuits and their locations in both GE and *PKP2* genotypes (100%, 94%, 96% in GE patient group; 86%, 90%, 89% in *PKP2* patient group). The Geno-DT approach thus has the potential to improve pre-ablation planning and to lead to tailored personalized ablation strategies. Our study further charts a pathway towards bringing computational modeling in clinical decision-making thus augmenting precision medicine approaches in cardiology.

With its incorporation of genetic EP information, Geno-DT is a novel development in heart digital twin applications. Although previous studies have included cellular remodeling in predicting VT risk for non-ischemic cardiac diseases such as hypertrophic cardiomyopathy and Tetralogy of Fallot (***Shade***

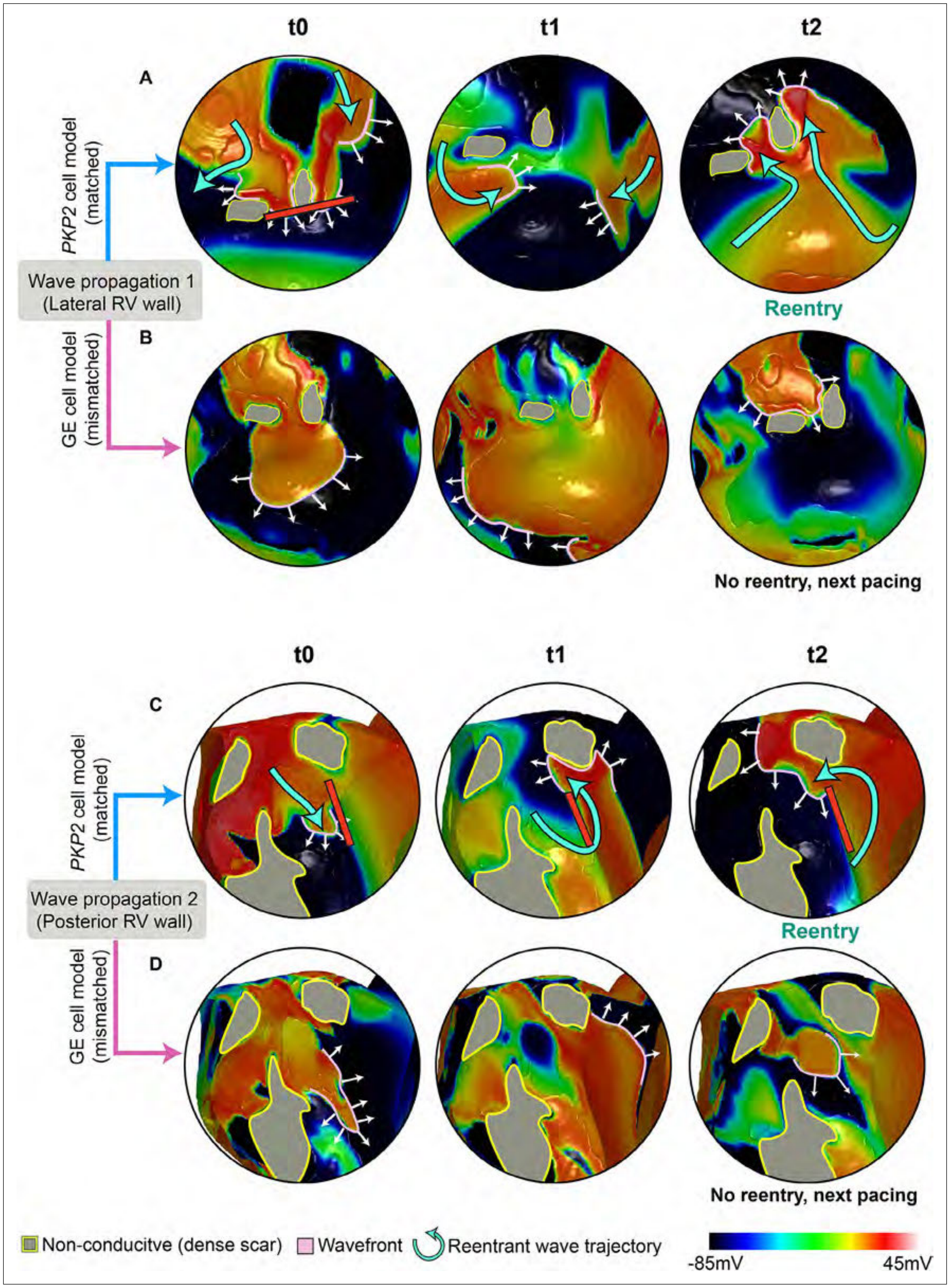

Figure 9. Comparison of propagation following pacing in a *PKP2* patient's ventricular model using different cell models. Each row of the figures shows a series of frames that depict the continuous wave propagation in a portion of the *PKP2* patient's DT from ***Figure 7B*** (genotype-matched conditions, [A] and [C]) and ***Figure 8B*** (genotype-mismatched conditions, [B] and [D]). The images in each column (**A and B, C and D**) show the same time instant. Pink lines mark the wavefronts, white arrows indicate direction of propagation and cyan curved arrows in (**A**) and (**C**) represent reentrant wave trajectories. Gray areas contoured by yellow represent the dense scar (DS) regions that are non-conductive. (**A, B**) (**A**) and (**B**) compare the wave propagation on the lateral RV wall between genotype-matched and -mismatched conditions. At t0, the wavefront in (**A**) propagates slower than that in (**B**), resulting in

Figure 9 continued on next page

Figure 9 continued

conduction block in (**A**) but not in (**B**). In (**A**), following wavefront fusion at t1, reentry is established at t2. In (**B**), no reentry forms and the next pacing stimulus captures. (**C, D**) (**C**) and (**D**) compare the wave propagation on posterior RV wall between genotype-matched and -mismatched conditions. At t0, the wavefront in (**C**) propagates slower than that in (**D**). Due to the extended refractoriness in *PKP2*, tissue adjacent to the wavefront is still recovering, and conduction block takes place (red line). In (**D**), tissue ahead of the wavefront is fully recovered, allowing it to propagate through. At t1, in (**C**), the wavefront, with a high curvature, travels around the conduction block. In (**D**), the wavefront is more planar and continues to propagate. At t2, a reentrant circuit forms in (**C**); while in (**D**), no reentry forms and the next pacing stimulus captures.

The online version of this article includes the following video for figure 9:

Figure 9—video 1. Animation of two VT circuits propagation corresponding to ***Figure 9***.
https://elifesciences.org/articles/88865/figures#fig9video1

et al., 2020; ***O'Hara et al., 2022***), personal genetics were never considered. ARVC is associated with several genotypes, each causing specific pathological alterations to ion channels (***Ohno, 2016***). However, it has remained unclear how the altered cellular EP is reflected at the organ and how it affects the likelihood of VT occurrence. Our study addresses these questions by developing a *PKP2* cell model that incorporates the EP effects of pathogenic variants and is compatible with whole-heart modeling. While a previous study had incorporated *PKP2* cell EP properties in a computational cell model (***Lyon et al., 2021***), the model was too complex to be incorporated into whole-heart simulations due to its focus on describing subcellular phenomena.

Our study offers new insights into the mechanisms underlying VT propensity in patients with ARVC. While previous clinical observations have suggested that sustained VTs are strongly associated with fibrotic remodeling in the basal anterior RV, it has been unclear whether this association holds true between the GE and *PKP2* genotypes (***Basso et al., 2008***; ***Corrado et al., 2005***). Studies of ARVC structural substrates have typically relied on electroanatomical mapping and biopsy, which do not provide a complete characterization of the 3D fibrosis distribution in the right ventricle (***Te Riele et al., 2013***; ***Basso et al., 2009***; ***Corrado et al., 2005***). Here, we reconstructed heart digital twins using LGE-CMR to quantify the extent and distribution of fibrotic remodeling in each patient's heart. We found that *PKP2* patients with clinical sustained VTs had more fibrotic remodeling in the basal posterior region of RV than the anterior, while the fibrosis distribution in the GE group was consistent with previous findings. These results demonstrate that different ARVC genotypes exhibit distinct distributions of fibrotic remodeling. Furthermore, while the number of induced VT morphologies was similar between GE and *PKP2* patients, our analysis revealed a weaker correlation between the locations of VTs induced during EPS and distribution of fibrosis in the *PKP2* group compared to the GE group. This suggests that, in addition to structural remodeling, unique *PKP2*-specific changes in cellular EP properties may contribute to the development of VT in *PKP2* patients.

Our findings further elucidate the important role of genotype-specific EP remodeling in sustaining VT circuits in ARVC. Previous study has shown that a decrease in V_{max} directly affects the conduction velocity in the cardiac tissue (***Issa et al., 2019***). Consistent with this relationship, we observed that the reduced V_{max} in the *PKP2* cell model, caused by downregulated I_{Na}, resulted in slower wavefront conduction, particularly in non-fibrotic regions adjacent to the dense fibrosis. The different restitution properties of the *PKP2* cell model resulting from the altered calcium handling also contributed to the formation of reentry. The rapid pacing rates used to induce VT corresponded to the steep initial phase of the restitution curves, where *PKP2* cell model had extended refractoriness compared to the GE cell. Hence in *PKP2* hearts, extended refractoriness and decreased conduction velocity resulted in wavefronts of higher curvature, subsequent source-sink mismatch and conduction block, setting the stage for arrhythmogenesis.

We identify several potential benefits of using Geno-DT in ARVC clinical management. Firstly, it could save time during the ablation procedure as all possible locations that sustain VTs could be known prior to the procedure. Secondly, it provides a new approach for substrate modification in ARVC ablation, in which the substrate is targeted at predicted VT locations instead of ablating fibrotic tissue or all regions with voltage abnormalities on electroanatomical mapping, as not all of these are arrhythmogenic (***Rottmann et al., 2019***). The latter ablation approaches could lead to excessive lesions, which have negative consequences on cardiac function, especially in ARVC, as it is characterized by abnormal inflammation response (***Asatryan et al., 2021***; ***Briceño et al., 2020***; ***Santangeli et al., 2015***). Lastly, our study demonstrated that the underlying mechanisms of sustaining VT reentrant circuits differ among various ARVC genotypes. This finding underscores the importance of genotype-specific ARVC management in clinical practice, which can be facilitated by the Geno-DT approach.

The success of our Geno-DT approach in predicting VT circuit locations underscores its potential for translation to the clinical setting. As the understanding of human genetic variation underlying cardiovascular diseases continues to evolve with advances in functional genomics (***Li et al., 2022***), Geno-DT could provide a generalized framework to integrate multimodal clinical data and improve precision health for each individual patient.

Materials and methods

Patient population

This retrospective study cohort included 16 patients from the Johns Hopkins ARVC database who were diagnosed with ARVC based on 2010 Task Force Criteria between 2010 and 2018. Patients were included if they (1) underwent genetic testing for ARVC risk variants that demonstrated either no pathogenic variants (GE patients) or pathogenic *PKP2* variant (*PKP2* patients), (2) had inducible VT during EPS, and (3) had LGE-CMR demonstrating the presence of RV fibrosis. Clinical reports from EPS were reviewed to identify both the number of distinct VT morphologies and the locations of induced VT within the RV. Patients' CMR images were reviewed clinically to identify the presence/absence of RV enhancement (S.Z.). Patient clinical characteristics are shown in ***Table 1***.

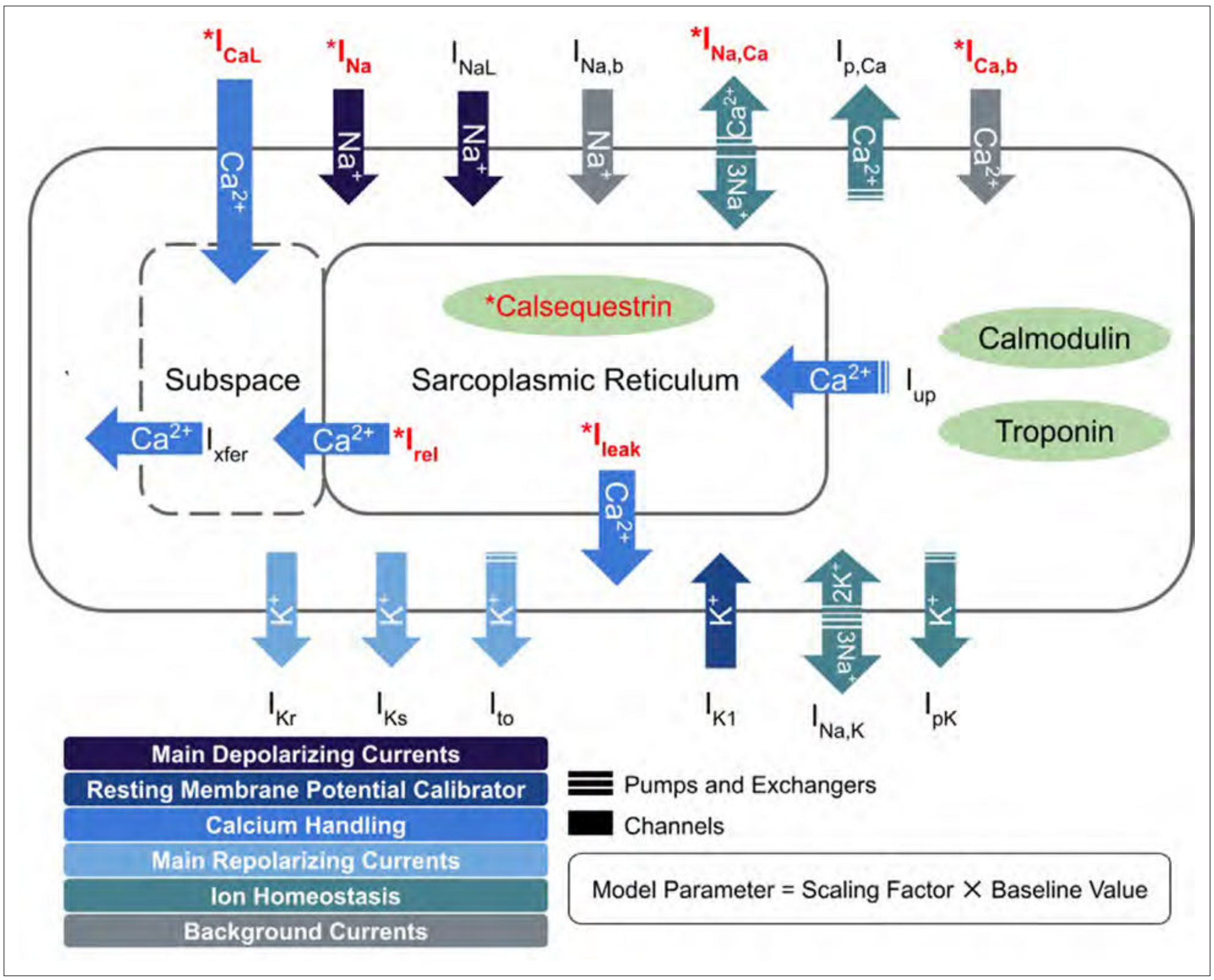

Figure 10. Schematic diagram describing the ionic currents across the cell membrane and sarcoplasmic reticulum of an adult human cardiomyocyte. Components with asterisks (red color) were modified from their baseline formulations to reflect *PKP2* pathogenic ionic remodeling.

Cell-level modeling

The different EP properties of cardiomyocytes in the GE and *PKP2* genotype groups were represented with two different cell ionic models. For non-fibrotic myocardium regions of the GE group, we used the ***ten Tusscher and Panfilov, 2006*** model with the addition of a late sodium current representation (***O'Hara et al., 2011***). A late sodium current (I_{NaL}) formulation was added, as done in our previous studies (***Cartoski et al., 2019***; ***Shade et al., 2020***; ***Arevalo et al., 2016***; ***Prakosa et al., 2018***; ***Shade et al., 2021***). For non-fibrotic myocardium regions of the *PKP2* group, we developed a new *PKP2* model by modifying the GE model based on experimental data (***Lyon et al., 2021*** and ***Sato et al., 2009***). These modifications are summarized in ***Figure 10***. Our resulting *PKP2* model recapitulates the altered sodium current dynamics and calcium-handling properties observed in experimental recordings of cardiomyocytes from ARVC hearts.

In our *PKP2* ionic model, the maximum channel conductance for sodium current (I_{Na}) was decreased by 70% to reflect reported experimental current dynamics from ***Sato et al., 2009***. The calcium-handling in our *PKP2* model was adjusted to reproduce experimental data from ***Lyon et al., 2021***, which reported a decreased L-type calcium current (I_{CaL}) and higher amplitude calcium transient (CaT). We scaled the maximal conductance of I_{CaL} by 50%, reducing its peak current (9.03 vs 6.84 pA/pF) proportional to the experimental values. To counteract the accompanying decrease in CaT amplitude produced by this modification, we also upregulated the background calcium current (I_{bCa}), representative of connexin 43 (Cx43) hemichannel-mediated calcium entry, by fivefold. This upregulation was in line with the in vitro properties of PKP2-deficient cells: disrupted cell-cell adhesion, functional dysregulation of Cx43, increased membrane calcium permeability, and excess free calcium concentrations.

Studies from Lyon et al. have further shown that *PKP2*-deficient cardiomyocytes have reduced ryanodine receptor (RYR2) channel expression but enhanced channel sensitivity to calcium. We incorporated reduced channel expression as decreases in maximal rate of calcium movement for both the RyR2-mediated SR release (0.102 vs 0.0816 ms-1) and leak (3.61E-4 vs 2.88E-4 ms-1) currents. Since the baseline TT2 model did not represent individual RyR2 channels, we indirectly accounted for increased sensitivity by increasing free calcium concentrations in the SR (CaSR) and subspace (CaSS). CaSR overload was achieved by decreasing calsequestrin affinity as a 40% reduction in the half-saturation constant for sarcoplasmic buffering (0.3 vs 0.18 mM). CaSS was increased from the reduced calcium diffusion gradient between the subspace and the cytosol; a 20% downregulation of the sodium-calcium exchanger current (I_{NaCa}) further contributed to this reduced gradient. The enhanced calcium concentration of all three compartments corresponded with the experimentally measured calcium levels for *PKP2*-deficient cardiomyocytes and effectively shifted the concentration vs RyR2-binding curve leftward.

To create the action potential duration (APD) restitution curves of the GE and *PKP2* models, we used a standard S1-S2 stimulus protocol similar to that described in ***ten Tusscher and Panfilov, 2006***. Twenty S1 stimuli were applied at a basic cycle length (BCL) of 1 Hz to allow the models to reach a steady state. A single S2 extra stimulus of twice the diastolic threshold was then delivered at some diastolic interval (DI) following the action potential generated by the last S1 stimulus. The model was allowed to retain steady state (5 beats at BCL) before another S2 stimulus was applied at a decreased DI. This step was repeated for DIs decreasing from 1000 ms to 50ms in intervals of 25ms. An APD restitution curve was generated by plotting the APDs at 90% repolarization generated by the S2 stimuli against preceding DIs.

EP properties for regions with structural remodeling

For regions of diffuse fibrosis, we used the TT2 model with modifications based on data reported by ***Coppini et al., 2013***. The EP properties of this modified model have been validated in previous studies (***Shade et al., 2020***; ***O'Hara et al., 2022***). Maximal conductance of I_{NaL} and I_{CaL} were respectively increased by 107% and 19%; maximal conductance of I_{Kr}, I_{Ks}, I_{to}, and I_{K1} were respectively decreased by 34%, 27%, 85%, and 15%; sodium-calcium exchanger activity was upregulated by 34%; sarcoplasmic/endoplasmic reticulum calcium ATPase activity was downregulated by 43%.

Geometrical model reconstruction

Geometrical model of each patient's ventricles was reconstructed based on the patient's 2D LGE-CMR scans. Each diastolic short-axis image stack had a median of 11 slices with an average of 9.58±2.16 mm slice thickness and average in-plane axial resolution of 1.56±0.49 mm. Both the RV and LV myocardium were segmented from the LGE-CMR using a semi-automatic function of CardioViz3D which has been previously validated by our team (**Arevalo et al., 2016**; **Shade et al., 2020**; **Cartoski et al., 2019**). This segmentation method utilized landmarks to define the endocardial and epicardial boundaries.

Unlike our previous digital twin studies in ischemic cardiomyopathy (**Arevalo et al., 2016**; **Shade et al., 2020**; **Cartoski et al., 2019**), patients in the current cohort were right-dominant ARVC patients with only RV fibrosis detectable on LGE-MRI. We used Otsu thresholding to binarize the segmented myocardium into high- and low-intensity regions. The mean value and the standard deviation (SD) of the low-intensity region was calculated. We used the mean value of the low-intensity region as the reference mean of non-fibrotic myocardium and an intensity of ≥4 SD above the reference mean was classified as the dense scar region. Voxels between 2 and 4 SDs above the reference mean were classified as diffuse fibrosis; all other voxels were labeled as non-fibrotic myocardium (**Zhang et al., 2021**).

After identifying all different tissue types, we generated high-resolution finite-element tetrahedral meshes with an average resolution of 398 μm from the segmentation using finite-element analysis software (Mimics Innovation Suite; Materialise, Leuven, Belgium), as done previously (**O'Hara et al., 2022**). We then used a validated rule-based method to incorporate fiber orientations to each element of the computational mesh (**Bayer et al., 2012**).

Simulation protocol and VT assessment

We used the openCARP software package to simulate electrical activity in monodomain representation of the myocardium (**Plank et al., 2021**). Full details regarding the simulation of electrical activity in the heart digital twins can be found in previous publications (**O'Hara et al., 2022**; **Prakosa et al., 2018**; **Sung et al., 2020**; **Shade et al., 2020**). Each heart digital twin was paced sequentially from 9 uniformly distributed endocardial RV locations (see **Figure 1**) using a validated rapid pacing protocol described in our previous studies (**Prakosa et al., 2018**; **Arevalo et al., 2016**; **Cartoski et al., 2019**). At each pacing site, six pacing stimuli (S1) were delivered at a 600ms cycle length, followed by a premature stimulus (S2) delivered 300ms after S1. If S2 did not result in reentrant arrhythmia, we shortened the S1-S2 interval in 10ms steps until arrhythmia was induced or the S2 failed to capture the tissue. If arrhythmia was not induced, we delivered additional stimuli (S3 and S4) in the same way as S2. Induced VT in the Geno-DT models was defined as re-entry after sustaining at least 2 cycles at the same critical site, as in our previous studies (**Sung et al., 2020**; **Shade et al., 2021**).

After inducing the re-entries, we analyzed activation maps to identify the VT morphologies and locations. Reentries induced from different pacing sites but occurring in the same location with the same morphology were classified as repetitive. Only unique VT circuits were counted. Simulations were conducted blind to the clinical data.

Study limitations

Our study has a small sample size, limited by the fact that ARVC is relatively a rare disease. Moreover, since the goal of this study was to develop an image-based heart digital twin approach to accurately predict VT circuit locations, LGE-CMR scans and EPS records were needed to reconstruct the model and validate our predictions respectively; only a few patients in the database had both. Additionally, our study focused on patients with only RV enhancement since research has shown that most clinical VT ablation sites are on the RV for ARVC, even for those with LV involvement (**Marchlinski et al., 2021**). Furthermore, we considered only two genotypes, GE and *PKP2*, as human experimental data on cellular EP properties for other pathogenic variants implicated in ARVC (e.g., *DSP, DSG-2*), from which to construct cell models, is lacking; in addition, because the prevalence of these causal variants is lower compared to that of *PKP2*, there were not enough patients in the database with the corresponding clinical data needed for model construction and validation (clinical images, EPS study, etc.).

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Author contributions

Yingnan Zhang, Conceptualization, Resources, Data curation, Software, Formal analysis, Validation, Investigation, Visualization, Methodology, Writing – original draft, Project administration, Writing – review and editing; Kelly Zhang, Software, Formal analysis, Visualization, Methodology, Writing – original draft, Writing – review and editing; Adityo Prakosa, Software, Funding acquisition, Investigation, Methodology, Writing – review and editing; Cynthia James, Crystal Tichnell, Brittney Murray, Resources, Data curation, Project administration, Writing – review and editing; Stefan L Zimmerman, Resources, Data curation, Methodology, Writing – original draft, Writing – review and editing; Richard Carrick, Resources, Data curation, Funding acquisition, Methodology, Writing – original draft, Writing – review and editing; Eric Sung, Conceptualization, Software, Validation, Methodology, Writing – review and editing; Alessio Gasperetti, Resources, Data curation, Writing – review and editing; Hugh Calkins, Conceptualization, Resources, Data curation, Supervision, Funding acquisition, Project administration, Writing – review and editing; Natalia A Trayanova, Conceptualization, Resources, Data curation, Supervision, Funding acquisition, Investigation, Methodology, Writing – original draft, Project administration, Writing – review and editing

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Ethics

This retrospective study was approved by Johns Hopkins Medicine Institutional Review Board (IRB) #1, IRB title: Clinical and genetic investigations of right ventricular dysplasia; IRB identifier: NA_00041248; IRB PI: Hugh Calkins. All participants provided written informed consent.

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Additional files

Supplementary files
- MDAR checklist

Data availability
Patient-derived data including CMR images are not publicly available to respect patient privacy. Interested parties wishing to obtain these data for non-commercial reuse should contact the corresponding author via email; the request will need to be approved by IRB. The image processing software CardioViz3D can be freely obtained from http://www-sop.inria.fr/asclepios/software/CardioViz3D. The cell models are freely available from the repository CellML (https://models.cellml.org/exposure/de5058f16f829f91a1e4e5990a10ed71). Documentation and instructions on the use of the openCARP cardiac electrophysiology simulator and meshalyzer visualization software are available via https://opencarp.org/.

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Federal Register Notice: 89 FR 51554, Federal Register :: Networking and Information Technology Research and Development Request for Information on Digital Twins Research and Development, June 18, 2024.

Request for Information on the National Digital Twins R&D Strategic Plan

Gabriella Waters

Via FDMS

Gabriella Waters, 6/18/2024

[redacted]

Establish a dedicated ethics board comprised of experts from multiple disciplines to develop ethical guidelines and oversight mechanisms for digital twin (DT) development and use, especially when developing DTs for behavioral applications. Invest in privacy-preserving AI techniques like federated learning, differential privacy, and homomorphic encryption to enable DT training while protecting individual data privacy. Mandate human-AI collaboration protocols that clearly delineate the roles of humans and DTs in decision-making processes, with humans retaining ultimate authority and accountability. Develop comprehensive testing frameworks that Involve diverse stakeholders to test DTs across a wide range of scenarios, edge cases, and potential failure modes before deployment. Establish a standard for DT TEVV to assess risks, impacts, and benefits. Foster public awareness and education initiatives to educate the public on the capabilities, limitations, and ethical implications of DTs to promote informed decision-making and critical trust. Establish robust data governance frameworks including standardizing data collection, curation, sharing, and usage protocols to ensure data integrity and security. Develop methods for real-time data integration to maintain the accuracy and relevance of DTs. Create standardized ontologies and data exchange protocols to ensure that DTs from different developers and sectors can work together seamlessly. Establish measures to identify and mitigate harmful biases in data and algorithms used in DTs to help ensure fair and equitable outcomes. Develop DTs with a focus on sustainability, including energy-efficient computational models and workflows as we consider their long-term impact on resources. Plan for the entire lifecycle of DTs, from development to decommissioning, to help manage their environmental footprint. Invest in educational programs that foster cross-disciplinary expertise in areas such as AI, data science, and domain-specific knowledge to advance DT research and application. Encourage diversity in recruitment efforts to facilitate capturing a broad range of perspectives and innovative solutions in digital twin development. Account for a variety of users who will interface with, or be impacted by DTs, including those with neurodiversity, cognitive differences, the aging population, mental health challenges, etc.

Federal Register Notice: 89 FR 51554, Federal Register :: Networking and Information Technology Research and Development Request for Information on Digital Twins Research and Development, June 18, 2024.

Request for Information on the National Digital Twins R&D Strategic Plan

Todd Lukesh

Gafcon Digital

gafcon DIGITAL

A Subsidiary of Anser and Accenture

Human & Building Digital Twin Integration

March 2024

Todd C. Lukesh, Assoc. AIA, LEED AP, WELL AP, DBIA, FitWel, CGBP
Digital Twin Architect | Building Performance & Sustainability |ESG+H

accenture

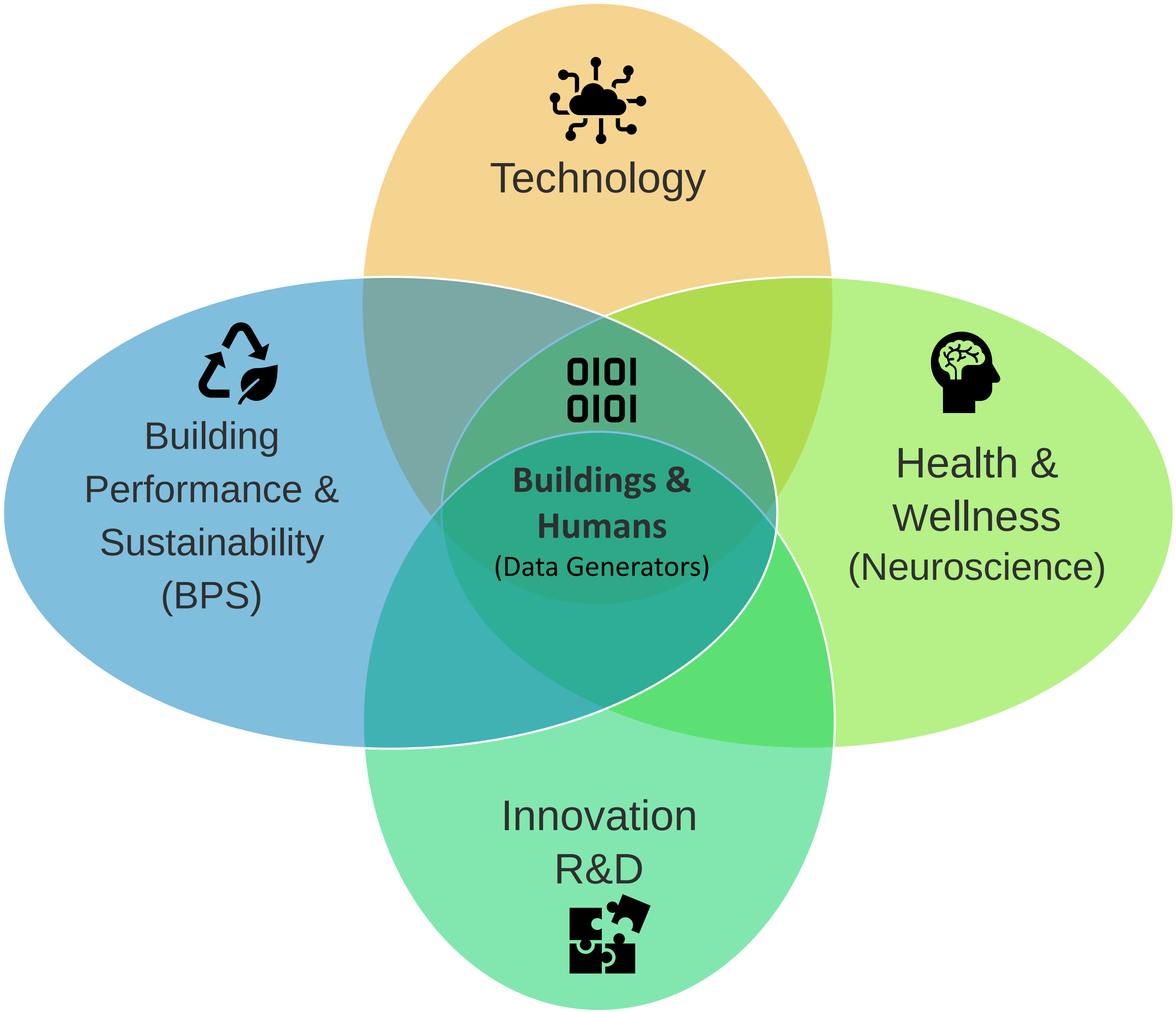
Building and Human Optimization

I am a **Human Digital Twin**…

I am an **architect** that has converted into a **digital architect**

Both **buildings** and **humans** generate meaningful data that empower insights to optimize performance

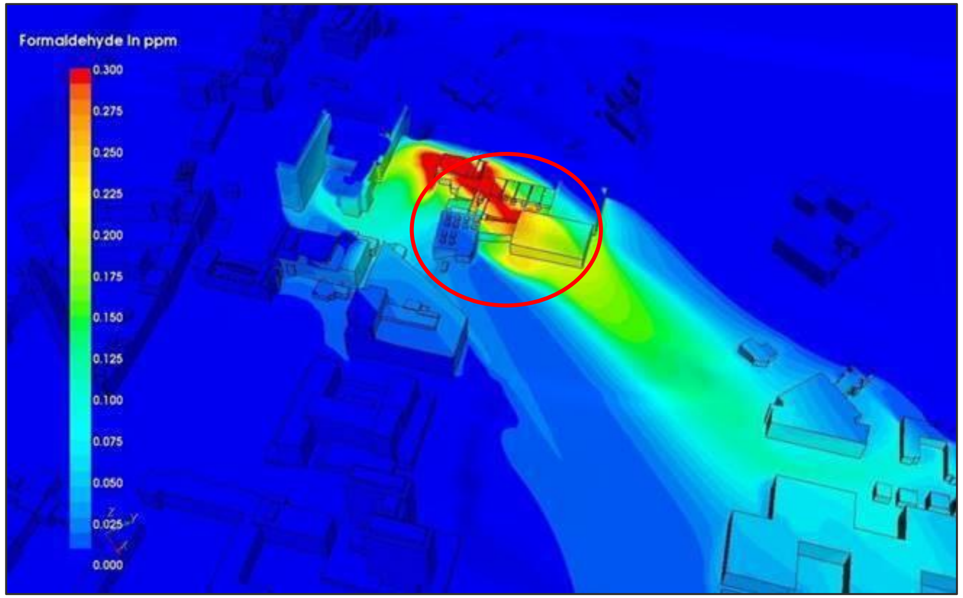
Environmental, **S**ocial, **G**overnance + **H**uman **(ESG+H)**



Digital Twins Used for Buildings

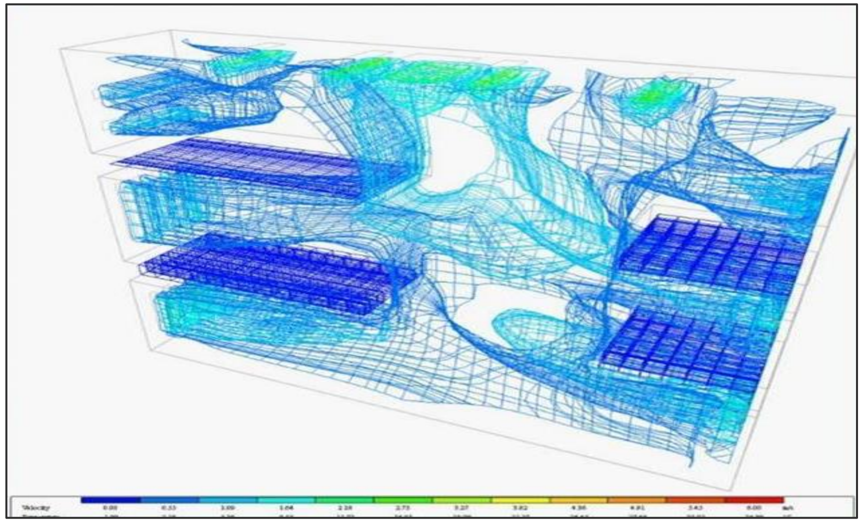
Physics-based building simulation & human-based design

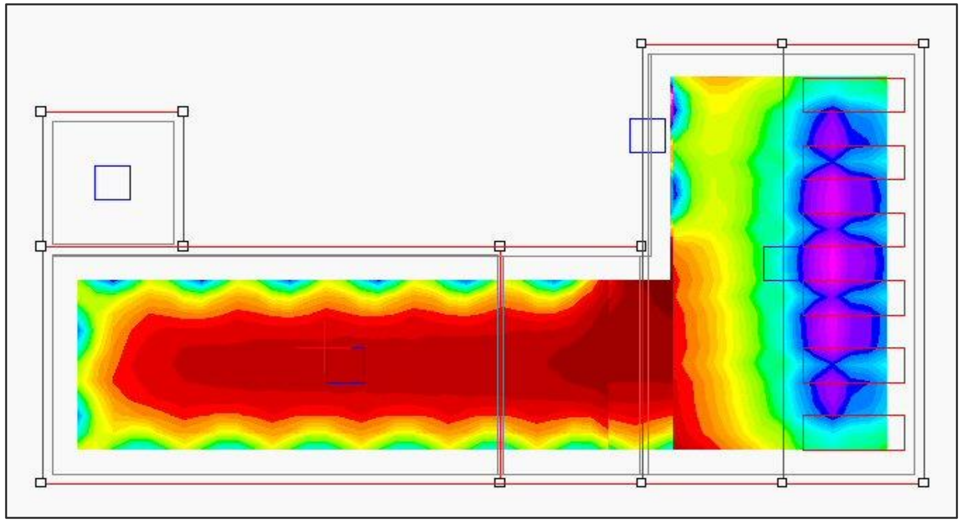
HVAC "hotspots" airflow problems



Exterior airflow around buildings

Multi-floor air dispersion CFD





Interior space thermal heat transfer

Source: IES, Ltd.

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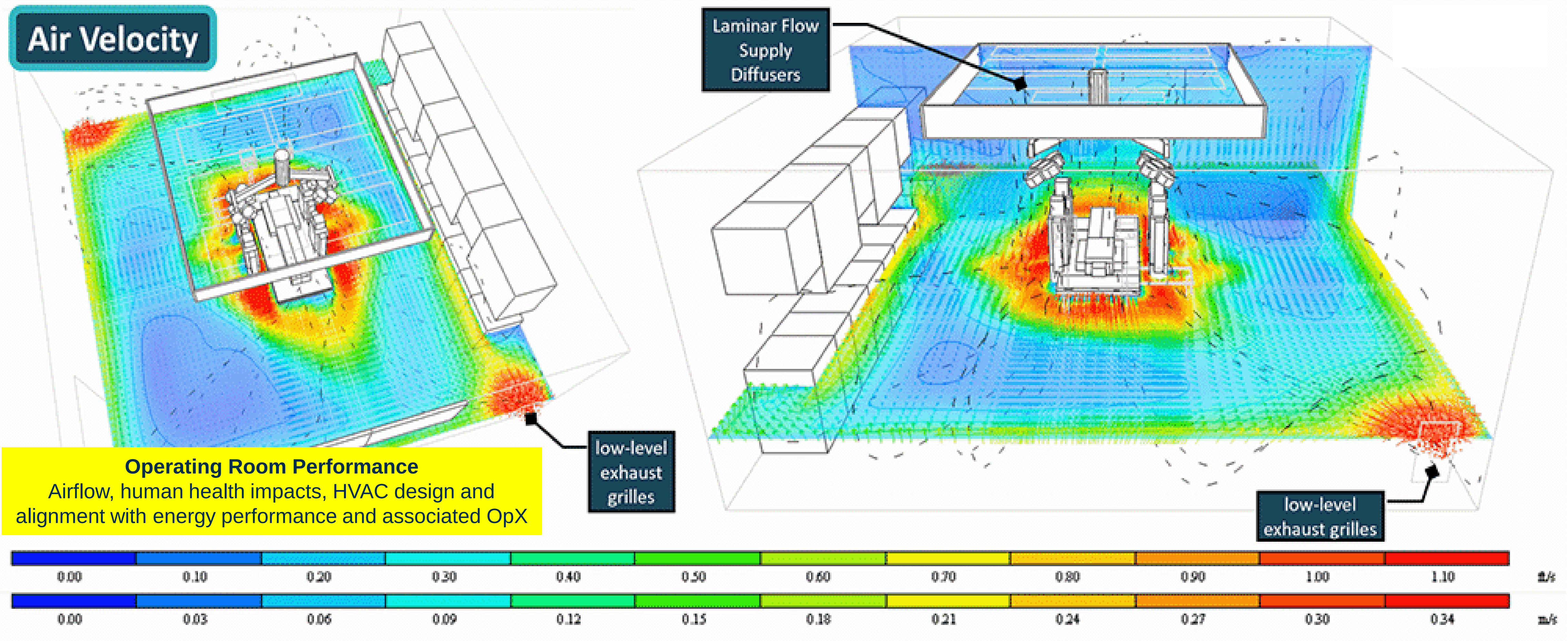
Use of Virtual & Physical Sensors

Application of Physics-Based Simulation

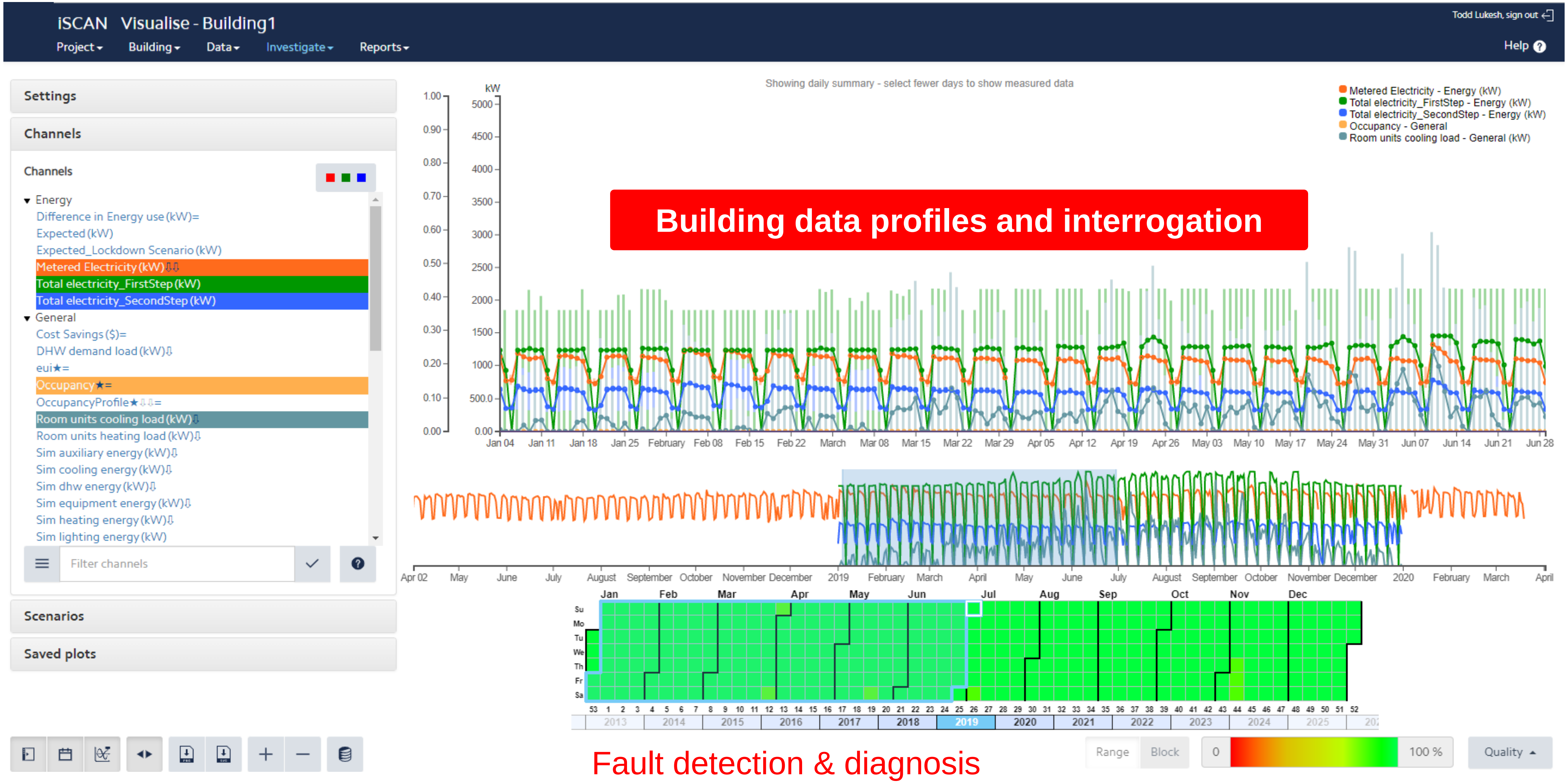
Uncover hidden problems before they become problems!



Operating Room Performance
Airflow, human health impacts, HVAC design and alignment with energy performance and associated OpX

Source: IES, Ltd.

Real-Time Digital Twin Data Profiles in Buildings



Source: IES, Ltd.

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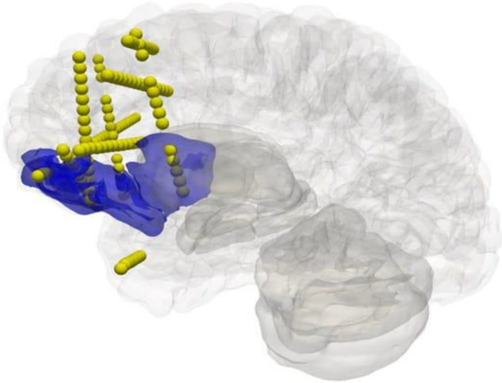
Creating a Human Brain Digital Twin

Optimize Human Health Through Human-Computer Interaction (HCI)

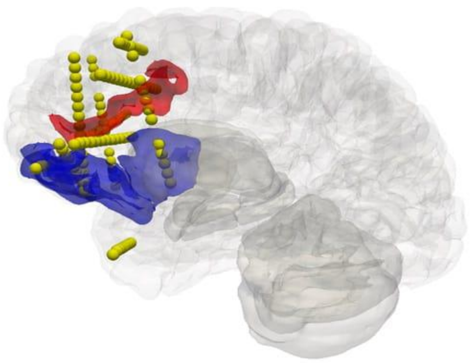
Personalized Brain Modelling:

- Virtual models of brains for treating drug-resistant epilepsy
- Data aggregation scans real-time collection to activate interventions
- Data interrogation improve abilities currently unobserved

Proactive Human Brain Modelling



Epileptic areas in patient's brain **(blue)** based on invasive electrode insertion **(yellow)**



Virtual Brain identifies areas for removal **(red)** that were undetected

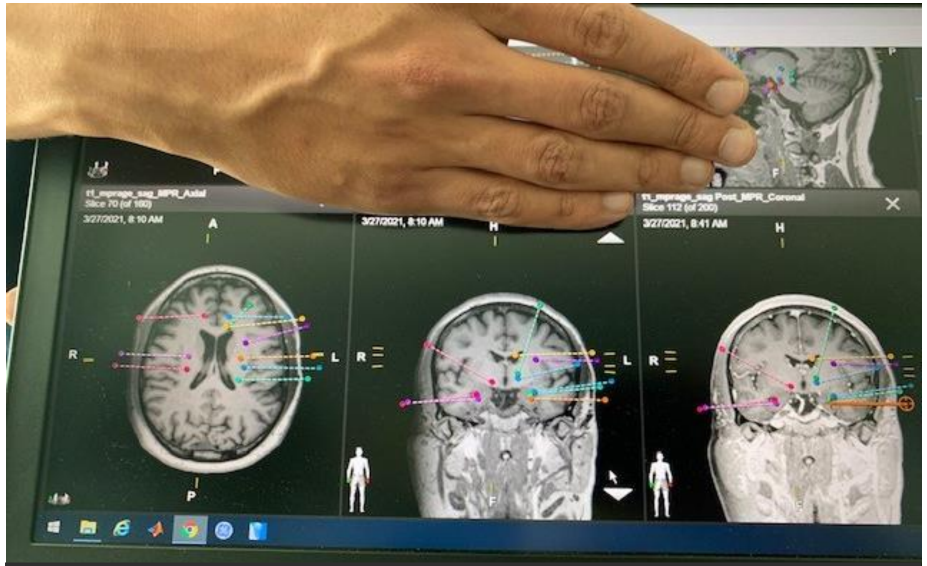
Uncover hidden problems before they become problems!

Source: physicsworld.com/a/virtual-brain

Digital Twins Assessment & Proactive Solutioning

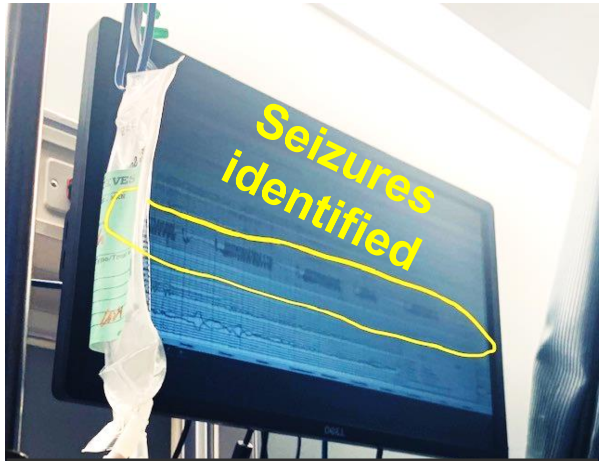
Human-Computer Interaction (HCI)

Deep brain electrode implants

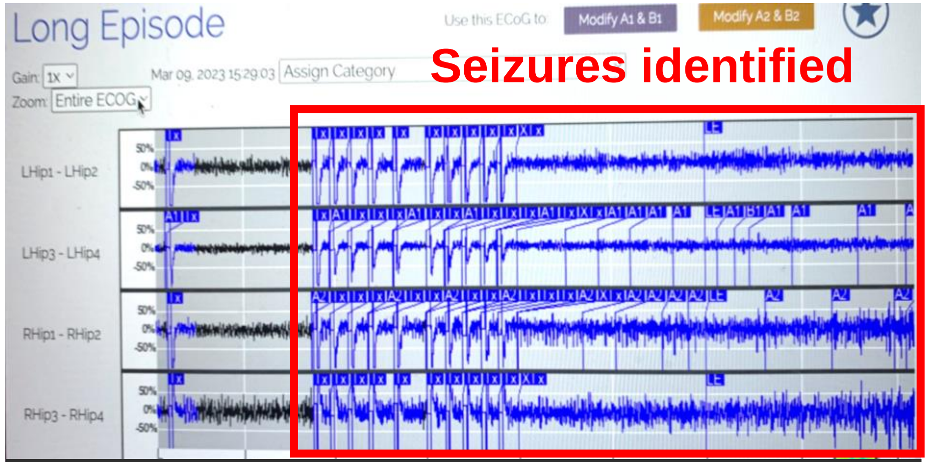


Testing “what-if” dynamic simulation, prior to surgery

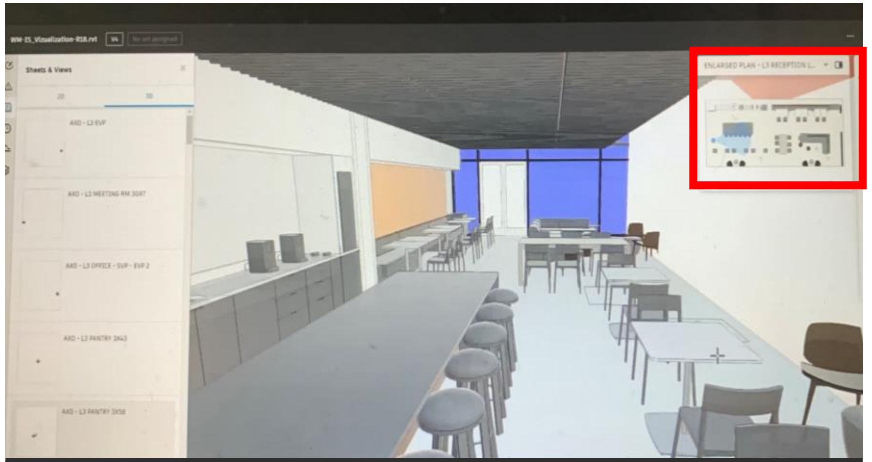
AR/VR integrated simulation and Brain-Computer Interface (BCI)



Measuring seizure activity



Identify pattern recognition, Machine Learning and AI



AR/VR simulation to study human reaction to stimuli

Source: UCLA Neurology

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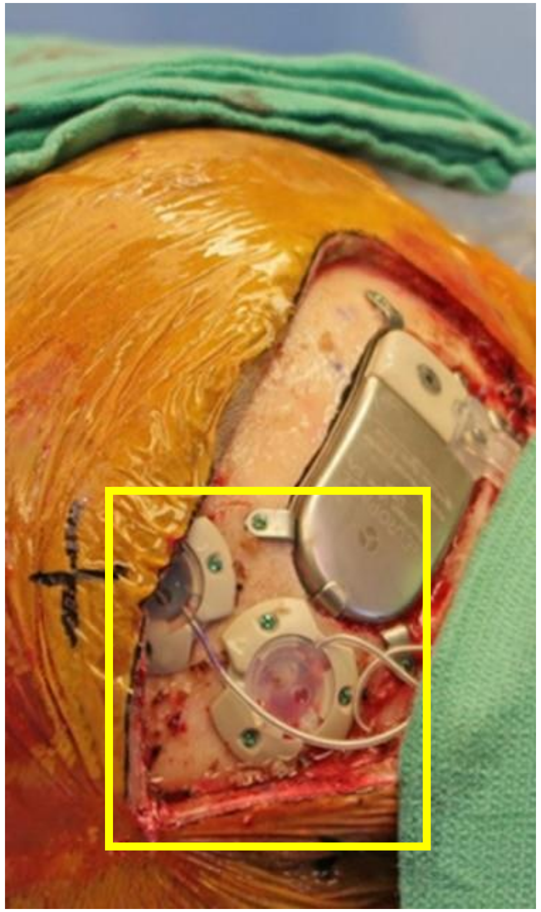
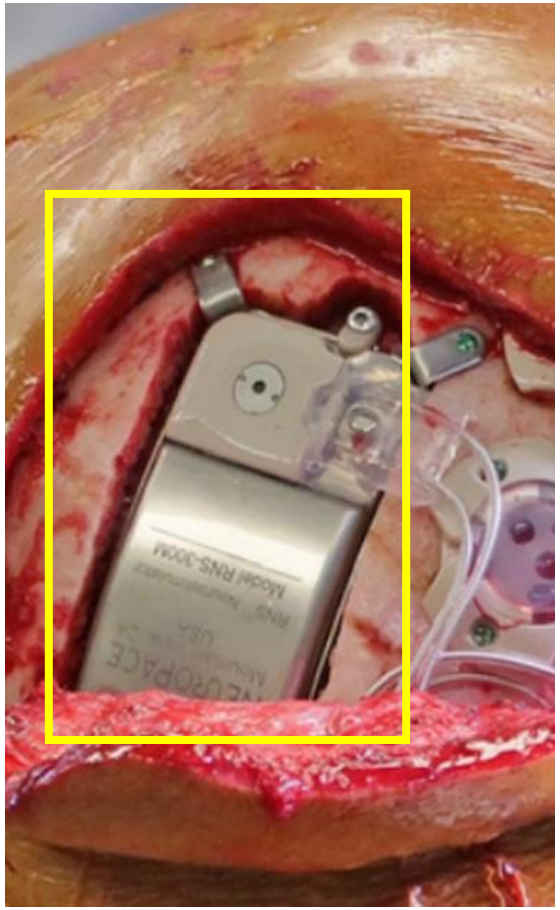
Invasive Proactive Solutioning to Optimize Human Health

Installation of Bluetooth and IoT-Enabled Stimulation Devices

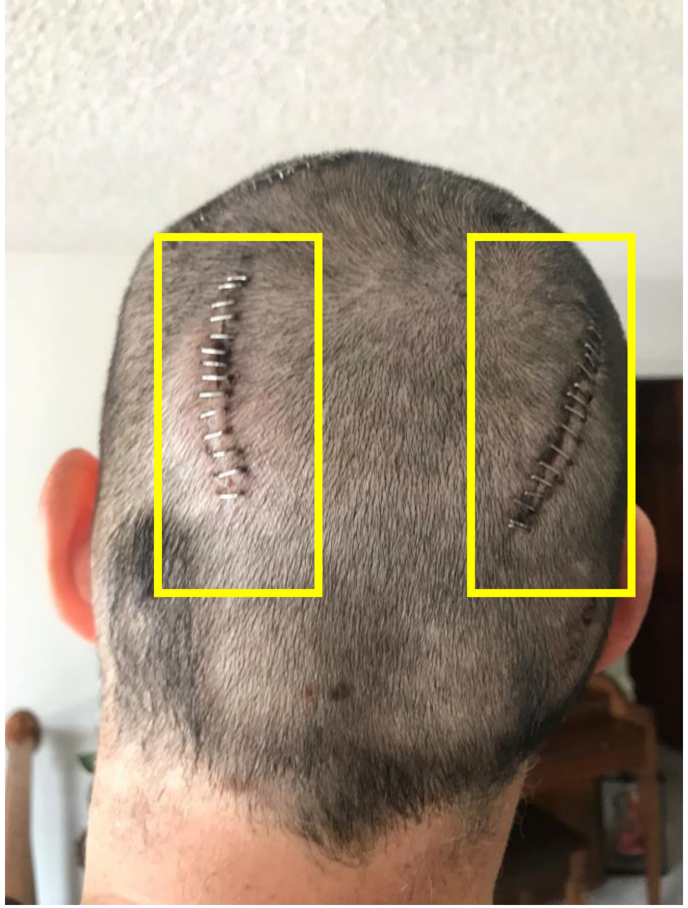


Deep stimulation electrodes connect to various electrical nodes



Implant device, sensors installation Bluetooth and IoT-enabled data

Implant recovery left accessible for future maintenance upgrades



Electrodes with AI and ML enablement (continuous improvement)

Light retrofits = medication
Deep retrofits = surgical intervention

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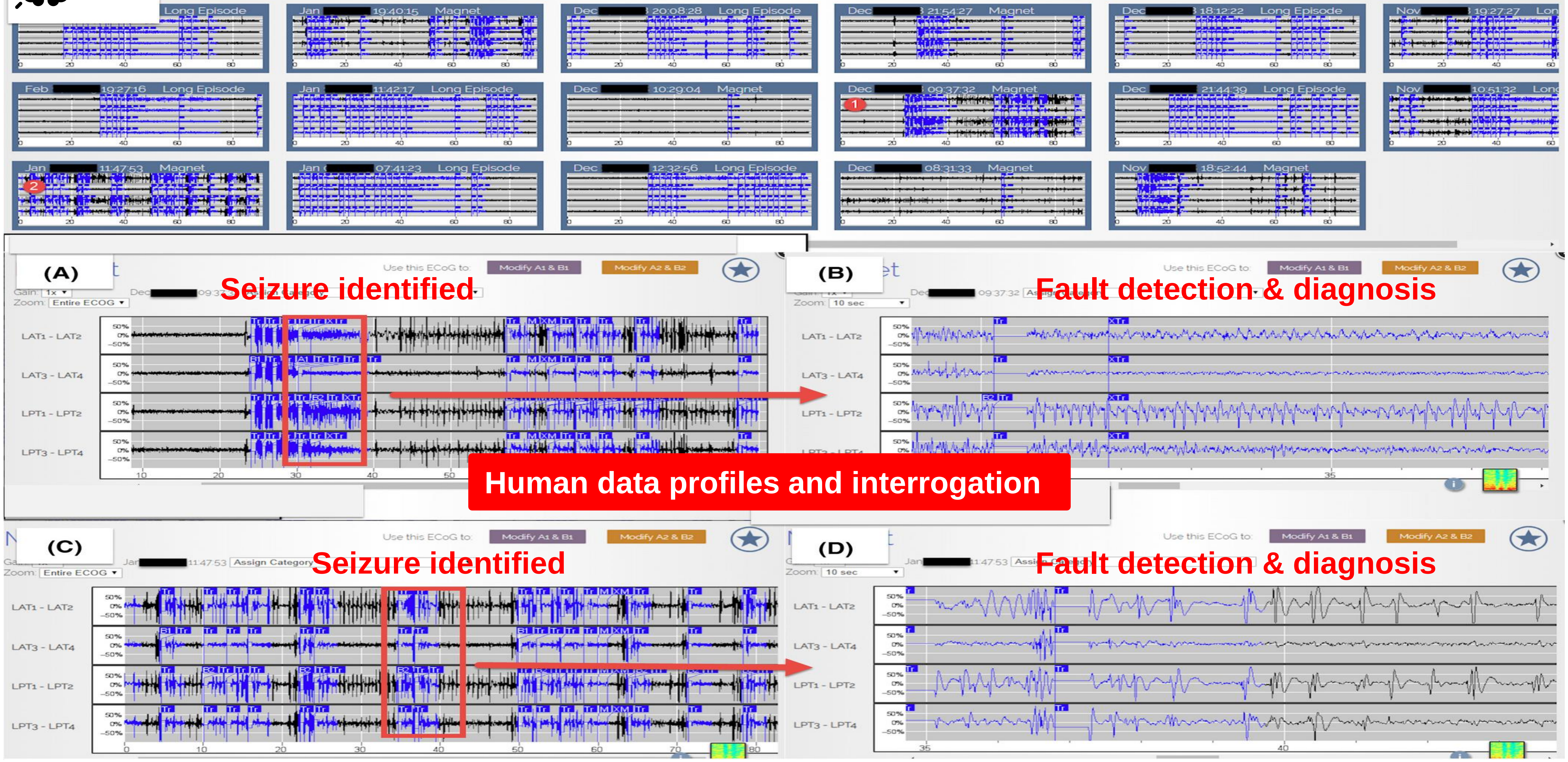
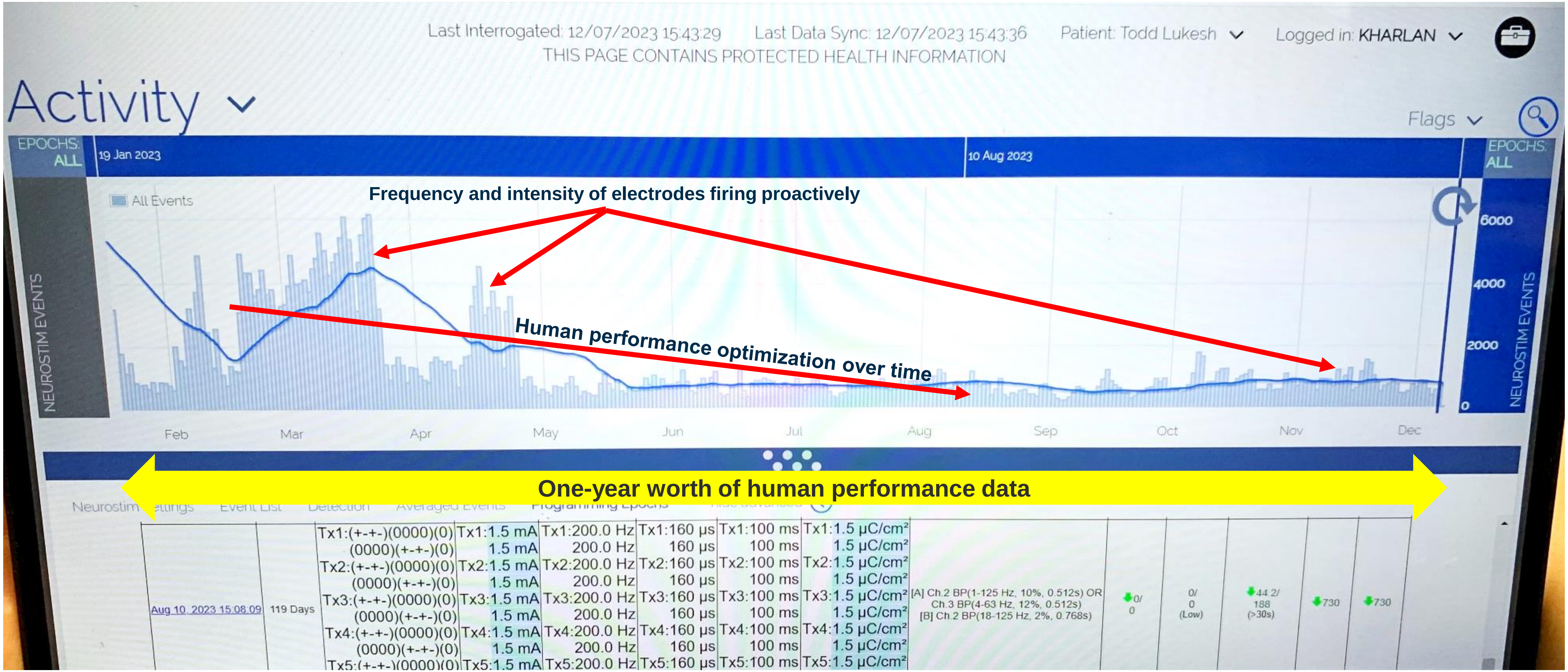
Real-Time Digital Twin Data Profiles in Humans



Source: Neuropace

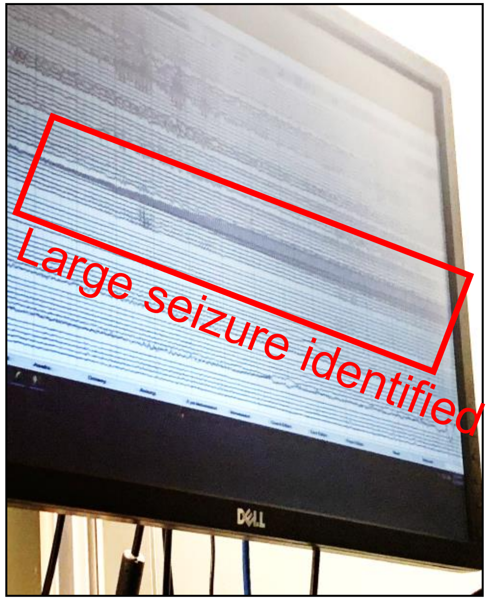
Human Data Optimization with Machine Learning & AI

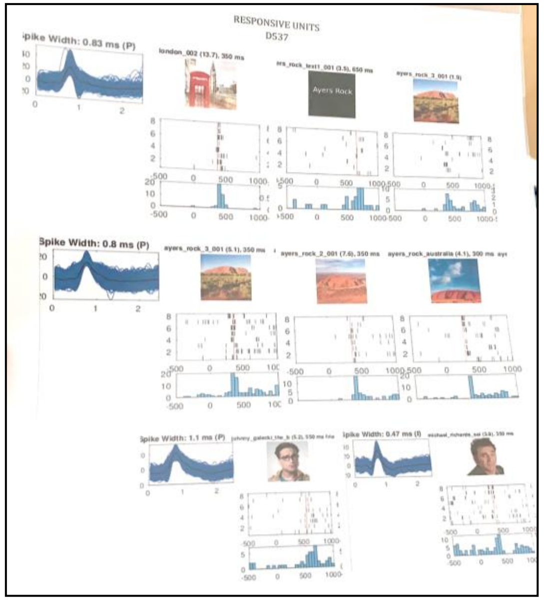
Performance Driven by Data Aggregation for HCI and BCI Improvements

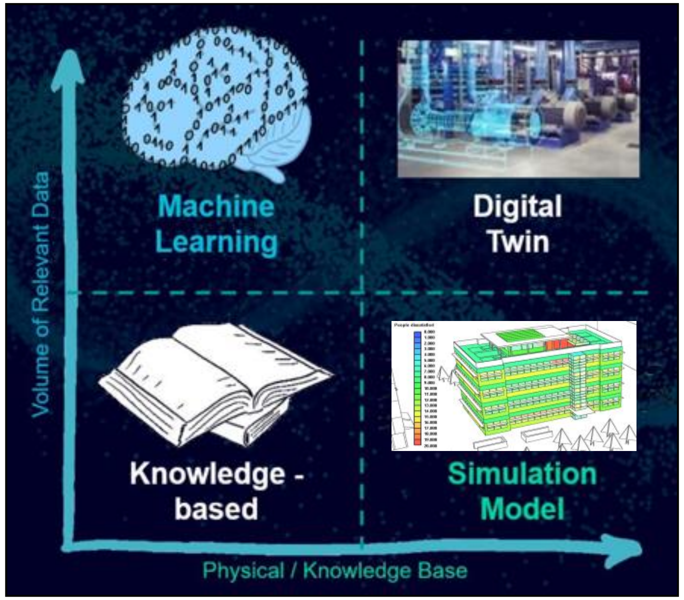


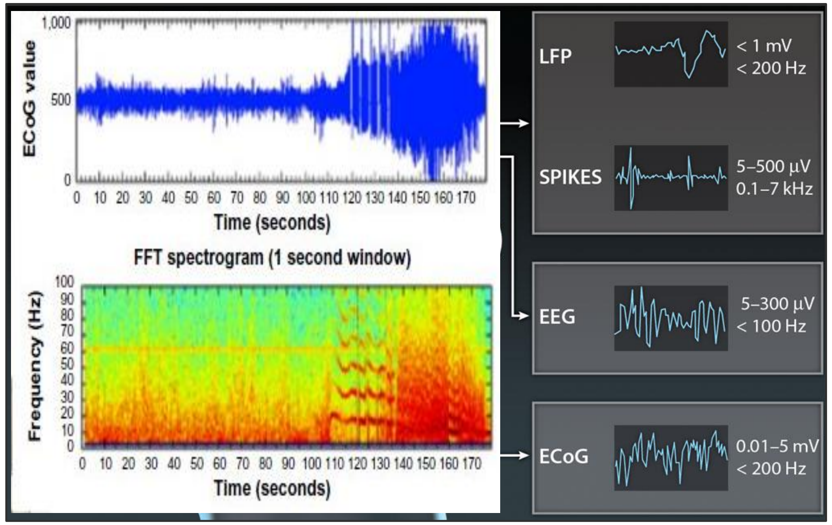
Metadata Collection, Transfer & Results

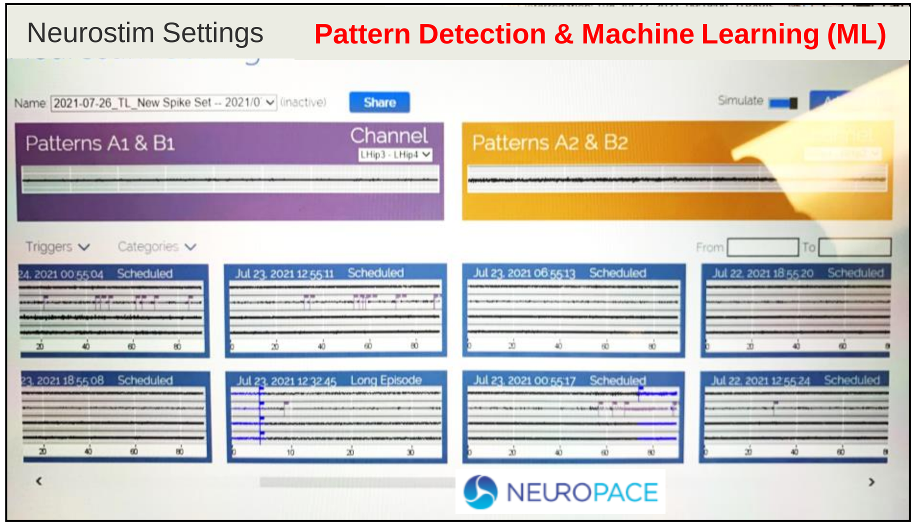
Bluetooth and IoT-Enabled Bidirectional Sensors









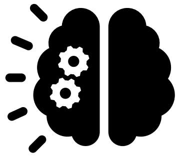


So, what's the value?

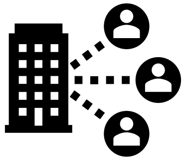
- Data is data – buildings or humans
- Performance assessment
- Closed-loop feedback analysis
- Improves operations
- Algorithms inform the 'BMS'
- Bidirectional communication
- Buildings respond to humans
- Understanding of human behavior
- Internet of Actions/Activity (IoA)
- Empowers meaningful insights

Building Digital Twins
integrated with
Human Digital Twins
Yields Powerful Results!

Human & Building Digital Twin Closed-Loop Interface



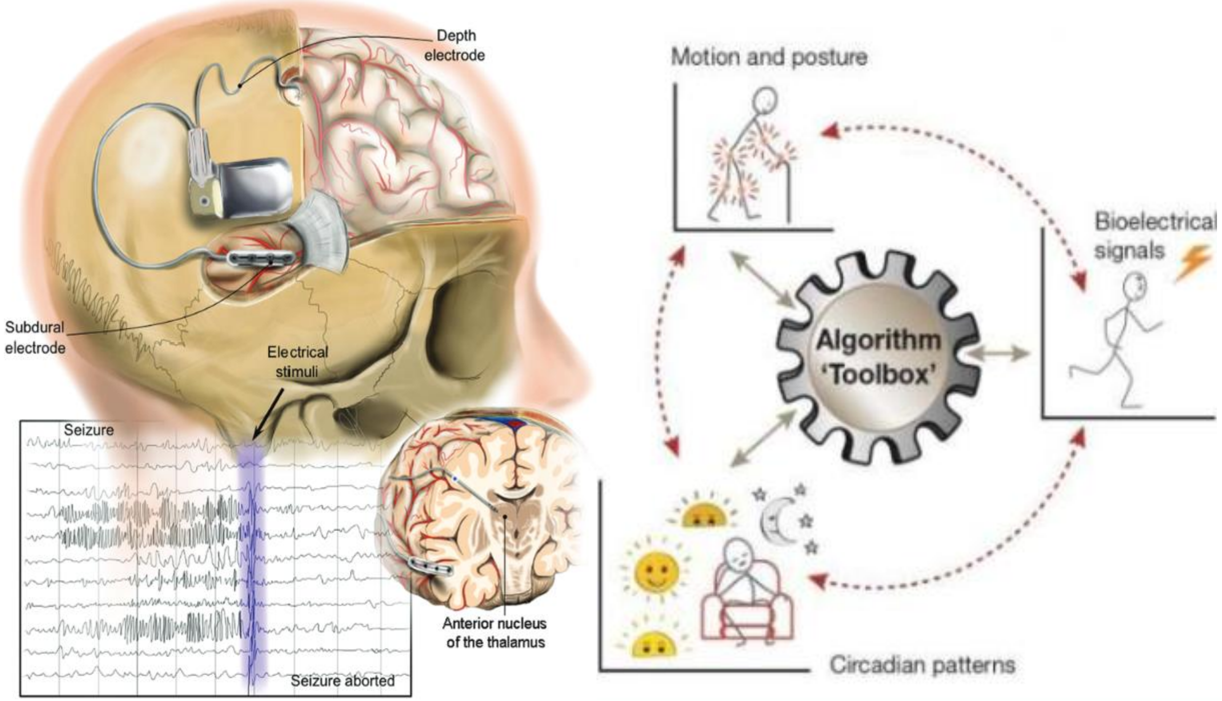
Bidirectional Communication

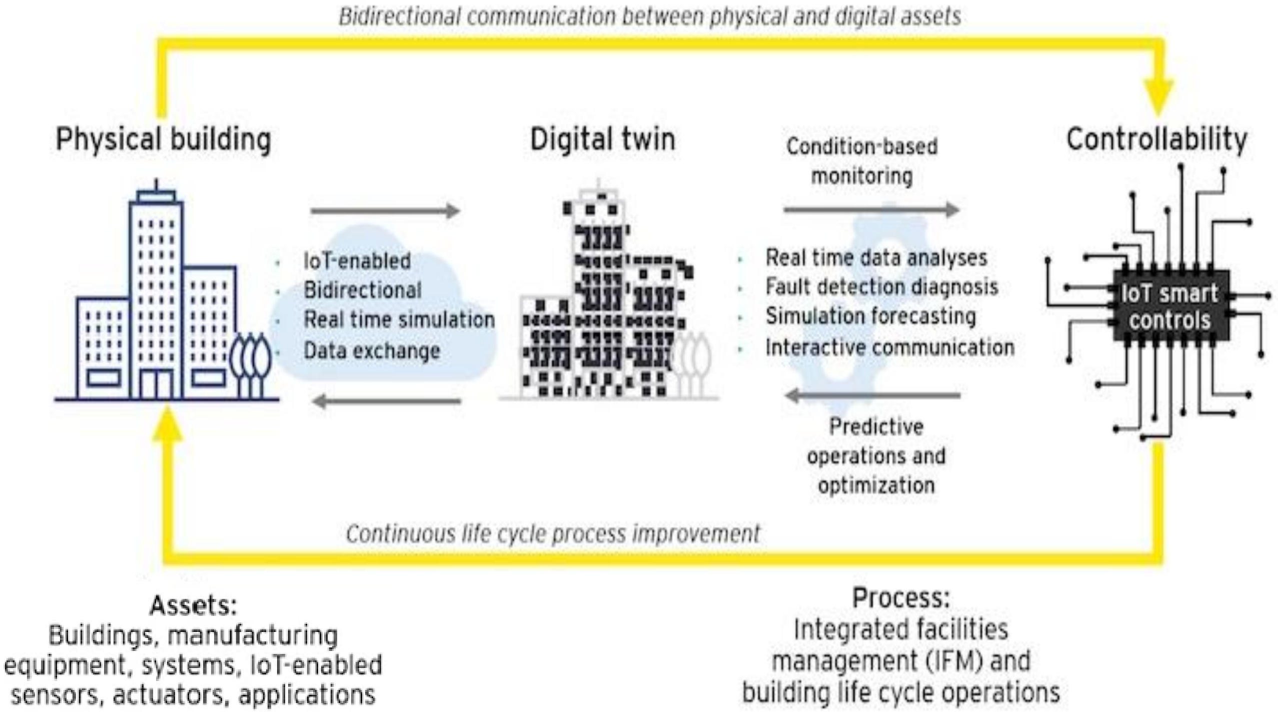


Asset = Humans

Asset = Buildings

NEUROPACE





Human Digital Twin Interface

Bidirectional Communication

Building Digital Twin Interface

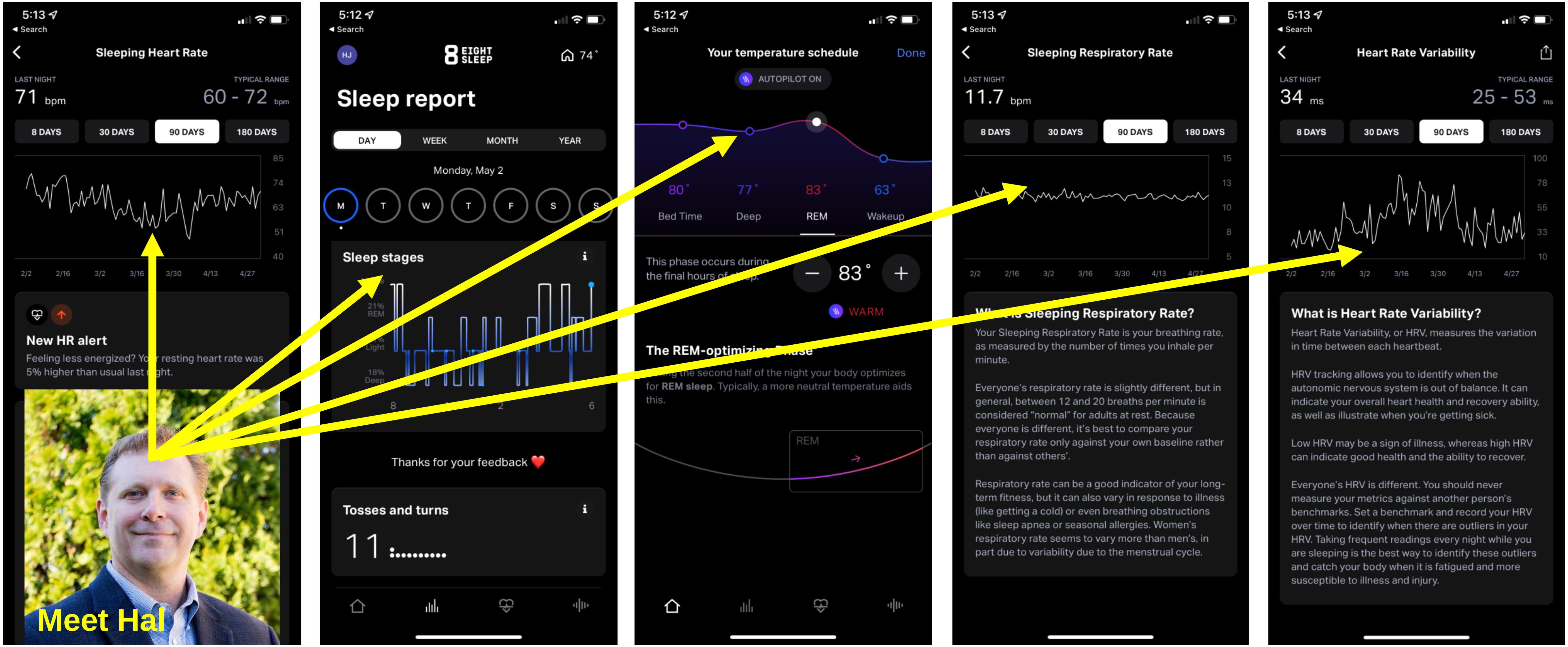
Non-Invasive Human Data Collection Hardware

Technologies for Human Improvement, Health and Wellness

Rapid data collection used to analyze, dashboard, trend and contextualize for empowered and informed decision-making

Non-Invasive Technology Platforms & Software Analytics

Wearable Devices for Data Collection, Trending, Forecasting and Improvement



Open-head surgery is not necessary for everyone

Technology for better quality of life without surgical interventions already exists

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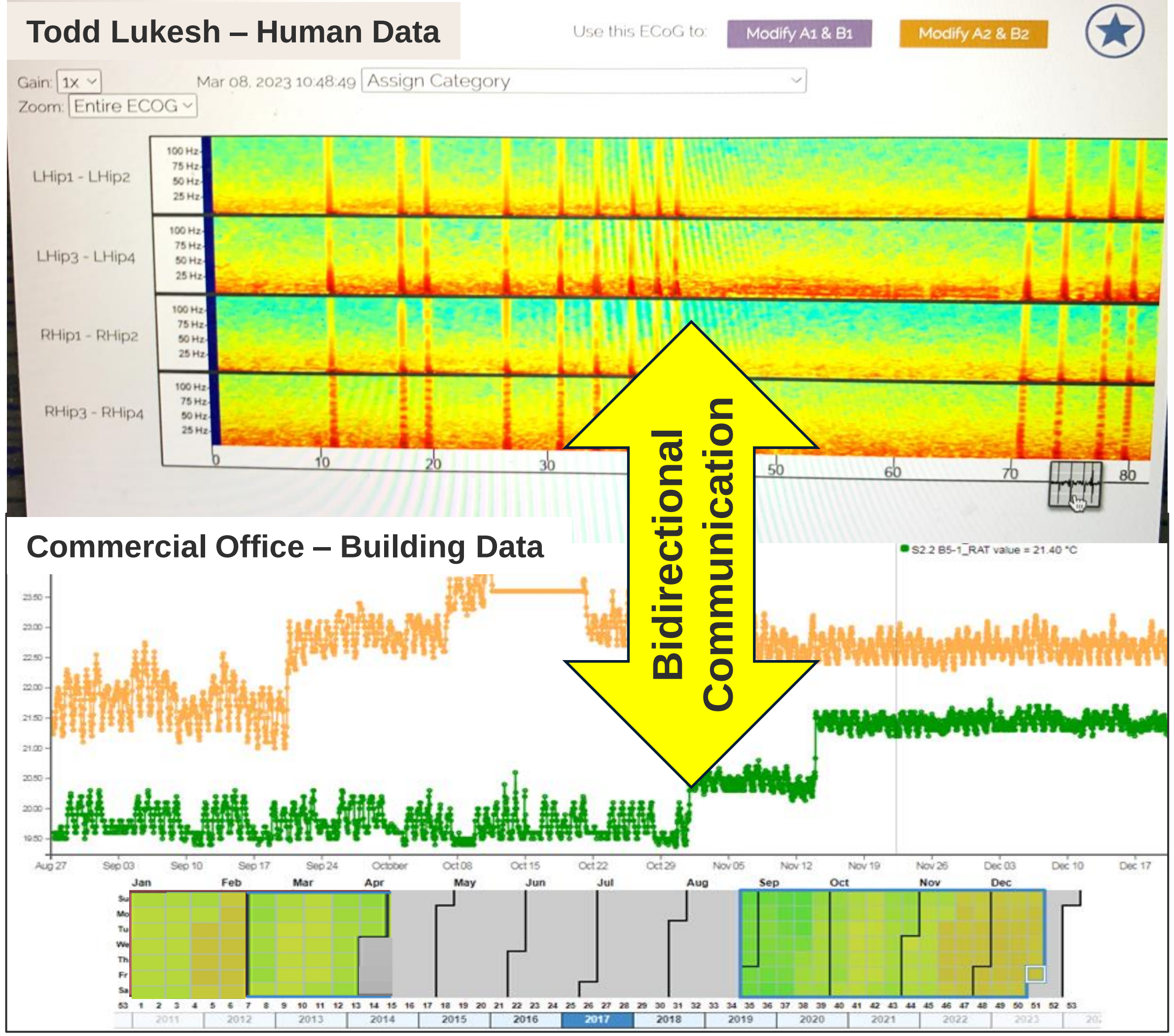
Simulation, Stimulation, Data Analysis & Innovation

Human DT "**Stimulation**" & Results

- Virtually experiment with data and leverage Digital Twins – **Design Team**
- Perform 'what-if' scenarios prior to investments – **ROI or LCA**
- Measure wavelengths through permanent electrodes – **IoT sensors**
- Preemptively eliminate seizures via stimulation – **Proactive Maintenance**
- Proactive and predictive maintenance – **Integrated Facilities Management (IFM)**
- Data transfer for continuous monitoring – **Building Management System (BMS)**
- ML and AI algorithms monitor brain electrical patterns – **Commissioning**
- Doctors adjust electrodes to improve operations – **Building Operators**
- Cybersecurity, hackability, data-lake aggregation and transfer – **Cyber Teams**
- Bring innovations to improve human and building functionality – **R&D Teams**



Use case example for human optimization:
Circadian rhythm alignment health recovery acceleration (e.g., light, HVAC, temperature, zoning, humidity, etc.)

Use case example for building optimization:
Simulation and data interrogation continuously commission, calibrate and optimize a facility

Building DT "**Simulation**" & Results

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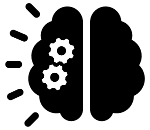
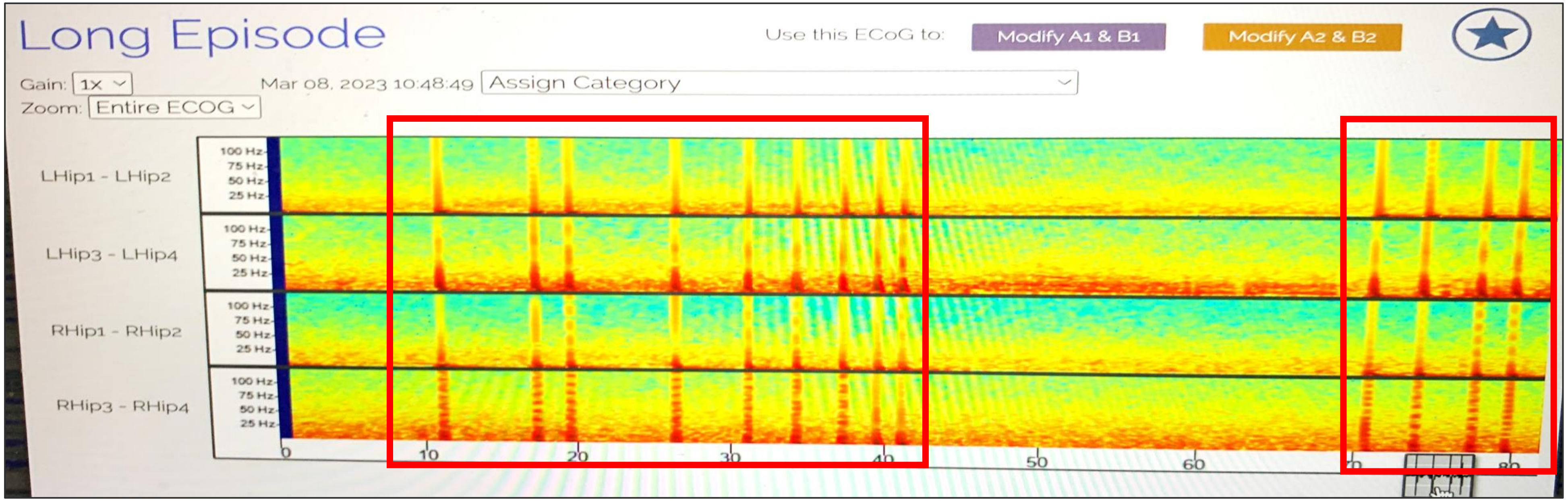
Optimize Long-Term System Performance Between Both Assets – Stop “Seizures”

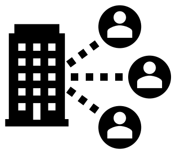


Human Asset Data (my brain)

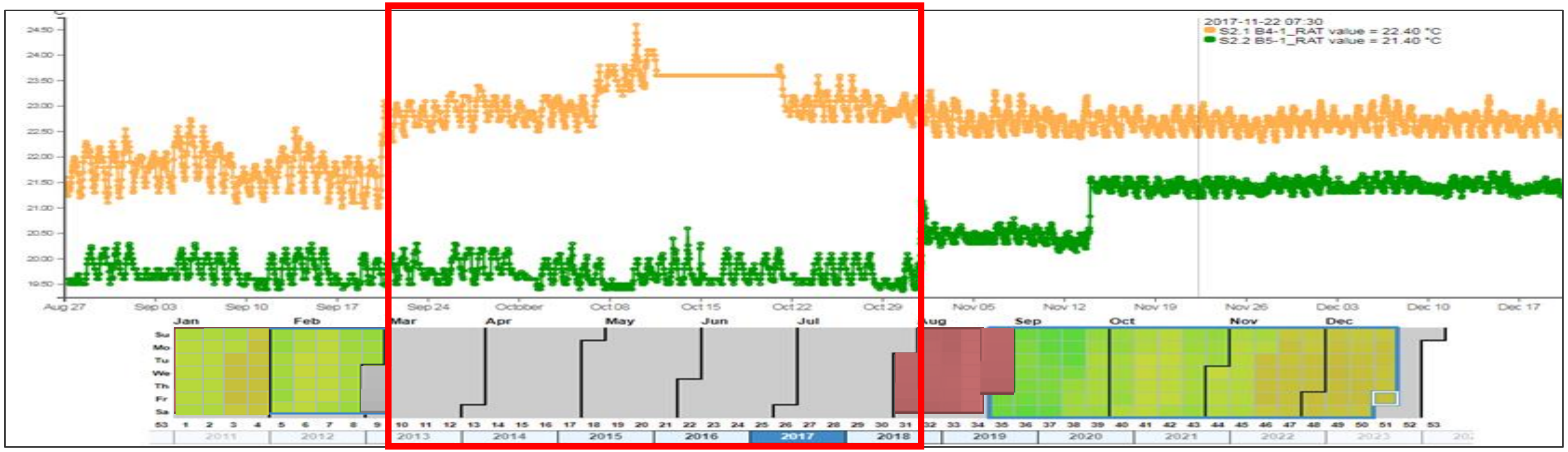


Human Seizures (incapacitated) Detected

Bidirectional Communication



Building Asset Data (BMS)



Building “Seizures” (downtime) Detected

Source: NeuroPace & IES, Ltd.

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Digital Twin Next Steps

Data Captured and Lessons Learned

Generate data and proactively optimize both building and human health in real-time for closed-loop analysis

SUMMARY:

Direct correlation of

Building Digital Twins and **Human Digital Twins**

Can buildings respond to humans?

THE RESULTS:

For me personally?

Neuro performance = human optimization

For our built environment?

Building performance = ESG+H optimization

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A Subsidiary of Anser and Accenture

Questions or comments?

Todd C. Lukesh, Assoc. AIA, LEED AP, WELL AP, DBIA, FitWel, CGBP
Digital Twin Architect | Building Performance & Sustainability |ESG+H

accenture

Federal Register Notice: 89 FR 51554, Federal Register :: Networking and Information Technology Research and Development Request for Information on Digital Twins Research and Development, June 18, 2024.

Request for Information on the National Digital Twins R&D Strategic Plan

Gary An

Regarding foundational challenges facing the development Biomedical Digital Twins

Gary An, MD, FACS
Department of Surgery
University of Vermont Larner College of Medicine

The primary challenge facing biomedical research

The most impactful and currently intractable challenge for translational biomedical research is the ability to reliably predict the effect of a potential pharmacological intervention (a drug or vaccine with a specific presumed mechanism of action) in the whole-person context for an individual patient. This gap is why the drug development pipeline is so inefficient, prone to failure at the most expensive (both in terms of money and human cost) phase, that of clinical trials, and, consequently, impacting the eventual cost of approved drugs[1]. Addressing this challenge requires:

1. Knowing how the target system works
2. Knowing the origins (mechanistically) of variability between individual instances of the target system and
3. Recognizing that disease and health are inherently dynamic processes that can change the responsiveness of the system to interventions over time.

I assert that addressing these three requirements can only be achieved through the development of biomedical digital twins that are compliant with the NASEM definition referred to in this Request for Information.

The case for compliance with the NASEM Definition specifically regarding Biomedical Digital Twins

Biomedical applications of digital twin technology face a contradiction between the messaging of the promise of digital twins and the reality of the current methodological readiness to deliver on that promise. The impact of this contradiction is accentuated by:

1. The fact that the term “twin” has its intuitive appeal due to the inherently biological origin of the term; upon hearing the term one immediately thinks of and pictures identical human twins (notably, not fraternal ones…).
2. The fact that biological systems are unable to meet the basic preconditions present for successful applications of digital twin technology, notably the lack of first-principles-based trustworthy computational specifications for the digital object and inability to characterize the ground truth of the behavior of the real world twin, namely in of describing the heterogeneity of the real-world population in terms of a “true” probability distribution; this latter fact due to perpetual and intractable data sparsity relative to the number of potential configurations of the real world system.

Because of the intuitive and reflexive lay interpretation to the term “twin”, there is a pervasive danger that projects not in compliance with the NASEM definition that are nonetheless portrayed as “medical digital twins” will invariably fall far short of public expectations by not delivering on what actual compliant digital twins could. This situation has three negative consequences:

1. Early public dissatisfaction with the concept of “medical digital twins” due to the implementations falling far short of the expected (and often promised) benefits. For example, “medical digital twins” are often portrayed as being able to personalize therapies for an individual, optimizing treatments by predicting their effects through execution via the “medical digital twin.” The relative dearth of effective therapeutics for many diseases functionally converts this idea of “having personalized treatments for me” to “this is the best we can do with the set of therapies we currently have.” This is not to say that there isn’t a benefit from being able to do the best we can at the moment (as a clinician I can appreciate this need), but it is a significant downgrade from the expectation a patient might have regarding a promised benefit inherent in the term.
2. Diversion of resources away from investigators actually interested in providing the expected capabilities present in the NASEM compliant digital twin paradigm by diluting such resources to support projects that by their very nature may be more readily implemented (but with an impact far short of what could be achieved with a “true” medical digital twin) at the exclusion of addressing the very real fundamental challenges that face the development, deployment and evaluation of NASEM compliant biomedical digital twins.
3. Limits the cross-disciplinary lessons learned from digital twin research in other domains that are compliant with the NASEM Definition. More explicitly, if the biomedical community assents to a diluted definition of a “medical digital twin” then the transferability of developments from fields that have true digital twins will be severely compromised in terms of a shared vocabulary, necessary preconditions of the system being twinned, and the nature of the challenges associated with digital twin development. Current examples of this disconnect are: 1) the lack of trustworthy computational specifications, 2) the lack of physical assets to provide the ongoing data and 3) inadequate identification of the “ground truth” present in the real world that allows for rigorous Validation and Uncertainty Quantification of the underlying computational specification. All three of these areas are open research and development questions regarding biomedical digital twins.

We believe that the NASEM definition of a digital twin describes unique capabilities that distinguish potential biomedical digital twins from other biomedical computational approaches, such as personalized predictive models, virtual cohorts and *in silico* clinical trials. These other methods, while demonstratively useful, do not incorporate the ongoing updating of the digital object with data from the real-world twin, and therefore are limited in achieving the goal of “true precision medicine.” The goal of medicine is to provide the right intervention(drug) at the right time for the right patient, and the goal of biomedical research is to provide this capability for every potential patient. We have previously presented Axioms of True Precision Medicine that explicitly note a fundamental description of these desired features[2]:

- Axiom 1: Patient A is not the same as Patient B (Personalization)
- Axiom 2: Patient A at Time X is not the same as Patient A at Time Y (Precision)
- Axiom 3: The goal of medicine is to treat, prognosis is not enough (Treatment)
- Axiom 4: Precision medicine should find effective therapies for every patient and not only identify groups of patients that respond to a particular regimen (Inclusiveness)

The NASEM Report definition of a digital twin with a fit for purpose that includes control discovery matches directly the goals represented in the Axioms of True Precision Medicine listed above.

The case for cellular-molecular mechanism-based NASEM-compliant biomedical digital twins, and challenges that need to be addressed

I assert the following to be true:

- Assertion 1: The primary means by which we seek to treat disease is through drugs.
- Assertion 2: Drugs function by molecular mechanisms that affect the behavior of cells, that result in changes in tissue/organ function that manifest systemically as disease and health.
- *Conclusion 1: Rational design of drugs requires knowledge and representation of relevant cellular and molecular pathways.*
- Assertion 3: Human beings have essentially the same functional cellular and molecular structure.
- Assertion 4: Human beings differ in the exact functional responsiveness of their shared cellular and molecular structure.
- *Conclusion 2: Human beings share a common specification that can be potentially rendered computationally, but individuals represent specific instantiations (e.g. parameterizations) of that common specification.*
- Assertion 5: It is currently (and likely perpetually) impossible to comprehensively characterize the entirety of the cellular and molecular features that make up the human species.
- *Conclusion 3: Any implemented computational specification of a human in perpetually epistemically incomplete.*
- Assertion 6: Even given this limitation of knowledge, the number of possible configurations of the known cellular and molecular features cannot be characterized by sampling the population (Curse of Dimensionality).
- *Conclusion 4: The ground truth of the real-world population distribution in terms of cellular/molecular features is perpetually uncertain.*

Conclusions 1 and 2 point to the need to develop cellular-molecular-based biomedical digital twins in order to meet the promise of “a treatment tailored to you” inherent to the label “medical digital twin.” Conclusions 3 and 4 point to fundamental challenges inherent to the development of such biomedical digital twins, and the difference between the biomedical area and other areas in which digital twins are being used/developed, namely that these latter areas have trustworthy computational specifications that can be subjected to “classical” verification, validation and uncertainty quantification. Conversely, biology requires a reconceptualizing of “validation” and “uncertainty quantification”. For example, regarding uncertainty quantification, physics-based models may be concerned with numerical error propagation as the equation these models solve is directly reflective of the underlying reality (e.g., a molecular dynamics simulation based on electronic configurations of the simulated molecules, while the uncertainty in knowledge-based cell-level mechanistic models comes primarily from both the epistemic uncertainty as to the causal and hierarchical mechanisms that govern the system behavior and the unquantifiable natural stochasticity and variation inherent to biological processes. We assert that models that represent cellular and molecular biology to generate tissue/organism/individual output have unique properties that call for a readjustment of what validation and uncertainty quantification mean, and the support of research on novel methods of characterizing such systems. The challenges that need to be addressed include, but are not limited to:

1. The transition of existing statistical methods that establish validity and uncertainty quantification at the population level to novel methods that characterize and evaluate individuals.
2. Generally, transitioning population-level statistical methods to novel methods that define individual trajectories.
3. Methods that move beyond traditional conformal prediction to account for model incompleteness/uncertainty and uncharacterized stochasticity.
4. Methods for evaluating potential control modalities for such systems.
5. The need to engage developers of physical assets such that the bidirectional data links can be established at the appropriate level of granularity given the representation level of the computational models.

I acknowledge that this list of challenges is not novel or unique; I make this comment to add emphasis to the importance of these issues to a specific class of potential biomedical digital twins that can both take full advantage of the capabilities inherent to the NASEM definition and meet the public expectation from the lay interpretation of the term “digital twin.”

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1. An, G. Specialty Grand Challenge: What it Will Take to Cross the Valley of Death: Translational Systems Biology, “True” Precision Medicine, Medical Digital Twins, Artificial Intelligence and In Silico Clinical Trials. *Front. Syst. Biol.* 2022 April 28 2:901159. https://doi.org/10.3389/fsysb.2022.901159
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Federal Register Notice: 89 FR 51554, Federal Register :: Networking and Information Technology Research and Development Request for Information on Digital Twins Research and Development, June 18, 2024.

Request for Information on the National Digital Twins R&D Strategic Plan

Genda Chen

ENTERPRISE DIGITAL TWIN IN THE BUILT ENVIRONMENT TO ENABLE MULTIFUNCTIONAL MODELING IN LARGE SCALE

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https://doi.org/10.3390/smartcities7020035

SYNOPSIS
Digital twin (DT) has been mostly developed for a single function in the literature, limiting its full potential in applications. This document introduces an enterprise DT empowered with a layered integration of multifunctional models in the built environment. The enterprise DT involves open-sourced and secure modeling capabilities for non-profit organizations and for-profit companies, respectively, so that the national DT framework can benefit all entities. The enterprise DT also defines a new concept of the degree of digital twinning (DODT) to a real world by the number of models enabled by a common DT platform. This multidimensional DT is a modular architecture in three hierarchical tiers: autonomous region, infrastructure asset, and operation system. While the asset and system DTs focus on the lifecycle management of buildings and infrastructure as well as systems to support daily operations, the region DT addresses diverse modeling approaches for a comprehensive management of the built environment. The DODT enables value-driven digital replications of a physical twin at different levels. In addition to building information modeling, the enterprise DT enables spatiotemporal analysis in multiple scales to couple nonstructural with structural building components and connect the built environment to planning constructions.

Keywords: Smart cities; Digital twin; Degree of digital twinning; Remote sensing; Asset lifecycle management; Cyber-physical-social system

1 INTRODUCTION

Building and civil infrastructure assets have been managed using a database since 1970 and with the aid of Building Information Modeling (BIM) since 1992 for value engineering and as-built information. The imperative for embracing digital twinning becomes evident in the aftermath of the 2007 Minneapolis Interstate 35W Bridge Collapse, a catastrophic event that claimed 13 lives and injured 145. This tragic incident underscores the critical need for spatiotemporal analysis and societal impact studies, highlighting deficiencies not only in extracting overlooked design information from BIM but also in the incapacity of BIM alone to assess the adequacy of bridge members. The urgency to adopt digital twin (DT) is amplified as the nation's infrastructure is aging, demanding more frequent condition assessment and maintenance, particularly in the face of accelerating climate changes and increasing natural disasters.

Most, if not all, of prior studies on DT have concentrated on a single function, either computational or informational, within a specific discipline such as civil engineering or architecture. For example, DT has been viewed as a computational platform for finite element model updating in a probabilistic context and as an information platform for BIM updating. While these advancements in their respective research fields are intriguing, the broader impact of these isolated applications of DTs is likely constrained.

This document aims to empower DT with a layered integration of multifunctional models in the built environment, creating a cyber-physical-social (CPS) system encompassing buildings, infrastructure, and the associated community. Depending on the specific value-driven use cases of interest, a DT can be tailored through various facets and phases of a physical twin with the following specific objectives:

1. Develop a rapidly implementable framework of DT modules in hierarchical tiers,
2. Replicate the real-world construction of partially completed buildings with spatiotemporal analysis in multiple scales,
3. Integrate computational and informational models into a CPS system for asset lifecycle management,
4. Evaluate the structural and nonstructural behavior of buildings under multiple hazards to address post-disaster resilience of the affected community, and
5. Demonstrate and quantify the values of a DT through a straightforward indicator that is easy to evaluate.

2 DT FRAMEWORK IN THE BUILT ENVIRONMENT

2.1 DT for Product vs. Asset Lifecycle Management

The DT concept originated from the modeling of product lifecycle management (PLM) that handles a product as it moves through the stages of its life. The lifecycle of a product starts when a product is introduced to consumers into the market and ends when it is removed from the shelves. Due to the availability of commercial products in large quantities and short term at relatively low costs, the integration of multiple products into a new system product can easily be viewed as an intended physical prototype. The DT of the system is used to ensure all component products fit together before investing a new system product line in a physical factory. This is a valuable design attribute of DTs in the era of digital manufacturing in addition to real-time monitoring as envisioned originally.

On the other hand, asset lifecycle management (ALM) for large-scale buildings and infrastructure works differently. A set of strategies (e.g., maintenance, rehabilitation, and replacement) is organized and implemented with the intent of preserving and extending the service life of public infrastructure assets, such as roads, bridges, and railways. Unlike commercial products, infrastructure assets are often unique for both esthetical and functional purposes and require capital investment over a long time. As such, the attractive attribute of DTs for product assembly in manufacturing may have no equivalence in infrastructure asset management. For buildings and infrastructure management, computational mechanics modeling is desirable as their physical and functional conditions affect the decision-making of asset management strategies. In addition, using sensing data alone to assess their conditions is costly due to their large scale or even impossible for hidden deterioration. Model updating with limited sensor data is one of the effective ways to provide the needed condition assessment capability.

The above difference between PLM and ALM determines the way in which DTs are applied effectively in the built environment. To start with, the definition of DTs must be modified from those targeted at applications in manufacturing. In the past decade, 29 definitions of DTs were used in academia, industry, government, and software sources. In the built environment, the term DT has been used mainly in three ways: (1) modifying the original DT definition to reflect a realistic digital representation of assets, processes, or systems; (2) extending BIM to enable real-world data capture and feedback or completely replacing BIM; and (3) formulating a closed-loop digital-physical system for built asset delivery and operation. In general, DT differs from BIM in two distinctive ways: (1) two-way digital threads between DT and its represented physical asset, and (2) focus on operation and maintenance instead of the entire lifecycle of an asset as BIM encompasses with an emphasis on design and construction. The BIM implementation for operation is also different from DT's. While the DT supports the operation of built assets, BIM for facility management focuses compiling information of the delivered built asset to support inventory and space management, general upkeep, and building services maintenance, which does not result in an accurate replica of the condition and performance of the asset. In other words, the BIM is a static representation of a structure that shows how it was designed and built. It does not reflect the temporal changes that take place after its construction. On the other hand, the DT is a dynamic imitation that is continuously updated to reflect the current condition, rate of deterioration, effect of restoration, etc.

2.2 **DT Definition in the Context of ALM**

This document consolidates the three uses of DT term in the literature to propose a novel definition. In this context, a multidimensional DT is defined as *a synergetic, multifunctional, value-added, realistic digital representation of an intended or actual real-world asset, system, or process - a physical twin in the built environment*. As schematically shown in Figure 1, the DT interacts with the physical twin in a closed loop with two digital threads. In the physical-to-digital thread, sensing data and monitoring information obtained from the physical twin can be used to update the digital representation. In the digital-to-physical thread, intervening strategies developed and optimized through scenario studies on the DT can help understand the outcomes of multi-faceted decision-making before they are implemented on the physical twin. On the digital platform, the collected multimodal data from sensors and tests will be fused and evaluated to detect, locate, and quantify abnormalities as well as to predict the remaining life of the physical twin using advanced deep learning-based data analytics.

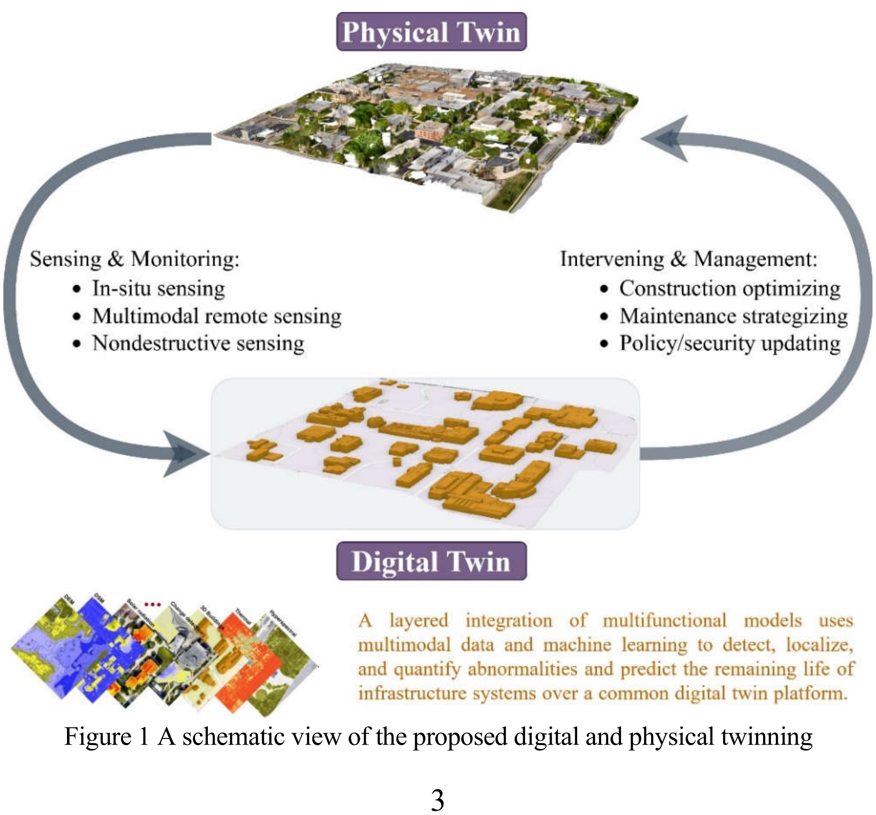

Figure 1 A schematic view of the proposed digital and physical twinning

2.3 Degree of Digital Twinning (DODT)

The state-of-the-art development of the DT technology is primarily focused on digital and physical twinning in computational mechanics or information only. A value-added solution expands the current single function paradigm to multiple functions. To quantify the values of a DT, the cost saving enabled by the DT is the most widely used indicator. However, this indicator requires the collection and use of a wealth of information that is difficult to acquire. In this document, DODT is introduced as a metric to simplify the estimation of the value of a DT by the number of digital models and feature mappings enabled and shared by the common DT platform to address societal needs in multiple disciplines, such as engineering, architecture, security, and social and political sciences. In the context of determining DODT, digital models are defined as a three-dimensional (3D) representation of agents (e.g., person or vehicle) and structures (e.g., buildings and infrastructure), including structural and nonstructural components.

2.4 Connections, Hierarchy, and Architecture of Modulated DTs

The CPS infrastructure concept stands as an innovative and emerging paradigm poised to revolutionize the built environment through the delivery of innovative services. It embodies a comprehensive framework that seamlessly integrates three pivotal components: cyber, physical, and social, as detailed in Table 1. The cyber system provides services to promote economic development and improve the quality of life and human wellbeing. The physical system includes an engineering-to-operation process to ensure safety, functionality, and resilience. The social system describes common traditions, cultures, patterns, and beliefs present in a population group. The main component, key function, and performance evaluation criteria of the three systems are described in Table 1.

Table 1. Characteristics of the three components in the built environment

System	Main Component	Key Function	Performance Evaluation Criteria
Cyber	Internet of Things	Enable people and objects to exchange data via wireless communication and store data in the cloud	Integration tool, security management, endpoint management
	Software	Provide computational modeling and intelligence	User interaction and support services
	Virtual reality	Create the virtual representation of the real world integrated with high-fidelity models	Latency, cybersickness, sense of presence, and technological advances
Physical	Load bearing components	Support service and extreme loads to provide living/working spaces or functions	Vulnerability, design consistency and optimization of elements
	Non-load bearing components	Provide utility facilities and communication infrastructure including computers	Function and security of workspace, economic considerations
Social	Economics	Estimate cost-benefit ratio of major projects	Maintenance costs, strategy development, and profitability
	Social work	Alleviate conditions of people in need of help or welfare	Social and emotional needs, an environment of respect and rapport

DT in the bult environment can be hierarchically structured in a simplified form as shown in Figure 2, extending from the regional level down to asset and system levels. Depending on the security demand, the infrastructure at the asset level can be clustered into two segments: (1) an open-sourced segment catering to public buildings and standard infrastructure, and (2) a secured segment designed for information-sensitive buildings and critical infrastructure. Furthermore, the hierarchal asset and system structure undergoes evolution throughout the planning, design, construction, and operational phases.

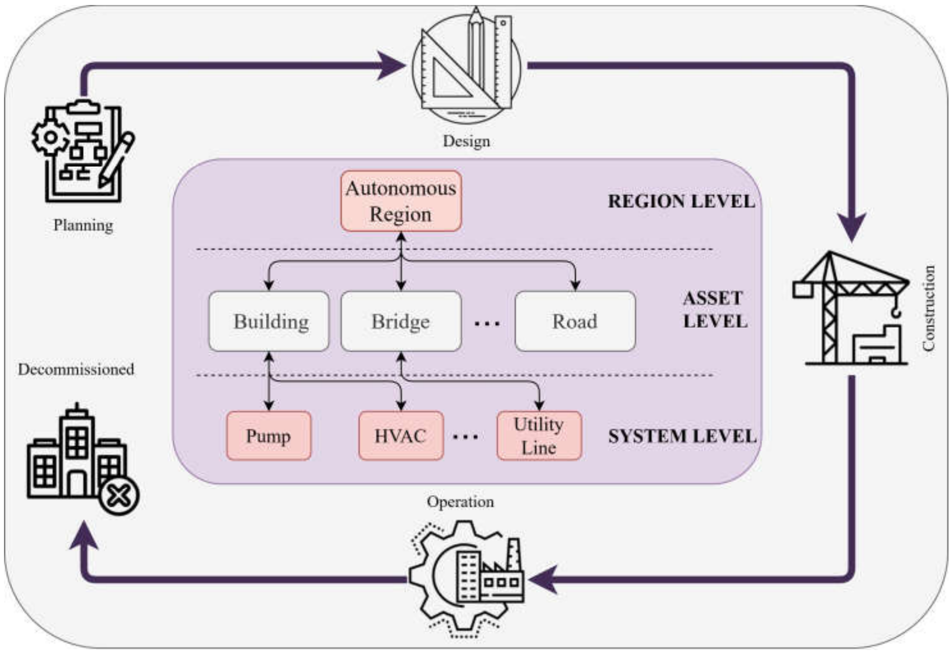

Figure 2 Temporal and spatial connections and hierarchy of modulated DTs

Many of the current DT research has been focused on information construct. In the built environment, however, damage assessment of existing infrastructure and design options of new infrastructure are important in the lifecycle management of region assets. Unlike the production application strategy in manufacturing, a creation application strategy is thus needed for buildings and infrastructure.

Table 2 presents the system architecture of DTs. It consists of five layers: data acquisition, data transmission, model analysis, feature mapping, and users collaboration. First, multimodal data are acquired from remote sensing, in-situ sensing, and nondestructive testing. Subsequently, the collected data are transmitted to a DT curation and storage facility in the region. Following this, the received data are analyzed using informational and computational models. Subsequent to the analysis, the features of interest in asset management and regional planning are extracted and presented in mapping formats in the DTs. Finally, the processed features are communicated with end users through visualizations, dashboards, and interfaces to assist in collaboration and informed decision-making.

Table 2. Five layers in the architecture of DT

Layer	**Key Function**
Data Acquisition	Collection of data from remote sensing in-situ sensing, and nondestructive testing
Data Transmission	Secure transferring of the acquired data from sensors and tests to the DT platform
Model Analysis	Data cleansing and integration to create the virtual representation (or model) of a real world, model analysis to transform raw data into meaningful insights and patterns, and predictive models that facilitate a deep understanding of object or system's behaviors
Feature Mapping	Feature extractions and their geospatial distribution in a 3D platform of the DTs
Users Collaboration	Visualizations, dashboards, and interfaces that help multiple users at various security levels connect with each other and navigate the DT for controlled data access and manipulation

To exemplify the impact of enhanced DT at the asset level, Section 3 presents the two foundational computation platforms that couple information and computation modeling as well as experimental and computational simulation. Section 4 presents a case study conducted on a university campus scale. This case study serves as a tangible demonstration of the practical application of DT principles within conventional infrastructure. By focusing on a specific campus environment, this study showcases how DT can be effectively employed to realize potential benefits and bring about transformative impacts on system, asset, and regional levels.

3 DT AT ASSET AND SYSTEM LEVELS

While employing computational models is crucial for addressing structural safety concerns, the information modeling of nonstructural components becomes necessary for comprehending the functionalities of a building system. This is underscored by the fact that the integrity of structural components significantly influences the operations of nonstructural elements. Consequently, the synergy of computational and informational modeling is essential for the efficient and effective management of building and infrastructure assets, with updates occurring nearly in real time. As a result, the establishment of two foundational computation platforms is imperative to facilitate the implementation of DTs for both computational and informational modeling:

1. *Spatial connection of structural and nonstructural components*. Current computational and informational modeling tasks are done by two completely isolated technical communities using different approaches. For the development of DTs, the two modeling techniques are transformed into one simple yet effective computational and informational engine to meet the multiple needs in performance evaluation as summarized in Table 1.
2. *Temporal connection between a built facility/environment and a new facility/environment to be built in part or entirety*. This platform plays a critical role in bridging planning, design, construction, and operation of a physical building and infrastructure system.

As previously mentioned, the forefront of DT technology advancement predominantly centers on digital and physical twinning within a single model, such as computational mechanics or information-only domains. To enhance infrastructure lifecycle management at the asset level, it is crucial to integrate computational, informational, and other relevant models. The following two subsections offer practical examples that illustrate the integration of these models.

3.1 Coupling of Computational and Informational Models

A building consists of structural components that primarily resist loading and nonstructural components that support building operation. The nonstructural components are further divided into two groups: A and B. Group A includes the pipeline system, hydraulic elevator system, and beams in the ceiling system, which are significantly interacted with their supporting structural components. Group B consists of the non-beam ceiling system, glazing system, and drywall partitions, which have negligible interaction with structural components.

Figure 3 shows a workflow diagram of the coupled computational and informational modeling to determine the probability of damage states and item costs in structural and nonstructural components. The computational and informational models are integrated into a seamless platform of fiber elements to address both mechanical behaviors (i.e., stress and strain at material levels) using OpenSees computational software and functional value properties (i.e., integrity and cost at component or system levels) using informational interrelation. To maintain simplicity and efficiency, macro-scale models are introduced for nonstructural components and meso-scale models are used for structural components. Specifically, the structural components and Group A nonstructural components are represented by fiber elements in a finite element model (FEM) and analyzed under external loading (earthquake) to evaluate the building responses and damage states. Group B nonstructural components are represented by their informational model for lumped effects to estimate their damage states from respective fragility curves based on the overall performance of the building.

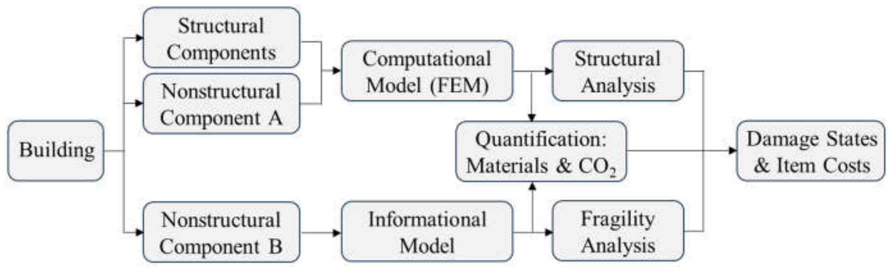

Figure 3 Workflow diagram in damage and cost analysis in structural and nonstructural components

In Group A nonstructural components, the pipeline system was meticulously modeled to reflect the pinching behavior of joints along with their supporting hangers and wire restrainers. Similarly, the hydraulic elevator system was modeled to capture primary types of damage that potentially affect the performance of chassis, cabin, and main supporting cylinder. The beams in the ceiling system were modeled to account for their stiffness and strength effects on the building responses. In Group B nonstructural components, the non-beam ceiling system was modeled in a lumped sum for various failure modes such as the dislodgement of ceiling tiles, loss of connections along the edges, and vertical movement. These types of damage were comprehensively assessed and quantified through the utilization of fragility curves. The informational model for Group B nonstructural components and the size information of the computational model for Group A nonstructural components and structural components include the material data for each component that was used to estimate CO_2 emissions resulting from producing these materials. This quantification was finally employed to determine the component costs under scenario damage states. Overall, the coupled computational and informational model offers a comprehensive dataset detailing the post-earthquake condition of building components and the environmental impact of the materials utilized in the construction of the building.

3.2 **Hybridization of Experimental and Computational Models**

Buildings and civil infrastructure are commonly instrumented with accelerometers for monitoring structural behavior. However, this method has two notable drawbacks. Firstly, the extensive processing of acceleration measurements is required to derive data related to structural behavior, such as crack width and steel mass loss. This intricate mathematical process often serves as a barrier to the widespread adoption of sensing technologies. Secondly, the deployment of accelerometers relies on the configuration of an entire structure, making it unsuitable for adaptability to partially erected structures or entirely new constructions.

In practice, all stories of a building are typically built with the same materials using the same erection process of prefabricated components during construction. The first story, resting on a rigid base, is often subjected to a larger drift than the second and above. Thus, a novel strategy of hybridizing experimental and computational modeling is proposed in this study, as shown in Figure 4. A structure is divided into two groups: experimental members in the first story and computational members above the first story. The experimental members are modeled by fiber elements and instrumented to measure the load-displacement response of the first story. The material properties extracted from the load-displacement curve are transferred in real time to update the FEM modeling and evaluation of the above stories using computational simulations. This hybrid experimental and computational treatment is compatible with the sequence of construction of a new building. This hybrid modeling strategy bridging existing to new constructions is also more accurate than conventional models. For a four-story, two-bay steel building structure, the hybrid treatment proved at least 25% more accurate than those simulations even from a post-earthquake calibrated model.

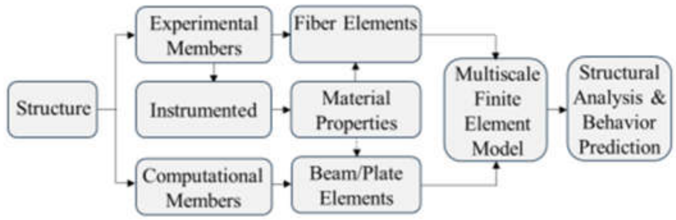

Figure 4 Workflow diagram in hybrid experimental and computational modeling and analysis

4 DT AT THE REGION LEVEL

A case study is presented to unlock potential DT benefits and create transformative impacts on asset management and regional planning of a university campus. Figure 5 shows the 3D rendering of the campus DT over an area of approximately 500m×500m.

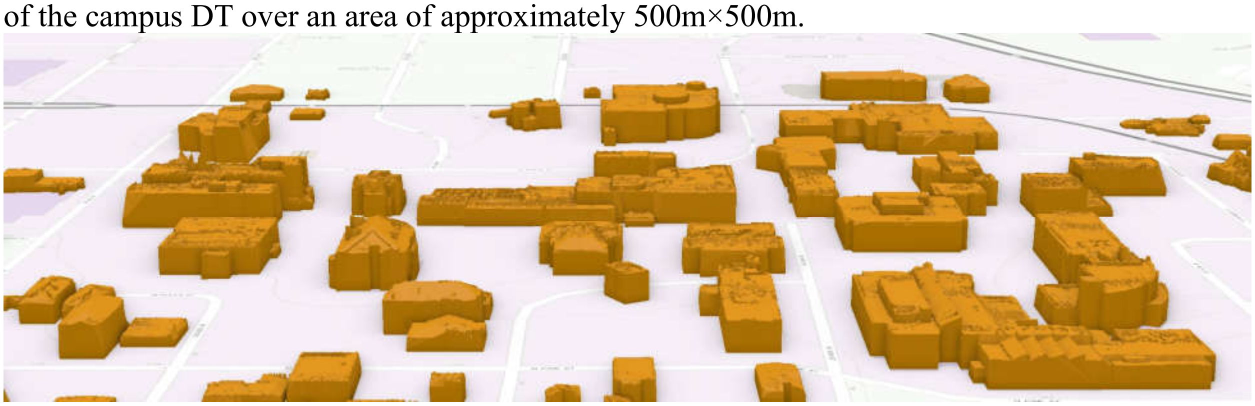

Figure 5 3D rendering of a university campus as a common platform of the DT modules

In this document, the DT expands beyond individual building assets to encompass the entire campus, including buildings, green areas, underground utilities, and other components. This broader scope is termed the DT at the regional level, emphasizing the scale of analysis. However, a closer examination indicates that the DT modules for buildings are at the asset level, while drainage systems can be categorized at the system level. This interconnectedness illustrates the hierarchical relationship between various levels of analysis as illustrated in Figure 2.

4.1 Workflow to Realize Multiple DODTs and Values

As indicated in Table 2, the workflow of creating a digital twin of the campus is shown in Figure 6. It starts with gathering data from various sources such as LiDAR, cameras (infrared (IR), hyperspectral, HiFi RGB), IoT sensors, and GIS databases to ensure a comprehensive and accurate representation. These data are then securely transmitted through robust protocols to a centralized or cloud-based storage platform on which the campus DT is hosted. The LiDAR data is used to generate a Digital Elevation Model (DEM) and a Digital Surface Model (DSM), representing terrain and surface features including buildings. Building extraction is then performed to isolate structures and their features from the DSM. Subsequently, these extracted building footprints are transformed into 3D models using various modeling techniques in the GIS platform. These 3D models are carefully integrated, georeferenced, and aligned within the campus DT, ensuring spatial accuracy and seamless integration. The models are continuously refined and enriched with real-time data to keep it up to date with the changing campus. Features relevant to the built environment are carefully defined within this model. These defined features enable detailed analysis and scenario simulations, presented as DODT, to support campus planning and sustainable decision-making. The created features encompass a broad array of domains, including infrastructural planning, building envelope diagnosis, construction management, responses to extreme events (earthquakes and floods), energy usage, development of green spaces, and security. The insights obtained from these features are thoughtfully disseminated through intuitive user interfaces, enabling stakeholders to navigate and interrogate the campus DT. Furthermore, creating a collaborative environment is crucial, encouraging the active involvement of various stakeholders and experts to embrace diverse perspectives and expertise, optimizing the campus environment's functionality.

It is evident from Figure 6 that the data acquired from an individual sensor is utilized to achieve multiple DODTs. Furthermore, some DODTs are developed using a combination of data from various sensors. Although each sensor's data are initially used independently, the spatial-enabled nature of the multilayer data makes it straightforward to fuse multiple datasets. Combining these fused data with fresh sensor data has the potential to create new DODTs. Additionally, given those data are collected biweekly to update the DT, the time-series data can track changes and utilize artificial intelligence (AI) and machine learning (ML) algorithms to forecast the future. This foresight enables predictive maintenance, which represents another novel DODT.

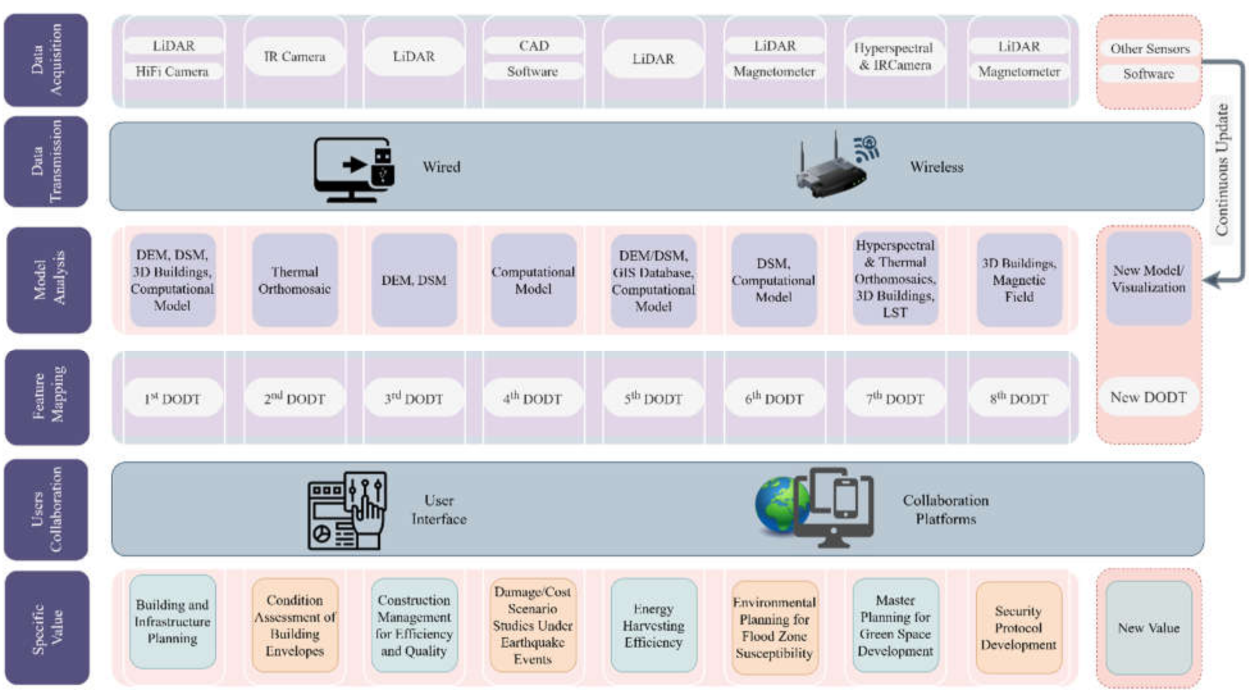

Figure 6 Simplified workflow of the campus-scaled DT modules to realize multiple DODTs

Figure 6 also demonstrates the specific values of the campus-scale DT. These values are realized through digital modeling and analysis. The output of each model and analysis provides a distinct value and is thus considered one DODT. A total of eight (1st to 8th) DODTs are presented in Figure 6. The numbering of the DODTs is presented in no particular order or hierarchy; instead, they are listed in alphabetical order of their values as presented below:

1. Building and infrastructure planning,
2. Condition assessment of building envelopes,
3. Construction management for efficiency and quality,
4. Damage/cost scenario studies under earthquake events,
5. Energy harvesting efficiency,
6. Environmental planning for flood zone susceptibility,
7. Master planning for green space development, and
8. Security protocol development.

Federal Register Notice: 89 FR 51554, Federal Register :: Networking and Information Technology Research and Development Request for Information on Digital Twins Research and Development, June 18, 2024.

Request for Information on the National Digital Twins R&D Strategic Plan

General Atomics

National Strategy for Scientific Innovation and Leadership Through Digital Twins and the Fusion Energy Exemplar

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Key topics: Artificial Intelligence, Business Case, Ecosystem, International, Long Term, VVUQ, Workforce

1. EXECUTIVE SUMMARY

"Intelligent" digital twins (iDTs) [1], integrating artificial intelligence (AI) and machine learning (ML) into traditional digital twin frameworks offer unprecedented potential to accelerate scientific discovery and technological innovation. By creating high-fidelity virtual replicas of complex systems, iDTs can enable rapid iteration, optimization, and testing of ideas in a low-risk virtual environment, allowing researchers to explore vast multi-dimensional parameter spaces, identify complex interdependencies, and make data-driven decisions at a pace and scale not possible with traditional methods alone. As the United States seeks to maintain its leadership in science and technology, the development of a national strategy for AI-enhanced digital twins is crucial.

To capitalize on the rapid pace of AI innovation and evolving iDT capabilities, we recommend the immediate initiation of domain-specific iDT pilot programs with clear objective outcomes. These pilots should adopt a "Fail Fast" approach, prioritizing swift deployment, iterative refinement, and continuous learning. Critically, the funding and management framework for the pilots must seamlessly integrate the three core pillars of advanced scientific computing—models, data, and compute—with the domain-specific expertise found at, for example, Department of Energy (DOE) user facilities. This integration is essential given the intrinsically interconnected nature of models, data, and compute in iDTs, where the computing spans from edge systems at the user facility to leadership-class computing centers nationwide, and where latency requirements are crucial for linking virtual and physical systems. This aligns with the recent DOE Advanced Scientific Computing Research (ASCR) Advisory Committee recommendation [2] advocating for innovative governance and funding models to prepare for a future where DOE user facilities are intimately linked with national computing and data facilities, enabling real-time decision making in control rooms and accelerating scientific breakthroughs.

Recent advancements in AI for both magnetic and inertial fusion energy (MFE/IFE), coupled with successful proof of concept (POC) demonstrations, underscore the immense potential of iDTs in fusion research. Given fusion energy's recent technical breakthroughs, its substantial economic and societal promise, the success of early POCs, and the White House Bold Decadal Vision [3] for fusion energy development, fusion stands out as an ideal candidate for a national iDT pilot program. By enabling rapid, cost-effective iteration, risk mitigation, and AI-driven discovery, iDTs could significantly accelerate timelines, reduce costs, and increase the probability of successfully achieving commercial fusion energy. The proposed pilot would aim to develop a high-performing iDT, tightly integrated with facility operations, combine high-fidelity AI models with live data streams, enabling bi-directional, low-latency interactions between the digital and physical realms. The iDT would continuously update its models based on real-time inputs, allowing for timely analysis, prediction, and optimization of fusion facility operations. To realize the transformative potential of iDTs in science and technology, we recommend the following actions:

- **Implement a domain-specific iDT pilot program** prioritizing rapid prototyping, iterative development, and continuous learning. Pilots must adopt a "Fail Fast" approach, have clearly defined objectives and integrated management for models, compute, and data.
- **Launch a national flagship initiative to develop a comprehensive fusion iDT,** building upon recent POCs in MFE and IFE, and integrated with experimental facilities to support the White House's Bold Decadal Vision for fusion energy.
- **Fund multi-disciplinary teams comprising domain science, computational, and data science experts.** These integrated teams will ensure the agile development of iDTs.

This request for information (RFI) response describes the rationale for a national strategy that focuses on domain-specific multi-disciplinary iDT pilots for the realization of fusion energy.

2. THE FUSION ENERGY CHALLENGE AND DIGITAL TWIN OPPORTUNITY

Fusion energy stands at the forefront of humanity's quest for sustainable, clean power, offering a potential solution to the pressing challenges of climate change and global energy demand. Recent breakthrough achievements in both inertial and magnetic confinement fusion have reignited enthusiasm for this transformative technology. The National Ignition Facility's (NIF's) demonstration of fusion ignition [4], and the sustained high-performance conditions in magnetic confinement systems [5], mark significant milestones in the field. These advancements have catalyzed unprecedented growth in the private fusion industry [6], with $6B invested in numerous startups now racing to commercialize fusion energy. Recognizing the momentum, the United States government has put forth a bold decadal vision for fusion energy development, aiming to demonstrate commercial viability within the next decade. This ambitious goal underscores the critical role of the government in fostering innovation, supporting basic and translational research [7], and creating a regulatory framework for this emerging industry. As we stand on the cusp of a new era in energy production, the development of comprehensive iDTs for fusion systems emerges as a key enabler, promising to accelerate progress in this complex, multidisciplinary endeavor.

The National Academies of Science, Engineering, and Medicine (National Academies) study on burning plasma science [8] highlights several critical challenges in achieving commercially viable fusion energy. These include maintaining plasma confinement and stability, managing heat and particle exhaust, developing fusion-compatible materials, and integrating complex systems for continuous operation. Importantly, the report emphasizes the need for accelerated learning cycles and improved predictive capabilities. iDTs integrated with a performant data platform (see high-performance data facility progress [9]) and advanced computing capability (see integrated research infrastructure development [10]) offer a powerful approach to address these challenges and accelerate progress towards fusion energy.

The iDTs have the potential to dramatically accelerate the development of commercial fusion energy by revolutionizing the design, testing, and optimization processes. They enable rapid, cost-effective iteration of reactor designs in a low-risk environment, while integrating operations, maintenance, and control into the design process, potentially reducing cost and risk in developing and operating physical systems. These virtual environments allow for the exploration of vast parameter spaces and parallel testing of multiple design variants, potentially accelerating development cycles and increasing the number of design iterations. By enabling early identification of design and potential operational issues, iDTs mitigate risks and reduce costs associated with developing and operating physical systems. On existing facilities, they open up possibilities for AI-driven discoveries of novel operating conditions and fusion configurations, which can translate to improved reactor concepts. Collectively, these advantages can compress decades of traditional fusion development into years, significantly reducing overall costs and increasing the probability of success. This acceleration can be highly enabling for the commercial development of fusion energy and the realization of the ambitious timeline set forth in the United States government's decadal vision.

3. FUSION PILOT PROGRAM

The recent convergence of multiple technological advancements presents a unique opportunity for rapidly advancing fusion iDT pilots. These advancements include the successful integration of AI into real-time control systems, the seamless incorporation of leadership-class computing capabilities into facility operations, and the development of community-driven data platforms that facilitate data curation and efficient AI and ML model creation. The synergy of these cutting-edge technologies provides the essential foundation for the rapid development of transformative fusion iDTs.

MFE: MFE is fundamentally a continuous process of energy production, in contrast to IFE, which is fundamentally a discrete process of implosions occurring multiple times per second. To fully grasp the role and impact of MFE iDTs, it is essential to consider the key stages of the MFE lifecycle and the corresponding latency requirements for information flow between the virtual and physical assets.

The MFE iDT must operate across multiple timescales, each with distinct latency requirements (Fig. 1). For real-time control applications, the fastest timescale, latencies must be extremely low, ranging from milliseconds to seconds. This enables rapid adjustments to plasma conditions and machine parameters through edge computing, coupling sensor data with real-time inference engines to predict future states and command actuator responses. On a longer timescale of minutes to hours, the iDTs provide interpretive and predictive analysis to inform operations. This intermediate timescale allows for more complex calculations and data processing at leadership-class computing centers, guiding operational decision-making with advanced insights. For the DIII-D National User Facility [11], this step is enabled through DOE's Integrated Research Infrastructure (IRI) operated by ASCR. Finally, for informing the design of future experiments or facility upgrades, the iDTs operate on the longest timescale, with latencies of hours to days. This extended timeframe enables comprehensive simulations and analyses to support long-term planning and design optimization. It also allows for the development of advanced inference engines, surrogate and "foundation models" that require significant time to optimize on high-performance GPUs, as well as data platforms capable of processing information at scale. For the DIII-D facility, this is enabled through the IRI and a fusion data platform (FDP) that we plan to integrate with DOE's High Performance Data Facility (HPDF). This multi-tiered approach ensures that the MFE iDT can address both immediate operational needs and long-term strategic goals in fusion energy research and development.

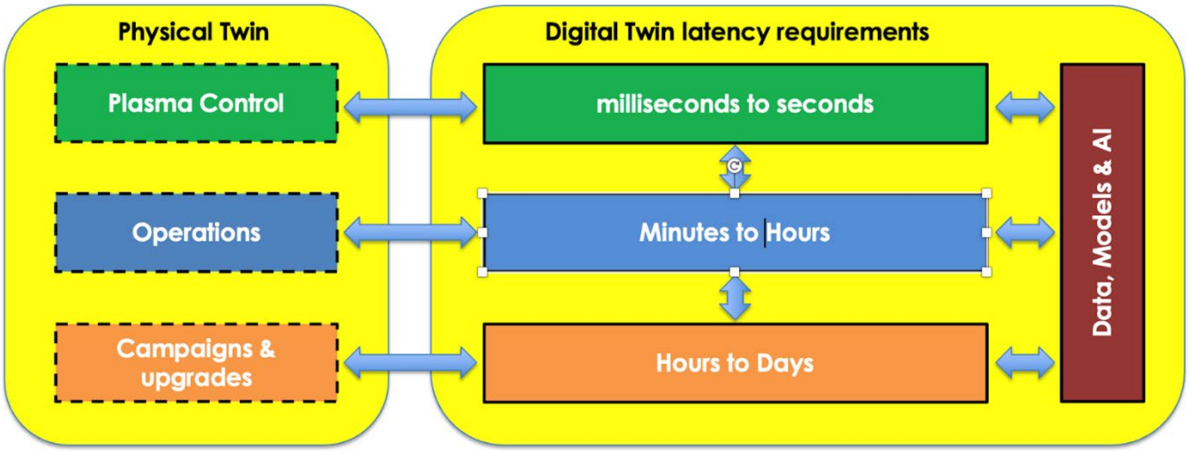

Figure 1: Latency requirements for a fusion iDT

In the following, we illustrate key advances in each of these different time scales that form the building blocks for integration into a performant MFE iDT.

Surrogate models for real-time control: A recent breakthrough in AI-driven real-time control for fusion plasmas has been demonstrated on the KSTAR tokamak [12]. Researchers from Princeton Plasma Physics Laboratory and collaborating institutions have developed an innovative approach that combines ML with adaptive control techniques to optimize the performance of tokamak fusion reactors. The study showcases a fully automated 3D-field optimization system that successfully suppresses edge magnetic instabilities while significantly enhancing fusion performance. By leveraging a ML surrogate model to rapidly calculate optimal magnetic field configurations, the system achieves real-time adaptability at millisecond timescales (Fig. 2). This approach led to remarkable improvements, including up to a 90% increase in fusion performance metrics and near-complete elimination of magnetic instabilities. The research represents a significant step towards realizing stable, high-performance fusion plasmas and demonstrates the potential of AI-driven control systems surrogate models derived from high-fidelity simulations to overcome long standing challenges in fusion energy development.

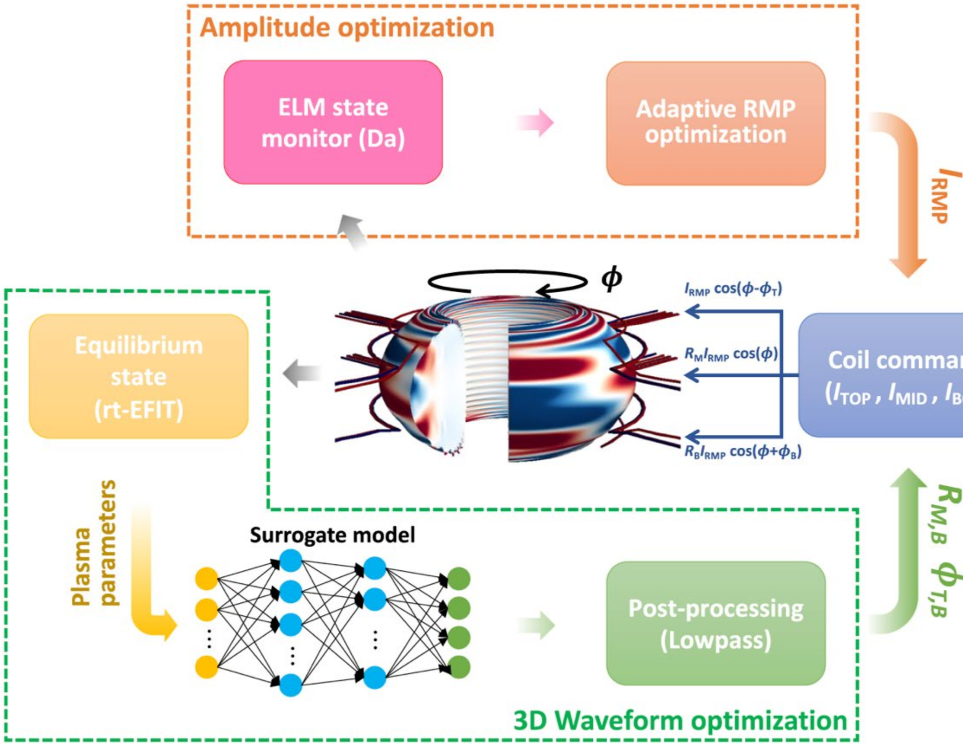

Figure 2: ML based real-time optimization using 3D magnetic field surrogate model in the KSTAR tokamak. [12]

Informing machine operations: In the minutes-to-hours timescale, the MFE iDT leverages DOE's IRI to rapidly perform complex calculations, such as neutral beam injection, ionization, and their impact on material surfaces, as shown in Fig. 3 [13]. By utilizing the IRI, DIII-D—an early IRI pathfinder—can seamlessly dispatch computations to high-performance computing centers like the National Energy Research Scientific Computing Center, the Argonne Leadership Computing Facility, and soon on the Oak Ridge Leadership Computing Facility, swiftly retrieve results to support decision making in the control room. This advanced tool can be integrated with other models, including surrogate and foundation models, to inform control room decisions on operational issues by comparing simulations with real-time machine data. Foundation models could provide a robust, pre-trained base for developing more specialized models for specific fusion-related tasks, potentially accelerating the development of accurate predictive capabilities. The combination of these capabilities with automated interpretive analysis between plasma pulses [14] enables informed decision-making on experiments and optimization of operational plans. This synergy of high-performance computing, advanced visualization, and AI-driven analysis exemplifies how the iDT can revolutionize the efficiency and effectiveness of fusion experimentation, allowing researchers to make timely data-driven decisions.

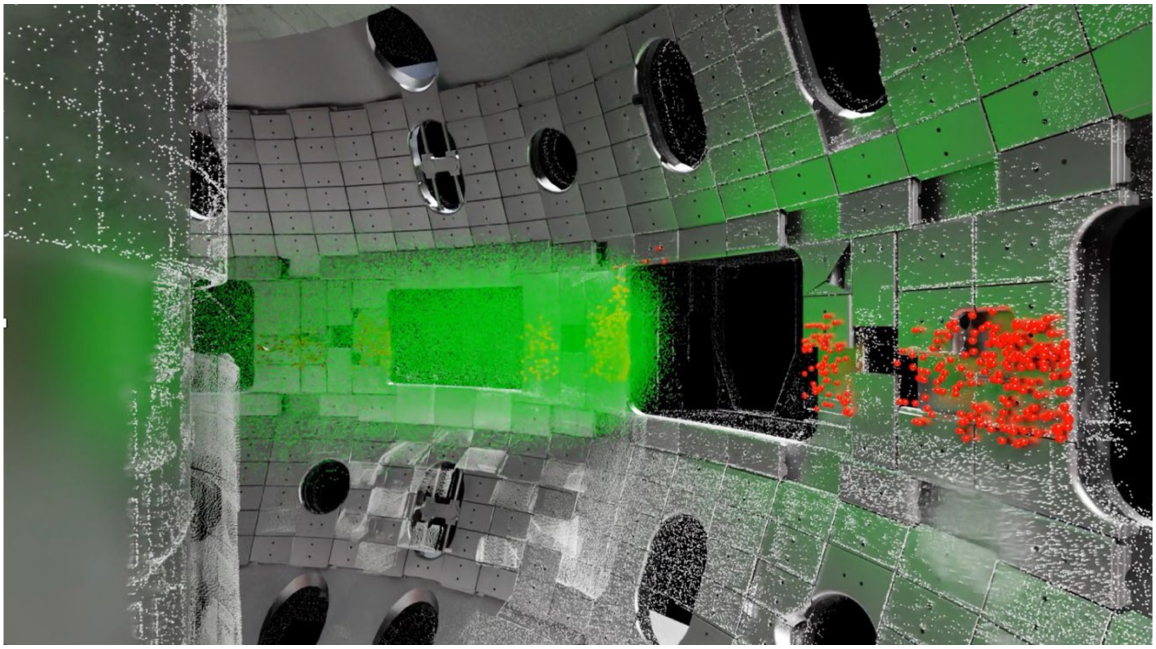

Figure 3: Calculations of neutral beam injection (right to left), beam ionization profile (green) and beam ion loss on tiles (red) inside the DIII-D vacuum vessel [13]

Long-term planning for experimental campaigns, upgrades, and new facilities: At the core of a fusion iDT's long-term planning capability is the development of a robust data platform that can analyze experimental and simulation data at an unprecedented scale. An FDP developed for the fusion research community is capable of handling several petabytes of data. This will expand significantly when integrated with the DOE HPDF and coupled to leadership class computing facilities through IRI. The platform's architecture enables the creation and refinement of AI/ML models derived from vast simulation and experimental datasets, which can then be deployed in real-time or between plasma pulses during operations to inform control room decisions. This could include the development and fine-tuning of foundation models specifically for fusion applications, leveraging the power of large-scale pre-training to enhance predictive capabilities across various aspects of fusion research and operations. Leveraging the open science data federation for efficient data distribution via caching, the platform maintains rigorous data provenance for all models, data, and artifacts through the open-source Common Metadata Framework [14]. This comprehensive approach to data management is absolutely essential for the iDT concept, as it provides a scalable solution for managing the enormous volume of models and data inherent to iDT. These various capabilities will form the backbone of a fusion iDT capacity for informed decision-making and long-term strategic planning in fusion energy development.

MFE pilot: In this RFI response, we present a few of the recent advancements in fusion research that lay a solid foundation for proceeding with confidence towards a fusion iDT pilot. Several critical components have been successfully demonstrated: AI-driven real-time control systems employing surrogate models of high-fidelity simulations used to suppress magnetic instabilities and optimize plasma performance, advanced data platforms capable of managing petabyte-scale experimental and simulation datasets, and the integration of national leadership class computing facilities for rapid between-pulse and long-term planning. These achievements, coupled with progress in simulation capabilities and visualization tools, provide a strong basis for embarking on a comprehensive iDT pilot. The fusion iDT pilot will build upon these proven capabilities, aiming to create a scalable, integrated framework that enhances our understanding, control and optimization of fusion systems from millisecond-scale control to campaign-level planning. This ambitious initiative represents a crucial next step in leveraging advanced computing and AI technologies to accelerate progress towards practical fusion energy.

IFE/IFT pilot: IFE provides a valuable complement to MFE for iDT development. IFE is fundamentally a batch-wise operation – making use of discrete implosions at multiple times per second. This contrasts with MFE, where operations are continuous. The complementary challenges introduced by this mode of operation provide a fertile ground for developing additional dimensions of iDTs and for further refining those dimensions that are shared with MFE.

IFE iDTs will make meaningful impact in three critical and interrelated stages of the IFE lifecycle. First, an iDT will provide critical information for target manufacturing operations. iDT of advanced and precision manufacturing processes will serve as a critical technology to reach production rates commensurate with the operation of an IFE reactor, or about 10 hertz in most applications. The iDT will ingest real-world metrology for targets in-situ, that is during the production process. This will produce a living in-silico copy of the target as it is being created. The iDT will present the in-silico target to a predictive model that can evaluate defects in real-time. That predictive capability can then assess the impact of observed defects while designing the mitigating "anti-defect" in real-time to be applied to the production job, such as in the next pass of a direct ink write printer. The two-way communication enabled by the iDT in this production example will enable high-throughput and high-quality operations required for future IFE power production. It will also deliver extensively metrologized targets and their iDT analogs for custom operation facilities to optimally match fusion driver execution with the particulars of the target being imploded at the current moment, thereby adding additional robustness to the operational cycle. Projects on iDT for in-situ metrology and real-time decision making are currently underway, paving the way for rapid expansion of the capability in the immediate future.

Second, the IFE iDT will require a strong and reliable predictive capability. It must be able to confidently predict what will happen to the physical twin of the system (the operating reactor and target system) based on the iDT (the simulated operations). Models have already been developed for inertial confinement fusion efforts at NIF. NIF researchers built AI-driven models of implosions using the combination of high-fidelity physics models (simulation codes) and experimental observations (actual implosion measurements). The resultant model successfully predicted ignition (the production of more fusion energy than used in the driving laser) for the first time and for the half-dozen subsequent successful events. Such a model is a critical component for ensuring two-way coupling of an iDT between the digital and physical world. It allows for real-time updating of model expectations that are both consistent with physical theory, but also accurate about observations in complex, evolving systems. This predictive capability will allow the iDT to "understand" the impacts of operational changes in the real-world system.

Finally, the ultimate goal of an iDT is to allow for optimal reasoning about a physical system based on the safer, cheaper, and faster digital model. For IFE, the iDT provides a route to full closed-loop or "self-driving" reactor operations. As presented here, the coupling of knowledge from an advanced target manufacturing system with a real-world-aware predictive model allows for optimal operation of facilities. For example, an iDT could perform rapid optimization of the fusion driver, such as a shaped laser pulse, to accommodate the particular target (and all of its individual defects and measurements) being fired in the reactor at the current moment.

4. EMERGING PUBLIC PRIVATE ECOSYSTEM FOR FUSION ENERGY

Scientific user facilities are the flagship of the DOE Office of Science ecosystem, advancing the frontiers of science, training the future high-tech workforce, and enhancing United States economic competitiveness. The rapid rise of the fusion industry, with recent investments exceeding $6 billion in MFE and IFE, and its growing engagement with national facilities like the DIII-D tokamak [11], underscores the critical role of public-private partnerships in developing a robust fusion ecosystem.

The creation of an iDT to support science and operations on DOE fusion facilities will provide a crucial link in achieving the bold decadal vision for fusion energy. Established world-leading AI companies, like Google DeepMind, are already engaged in AI research for fusion energy, along with many early-stage companies developing the underlying technologies needed for realizing commercial viability. Initiating a fusion iDT pilot program will further strengthen the synergy between national research activities and industry, both in the fusion technology and IT industries.

Recent DOE initiatives, such as the FIRE collaboratives for translational research, public-private partnerships, and the emerging public private consortia, combined with a national priority for a fusion iDT pilot and the DOE user facilities will accelerate fusion energy development, strengthen United States leadership in the field, and foster innovation and technology transfer. By bringing together industry, universities, and national laboratories, this pilot program will be instrumental in realizing the potential of commercial fusion energy.

5. DIGITAL TWIN PILOT PROGRAM ELEMENTS

To fully realize the potential of iDTs, the Office of Science and Technology Policy should consider the following key points in formulating a national policy for iDT development.

- Establish a cross-agency initiative for rapidly identifying high-impact iDT pilots, with fusion energy as a flagship project within the DOE. Such a cross-agency initiative will drive innovation across multiple fields while addressing critical national priorities, such as energy security and climate change mitigation.
- Implement an integrated funding and management model that breaks down traditional boundaries between domain sciences, computational sciences, and data sciences. This model should ensure that iDT pilots work efficiently towards clearly defined objective outcomes, avoid duplication of efforts and efficiently share progress and insights.
- Establish strategic partnerships among industry, national laboratories, and universities, on the regional and national level, integrating sector and regional strengths to accelerate iDT innovation, and enhance United States technological leadership and economic competitiveness. Within the DOE Office of Fusion Energy Science, these partnerships can

be enabled through the recently initiated FIRE collaborative program [15] for translational research and the proposed public private consortium framework [16].

- Prioritize the development of a flexible, adaptable computing and data infrastructure to support diverse iDT needs across domains. This infrastructure should be capable of supporting the development of large-scale foundation models tailored for iDT applications. DOE's IRI initiative aims to integrate edge computing at experimental facilities with leadership-class computing centers, addressing iDT latency demands. NSF's National AI Research Resource pilot uses cloud and on-premise infrastructure for large-scale AI. These programs should be informed by requirements to support the development of an intelligent twin for fusion.
- Invest in workforce development programs that cultivate the interdisciplinary skills required for effective iDT development and utilization. The traditional silos of domain science, computational science, and data science need to be bridged by an emerging workforce that comfortably spans these disciplines. University partnerships in these pilot programs can play an important role in cultivating a robust workforce pipeline.
- Establish guidelines for data sharing and interoperability standards to maximize the value of iDTs across different science domains and sectors. Within the DOE, the establishment of the HPDF will help to enable the development of such standards.

To accelerate the development of a functional iDT, the pilot program should adopt a "Fail Fast" management model. This approach emphasizes rapid prototyping of small-scale components within each functional area required for a complete DT. A crucial element of this strategy is the early deployment of a minimum viable product (MVP). By prioritizing the release of an MVP early in the development cycle, the project team can gather vital feedback from users at major scientific facilities. This real-world user experience provides invaluable insights, guiding subsequent development and enabling the team to swiftly iterate and refine the iDT capabilities. Such an approach ensures that the project's trajectory and outcomes are continuously improved from the earliest stages, maximizing the likelihood of success and accelerating the path to fully functional, high-impact iDTs.

6. CONCLUSION

The development of iDTs represents a critical opportunity for the United States to maintain its global leadership in science, technology, and innovation. As demonstrated by recent advancements in fusion energy research, iDTs have the potential to dramatically accelerate progress in complex, multidisciplinary fields of national importance.

To fully realize the potential of iDTs, we recommend the establishment of a cross-agency initiative for identifying high-impact iDT pilots, with fusion energy as a flagship project. This initiative should implement an integrated funding and management model that breaks down traditional boundaries between domain, computational, and data sciences, ensuring efficient progress towards clearly defined outcomes. The policy should invest in workforce development programs to cultivate interdisciplinary skills, foster public-private partnerships to accelerate the transition from research to commercial applications, and establish guidelines for data sharing and interoperability standards.

By implementing a coherent well-coordinated cross-agency initiative, the United States can create a robust ecosystem for iDT development that will drive scientific discovery, technological innovation, and economic growth. This forward-looking approach will position the nation at the forefront of the next wave of scientific and technological advancements, ensuring continued leadership in an increasingly competitive global digital landscape.

7. BIBLIOGRAPHY

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Federal Register Notice: 89 FR 51554, Federal Register :: Networking and Information Technology Research and Development Request for Information on Digital Twins Research and Development, June 18, 2024.

Request for Information on the National Digital Twins R&D Strategic Plan

Guo Luanzheng

Via FDMS

Guo Luanzheng, 7/12/2024

[redacted]

For International Collaborations on Digital Twins, Japan has a key investment in Digital Twins as well, especially on disaster/diseases simulation/prevention, e.g., the Society 5.0 Realization Research Support Project. For Sustainability, carbon emission (net zero) could be one of the key dimensions

Federal Register Notice: 89 FR 51554, Federal Register :: Networking and Information Technology Research and Development Request for Information on Digital Twins Research and Development, June 18, 2024.

Request for Information on the National Digital Twins R&D Strategic Plan

Hashim Shaik
Irene Tsapara

[redacted]

Melissa Cornelius
[redacted]
July 25, 2024

Re: RFI Response: Digital Twins R&D Plan

Dear Ms. Cornelius,
On behalf of the National University, we are pleased to submit our response to the Request for Information (RFI) on the National Digital Twins R&D Strategic Plan. Our institution has extensive experience in [relevant field], and we believe our insights will contribute significantly to its development.
We appreciate the opportunity to provide input and look forward to collaborating further on this important initiative.

Sincerely,

Hashim Shaik
Ph.D Candidate
[redacted]

Irene Tsapara, Ph.D
Academic Program Director – Ph.D Data Science program.
[redacted]

National University

[redacted]

Digital Twin Representation of Foliage Through Computer Vision, Aerial Image Analysis and Machine Learning techniques to enhance the Network Planning and Deployment Problem

In telecommunications, the emergence of millimeter-wave (mmW) networks is a pivotal development aimed at fulfilling the surging demand for greater bandwidth, enhanced throughput, and minimized latency (Abdullah et al., 2020; Hong et al., 2021). This progression is vital for the progression of 5G wireless networks to meet the escalating needs of the mobile industry. However, mmW networks are challenged by issues like signal scattering, atmospheric absorption, and the obstruction caused by foliage and building structures; these are critical to navigating the successful roll-out of 5G networks, ensuring optimal coverage and data speeds. (Barb et al., 2022; Bose et al., 2024; N. A. Khan & Schmid, 2024; Pradeep et al., 2021; Y. Zhang et al., 2019).

The process of accurately capturing foliage data, crucial for the deployment of high-frequency networks like mmW, has traditionally relied on costly and time-consuming methods such as Light Detection and Ranging (LiDAR) and unmanned aerial vehicles (UAVs) (Q. Chen et al., 2022). However, the dynamic nature of our surroundings and the need for frequent data updates make traditional methods less viable for continuous application (Gaspari et al., 2022). In contrast, digital twin technology, with its adaptability and versatility, offers a groundbreaking alternative (Attaran & Celik, 2023)

Digital twins have emerged as a game-changing strategy with applications across various sectors, including urban development and industrial operations, particularly in the planning of wireless networks (T. Deng et al., 2021; Gabriele et al., 2023). One of the most promising applications of digital twin technology is in the detailed modeling of foliage or vegetation. By creating a virtual representation of the natural environment, focusing on the variety, distribution, and properties of plant life, digital twins provide network planners, environmental experts, and other stakeholders with a comprehensive understanding of how vegetation influences signal behavior, including path loss and network coverage, in high frequency mmW networks crucial to 5G and 6G technology (L. et al., 2022; Kuruvatti et al., 2022).

The sample image (Figure 1) depicting a digital twin representation of an urban area has been created for illustration purposes. It includes 3D models of buildings, streets, and foliage, presenting a clean and simplified city landscape that could be used for architectural visualization or city planning simulation. The design conveys a modern and futuristic tone, indicative of advanced urban planning and smart city concepts (T. Deng et al., 2021; Shahat et al., 2021).

National UNIVERSITY

[redacted]

Proposed Solution

Accurate modeling of foliage's channel propagation is vital for wireless network design, particularly in rural, suburban, and urban environments. The blockage effects of foliage, especially at mmW frequencies, can be severe because of the comparable size of leaves and branches to the transmitted signal wavelength. Overcoming these challenges is crucial to developing reliable channel propagation models that effectively consider foliage's impact on wireless communication systems (Anzum, 2021; Chikhale et al., 2022; Lai et al., 2023). Network operators must consider all these factors while deploying mmW technologies (5G, 6G) to improve user coverage and throughput.

Currently, foliage data is acquired using costly methods such as UAVs and LiDAR, requiring substantial physical effort (Q. Chen et al., 2022; Hematang et al., 2022; Mazzacca et al., 2022; Shen et al., 2023; Suhaizad et al., 2023). The continuous growth and transformation of foliage necessitates regular data collection to keep information current. The impracticality of repeating these tasks for regular foliage updates becomes clear because of their high cost, labor, and resource intensity. A more cost-effective and efficient approach involves leveraging Google Street View and satellite images in conjunction with state-of-the-art computer vision, image analysis and machine learning models for object detection (Aikoh et al., 2023; Sun et al., 2023; Y. Zhao et al., 2023), presenting a promising way forward to address the challenges on collecting foliage or vegetation data.

As foliage is one of the main characteristics impacting the higher frequency like mmW network deployment, this study addresses the problem of providing foliage information by creating a digital twin (DT) of an environment with foliage with which network operators planning to deploy networks with higher frequency can use in their network planning to place the nodes at right locations for better coverage and user experience (Gabriele et al., 2023; Nguyen et al., 2021; Qi & Tao, 2018; Thuvander et al., 2022; D. Zhao et al., 2022).

The aim is to develop a sophisticated digital twin that mirrors the physical environment, particularly integrating detailed foliage information (Lai et al., 2023; Pradeep et al., 2021; Y. Zhang et al., 2019). The digital twin will serve as a critical tool for network operators, enabling them to estimate the path loss attributed to foliage within the context of high frequency mmW network planning (Lai et al., 2023). Such estimations are pivotal for optimizing network performance and reliability in environments where vegetation can significantly impact signal propagation (Farooq & Lokam, 2023; Pradeep et al., 2021; Y. Zhang et al., 2019).

[redacted]

In order to accomplish this, a machine learning model based on computer vision will be used, which will be meticulously trained on a large dataset of foliage imagery. This model will employ advanced instance semantic segmentation techniques to identify and categorize foliage or vegetation within images. The study will dissect images into precise regions or objects using image segmentation, classification, and object detection methodologies (J. Chen et al., 2021; He et al., 2018; Sun et al., 2023; Y. Zhao et al., 2023).

This approach enables a pixel-level analysis of each scene, facilitating a deeper understanding of the vegetative elements within the digital twin environment (Jiang et al., 2023; Savelonas et al., 2022). The study will explore the nuanced interactions between vegetation and signal propagation, offering network operators a robust framework for mitigating the adverse effects of foliage on mmW network signals (De Beelde et al., 2023; Pradeep et al., 2021; Y. Zhang et al., 2019). This comprehensive approach representing foliage in a DT aims to bridge the gap between theoretical network planning and the practical challenges of natural vegetation, fostering more resilient and efficient communication networks in the face of environmental obstacles. The study will utilize aerial and street view imagery from broad geographic areas in the regions where building of digital twin takes place.

The following sources are used to collect the aerial (satellite) images and street view images:

1. Maps Static API from Google (Google Maps Platform Documentation | Maps Static API | Google for Developers) (Google for Developers Maps Static API, n.d.).

2. Street View Static API from Google (Google Maps Platform Documentation | Street View Static API | Google for Developers) (Google for Developers Street View Static API Overview, n.d.).

3. Google Earth (https://earth.google.com/web/)

a. The following open source, Open Street Map (OSM), Java Open Street Map (JOSM), is used to collect information on streets, roads, and building outlines.

4. Open Street Map (https://www.openstreetmap.org/)

5. Java Open Street Map (https://josm.openstreetmap.de/)

Proposed Framework and Methodology

[redacted]

The framework for employing digital twin technology in enhancing mmW network planning and deployment pivots around the Cross-Industry Standard Process for Data Mining (CRISP-DM) process model (Blume et al., 2020; Hayat et al., 2023). This framework is specifically tailored to address the unique challenges posed by foliage in urban and suburban environments, which can significantly impact mmW signal propagation due to its high frequency and susceptibility to attenuation by physical obstacles, such as trees and dense vegetation (Barb et al., 2022; De Beelde et al., 2023; Rogers et al., 2020). The digital twin representation of foliage, built upon the CRISP-DM framework, is a foundational tool for simulating and analyzing the interaction between mmW signals and urban foliage, facilitating optimized network infrastructure placement and configuration. This initial phase is crucial for delineating the scope and objectives of the mmW network planning project, with a specific emphasis on understanding how foliage impacts signal integrity and network performance (Lai et al., 2023). The aim is to leverage the digital twin to simulate real-world scenarios, thus enabling network engineers to preemptively identify and mitigate potential signal interference or blockage caused by vegetation. Identifying the specific needs, such as improving telecommunications infrastructure, enhancing urban green spaces, or optimizing environmental conservation efforts, will dictate the direction of the subsequent phases.

The second phase involves an initial data collection and familiarization process. For foliage digital twins, this entails gathering high-resolution aerial and street view imagery (Aikoh et al., 2023), LiDAR data, and any available UAV survey data (Q. Chen et al., 2022). Understanding the types, densities, and heights of foliage within the proposed network area is essential for assessing potential mmW signal attenuation or reflection issues. The following Data collection phase is Data preparation. This phase prepares the data for analysis, which may involve cleaning, selecting subsets, constructing data sets, annotating, and formatting data to suit the modeling needs (Dutta & Zisserman, 2019). Given the complexity of urban environments and the diverse data sources involved, this stage is critical for ensuring that the inputs to the machine learning models are of high quality and appropriately structured for detecting and analyzing foliage (J. Chen et al., 2021; He et al., 2018; Sun et al., 2023; J. Zhang et al., 2021; Y. Zhao et al., 2023). With the data prepared, various modeling techniques are applied to extract patterns and generate the digital twin representation. In the case of foliage, machine learning models such as convolutional neural networks (CNNs) or Mask R-CNN are employed to identify, classify, and analyze foliage from the aerial or street view imagery (J. Chen et al., 2021; He et al., 2018; Sun et al., 2023). This involves training models on annotated datasets, selecting the most effective models, and tuning parameters to optimize accuracy and performance (Rezatofighi et al., 2019).

Before proceeding to full-scale deployment, the models and their representations need to be evaluated against predefined success criteria, such as accuracy, reliability, and usability in practical applications (Rezatofighi et al., 2019). This could involve comparing the digital twin outputs with ground-truth data from LiDAR or UAV surveys and assessing the model's ability to represent foliage in various urban scenarios accurately. The final phase involves integrating the digital twin into the mmW network planning and deployment workflow. This enables planners and engineers to visualize signal propagation in the context of urban foliage, identify optimal equipment placement, and anticipate potential maintenance or signal-boosting requirements. The deployment also includes mechanisms for updating the digital twin with new data, ensuring it remains a relevant and effective tool for mmW network optimization (Rogers et al., 2020). By focusing on the unique challenges of mmW network planning in environments with significant vegetation, the CRISP-DM-based digital twin represents a targeted approach to enhancing network reliability and performance. Through detailed simulation and analysis of foliage interactions with mmW signals, network planners can make informed decisions that optimize coverage and capacity while minimizing interference and attenuation, thereby ensuring robust, high-speed wireless connectivity in urban and suburban settings.

Figure 1
Digital Twin Representation of Foliage – Example

[redacted]

The current approach focuses on constructing a digital twin model to represent foliage in various environments, leveraging cutting-edge computer vision and machine learning techniques. The flowchart in Figure 3 outlines the process for constructing a Digital Twin model of foliage, starting with the region of interest as the initial input.

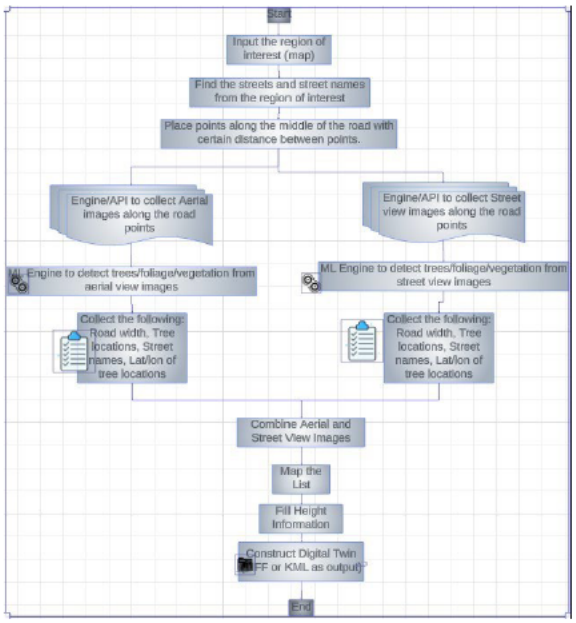
The significance of the digital twin representation of foliage primarily revolves around its pivotal role in advancing network planning and deployment strategies, especially pertinent to the challenges posed by urban environments on telecommunications infrastructure. This research is critical as it provides a novel approach to understanding and mitigating the impact of urban foliage on signal propagation, a significant concern for the deployment of high-frequency networks such as 5G and beyond (Barb et al., 2022; De Beelde et al., 2023; Lai et al., 2023; Pradeep et al., 2021; Y. Zhang et al., 2019). By creating virtual replicas of urban landscapes that accurately reflect the spatial distribution and physical characteristics of foliage (Attaran & Celik, 2023; Kuruvatti et al., 2022; Shahat et al., 2021), network engineers and planners can simulate and analyze how vegetation impacts network performance, leading to more informed decision-making and optimized network designs.

We want to provide a data-driven framework that can be used to improve the accuracy of predicting signal interference caused by foliage and thereby identifying the suitable locations for mmW node placements, which provides increased network coverage and user data connectivity (Abdullah et al., 2020; Pradeep et al., 2021; Y. Zhang et al., 2019). The research methodically applies machine learning and computer vision to create digital twins that serve as a sandbox for testing various network configurations and their interactions with urban greenery. This approach not only improves the reliability of network services in densely vegetated areas but also assists in identifying ideal locations for network infrastructure, minimizing environmental disruption and costs associated with physical trials (Rogers et al., 2020).

Several studies highlight the potential for digital twins to contribute to more sustainable urban development practices (Attaran & Celik, 2023; T. Deng et al., 2021; Kuruvatti et al., 2022; Shahat et al., 2021). The interaction between urban green spaces and network infrastructure can help planners design strategies that protect and enhance vegetation while ensuring technological advancement. Keeping this balance is essential for future smart cities since connectivity needs to be harmonious with the conservation of the environment and aesthetics in the urban context (Pradeep et al., 2021; Y. Zhang et al., 2019). The research enriches the data science literature by highlighting an innovative application of digital twins grounded in rigorous data analysis and modeling. It advances the telecommunications field by providing a novel tool for addressing one of the key challenges in network deployment (Bose et al., 2024; Pradeep et al., 2021), offering insights directly applicable to the design and optimization of next-generation wireless networks.

Figure 2

Flowchart: DT Representation of Foliage (AI-Driven Foliage Detection Using ML & CV)



Business Case Analysis

Implementing a digital twin representation of foliage in urban areas offers a transformative approach to urban planning, environmental monitoring, and resource management. By leveraging advanced technologies like satellite imagery, street view images, and LiDAR data, this project aims to create a comprehensive and accurate digital model of urban vegetation. This business case analysis evaluates the research cost, the potential value and return on investment (ROI), and the cost and time required for implementation.

Timeline and Implementation of Digital Twin Representation of Foliage

Stage	**Duration**	**Timeline**
Stage 1: Data Acquisition	3 months	Month 1 - Month 3
Stage 2: Data Processing	4 months	Month 4 - Month 7

[redacted]

Stage 3: Model Development	6 months	Month 8 - Month 13
Stage 4: Deployment	2 months	Month 14 - Month 15
Stage 5: Full Implementation	1 month	Month 16
Total	16 months	

Business Case Analysis Summary for Digital Twin Representation of Foliage

Focus Area	**Details**	**Cost**
Foundational Research Cost		
Data Acquisition	Satellite imagery	$50,000
	Street view images	$50,000
	Other sources of data (LiDAR/UAV/OOKLA)	$100,000
	Total Data Acquisition Cost	**$200,000**
Data Processing and Storage	Image processing software and tools	$75,000
	Cloud storage & computational resources	$100,000
	Total Data Processing and Storage Cost	**$175,000**
Research and Development	Personnel costs (data scientists, GIS specialists, software developers)	$500,000
	Research materials and supplies	$50,000
	Total R&D Cost	**$550,000**
Miscellaneous Expenses	Project management	$50,000
	Contingency fund (10% of total cost)	$97,500.0
	Total Miscellaneous Expenses	**$147,500.0**
Total Foundational Research Cost		**$1,072,500.0**

[redacted]

Summary

This constructive research design aims to bridge the gap between theoretical computer vision techniques and practical applications in digital twin technology for foliage representation. This multidisciplinary approach, combining remote sensing, computer vision, machine learning, and digital twin technology, offers a comprehensive method for accurately representing foliage in digital models, which is essential for effectively planning and deploying next-generation wireless networks. The study seeks to offer a cost-effective, scalable, and accurate tool for urban planners and network engineers (Alkhateeb et al., 2023; Fett et al., 2023; Kuruvatti et al., 2022; Lehtola et al., 2022). The approach is grounded in rigorous data analysis, ethical considerations, and acknowledging its scope and limitations. It sets a foundation for future advancements in digital twin technology and its applications in innovative city development and environmental monitoring.

The current research significance of digital twin representation of foliage, utilizing computer vision image analysis methods, compared to traditional approaches like LiDAR and UAV, stems from its capacity to overcome inherent challenges and constraints in conventional methodologies. Traditional techniques such as LiDAR and UAV surveys are often cost-prohibitive (Rogers et al., 2020), labor-intensive, and require extensive human involvement for data collection and processing (X. Deng et al., 2022; H. Li et al., 2021). Moreover, these methods could be more extensive in their coverage, resolution, and ability to maintain up-to-date information. In contrast, the digital twin representation of foliage harnesses advanced computer vision, AI, and machine learning techniques to analyze aerial and street view imagery. This approach offers several advantages, including cost-effectiveness, scalability, and the potential for real-time or near-real-time data updates (Attaran & Celik, 2023; Mylonas et al., 2021).

By automating foliage detection and analysis, digital twin representation enables swift and accurate data collection, facilitating more efficient network planning, urban development, and other applications. The impetus behind developing a DT representation of foliage arises from the escalating demand for precise and current foliage information across diverse sectors, encompassing telecommunications, urban planning, and environmental conservation. Industry reports and white papers underscore the critical role of digital twin technology in optimizing telecommunications infrastructure and enhancing service quality (Alkhateeb et al., 2023; L. U. Khan et al., 2022; Kuruvatti et al., 2022). Several government initiatives, including ones aimed at sustainable urbanization and environmental

[redacted]

stewardship, emphasize using digital twins to inform data-driven decision-making (Mylonas et al., 2021; Shahat et al., 2021).

Digital twins in urban and city planning will significantly displace traditional methods, like LiDAR and UAVs. The benefits include improved data integration, faster iterations, sustainability, and innovative city applications. AI and computer vision are driving the development of digital twins, which can be used to solve the challenges and limitations of conventional methods, offering more efficient, cost-effective, and scalable solutions.

References (Upon Request)

Federal Register Notice: 89 FR 51554, Federal Register :: Networking and Information Technology Research and Development Request for Information on Digital Twins Research and Development, June 18, 2024.

Request for Information on the National Digital Twins R&D Strategic Plan

Herbert Sauro

Via FDMS

Herbert Sauro, 7/22/2024

[redacted]

I’m surprised that the NSF is considering this request for developing digital twins since it requires a highly disciplined approach and not the cottage industry like approach we now use for model development in the biological sciences. NSF has never championed data or model standards or funded advanced modeling of biological systems at the sub cellular or multi scale level. The NSF has not funded the required theoretical underpinnings for this work either. The workforce is also woefully inadequate and there are few high quality research groups in the US with the requisite skills or broad knowledge and understanding of what it might take. Europe, on the other hand has invested in these areas. In addition, the use of new AI needs to be carefully thought out since AI not only provides, black box solutions with unknown failure modes, but without proper validation, AI responses can be unreliable. Unleashing this in a clinical situation could be problematic. The key to this is building a model credibility assessment system without which there’s no way to determine quality of a given digital twin. I’m sorry to sound so negative but this is the landscape I see.

Federal Register Notice: 89 FR 51554, Federal Register :: Networking and Information Technology Research and Development Request for Information on Digital Twins Research and Development, June 18, 2024.

Request for Information on the National Digital Twins R&D Strategic Plan

International Business Machines (IBM) Corporation

International Business Machines (IBM) Corporation

July 26, 2024

Networking and Information Technology Research and Development (NITRD) National Coordination Office (NCO), and National Science Foundation (NSF)

Response to Request for Information on National Digital Twins Research and Development Strategic Plan

In Response to Federal Register Notice: 89 FR 51554

Submitted to:
Melissa Cornelius
[redacted]

Submitted By:
Stephen Piper
International Business Machines Corporation ("IBM")
IBM Consulting
[redacted]

This document is approved for public dissemination. The document contains no business-proprietary or confidential information. Document contents may be reused by the government in the National Digital Twins R&D Strategic Plan and associated documents without attribution.

IBM Consulting is a global leader in technology and consulting services and brings a wealth of experience across the entire spectrum of projects in Digital Twin technology. IBM Consulting has helped organizations in developing their enterprise strategy for Digital Twins, helped organizations with Digital Twin maturity assessments, frameworks, roadmap planning and prioritization, developed point solutions for specific use cases leveraging Digital Twins, and created full-scale Digital Twins of physical environments with real-time bi-directional data flow. IBM is a leader in this field, and we have over 50 years of experience in connected operations technology with more than 900 IBM Consulting practitioners in Digital Twin services alone. IBM Consulting has been ranked # 1 in Digital Twin services by Everest PEAK Matrix 2022 and 2023 and has assisted 6,000+ clients through our Connected Operations and Digital Twin global practice. At IBM, we also leverage our IBM Research colleagues to develop powerful assets to fast-track innovation and harness emerging technologies for solution development and deployment. With the powerful backing of our experience and expertise, we are pleased to provide perspective on areas which the strategic plan should focus. IBM has chosen the topics below as the focus of our response:

1. Digital Twins to drive Sustainability

IBM believes that Digital Twin technologies will play a significant role in the process of decarbonization, and additional research funding in this space is expected to yield net positive outcomes for humanity. Several key focus areas are detailed below:

1.A - Digital Twin of Ports

According to the Transport and Environment Organization, the shipping industry contributes approximately 3% of global carbon emissions, with expectation to rise to 10% of all global emissions by 2050 and hence this is a key area for research[1].

[1] https://www.transportenvironment.org/topics/ships/climate-impact-shipping#:~:text=What%20is%20the%20impact%20of,emissions%20–%20the%20same%20as%20flying

Digital Twins have shown benefits in reducing carbon emissions using a digital twin of a port to enhance real time operations including optimizing ship berthing time and routing to minimize idle time of ships in the harbor. The IBM solution for this use case features functionality to coordinate pilots, tugboats, captains of the ships, and parties onshore. The solution delivers the application for the harbor master (ships, charts, routes, GPS, sensors all powered by real-time data) and drives intelligence into the operations to enhance safety, **sustainability,** and service. IoT sensors, Augmented Intelligence (AI) and smart weather data measure things like the availability of berths and accurate water (hydro) and weather (meteo) data to allow shipping companies to **predict the best time to enter the port by identifying the most favorable conditions.** With the new digital twin dashboard, the port can view operations of all parties at the same time and increase efficiency of shipped goods that pass through the port.

The solution optimizes Port of Call Services through Real-Time Tracking of vessels arriving and leaving port, along with their size, cargo types, container types; the solution also allows for simulating the unloading of cargo into each port, to identify where ports may be at overcapacity. The **solution includes a predictive feature to identify optimal routes for vessels arriving into port based upon fuel consumption,** arrival time, and other important dimensions which **enables safe entry into the port.**

IBM recognizes that port security supports national security. A robust and efficient supply chain is of national importance, and investment in research in these domains will yield positive outcomes through the increased use of Digital Twins for advanced visibility and monitoring of real time operations to secure the supply chain.

1.B - Digital Twin of Shipping Vessels

In addition to creating Digital Twins for ports, to assist in tracking shipping vessels and optimizing port operations, another critical focus area in the shipping industry is developing Digital Twins for ships. IBM solution for a global energy provider with a large fleet, helps the client facilitate remote monitoring and performance/voyage analytics, aiming to optimize fuel consumption. The Digital Twin of the vessel is created using IoT and visual sensors to transmit data ashore in real-time for performance monitoring and live voyage analytics. Additionally, the solution equips the ship's machinery with IoT sensors to monitor key parameters and ensure operational efficiency. The solution reduces overall fuel consumption through improved monitoring, and hence performance of the ship's machinery and understanding of weather impact on shipping performance and routing. The improved visibility and monitoring of the ships machinery enables the onshore teams to carry out condition-based maintenance using predictive data analysis from data captures through the digital twin; the proactive condition-based maintenance results in increased efficiency of the equipment, decreasing maintenance costs, reducing unscheduled downtime, and **most critically, reduces failure during voyage**. The twin also helps with **improved carbon emissions tracking**. In addition to sustainability improvements, the client notes the **digital twin of the ship enables improvements in crew safety, and vessel security**.

1.C - Digital Twins in Manufacturing

According to research conducted by the Boston Consulting Group, the Consumer-Packaged Goods (CPG) industry will play a central role in the ultimate success or failure of decarbonization efforts because the agri-food supply chain (in which CPG is a prominent player) accounts for an estimated 31% of annual global GHG emissions.[2]

IBM's work with a leading global consumer packaged goods (CPG) organization to advance their factory of the future project, which is part of their broader Industry 4.0 and supply chain initiatives has yielded positive results. IBM has helped the client to develop a transformation roadmap using Digital Twins technology, and to design a scalable template for global factory rollouts of Digital Twins. The platform places data and connectivity as the foundation, enabling the client to replicate digital capabilities across multiple factories

[2] https://www.bcg.com/publications/2023/why-cpg-leaders-must-reimagine-business-models

easily. IBM helped the client create a Digital Twin of the factory and its underlying assets to support three primary use cases: Overall Equipment Effectiveness (OEE), factory maintenance, and energy efficiency and sustainability. The solutions are designed for ease of use and ensure data visibility from the factory floor to the boardroom. The IBM solution helps enhance and improve operational and manufacturing efficiency by improving visibility of real-time operations through the "Connected OEE" solution, which automatically collects productivity data and provides monitoring of factory assets. Operators now have access to real-time information at their fingertips through a powerful digital UI. The increased visibility to equipment data is brings insight for root cause analysis that drives significant productivity gains. The client also wanted to improve energy efficiency by connecting their energy meters to the cloud platform. Now, **site managers use digital twins / dashboards to track energy use, spot trends or anomalies, and track their progress towards ambitious sustainability targets**. The solution has resulted in 3% decrease in electric power consumption annually.

1.D - Digital Twins in Infrastructure

IBM, in collaboration with Autostrade Tech Group, developed a Digital Twin system for road network security and infrastructure monitoring. The client, an integrated mobility manager responsible for maintaining infrastructure across road networks in Italy, faced significant challenges in collecting asset information, visualizing current data and asset status, and comparing this information with historical data. This comparison was crucial for understanding asset degradation and planning maintenance and replacement of infrastructure-related assets. The newly built Digital Twin platform uses IBM AI, drones, IoT (Internet of Things) and 3D digital modeling to deliver innovation in the surveillance and monitoring activities of the more than 4,500 structures managed by the client including bridges, viaducts, flyovers and tunnels, resulting in improved efficiency and transparency in these processes. The system also introduces advanced technologies never used before on

Italian road networks, i.e., **the ability to analyze a structure through three-dimensional Digital Twins**. These Digital Twins reproduce a structure's features using drones equipped with topographic laser-scanners and high-resolution cameras, which can then be analyzed by AI to assist in the detection of imperfections. This visual defect detection model is specifically developed to support technicians to recognize and classify defects and better plan maintenance activities.

The platform improves the process of conducting civil infrastructure inspections in several ways. Engineers can carry out inspections on the condition of each structure and access key information in the field via a mobile device updated in near real time, including calculations and drawings of the original project and subsequent interventions; scheduled checks and maintenance; investigations and tests on materials; and the results and details of previous inspections. Additionally, the solution traces and manages the various steps necessary for the care of each structure, from inspections to planning and maintenance following activities according to the priority criteria developed with the Ministry of Infrastructure and Transportation.

The work in building a Digital twin of the network infrastructure, modeling & 3D reconstructions of different assets and building maintenance assistance for engineers helped the client **increase the total lifespan of the assets by decades**, hence **reducing thousands of tons of CO_2 emission** related with decommissioning and reconstruction of such large infrastructure assets.

As outlined in the above use cases, IBM has witnessed the power of Digital Twins in sustainable development and sustainable supply chains; a continued and sustained investment in R&D to further enhance Digital Twin implementations for sustainability should be considered by the NITRD.

2. Digital Twins and Smart Cities

IBM believes that Digital Twin technologies will play a significant role in improving city operations, both from the viewpoint of the city manager and city inhabitants, and additional research funding in this area is recommended. Vision for smart cities start with smart manufacturing and smart supply chains, and a couple of key pointers are detailed below:

2.A – Smart Supply Chains

Effective city planning is a critical matter that impacts the life of residents in meaningful ways – not the least of which is the efficient movement of people and products across the city. IBM has been involved in the design and development of a new purpose-built urban area in Saudi Arabia which is a state-of-the-art model for digitally enabled smart supply chain. The total planned area of the city is 26,500 km^2 and IBM is helping with the smart supply chain strategy as well as building Digital Twins.

IBM **created a Digital Twin simulation platform by utilizing scanned point-cloud images** and fusing together using AI based mesh generation and segmentation. The GenAI based model and texture generation, and environment interaction reduces the simulation to real gap with visually and physically accurate replicas of the real-world environment. The client was able to use the **Digital Twin environment to train a hybrid fleet of autonomous robots for various use cases including last mile delivery**. In typical scenarios, the training of robots in a new environment takes 3-6 months without trustworthy GPS data, but the use of the powerful Digital Twins of the environment to train robots fast-tracked the training time significantly. The faster training of the autonomous robots in the Digital Twin environment was made possible through the richer 3D experience and seamless execution of testing and training scenarios. Cities such as the City of Singapore, and the City of Madrid are some other examples of cities across the world that have invested heavily in creating the Digital Twin of the city for improved services and decisions across their operations.

2.B - Smart Manufacturing

IBM created an Assembly Digital Twin for a leading aircraft manufacturer to help significantly optimize assembly line operations through reduction in cycle time. The Original Equipment Manufacturers for doors and fuselages manufacture the parts with a considerable tolerance to maintain economic viability of their process, and these parts are never perfectly identical causing delays on the final assembly line at the aircraft manufacturer. Final assembly is one of the most important steps in the aircraft building process, and its quality determines reliability and service life of the aircraft directly.

IBM made **Digital Twins of aircraft doors and fuselages consisting of 3D geometry models** (as-designed) **and 3D laser measurement data** (as-manufactured) and these twins are processed in a digital world to match best fitting components together. The analysis output is automatically communicated to the assembly line for optimum mix and match of the components to ensure near perfect assembly of these components with the rest of the aircraft body resulting in significant reducing in re-work and cycle time of operations.

Additionally, IBM has our own manufacturing facility in the United States producing mainframe servers that power the most mission critical processes for key industries globally. IBM Consulting has created an **immersive Digital Twin of the IBM Server manufacturing facility to model, simulate and test innovations** across the manufacturing environment. IBM scanned and built 3D models of the assets as the site did not have existing models to use in the Digital Twin. IBM then created the Digital Twin environment bringing data from various sources and integrating operations data as well. To further **enhance the usability of the Twin, IBM infused AI based simulations to enable faster decision making** that is supported by real-time data and effective visualizations.

Manufacturing critical products such as aircrafts and servers within the borders of the United States is of national importance, especially given the rising challenges with supply chain security. This becomes even more pronounced with the ever-increasing scrutiny from the public on civil aviation safety – use of the Digital Twin technology has shown improvements in the assembly of such products as it enables the manufacturer to enhance system/subsystem reliability and useable lifespans.

3. AI, Trust, and Responsible use of Digital Twins

IBM is a leader in trustworthy AI and our flagship product, WatsonX.governance is a full lifecycle governance methodology to manage, monitor and govern AI models. IBM champions responsible use of technology and prioritizes compliance as well as "do not harm" approach to technology implementations in Digital Twins and beyond. IBM recognizes the compounding power of bringing together exponential technologies but realizes the importance of responsible use of technology as detailed in below examples:

3. A – AI integrations with Digital Twins

A Digital Twin that is powered by an intelligent agent can compound the impact of the technology, especially when it is used in use cases where direct human intervention is dangerous/slow/ineffective. As an example, IBM collaborated in creating the Digital Twin of a ship powered by an AI captain, which converted the ship into an autonomous research vessel for real-time **monitoring of the ocean**; this has shown improvements in data collection across the waters, and **improved decision-making efficiency "on-board",** leading to reduced carbon emissions as well.

Covering 71% of the Earth's surface, the ocean generates more than half of the world's oxygen, regulates global climate and provides a heat sink to reduce the effects of global warming. However, despite the ocean's enormity, it is not immune to human activity and today, the ocean is more polluted, warmer, more acidic and stormier than ever. Nevertheless, gathering data about a system as vast and complicated as the ocean is enormously expensive. Conducting research in an environment as unforgiving as the ocean also puts ships and crews at high risk. The practical impact of this cost and risk is that vast areas of the ocean's surface remain unexplored. Huge gaps in knowledge persist about climate change, plastics pollution, habitat degradation, marine life conservation and other important topics. Autonomous research vessels — integrated with other shore-based, ship and satellite networks — can collect data about the ocean at a scale and cost-effectiveness far beyond what is possible with today's relatively small fleet of crewed research vessels. While the autonomous shipping market is set to grow from USD 90 billion today to over USD 130 billion by 2030, many of today's autonomous ships are just automated robots which do not dynamically adapt to new situations and rely heavily on operator override.[3]

IBM partnered with a marine research and exploration organization to develop a **research-first, true autonomous ship** that has no human captain or onboard crew **and uses AI** and the energy from the sun to travel across the Atlantic collecting data and revealing more about the ocean. Using the integrated **set of IBM's Digital Twin of the vessel, AI, cloud and edge technologies**, the autonomous research vessel set a new course for ocean research by operating independently in some of the most challenging conditions on the planet.

IBM understands the importance of the blue economy, and of securing United States vessels and personnel while on the sea, and investment in research for expanded usage of Digital Twin in these domains is recommended.

3.B – Digital Twins for Serious Gaming

Serious games can be defined as any piece of software that merges a non-entertaining purpose (serious) with an immersive video game structure (game). The purpose of the game could be message-broadcasting, designed to broadcast educative, informative, persuasive, and/or subjective messages. **Serious gaming is a form of advanced simulation (Digital Twin)**, but it differs from traditional simulation in that player decisions could guide the

[3] https://www.ibm.com/case-studies/mayflower

progression of the simulation, and is powered by Digital Twins, AI/ML/Decision Optimization to assist the player to make more effective decisions, providing recommendations and/or real-time impact assessment of choices.

There are several use cases for using an immersive Digital Twin environment including:
1. Citizenry outreach to support civic learning and engagement to crowdsource solutions

2. Workforce training as it provides a safe environment to practice skills with little risk

3. Operational war planning in defence activities

4. Emergency management, e.g. improve nursing students understanding of COVID-19

For the US government - obviously a very highly regulated industry - finding specialized tech partners that can ensure the model risk management framework meets supervisory standards and that these standards are adopted by procurement offices such that they know exactly what kinds of audits, and features/function they need to see in AI models to meet standards is critical. **Earning trust in serious games (and certainly Digital Twin and AI in general) is important** and further funding for research and collaboration with private organizations (such as IBM) is essential.

Conclusion:

As with other fast-advancing technology, Digital Twins have the capacity to play a pivotal role in driving development and improving outcomes for the United States, across sectors and use cases. IBM's Digital Twin solutions in sustainability, smart operations, and AI and Trust highlight the transformative potential of these technologies.

As we look to the future, sustained investment in research and development in the right areas is crucial for furthering these advancements and maximizing their benefits. IBM remains committed to leading this charge and supporting the strategic initiatives necessary for extending Digital Twin innovation.

Federal Register Notice: 89 FR 51554, Federal Register :: Networking and Information Technology Research and Development Request for Information on Digital Twins Research and Development, June 18, 2024.

Request for Information on the National Digital Twins R&D Strategic Plan

Commenting Organizations:

Idaho National Laboratory

National Renewable Energy Laboratory

Pacific Northwest National Laboratory

Fermi National Accelerator Laboratory

Argonne National Laboratory

Princeton Plasma Physics Laboratory

Response to NITRD RFI on Digital Twins Research and Development

Commenting Organizations:
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1. Artificial Intelligence (AI):

1.1. Integration of Digital Twins (DT) with AI

Integrating machine learning (ML) models with DTs has a profound gestalt enhancement, and more research is needed to realize these benefits for diverse national assets (facilities, laboratories, and their key systems). For example, a DT's utility can be greatly augmented by adding a fast-executing, lower-fidelity "data-only" prediction capability that is computationally cheaper than using higher-fidelity, slower-executing physics-based simulations. For example, in real-time control applications on complex, nonlinear problems such as controlling traffic lights in a city to reduce the emissions created from traffic, reinforcement learning based on pre-trained ML models could be deployed to map the state of the system to the control action to be taken, which may be quicker, yet perhaps less accurate than, say, deploying a high-fidelity simulation. These lower-fidelity models may be purely data-driven and trained from data gathered by the physical device, or trained using simulation data produced by higher-fidelity physics models.

DTs can also leverage AI surrogates built using a mixture of many lower-fidelity simulations complemented with higher-fidelity simulations. Advancements in AI models such as diffusion models enable comparing higher-dimensional data (e.g. video) between the digital and physical assets. Investment in the development of these capabilities to integrate simulations of different fidelities and AI architectures for physical-world realistic comparisons will greatly enhance the generalizability of DTs.

Integrating ML models with DTs can also enable real-time anomaly detection. ML algorithms can be trained to identify irregularities in data that deviate from the norm. Unlike traditional anomaly detection methods that compare the incoming data to a predefined threshold value, AI anomaly detection relies on complex models that can adapt to changing underlying conditions and can accommodate situations where many different variables impact the anomaly being detected. Despite its benefits, several challenges in integrating anomaly detection methods with DTs remain. Investment is needed to ensure that methods for data-driven anomaly detection that are integrated with DTs are secure, safe and assured. In addition, there is a need to better understand how DTs can be used in combination with risk analysis methods for identifying anomalies that can't be easily anticipated.

When integrated with DTs, ML technology can also be used in applications where systems performance needs to be optimized. In high-complexity assets such as particle accelerators, high-throughput scientific computing, and the civil infrastructure of large facilities, we find all of these

DT-plus-AI applications, as well as a need for using DTs in the context of control and forecasting when maintenance is required. In applications such as cryogenic facilities where the effects of control actions take long and variable times to observation, the predictive function of a DT may be used by the controller to take precise action without over- or under-correcting. For all of these applications, investment is needed for both research and implementation.

1.2. Generative AI for DT Modeling & Simulation

Investment is needed in the application of generative AI to augment data from physical systems. In many applications there is a lack of data, and this is a hindrance to optimal decision making. In some applications, collecting data is highly resource intensive, and collecting a sufficient amount of data for calibrating models that underlie DTs is hardly possible. In other applications, one may wish to deploy DTs for a wide variety of scenarios, with particular interest in scenarios that have not been observed in the past, but that could have huge implications for resiliency and planning. For such cases, generative AI capabilities are highly relevant. If generative AI can create data to reliably fill in data-sparse regimes, whether rare or simply prohibitively costly, we will be able to better calibrate models and understand behaviors of the system in unexpected and rare settings, increasing resilience and safety. Yet this work remains to be researched.

1.3. AI Trustworthiness

The use of AI in DTs can enable safety because different (AI-generated) scenarios or underlying data driven models allow to explore a wide range of possibilities. However, with AI models mostly being black boxes that lack explainability, there is a danger that blindly relying on AI within DTs may not be safe. Especially when exploring scenarios that have never been seen before (but that are plausible), the amount of trust put into AI should be limited as AI models are known to not extrapolate well. To this end, when leveraging AI models in DTs, uncertainty quantification methods must be integrated that will accurately reflect how trustworthy a DT based on AI is.

In addition, explainable AI methods and techniques offer insights into the decision-making process of AI, creating transparency and understanding around a particular decision or prediction. Explainable AI plays a key role in enhancing accuracy and reliability of AI models. By providing developers insights into the decision-making process of their models, these tools allow them to identify and rectify flaws within the model. Although AI models themselves are computationally cheap, explainable AI tools are computationally expensive, challenging real time implementations.

2. Data:

2.1. Data Collection

DT reusability depends heavily on data collection practices. Data collection frameworks used today vary between domain applications, and even within domains, due to a lack of guidance on best practices. There is a need for governance on communication protocols, that bring DTs closer to real-time and to industrial standards, that can be reusable across DT applications. Often data is collected through domain specific enterprise level data management software and vary from system to system. The enterprise software consumes proprietary data and codes that are not shared with external parties. It would be beneficial to develop a template for non-disclosure agreements that third parties can sign up to access the data and code for the larger good of the domain.

2.2. Data Curation and Provenance

Data and metadata standards and curation methods differ from domain to domain and are needed to bridge the gap between raw observed data with machine readable scientific knowledge. Although some of the data curation can be automated, often a domain expert may be required to tag and standardize the data and metadata. Once data and metadata are standardized, data may also need to be converted to common formats especially with time series data. Time should be standardized across all raw and observational data and any transformation to a common grid should use standard protocols to propagate errors and uncertainties. Standardization and curation should follow protocols to ensure that the data is Findable, Accessible, Interoperable and Reusable (FAIR). Quality Assurance/Quality Control documentation is required as one type of metadata when datasets are curated, disseminated and published. Published datasets should use persistent (i.e., digital object identifiers [DOIs]) when data are shared. The provenance of the data is important to capture in the standardized metadata to help enable reproducibility. A broad notion of data should be taken, where the data includes the DT models themselves, such as the hyper-parameters and weights for machine learning models.

2.3. Data Sharing and Usage

There is a need for investment in data sharing solutions that ensure an integrated data usage across domains and across system lifecycle phases. Data collected during system design (i.e. requirements, system assets, system functions, spatial footprint) is produced by different stakeholders within different domains and may go from micro-scale to system level scale. Traditional documents centered design data management can lead to silent errors, cost overruns and schedule delays. There is a need for the implementation of model-based systems engineering practices that provide an authoritative source of truth and enable data transfer across domains and scales. Models generated using model-based system engineering can then serve as early maturity DTs, and be used to validate the system, accelerate operator training, and produce data required for AI algorithms training and testing.

Data sharing across system lifecycle phases is equally as important as data sharing within design teams. Early maturity DTs described above can evolve into DTs that enable autonomous operation at their highest maturity level. The advancement of digital thread technology is essential for taking model-based systems engineering models out of isolation and providing an interface with external digital definitions created later in the system development process.

Data collected during system operation is produced by different domains and also need tools that enable integration and transfer of this data across models and spatial and temporal scales that support system operation (e.g., optimization models, high-fidelity physics models, reduced order models, anomaly detection models, etc.)

Some domains sensitive to national security may require that the data are not shared among users outside their project. As an example, hydropower facilities prefer to keep their operational data secure and accessible only to their operational teams. Data Management and dashboards need to be set up with the right access controls to ensure that the data is securely shared only among project members.

2.4. Shared Public Datasets and Repositories

Data is essential for training of AI algorithms and tunning control methods. While data is abundant, its format, availability and provenance are highly inconsistent. Investment in structured public datasets and repositories can enable the advancement of AI and control technology within a domain. In addition, these datasets and repositories enable cross-cutting DT development. Leveraging commonly adopted and standardized API’s to access data and metadata from publicly managed data repositories will advance the use of AI to train and validate DT for complex systems.

Having access to the underlying data and provenance helps to enable reproducibility and derive common benchmarks that can drive long-term research and development activities.

2.5. Real-Time Data Integration

DTs are widely used for optimizing operations and controlling complex systems, e.g., DFW airport terminal. To do this effectively, DTs need access to real time data, and use it in continuous recalibration and adaptation of models to adjust to system dynamics and enable decision making. This requires investment in data infrastructure and data processing tools that can integrate heterogeneous data and use it to optimize models on the fly. High performance computers and data centers as well as edge-computing will be essential for collection and further processing of data not only in real-time but also over longer timescales for recalibration of the DT. Particularly important for distributed sensor environments. Depending on the application, questions may arise as to how data changes over time, if older data could be discarded, which data are important for a certain task and uncertainty/noise associated with real time data. Historical data can also be used to predict or prescribe maintenance of complex systems. For aging complex systems such as hydropower facilities, historical maintenance data need to be digitized and may require the need to use machine learning and image processing to sort, filter, and tag data. High throughput and high volume (near-) real time data integration is critical for safety and response type applications.

3. Ecosystem:

DTs are being developed and deployed in a wide variety of scientific applications. These include materials synthesis and discovery; real time traffic control to reduce congestion in cities and reduce associated emissions; in virtual biofuels engineering; future climate modeling; offshore wind farm design and control; buildings modeling and control; modernizing electricity infrastructure and attaining 100% renewable electricity goals (e.g. LA100, PR100, LT100); buildings modeling and control; and grid resiliency.

While some of these applications appear similar in nature, there are no standards that would allow for interoperability of models, including a lack of agreed-upon communication protocols, data naming conventions, data QA/QC and other processing steps, or DT updating rules. While the smart buildings sector is increasingly using a common language to allow various sensors to talk to each other, such advances are missing in other scientific domains where DTs are developed for bespoke control actions. This leads to a lack of scalability and reusability. Moreover, even within a specific science domain, there is a variety of tools that can be leveraged leading to a potentially confusing landscape of which tool to use when and how the tool's input requirements fit with the data collection mechanisms.

3.1. Cross-cutting Collaborations

To address the challenges of interoperability, sensor communication and availability, and cascading effects of interruptions, investment in a holistic systems approach is needed. Such approaches can only be realized through tight cross-cutting collaborations that involve domain scientists from all areas, e.g. every entity that may be affected by disturbances and failures (directly and indirectly), as well as computational and data scientists who will be able to devise optimal control strategies and visualization capabilities that enable informed decisions by providing a holistic picture of the physical process under investigation.

3.2. Twin-of-Twins Demonstrations

Along with the need for investment in cross-cutting collaborations there is a need for investment in cross-cutting DT demonstrations and testbeds. Multiple DT demonstrations have been performed to this day within domain boundaries. These DT applications are built to meet their physical counterpart's needs and objectives. However, in order to overcome challenges associated with interoperability, sensor communication, and cascading effects of interruptions, the next generation of DT demonstrations will need to allow for communication between domain specific twins, that not only meet their individual system's needs and objectives, but also collaborate to meet global needs and objectives. For example, the DT of a nuclear reactor may assist operational process in maintaining high performance and enforcing security, while also communicating with the DTs of hydrogen, solar, wind and biomass systems, that coexist with the reactor in an integrated energy grid, to assist the entire system in meeting the grid's demand. For such demonstrations to take place, interdisciplinary testbeds with DTs will need to be built and be operating.

4. International:

Certain systems that may benefit from the application of DT technology cross national boundaries (e.g., air traffic control systems, supply chain systems). To overcome the challenges of interoperability and cascading effects of disturbances or interruptions at a global scale, DT demonstrations that cross national boundaries are needed. These demonstrations will require investments that support international collaborations and the establishment of international DT standards.

5. Long Term:

Long term research and development questions revolve around the updating and/or maintenance of DTs and their adaptation to changing systems or environments, e.g. add-ons of new data collecting sensors, integration of new tools, new processes, changing risk profiles, etc. The heterogeneity and multi-scale nature of the tools, models, and data that come together in a DT can be vast and require documentation to enable updates, integration, and long-term support. There needs to be a built-in flexibility in the design-build-operate cycle that allows changes and modifications, with the goal to not limit operability to the specific conditions present when the DT was first created. If funding were available to develop standards and best practices for these long-term concerns in the DT field, considerable expense could be saved.

In applications such as buildings control, traffic control, wind farm operation, user facility operation, or materials synthesis, a continuous feedback loop between the DT and the physical counterpart is used, where data informs the models in the DT. These models are currently used to inform operations or experimental control, and newly acquired data from the physical system is utilized as input to the DT for model recalibration and updating. Enabling predictive nature of digital twins, going beyond reflecting what happened in the past and what is happening now would be a natural next step. Therefore, determining what is "right" data to be collected to infer information critical for model calibration, and adaptation, and minimizing overheads arising from data transfer is essential to allow for optimal and predictive real-time controls. Moreover, the data infrastructure must be in place, e.g., in laboratory settings, the transfer of data from diagnostics instruments to the DT must be enabled, which may require infrastructure investments.

Experimental facilities have very long lifetimes and the DTs need to evolve with the technology. The existence and performance of the underlying software needs to be ensured over the lifetime of the experiment. Hence, investments in software sustainability and long-term reproducibility are necessary for DT technology to penetrate into the experimental facilities.

To ensure the benefits of DTs in the long term, it is critical to invest in developing and promulgating best practices for support, documentation, and human-in-the-loop operation, mitigating the risk to knowledge retention which otherwise threatens a DT with loss of functionality or performance.

6. Regulatory:

DTs have a role to play in regulation, if the investment is made to realize it. The compulsory licensing and regulatory process in several industries can be slow, expensive and convoluted. For instance, the currently mandated process to obtain a construction permit and operating license for a nuclear reactor can take up to decades and incur costs that escalate to hundreds of millions of dollars. From design, to construction, to operations and eventual decommissioning, the nuclear reactor goes through rigorous scrutiny from the regulator who is charged with ensuring adequate protection of public health and safety. DT technology can potentially accelerate these processes as the DT allows the regulator to virtually test scenarios, evaluate potential impacts, and verify compliance with regulations while avoiding the time-consuming burden of document review, information retrieval, and reasoning through safety and security compliance. In addition, DTs can continuously monitor operations and conditions. This real-time data can be used by regulators to ensure ongoing compliance with licensing requirements. There is a need for investment in the integration of DT technology with licensing and regulatory processes.

7. Responsible:

7.1. Ethical Use of DTs

Investment in DT safety, security, and assurance solutions is critical for ensuring the ethical use of DTs, especially in high-risk use cases. Ensuring robust security measures protects sensitive data and upholds ethical standards for privacy protection. Ensuring safety of DTs involves rigorous testing and validation to prevent malfunctions or harmful outcomes, protecting users from potential risks with the deployment of DTs. Assurance processes ensure information generated by DTs is trustworthy and will not lead to harmful decisions.

7.2. Data Privacy

Often there are two categories of data used to derive DTs, public data captured and made accessible, and private data that is not shared. The private data may be proprietary or have other restrictions on its usage. To maintain data privacy, an investment in privacy preserving and federated learning methods may be appropriate. In these methods, the public data can be used to generate a DT and the private data can be used by those with appropriate access to refine the DT for their particular situation. By passing model parameters back to the public repository, the public DT may be improved without compromising the private data, but checks should be devised to ensure that private information cannot be extracted inadvertently from such a public repository. In practice, maintaining data privacy will require investment in "red teaming" exercises that simulate an attack on the DT to identify vulnerabilities and weaknesses.

8. Standards:

8.1. Standardization of DTs across Asset Lifecycle

There is a need for investments that support standardization of DT technology across the system lifecycle to ensure consistency in how DTs are developed, deployed, and utilized. This consistency will facilitate seamless transition and integration of data and models used for design, manufacturing, operation, and maintenance to new applications, and to improving existing DT applications.

8.2. Standardization of DTs across Domains

Standardization of DT technology by individual domains ensures consistency in how DTs are developed, deployed, and utilized within that domain. However, many industries increasingly rely on interconnected systems that work together to achieve common objectives in addition to their individual objectives. In order to do so, DTs of specific domains need to work together seamlessly through data sharing and coordination. There is a need for investment in federated common data interchange formats at the domain boundary to facilitate easier integration and analysis of data from diverse sources, enhancing decision-making processes.

8.3. Shared Public Domain Ontologies

Ontologies provide a common vocabulary and framework for defining concepts and relationships within a specific domain. By investing in efforts that make specific domain ontologies available to other domains to access, different organizations in multidisciplinary systems can ensure consistency in terminology and data representation, promoting interoperability and data integration.

9. Sustainability:

9.1. DTs Computational Requirements

DTs rely heavily on computational resources (e.g., high performance computing, data centers, etc.). There is a need for investment in solutions that help to minimize computational requirements of DTs, and reduce the strain on these computational resources, which will lead to decreased energy use and reduced carbon foot-print of DT operations, and expanded adoption in applications which can benefit from the DT approach.

9.2. DT Lifecycle Continuum

DTs are evolutionary by nature, and their scope changes as their physical counterpart evolves through the different phases of its lifecycle. A DT built during a system's design phase can be used for extensive simulation and testing before physical prototypes are built, reducing the need for material resources and minimizing waste. As the DT evolves, "digital threads" allow for the seamless flow of data across all phases of a system's lifecycle. This data continuum can ensure consistency and accuracy, helping organizations avoid silent errors that lead to redesigns and additional resource consumption and waste. There is a need for investment in solutions that foster this DT lifecycle continuum, such as digital threads and semi-autonomous design.

9.3. Cross-cutting software ecosystem

There is a need for investment in the development of a cross-cutting software ecosystem. Having a cross-cutting software ecosystem for multi-disciplinary DT applications could avoid the duplication of data and models across organizations and minimizes the computational resources needed to maintain a DT operational. As mentioned previously, minimizing computational resources lead to lower energy consumption by the DT, making the technology more sustainable and its adoption more feasible.

9.4. Reusable, Repeatable and Transferable DTs

Similarly, there is a need to ensure that new iterations of DTs are reusable, repeatable and transferable, leading to twins that can be deployed multiple times within similar domain scenarios, can be replicated across different domain scenarios, and can be adapted for different domains, respectively. This also minimizes computational resources and lowers energy consumption, making DTs more sustainable. Work is needed in order to realize these benefits.

10. Trustworthy:

10.1. System Engineering Practices for DT Design

DT design often involves multiple disciplines, such as mechanical engineering, electrical engineering, software development, and data science. Systems engineering practices facilitate the integration of diverse knowledge into a cohesive and effective design, while providing means for risk identification, assessment, and mitigation throughout the design process. There is a need for federated integration of this holistic approach to DT design, not yet widespread in the national labs. Systems engineering can help align the scope for the DT, and anticipate potential challenges and uncertainties associated with its components, ensuring reliability. Another important characteristic of DTs is their evolutionary nature, with maturity levels being reached at different stages of its lifecycle. Systems engineering practice considers the entire lifecycle of the twin, ensuring that the twin is designed with scalability, sustainability and long-term usability in mind.

10.2. Integration of DT Design and Cyber Security Processes

DTs often handle sensitive data related to physical systems, operations or even personal information in sectors like healthcare. Investments in the integration of cybersecurity considerations into the DT design process ensures that this data is protected from unauthorized access, breaches and cyberattack. In addition, cybersecurity measures implemented at the design phase can help prevent malicious actors from disrupting the DT processes during system operation (e.g, unauthorized control of critical systems). Cybersecurity safeguards can also help maintain the integrity of the data within DTs. This includes ensuring the data is accurate and has not been tampered with, which is essential for making informed decisions based on DT outputs. Here, a coherent program of investigation in the very near term can save much hassle and redesign in the future.

10.3. Risk Analysis and DTs

DTs can simulate different scenarios to determine the likelihood and impact of various risks. This can help organizations prepare response strategies tailored to specific risk events and enhance resilience. This is particularly important in multi-domain environments, where DTs can be used for cross-disciplinary risk analysis by integrating data and insights from different domains, and enhance resilience to cascading failure scenarios. However, it is equally important to include DTs as a potential vulnerability when performing risk analysis. As mentioned previously, DTs are vulnerable to cybersecurity threats, and are as much part of the system as the other physical components. Therefore, it is extremely important to understand, detect and mitigate the risks associated with its implementation, including potential malicious use and ingestion.

10.4. DTs Interdependence Analysis

DTs often model complex systems with interconnected components and processes. Investment in DT interdependencies analysis is needed to help stakeholders gain a comprehensive understanding of how different elements interact and influence each other within the DT. It can also help identify critical components and relationships that are essential for the accuracy and reliability of the information generated by the twin.

10.5. Assurance

Investment in assurance methods is critical to ensure that DTs are reliable, safe, and perform as expected. This involves rigorous validation and verification processes to check the accuracy and fidelity of the DT models. Techniques such as formal verification, simulation-based testing, and hardware-in-the-loop (HIL) testing are used to validate DTs against real-world scenarios. Assurance methods also include continuous monitoring and diagnostics to detect and address any discrepancies between the DT and the physical system. Ensuring high levels of assurance is vital for applications in critical sectors such as healthcare, aerospace, and energy, where failures can have significant consequences.

11. Verification, Validation, and Uncertainty Quantification (VVUQ):

11.1. DT Key Performance Indicators (KPI)

There is a need for identification of DT KPIs across different applications. KPIs provide a quantifiable way to monitor the performance of DTs over time against some predefined objectives such as improving efficiency, reducing down time, or enhancing product quality. KPIs can highlight areas where the DT may be underperforming and enable targeted improvements to DT models, processes or data inputs. This is crucial for maintaining the reliability of information and control actions generated by the twin.

11.2. Integration VVUQ Practices and DT Deployment

Uncertainties are inherent in any physical system, and accurately modeling these uncertainties is crucial for the effectiveness of DTs. Well-modeled uncertainties allow the DT to capture the variability and unpredictability of the real world, providing more reliable simulations and predictions. This is particularly important in use cases such as predictive maintenance, where understanding the range of possible outcomes can inform better decision-making. Techniques such as probabilistic modeling, Bayesian inference, and Monte Carlo simulations are commonly used to account for uncertainties. There is a need to integrate VVUQ methods with DT development and deployment. By incorporating these methods, DTs can provide more robust and resilient solutions across various applications.

11.3. Propagation of VVUQ across domains

There is a need for investment in the propagation of VVUQ methods across disciplines. Different disciplines often have unique methods for VVUQ. Propagating these processes across domains ensures that DTs developed by multidisciplinary teams can be consistently applied and trusted across various applications.

11.4. UQ for DT

Uncertainty quantification is needed for reliably deploying DTs, especially when high risk decisions are at stake. DTs may be used to understand scale-up processes, for example, and reduce the risk associated with decisions. Thus, uncertainties in the DT must be properly quantified. This includes the quantification of both aleatoric and epistemic uncertainties and their propagation through the DT, ideally delineating what part of the total uncertainty should be ascribed to the data (aleatoric) and the model (epistemic) including underlying simulations, modeling choices, or ML models used within the DT. Depending on the computational expense associated with DTs, different UQ approaches must be considered, including multi-fidelity, Monte Carlo, Bayesian, and ensemble methods. The outcome of the DT should therefore be quantities that can be used in visualization approaches that indicate to the decision maker or control process how much trust to have in the DT, and which parts of the DT to attribute the uncertainties to.

11.5. DT for UQ

Conversely DTs have the potential to be used to enable uncertainty quantification of the physical processes they represent, if research into this is funded. For instance, to understand the variability associated with stochastic processes, it is in practice often impossible to create a large ensemble of these processes. Here, a DT can enable and significantly accelerate the needed UQ by repeatedly executing it for the same state, assuming it represents the underlying physical processes accurately.

In the same vein, DTs can be used to execute multiple what-if scenarios that would otherwise not be possible to study by experimenting with the real physical processes.

12. Workforce:

12.1. Cross-Disciplinary STEM Education

While there is benefit in teaching individual disciplines in separate pillars to hone in on the intricate details and enable students to fully understand the fundamentals, more cross-disciplinary classes must be taught to elucidate the tight connection between diverse disciplines. These classes would enable students to better understand the complexity of systems and systems of systems, allowing them to make connections as to how topics learned in one class can be leveraged to solve problems in a different discipline. Such classes would also enable students to learn how to engage with non-experts from other backgrounds, and thus improve their interdisciplinary communication skills as well as broaden their horizons with respect to the usefulness of their area of specialty. DTs in particular are approximations of complex systems and require the collaboration of experts in various fields to be successful and capture all aspects of the physical process under investigation.

12.2. DT Addition to STEM Curriculums

DTs are increasingly used in various industries. Integrating DT education into STEM curriculums can thus better prepare students for future careers, and equip them with the necessary skills to succeed in an increasingly digital world. As DT technology becomes more widely used, regulatory standards and compliance requirements are likely to arise. There is a need to reform STEM curriculums to include DT education and ensure students adhere to industry standards and best practices.

12.3. DT for Workforce Training

DTs provide a powerful tool for workforce training by creating realistic and interactive simulations of physical systems. These simulations can be used to train employees in a risk-free environment, allowing them to practice and develop their skills without the consequences of making mistakes in the real world. This is particularly valuable in industries where errors can be costly or dangerous. By using DTs, organizations can enhance the training process, improve safety, and increase the overall competence of their workforce. Additionally, DTs can be used to develop and test new training programs, ensuring they are effective before implementation. There is a need for integrating DTs into workforce training processes.

12.4. Democratization of DT

There is a need for investment in the democratization of DT technology. Making DT technology accessible to a wider audience ensures that more organizations, regardless of size and resources, and more individuals, regardless of their circumstances, can benefit from its capabilities and career-enhancing capabilities. This promotes inclusivity and fosters a broader range of innovation and collaborative efforts.

12.5. Education on Operating with DTs

As DT adoption increases across industries, it is likely that system operation will require some level of interaction between operators and DT technology. There is a need for education on operating with DTs. DT education for operators can ensure their interaction with the technology is efficient and allows them to leverage the full capabilities of DTs to monitor, analyze and optimize processes. At the same time, the organizational leadership must be educated about DTs, so that they realize the challenges and the great potential of putting DT technology to work.

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Request for Information on the National Digital Twins R&D Strategic Plan

Irving Weinberg

Via FDMS

Irving Weinberg, 7/13/2024

[redacted]

The broader use of digital twins for medical devices would potentially streamline regulatory approvals of products as well as improvements in products.

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Request for Information on the National Digital Twins R&D Strategic Plan

Dr. Ivo Dinov and Dr. Brian Athey

July 28, 2024

RFI Response: Digital Twins R&D Plan
Digital Twins R&D Strategic Plan Recommendations

by Ivo D. Dinov and Brian D. Athey, University of Michigan – Ann Arbor

Outline

This RFI Digital Twins R&D Strategic Plan response is focused on leveraging the advanced capabilities of modern AI services, tools for statistical obfuscation of sensitive data (e.g., DataSifter), and techniques for quantifying risks of deidentification (e.g., $\epsilon -$differential privacy) to create, manage, and utilize synthetic digital-twin pairs for biomedical and health datasets. The primary goal is emphasizing the utility of desensitizing, sharing, aggregating, and performing AI-driven analysis on massive (human-identifiable) datasets without compromising participant identifiable human information. Integrating these technologies will facilitate powerful research innovation (preserving the information energy in the biomedical data) while ensuring data privacy and security. Generative Artificial Intelligence enabled Large Language Model platforms offer new opportunities to address these opportunities. This should reduce the barrier of utilizing personal health and other private information resources for research and for legitimate business uses currently hosted in overly protected IT environments built to be resistant to hackers and ransomware attacks.

Background

Digital twins, virtual representations of physical entities, have transformative potential across various domains, including biomedical research and healthcare. This RFI Digital Twins R&D Strategic Plan response outlines the development and implementation of a digital twin R&D framework that integrates foundational AI models and various techniques for data desensitization to generate realistic, representative, and safe (and synthetic) 'digital-twinned' versions of heterogeneous data, without compromising the fidelity or release of personal information. The focus is on creating synthetic digital-twin pairs to facilitate safe and effective research, data sharing, and AI-driven interrogation of biomedical datasets.

Goals & Objectives

1) *Enhance Data Privacy and Security*: Utilize epsilon-differential privacy to quantify risk of leaking personal information and ensure that synthetic digital twins do not contain identifiable human information.
2) *Enable Safe Data Sharing and Aggregation*: Develop protocols and frameworks that allow full-spectrum control of the balance between privacy-protection (security) and value (utility) of the desensitized digital twin computable objects. This would allow data governors (or Honest Brokers) to selectively dial up or down the level of privacy-protection and promote secure sharing and aggregation of biomedical datasets using DataSifting.
3) *Advance AI-Driven Biomedical and Healthcare Research*: Leverage contemporary model-based statistical techniques and model-free AI computational tools to perform advanced

AI-driven analytics on the synthetic digital twin objects and quantitatively compare the results to their counterparts computed on the native raw datasets.

4) *Provide a New Means to Study Bias in AI systems*: Systematic bias introduced by flawed training sets can be addressed by utilizing these Digital Twin methodologies to create synthetic populations of Digital Twins that can uncover bias while preserving privacy.
5) *Foster Interdisciplinary Collaboration*: Encourage collaboration between data scientists, healthcare professionals, and researchers to maximize the impact of digital twin technologies.

Key Elements

1) Existing and upcoming model-based statistical methods and model-free AI algorithms, accelerated by the proliferation of Generative AI platforms are the substrate of this opportunity. There is a wealth of offline tools, online services (including Cloud-services), and computational resources for statistical analysis, visualization, dynamic interrogation and computational modeling of both raw data and their corresponding derived digital twins. These resources form the backbone of the dynamic digital twin ecosphere where core data desensitization, synthetic data generation, and data analytics will take place.
2) DataSifting is a rigorous statistical obfuscation process designed to desensitize data elements, anonymize personal information, and synthetically generate realistic versions of digital twins that are complete simulated data archives matching the data type, characteristics, interdependencies, and features of the original (sensitive) data into the digital twins as computable simulated data objects. This sifting process controls the delicate balance between preserving the value (energy and utility) of the data while protecting the sensitive information (risk-reduction). DataSifting ensures that the synthetic digital twins generated from raw biomedical datasets are free from identifiable information, facilitating secure data sharing and aggregation. Use of Generative AI platform API functionality and deep prompt engineering can industrialize this process to create cohorts and populations of safe and secure synthetic digital twins.
3) Epsilon differential privacy ($\epsilon -$DP) is a rigorous mathematical framework that ensures individual privacy in data analysis. By quantifying the risk of reidentification of sensitive information, the $\epsilon -$DP framework provides strong privacy guarantees for the synthetic digital twins, enabling their use in sensitive biomedical research without compromising personal information.

Implementation Plan

1) <u>Phase 1</u>: Infrastructure Development
    i. Develop/deploy the computational infrastructure required to support the creation and analysis of synthetic digital twins.
    ii. Integrate AI services with DataSifter, and $\epsilon -$DP to generate an end-to-end comprehensive (modular) platform.
    iii. Identify datasets and establish data pipelines for ingesting raw biomedical datasets and generating synthetic digital twins.
2) <u>Phase 2</u>: Digital Twin Pilot: Data Synthesis and Desensitization

i. Use DataSifter to desensitize raw biomedical datasets and compute a range of quantitative metrics quantizing the privacy-protection (risk) vs. data value (utility) retained in the digital twin objects.
ii. Generate synthetic digital twins using epsilon differential privacy and quantify the level of privacy guarantees.

3) Phase 3: AI-Driven Analytics
    i. Utilize existing computational tools to perform AI-driven analysis, powered by Generative AI platforms, on the derived synthetic digital twins and contrast these to their counterparts computed on the original raw data.
    ii. Develop and implement (novel) AI models for various biomedical research applications, such as disease progression modeling, treatment efficacy analysis, and patient outcome prediction.
4) Phase 4: Validation and Testing
    i. Conduct extensive validation and testing to ensure the accuracy and utility of synthetic digital twins.
    ii. Compare the results of AI-driven analysis on synthetic digital twins with those obtained from raw datasets to assess the fidelity of the synthetic data.
    iii. Systematically study bias in existing data sets leveraging social determinants of health (SDOH) and health outcomes knowledgebases.
5) Phase 5: Collaboration and Dissemination
    i. Foster interdisciplinary collaboration by organizing workshops, seminars, and collaborative research projects. Partner with NIH, NSF, DARPA, and industry participants, working with national consortia such as the Coalition for Health AI (CHAI) and other such organizations.
    ii. Disseminate findings through academic publications, conferences, and online platforms.

Expected Outcomes

1) *Enhanced Privacy and Security*: Robust privacy guarantees for biomedical datasets, enabling secure data sharing and aggregation.
2) *Increased Research Capabilities*: Advanced AI-driven analysis on synthetic digital twins, facilitating novel biomedical research and innovation.
3) *Broader Collaboration*: Increased collaboration between data scientists, healthcare professionals, researchers, and industry leading to more comprehensive and impactful research outcomes.

Challenges and Mitigation Strategies

1) *Data Privacy Concerns*
    Mitigation: Utilize epsilon differential privacy and DataSifter to ensure strong privacy guarantees for synthetic digital twins. Quantify the quality of the digital twin computational objects by computing a wealth of numerical metrics capturing the privacy protection (reidentification risk) and data value (digital twin utility).
2) *Computational Complexity*

Mitigation: Leverage existing AI computational resources and optimize data processing pipelines to handle large-scale data synthesis and analysis efficiently.

3) *Interdisciplinary Collaboration*

   Mitigation: Organize regular workshops, seminars, and collaborative projects to foster communication and collaboration between different stakeholders.

The integration of modern Generative AI platform services, DataSifting, and epsilon differential privacy algorithms into a comprehensive digital twin R&D framework holds immense potential for advancing future biomedical research and healthcare. This process offers enormous risk mitigation, cost-savings, increased ROI, and opportunities to expedite R&D and translation of basic data-STEM discoveries into biomedical and health applications. By creating synthetic digital-twin pairs that preserve privacy and enable advanced AI-driven analysis, we can unlock new opportunities for innovation while ensuring the security and confidentiality of sensitive data. This strategic plan outlines one clear and actionable roadmap to achieve these goals and drive transformative advancements in the field.

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Request for Information on the National Digital Twins R&D Strategic Plan

James P. Sluka

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Domain of These Comments

These comments are written from the perspective of **medical digital twins (MDT)**. They may apply in other domains, but they were not written to apply to all domains where Digital Twins might be applied.

Definition of "Digital Twin" and need for data collection

The definition of a "Digital Twin" (DT) in the Request for Information omits a key part of all digital twins*: a central data repository that shares data*. In other domains, an individual DT always constantly draws data from a central repository aggregating current data from all active DTs. At the same time, all individual DTs supplies data back to the central repository so that the aggregate of DTs can be kept up to date with the most recent data describing both the individual and the population. *If this is not done, then the system is not a DT.* Data sharing and aggregation present significant challenges in data security and patient privacy, but an effort must be made to overcome these challenges if the promise of DTs is to be fully realized. Note that data sharing is the ONLY method of validating that the DTs work in the real world. It is the ONLY way to correct and refine deployed DTs.

During the Covid pandemic, aggregated medical data from smart watches showed promise in being able to detect pre-symptomatic Covid in individuals, and predict rising infection rates in populations[1]. Data collected was limited by the technology of the smart watches and included only heart rate, sleep patterns and walking patterns. But even that sparse data showed promise. Note that a rising *local* infection rate is the type of data that should be fed back to the individual's DT to help provide the best interpretation of the individual's own data and their best course of action. This is an example where the DT must send data back to the central repository, and that data must be made available for other instances of the DT.

[1] Mishra, T. *et al.* Pre-symptomatic detection of COVID-19 from smartwatch data. *Nat Biomed Eng* **4**, 1208–1220 (2020). https://doi.org/10.1038/s41551-020-00640-6

Ownership of digital twins

One issue I have not seen discussed in the domain of medical digital twins (MDTs) is the issue of ownership. **Who owns an MDT?** Who owns the data collection device(s)? Who owns the MDT host computer system? Who owns the data? Who owns the predictions?

HIPPA would suggest that the patient owns their own data, but HIPPA does not address ownership of devices or computer resources. Ownership is of critical importance to medical care providers (physicians, hospitals), medical device manufacturers (suppliers), insurers (payers), and to patients (customers and end users). Clearly, there will be different scenarios with each perhaps having different ownership patterns.

One case might be a digital twin deployed in a critical care unit for a sepsis patient. In this case the sensors, data collection pipeline, data repository, digital twin code, computing system, user (physician) interface, etc. are likely owned by the hospital. The payer for the system, in the USA, is likely an insurer. The patient's data is of course owned solely by the patient. But the rest of the MDT environment is owned by someone else.

Contrast that with an individual wearing a MDT equipped smart watch or carrying a smart phone. In this case, the sensors, data collection stream, MDT software and user interface all belong to the patient. (The system might be paid for by an insurer, but the purchased system would still belong to the patient.) What if (or "can") the MDT provider lock down access to the system? This is often seen in complex deployed software systems such as self-driving cars where the "owner" has no access or control over the software. In this case does the patient "own" their own MDT system? Clearly then, "ownership" of a smart device MDT is significantly different than "ownership" in a clinical setting.

Regulatory issues for personally owned Digital Twins

Medical devices, defined here as any device that **claims to have medical utility**, are strictly regulated. Therefore, devices in a clinical setting are regulated. A personal MDT deployed on a smart device and owned wholly by an individual, may or may not have medical claims. Existing digital personal monitors that claim medical utility (e.g., clinically relevant EKG recordings, or the "artificial pancreas") are regulated as medical devices. On the other extreme, the maker's claims may be sufficiently vague and include a footnote disclaimer ("These claims have not been verified by …") as is often seen in unregulated claims on the health benefits of dietary supplements. Does a smart watch that monitors the wearer's motion and detects they have been sedentary for too long, and suggests the wearer get up and move, a regulatable device? At what point do these personal device hosted MDTs become regulated devices?

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Request for Information on the National Digital Twins R&D Strategic Plan

Jasmine Foo

Comments on digital twins

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The “Ecosystem” topic seeks to establish a national digital twin R&D ecosystem that establishes inter-agency collaborations to address foundational research gaps. I believe this is a critical need, as differences in the challenges and use cases across applications drive methodology development in distinct directions that can be valuable for other communities.

In the mathematical biology / medicine setting, digital twins or mathematical models of living systems have long been used as a tool in the scientific discovery of biological mechanisms (testing/refining mechanistic hypotheses using bidirectional feedback between experimental/clinical data and models), as well as in prediction, e.g. of disease progression and treatment strategy optimization. With exciting current developments and tremendous interest in the space of living biologic therapies, e.g. immune cell therapies, protein replacement using living cell populations, base editing, etc, it is especially critical to develop digital twin models of the complex interactions between living these therapeutic agents and their in vivo, dynamic microenvironment. Such models can aid in therapy design and feasibility analysis (e.g. determining gene editing targets, quantifying achievable protein levels), therapy use recommendations (e.g. understanding optimal/minimum sufficient dose and timing), and trial design (e.g. patient selection, trial endpoint design).

To meet these challenges, I believe it will be very important for researchers in different applications to be able to work together to address similar obstacles in development and use of their digital twin models, and to share technologies and best practices. Some of the specific challenges and questions from my perspective of mathematical medicine include:

- **Data limitations and heterogeneity** - specifically, limited longitudinal observations for validating/refining digital twin models, high noise, high variability between samples (patients), highly multimodal data (e.g. ex vivo sample testing + in vivo clinical follow-up, electronic health records, imaging + genomic + phenotypic profiling) often at a single or limited time points. Need for principled data augmentation approaches incorporating domain specific knowledge or invariances.
- **Need for robust, mechanistically justifiable predictions** - need for treatment design and predictions to meet ethical and regulatory considerations, cost considerations, equity considerations, as well as cultural considerations associated with adoption of digital twin recommendations, etc.
- **Development of mechanistic learning approaches** - need for methods for integrating biological mechanism knowledge (possibly encoded via mathematical models) with ML/data driven methods

- **Multiple models at different scales** - in many cases, data informing digital twin models come from a variety of experimental models at different scales (e.g. mouse models, in vitro 2D culture (plates), in vitro 3D culture (spheroids, organoids, organ on chip) and mathematical models or digital twins are developed at each scale. There is a critical need for developing an understanding of mapping digital twin models between experimental platforms and the in vivo setting.

While these are a few challenges currently addressed in the mathematical biology/medicine community, I would be quite interested in learning about challenges addressed by other communities (e.g. climate modeling, agriculture, military planning, etc) - and in leveraging different perspectives to collaboratively develop solutions. Developing the scientific infrastructure and opportunities to form these connections may include the organization/facilitation of working groups, collaborative research and education funding opportunities targeted at the methodological challenges described above, etc.

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Jason Hsu

Via FDMS

Jason Hsu, 7/27/2024

[redacted]

When Digital Twins techniques are applied to assess the efficacy of a new medical treatment relative to a control (a placebo or a Standard of Care), the FDA should be cautious in accepting claims of unbiasedness in the estimation, especially when such claims are based on Real-World Evidence (RWE) data instead of Randomized Controlled Trial (RCT) data. For example, using a Digital Twins technique to predict, for a patient given the new treatment, what the outcome would be had that patient been given the control requires deep statistical knowledge to overcome potential bias from a lack of randomization and/or noise in predictive covariates.

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Request for Information on the National Digital Twins R&D Strategic Plan

Jayson Vavrek, Marco Salathe, Brian Quiter, Reynold Cooper

RFI Response: Digital Twins R&D Plan

Jayson Vavrek, Marco Salathe, Brian Quiter, Reynold Cooper
Applied Nuclear Physics Program, Lawrence Berkeley National Laboratory

In many applications relevant to the Department of Energy, National Nuclear Security Agency, Department of Homeland Security, and Department of Defense, such as nuclear detection, nuclear safeguards, nuclear safety, radiological emergency response, and environmental contamination mapping, it is highly important to understand the distribution of radioactive material and the transport of emitted radiation in an area of interest. In these scenarios, contextual sensors such as lidar can create a three dimensional digital model of the mapped environment, while radiation detectors can make measurements of radiation fields within the environment. Increasingly, multi-sensor systems that combine radiation detectors with contextual sensors are deployed on robotic platforms.

It is possible to enhance the scene model with information extracted from the contextual data by, for example, analyzing data from cameras with semantic segmentation neural networks to extract material composition. Ultimately, this process results in the real-time generation of a detailed digital twin of the measurement environment.

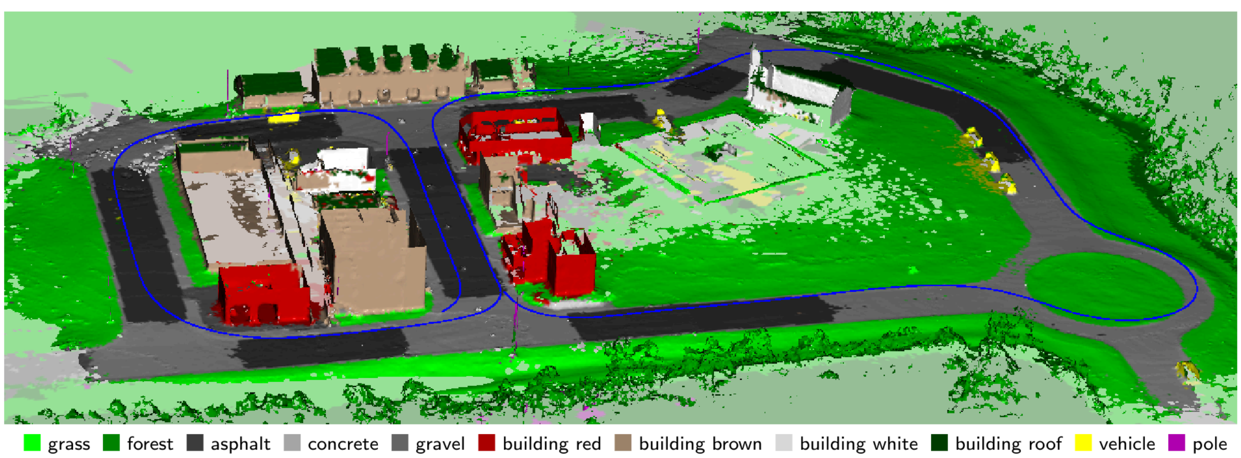

Figure 1: Digital twin of an urban scene. The 3D model is constructed with lidar data collected on a vehicle-based system. The path of the vehicle is indicated in blue. The segmentation of the facility is done by neural networks, processing 360 degree images collected with cameras installed on the vehicle.

This digital twin can be used as a basis for modeling the real-world measurement and enabling real-time analysis of the experimental data. For example, knowledge of the physical environment is essential for the inversion of measured radiation data to time and location dependent dose rates or activity concentrations, and to inform the navigation of the robotic platforms that may be tasked with performing actions in radioactive environments. The combination of the digital scene model and radiation map(s) can inform further responses by providing estimates of optimal sensor placement, required dwell times, or remedial actions. In order to do this, continuous, low-latency feedback between the digital twin and the physical system is required; new sensor data flows to the model and the model informs further actions taken in the real world, leading to new sensor data.

This approach is relevant to operators of nuclear facilities, in nuclear safeguards, emergency response, and environmental cleanup and sampling efforts. It can inform radioactive activation and contamination at classical and small modular fission reactors, fusion facilities, scientific research facilities (accelerator beam lines, etc), and medical institutions. Similarly, the characterization and clean up efforts related to nuclear dispersals (accidental or otherwise) and from legacy nuclear activities can inform navigation of operators and autonomous systems, for example to allow responders and troops to navigate a contaminated area safely. Likewise, transport and disposition of radioactive materials in clean-up scenarios can be studied and optimized to minimize exposure risks to the public and personnel. In emergency response scenarios a digital model could be used to understand the probing of an item of concern, informing the placements of detector systems and advising actions to render the item safe. The use of off-the-shelf sensors, the creation of a digital version of a specific region of the real world, modeling physics, that then influences further data collection, is an important application of a digital twin to real world problems.

Ongoing and future research and development efforts for digital twins in radiological mapping should focus on using the digital twin to drive decision making for autonomous systems as well as for humans-in-the-loop analyses of potentially high-consequence actions in, for example, radiological emergency response. When deployed on a robotic platform such as a ground vehicle, quadruped, or unmanned aerial system, autonomous decision making algorithms can remove human operators from laborious and/or dangerous activities related to performing radiological measurements and gaining situational awareness. Existing robotic workflows are largely automated but not fully autonomous (e.g., following a predefined survey pattern, perhaps with some level of obstacle avoidance), and basing autonomy algorithms on the radiation map (rather than just the digital scene model) remains an ongoing research topic deserving of much more effort.

When humans are engaged in the decision making process, a digital twin can help inform 'what-if' scenarios imagined by the decision-maker, and that can be investigated digitally prior to allocating resources and/or providing directives. An example of such a use could be a nuclear emergency response scenario. Such a scenario can involve first responders encountering an item containing radioactive material that could potentially be associated with a nuclear weapon or radiological dispersal device. In these cases offsite experts are tasked with providing guidance to onsite personnel to make measurements and potentially perform high-risk actions with the goal of reducing the potential health and economic impacts of the radioactive item. During the response, the ability to rapidly generate a digital twin to support decision making and physics-based what-if analyses would be a great asset to the country.

Fundamental improvements to the quality of radiological digital twins would motivate their use more widely. In particular, while the current-generation digital scene models help to constrain the domain over which radionuclide concentrations can be reconstructed, it is computationally challenging to use these scene models to correct for attenuation from objects in the environment. This lack of attenuation correction is known to bias reconstruction results, potentially limiting the real-world fieldability of radiation mapping technology in certain complex environments. Computationally-efficient attenuation modeling should therefore be a high research priority for radiological digital twins.

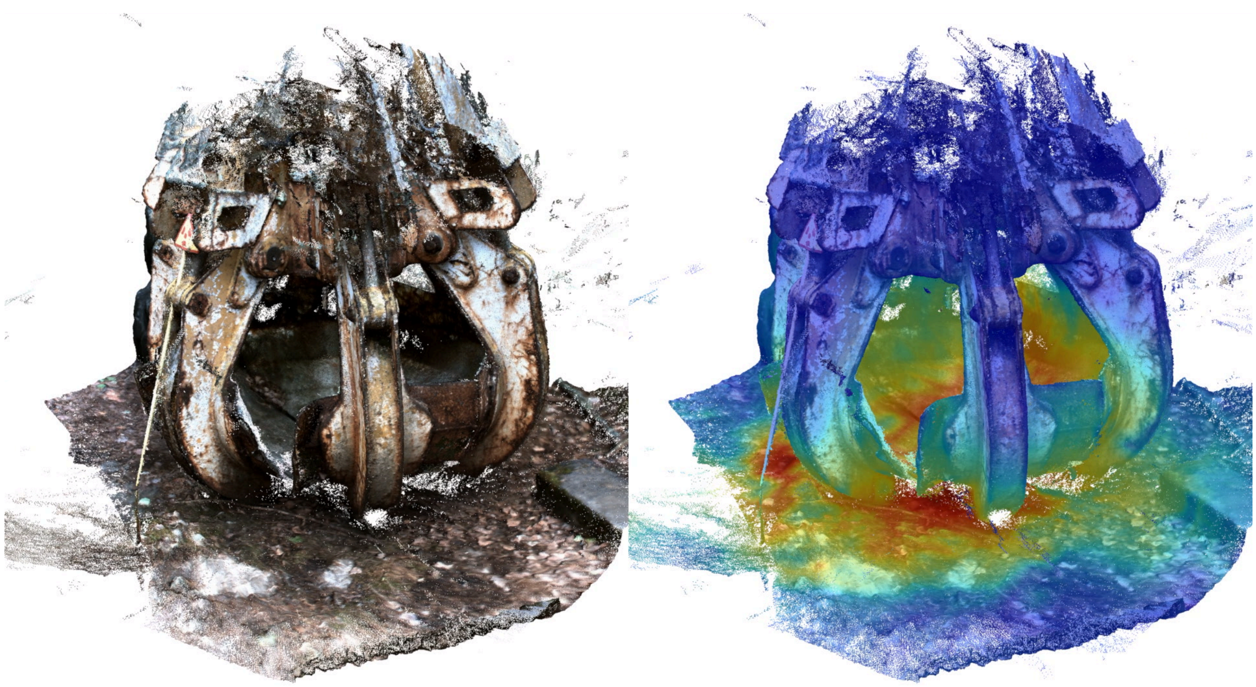

Figure 2: The left panel shows a 3D reconstruction of a crane claw that was used to move nuclear fuel and debris in the Chernobyl exclusion zone. It is created by processing a video with photogrammetry. The right panel shows the same view, overlaid by a map of contamination (red indicates high contamination, blue indicates low

contamination). It is created by modeling the transport of radiation through the "digital twin".

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Request for Information on the National Digital Twins R&D Strategic Plan

Jineta Banerjee, Ann Novakowski, Milen Nikolov
Institution: Sage Bionetworks

RFI Response: Digital Twins R&D Plan

Responders: Jineta Banerjee, Ann Novakowski, Milen Nikolov
Institution: Sage Bionetworks

Response:

We appreciate NITRD's efforts towards collecting information about the status and needs for digital twins in various disciplines of science. While widely utilized in the aerospace and automobile industry to test innovations safely, digital twins' adoption is emerging yet limited in healthcare. In healthcare, drug development research remains a slow process due to limited understanding of disease biology and the need for extensive and labor-intensive clinical trials for drug validation. Computational approaches using digital twins to improve trial design or drug screening could revolutionize drug development research. With the increase in high throughput data generation in medicine and biomedical research and recent advances in multi-modal generative models, we are increasingly optimistic about the era of biomedical digital twins. Our response here will focus on addressing the following focus areas: *Data, Standards, Trustworthy.*

Lack of access to adequate and appropriate data is a considerable challenge for development as well as deployment of digital twins in medicine. Models that can generate digital twins of patients for various diseases will require training a combination of mechanistic, AI-based generative, and forecasting models. Developing such models will require a large amount of unbiased data from various scales of biology - cellular-level, tissue-level, and organism-level. It is unlikely that one medical or research organization will have all the required data and expertise for these models. So we foresee the need for coalitions of researchers from biology, medicine, AI, and physical sciences to generate such models based on data that are generated across institutions and disciplines as well as across a multitude of patient populations. To facilitate the cross-institutional research and development, large organized data management efforts will need to be in place for the success of such cross-institutional coalitions.

The nascency of digital twins research provides a unique opportunity to proactively develop purposeful tools and platforms to ensure transparent and patient-centered digital twin development and seamless data transfer between data-generating groups and data-using groups (AI/ML researchers or model generators). In our opinion, data management for digital twins would require considerations at two stages. One at the level of model generation, and second at the level of twin generation.

Model generation phase:

<u>Platform for data sharing and improvement:</u>

1) A cloud-based, scalable, institution-agnostic, and platform-agnostic data management

system will be needed that can ingest large amounts of data from multiple institutions and prepare them for egress as needed.
2) Digital twins and models generating the twins will need continuous updating and inclusion of new data modalities as necessary. So platforms that can provide an avenue for iterative feedback between data collectors and model generators will be needed to ensure collection of appropriate data and data modalities for model improvement.
3) Optionally, the ability to provide continuous benchmarking of models on gold standard datasets to examine the accuracy of models would be important in providing transparency for expectations in model output.
4) Platforms that can provide metrics on the level of disparity between data generated from different institutions and ability to harmonize data across institutions will enormously accelerate digital twin research.

<u>Standards for data and metadata for model generation:</u>
1) The data used in model generation would need to be quality checked and prepared to meet the FAIR standards with as much detailed metadata as possible to account for any and all nuances and biases of data capture.
2) Tools that provide easy ways to annotate data files with appropriate metadata leveraging automated capture from LIMS or electronic laboratory notebooks in addition to manual addition by researchers will become important to approach scalability while maintaining quality of data.
3) The data would likely come from various scales, i.e. cellular-level, tissue-level, and organism-level. Currently available data models would need to be enhanced to accommodate successful linking of such multiscale data.

Twin generation phase:
Once models to generate digital twins are developed, additional data management considerations would be required to facilitate generation and storage of digital twins of individual patients.

Such platforms should include the:
1) Ability to connect to clinical sites to enable data ingestion for individual patients.
2) Ability to continuously integrate newly acquired data with existing data from each patient.
3) Ability to preserve provenance of data from patients to the users generating digital twins to improve transparency of data use
4) Ability to store and update digital twin data using unique patient identifiers while being HIPAA compliant.

Data governance for model training and digital twins:
Since digital twins cannot be completely deidentified, special attention needs to be given to data governance. Robust governance frameworks will be essential to prevent privacy breaches, preserve data context, and minimize misuse or exploitation, e.g., using data to approve or reject health insurance claims or making generalized predictions that could harm specific groups. Adherence to data minimization principles would help mitigate these risks. Access to data and digital twins would need to be strictly controlled, with release limited to authorized parties in a secure environment. This access may be tailored to the stages of twin development, including data collection, twin exploration, and twin deployment to maintain compliance with research objectives and ethical guidelines.

Additionally, the digital twins themselves would need to be subject to control measures that protect the privacy and interests of the individuals they represent. A dynamic attribution and consent process will enable research participants to provide informed consent for twin deployment and monitor the status of their data in digital twin studies. The concept of “digital dignity” may be gaining traction as public awareness grows regarding the ubiquity of personal data collection and its uses in tracking, marketing, and other potentially invasive applications. Extending principles of digital dignity with unbroken data provenance to research participants would enable them to monitor the use of their data in current and future studies. Ethical, Legal, and Social Implications (ELSI) frameworks should also be considered in the return of results from digital twin studies. While this type of transparency could enhance model validity and clinical reliability in research outcomes when shared with clinical care teams, the insights gained would be carefully balanced against the potential benefits and risks to the participants.

Standards for models:
Since digital twins are as good as the generative models are, implementing specific standards for describing and deployment of such models will be key. We expect to see emergence of digital twin model repositories in conjunction with repositories for the data and twins. Such repositories would need to implement standards for describing models to make them findable and accessible. Special care should be taken to define model parameters including the accepted range of values and units of measurement. Model metadata should also include whether model parameters are cell-level, tissue-level, or organism level. Additionally, it would be important to surface metrics that measure congruence between specific parameters for real patients and those predicted for digital twins to provide transparency about the strengths and weaknesses of the models and the twins. We also expect that containerization of models and ability to be deployed by users other than the model generators will be encouraged to enable testing generalizability of the models.

Trustworthiness of digital twins:
Given that drug discovery and clinical decision support will be among the most important use cases of digital twins, special care needs to be taken to ensure the trustworthiness of the twins. For any data generated and used for model generation, special care should be taken to define and surface metrics regarding data quality and harmonization and should be updated continuously. Digital twin data predicted by these individualized models is generally accompanied by uncertainty of prediction. Such uncertainty metrics should be documented and surfaced adequately to prevent misinterpretation of the twin data.

Federal Register Notice: 89 FR 51554, Federal Register :: Networking and Information Technology Research and Development Request for Information on Digital Twins Research and Development, June 18, 2024.

Request for Information on the National Digital Twins R&D Strategic Plan

Joe Gallo

Via FDMS

Joe Gallo, 6/27/2024

[redacted]

As a former mayor and technology enthusiast, I invested a lot of energy into exploring the deployment of a digital twin for my community. There were many findings, but the most important finding was makig sure the community had a pre-existing, robust infrastructure of sensors and other data delivering solutions to feed my virtual municipal environment. It's one thing to lean on outside agancies such as transportation departments for traffic metrics or environmental agancies for weather data, but my community is left at the mercy of the frequency in which their data is available, which greatly reduces the "real-time" nature of my digital twin. So data generation, data access, and data ownership are critical topics to cover. In order to ensure a municipal digital twin is a real-time virtual replica and not a six month or older representation of my community, the community must invest in the systems, software and sensors vital to their landscape and interests to have a twin that will deliver as intended for their needs. Before investing in a digital twin, the community must develop a well thought strategy outling the goals and what they intend on accomplishing using a digital twin as a tool in their smart city arsenal.

Federal Register Notice: 89 FR 51554, Federal Register :: Networking and Information Technology Research and Development Request for Information on Digital Twins Research and Development, June 18, 2024.

Request for Information on the National Digital Twins R&D Strategic Plan

Joseph O. Olusina

<u>Title:</u> "RFI Response: Digital Twins R&D Plan"

<u>Name:</u> Prof. Olusina, Joseph O.

<u>Address:</u> [redacted]

<u>Email:</u>[redacted]

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According to Committee's definition builds on a definition from an AIAA and AIA Position Paper (2020), Digital Twin (DT) is defined as "a set of virtual information constructs that mimics the structure, context, and behavior of a natural, engineered, or social system (or system-of-systems), is dynamically updated with data from its physical twin, has a predictive capability, and informs decisions that realize value".

Policies on Digital twins must cover the three types of Digital twins: *Digital Twin Prototype* (DTP), *Digital Twin Instance* (DTI), and *Digital Twin Aggregate* (DTA). The policies will include process formulation, sensors integration, product delivery and product testing and maintenance/sustainability just to mention but a few. And the use of different technologies such as, Internet of Things (IoT), Big Data, 3D Visualization, etc. will come to play.
A Digital Twins should be Fit for Purpose system that is complete and that can deliver.

Therefore, policies on Digital Twins (DT) technology for each application must address the following challenges: Data Availability (e.g. Accuracy and currency, …), Complexity (e.g. personnel, technology, and software), Security (e.g. data from many sources), Integration (e.g. systems and practices), and Accuracy (data and models). All these can affect simulation accuracy and performance. This will also involve various experts/professionals, technologies, environment and rules.
For each field and application, the policy must cover these areas of Digital Twins (DT):

1. **Data-** Generally, before collecting data for DT one must consider: (i) data identification, (ii) data verification, (iii) data unification, and (iv) data enrichment. All these will come to play in:

    a. Data Collection: specific data collection must ensure, accuracy and precision, completeness, reliability, validity, accessibility, action research, detailed (data sets contain all necessary information), observation and timeliness

    b. Data Quality: this will include, completeness, accuracy, timeliness, validity, consistency, uniqueness, integrity, data governance, precision, relevance, reliability, accessibility, data quality management, data validation, data profiling, clinical data management, data quality dimensions, understandability, appropriate amount of data, comparability, compliance, conformity, data cleansing, and data granularity and relevance.

    c. Data Security: data security has many characteristics, including: encryption, data masking, access control, authentication, data erasure, data resiliency, compliance. data security must ensure, confidentiality, integrity (authenticity) and availability.

    d. Data Interoperability: this has to do with, syntactic and semantic, (technical), and cross-domain or cross-organization (legal).

    e. Data Transfer/Migration: this will include, accuracy, precision, speed, timeliness, reliability, bandwidth, error detection, data compression and data encoding.

    f. Data Management: Data management involves collecting, storing, organizing, maintaining and analyzing data to assist decision-makers. Data management characteristics include: data security, data quality, data governance, data redundancy, data backups and data integrity. A good data management techniques should be able to: improved data quality, increased data security, lower costs, better decision making, faster access to information and improved productivity.

        Crowdsourced or multi-sectoral data sources and enforcing multi-level security approach may reduce both cost and cybersecurity challenges. Pulling resources together for similar businesses e.g. SMEs that are geographically located or through IoT for distant ones can reduce cost.

2. **Modelling-** This will include policies on, user requirements survey, conceptual design, logical design, physical design, and implementation. The modelling will assist in operation, predicting, prescription, and visualization.

3. Linking- Policies on how the digital twin results can be escalated to enhance improvements and developments must be put in place.

With the Digital Twin (DT) technology, accuracy of geospatial applications (virtual maps) can be improved through:

1. Real-time data capture- to update geospatial simulated systems
2. Data analysis and visualization- to assist in analyzing data content, completeness, accuracy, quality, etc. and simulate the system for a real-time 3D visualization
3. Collaboration and communication- to assist in joint collaboration between the different stakeholders including users and provide a seamless data and information flow or transfer among the stakeholders for efficiency and accuracy, and
4. Decision-making and risk management- to assist in making informed decisions and access risk(s) involved and how to share the risk.

Policies on virtual maps must cover, creating digital models (maps), computer algorithms, techniques, data from different sources, different software and hardware and standards, data processing and analyses, and visualization to simulate physical world entities and assess various designs and planning options.

Policies on several application areas of Geospatial Digital Twins include:

- <u>Energy Applications policies</u> e.g. Wind energy, Solar energy, etc.
    - Wind energy- Geospatial Digital Twins application that will mimic (simulate) the direction of the flow of wind to attain maximum wind efficiency
    - Solar energy- Geospatial Digital Twins application that simulate and determine the best location for obtaining maximum energy radiation from the sun.
- <u>Transportation policies</u> e.g. traffic simulation, proposed road modelling, etc.
    - Traffic simulation and Traffic monitoring- The policies must cover a real-time data collection and streaming from traffic sensors (cameras) on the roads to the server

in the control room to simulate and update traffic data that will assist traffic managers in decision making.

  - 3D Modelling and Visualization of Proposed Roads- A proposed road can be modelled in 3D and visualized to see how it is going to perform after construction. Different components/parts of the road can be simulated and tested e.g. road alignment, drainage type, volume of traffic, turnings on the road, etc.

- Soil test policies- For a multi-storey building, a prototype soil (texture and strength) and building simulations can be created that will test how long a building can last under different weights attached.
- Architecture, Engineering & Construction (AEC) policies- A complete engineering project can be simulated in the Geospatial Information Science (GIS) environment to test every component of a proposed building or factory. *Building Information Modelling (BIM),* will also be an advantage here.

Geospatial Digital Twin applications' policies shall cover these areas so that there will be efficiency, accuracy, trust and product delivery.

Federal Register Notice: 89 FR 51554, Federal Register :: Networking and Information Technology Research and Development Request for Information on Digital Twins Research and Development, June 18, 2024.

Request for Information on the National Digital Twins R&D Strategic Plan

Kevin Shelburn

Via FDMS

Kevin Shelburn, 7/22/2024

[redacted]

First of all, thank you for the excellent study and report, I truly appreciate the hard and thoughtful work of the committee and reviewers. I broadly and strongly support the recommendations and hope that the potential high impact of digital twins will be realized. My main comment is to strongly emphasize the need for much greater sharing of models and data, particularly in work supported by the NSF and NIH pertaining to medicine. In medical-related research, intellectual property concerns strengthened by the collaboration with for-profit organizations have led to a strong culture of not sharing data, tools, and models for their potential strategic advantage. While understandable from industry, this culture permeates throughout academia as well and includes granting institutions such as NSF and NIH. Recently, greater emphasis on sharing has resulted in talking points in some requests for proposals, and some researchers are sharing out of a sense of duty to the public and the federal money they accept, yet not sharing remains the guidance to every researcher. Without an enforceable change in this culture, the recommendations of your study of digital twins will remain forever aspirational. Sharing the data, models, and the tools that help create them must be a scoreable requirement for any proposal seeking funding from a public institution, with follow-up by program managers on granted proposals. I believe that changing the culture that overly emphasizes intellectual property will also demonstrate that sharing results in research output with a much greater positive societal impact. I appreciate the opportunity to comment on the excellent study. I would be glad to further discuss the study and my comments in more detail if you wish to get in touch. Sincerely, Kevin Shelburne, PhD Research Professor, Mechanical and Materials Engineering The University of Denver, [redacted]

Federal Register Notice: 89 FR 51554, Federal Register :: Networking and Information Technology Research and Development Request for Information on Digital Twins Research and Development, June 18, 2024.

Request for Information on the National Digital Twins R&D Strategic Plan

Lawrence Livermore National Laboratory (LLNL)

To whom it may concern,

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Herein, Lawrence Livermore National Laboratory (LLNL), provides perspective and insights on digital twin (DT) models, specifically to enable, advance, or accelerate DT usage within the manufacturing technological sector. From our stance as a Department of Energy (DOE) National Nuclear Security Administrational (NNSA) Laboratory, LLNL defines manufacturing in the broadest sense, including all types, e.g. conventional (or "subtractive"), additive and 3D printing, industrial and boutique scale, and for all applications, e.g. parts and part assemblies, hardware, chemical, pharmaceutical, and food, national security, etc. When manufacturing is coupled with any or all of sensing, analytics, and modeling as is the case for creating DTs of manufacturing process and/or parts, it is commonly referred to as "advanced manufacturing" (AM). This document uses this terminology for the remainder of the document and thus discusses advanced manufacturing digital twins, or "AM DTs."

Given the state of global manufacturing, the United States' competitive edge involves AM technologies that leverages many of the suggested topical areas of this request for information (RFI) . Our RFI response will be organized according to these topical areas. Digital twins represent the culmination of these capacities and, if pursued, will strengthen the US's industrial sector, economic strength, and technological leadership in AM. Such concepts are frequently discussed by business thought leaders, e.g. McKinsey & Company, Andreessen Horowitz venture capital, etc., and major US manufacturers. Thus, investments in these areas (and digital twins in general) will have long-standing impact in both research and industry AM communities.

Artificial Intelligence (AI):

Integration of Digital Twins with Artificial Intelligence (AI):

The integration of artificial intelligence (AI) with digital twins represents a transformative approach to advanced manufacturing (AM). By embedding AI algorithms within the digital twin framework, we can enhance the predictive capabilities and operational efficiency of the manufacturing process, leveraging data driven insights from actual AM processes. Furthermore, these AM processes can leverage these techniques with or without underlying physical models. This is because AI can analyze vast amounts of data generated by both the physical and digital twins, identifying patterns and correlations that may not be immediately apparent to human operators. This integration allows for real-time monitoring and adaptive control of the manufacturing process, ensuring that each part meets the required specifications with minimal variation. Furthermore, AI-driven insights can facilitate root cause analysis and error detection, significantly reducing the time and resources required for post-build inspections.

Leveraging Generative AI for Digital Twin Modeling & Simulation:

Generative AI offers a powerful tool for enhancing digital twin modeling and simulation. By utilizing generative models, we can create highly accurate and detailed digital representations of the manufacturing process and its outcomes. These models can simulate a wide range of scenarios, including variations in process parameters and environmental conditions, providing valuable insights into the potential performance of the manufactured parts. The ability to generate realistic simulations enables us to predict and mitigate potential issues before they occur, thereby improving the overall quality and reliability of the AM process. Additionally, generative AI can assist in optimizing design parameters, ensuring that the digital twin accurately reflects the intended design and performance characteristics of the physical counterpart.

Impact of AI on Digital Twins' Physical Counterparts:

The integration of AI with digital twins has a profound impact on their physical counterparts. By continuously refining the digital twin models through AI-driven data analysis, we can achieve a higher degree of fidelity between the digital and physical representations. This alignment ensures that the virtual inspections and simulations conducted on the digital twins are directly applicable to the physical parts, reducing the need for extensive physical testing and inspection. Moreover, AI can facilitate adaptive control of the manufacturing process, dynamically adjusting parameters to account for real-time variations and ensuring consistent quality. This capability not only accelerates the production process but also enhances the overall reliability and performance of the manufactured parts, ultimately leading to more efficient and cost-effective AM operations.

AI-Driven Data Analysis for Process Optimization:

AI-driven data analysis plays a crucial role in optimizing the AM process by leveraging the rich datasets generated by digital twins. Machine learning algorithms can process and analyze data from multiple sources, including sensor readings, process parameters, and inspection results, to identify key factors influencing part quality and performance. This analysis enables the development of predictive models that can forecast potential defects, recommend corrective actions, and accelerate root cause analysis. By incorporating these insights into the digital twin framework, we can implement proactive measures to prevent defects and optimize the manufacturing process. The continuous feedback loop between the physical and digital twins, facilitated by AI, ensures that the process remains adaptive and responsive to changing conditions. For instance, predictive maintenance can ensure AM platforms do not drift from their desired operation regime. Similarly, defective, damaged, or out-of-calibration sensors can be identified by comparisons of the digital twin, which contains insights from production campaigns, against the physical twin.

***Data**:*

Robust Data Engineering Practices:

To ensure the effectiveness of digital twins in advanced manufacturing, robust data engineering practices are essential. The ability to collect data in real time is paramount, as it allows for immediate analysis and adaptive control of the manufacturing process. This real-time data collection ensures that any deviations from the desired specifications can be promptly identified and corrected, minimizing the risk of defects. Additionally, multi-modality is a critical aspect, as it involves gathering data from various sources and sensors, such as thermal cameras, laser scanners, acoustic sensors, contact-based sensors, etc. This diverse data collection provides a comprehensive view of the manufacturing process, enabling more accurate and holistic digital twin models. Synthetic data generation also may play a vital role, particularly in scenarios where real-world data may be scarce or difficult to obtain. By generating synthetic data, we can augment the existing datasets, enhancing the training and validation of AI models used within the digital twins. Lastly, edge deployments are crucial for processing data at the source, reducing latency and bandwidth requirements. By deploying data processing capabilities at the edge, we can ensure that critical insights and decisions are made swiftly, further enhancing the responsiveness and efficiency of the digital twin framework.

Governance Methods for Data Collection, Curation, Sharing, and Usage:

Distinct from data engineering practices, effective governance methods are essential for the successful implementation of digital twins in AM. Establishing clear protocols for data collection ensures that the data gathered is accurate, relevant, and consistent across different stages of the manufacturing process. Curation practices are equally important, as they involve organizing and maintaining the data to ensure its quality and usability over time. Sharing and usage policies must be defined to facilitate collaboration among different stakeholders while protecting sensitive information. By implementing robust governance methods, organizations can ensure that the data used in digital twins is reliable and can be leveraged to its full potential, ultimately enhancing the accuracy and effectiveness of the digital twin models.

Shared Public Datasets and Repositories:

The adoption of shared public datasets and repositories can significantly accelerate the development and deployment of digital twins. Public datasets provide a valuable resource to train researchers (in data handling, AI model development, software pipeline construction, etc.), reduce barrier to academic investments in digital twins, and facilitate collaborations. Repositories that host these datasets should adhere to standardized formats and metadata conventions to ensure interoperability and ease of use. Since retrieval and storage of large datasets can be expensive, research in effective compression or creative solutions to data distribution could aid in the increase of public datasets. By encouraging the use of shared public datasets, the digital twin community can foster innovation and collaboration, leading to more advanced and effective solutions for the manufacturing industry. Additionally, public repositories can serve as a benchmark for evaluating the performance of digital twin models, promoting transparency and accountability in the field. It's worth noting data sharing is not always possible or incentivized in classified, export controlled, proprietary, or otherwise

[redacted]

restricted datasets. It is unclear if data obfuscation could offer a method in reducing unwanted data leaks.

Real-Time Data Integration:

Real-time data integration is a critical component of effective digital twin implementation. Integrating data from various sources in real time allows for immediate analysis and decision-making, enhancing the responsiveness and adaptability of the manufacturing process. This capability is particularly important for monitoring and controlling complex systems, where delays in data processing can lead to suboptimal performance or even failures. By leveraging real-time data integration, digital twins can provide a dynamic and accurate representation of the physical system, enabling proactive maintenance, optimization, and quality control. Ensuring seamless integration of real-time data requires robust infrastructure and advanced data processing techniques, which are essential for the successful deployment of digital twins. More mature implementation of digital twin systems will take the form of industry-grade software pipelines.

Since digital twins often rely on continuous and multi-modal data sources to provide a comprehensive and dynamic representation of physical systems, developing methodologies and tools for integrating and analyzing these diverse data streams is essential for the effective implementation of digital twins. This includes addressing challenges related to data synchronization, fusion, and real-time processing. By promoting the development of advanced data integration techniques, organizations can ensure that digital twins can leverage the full range of available data, enhancing their accuracy and utility.

Leveraging Archival Datasets:

Archival datasets, despite often suffering from bad organization and incomplete information, likely represent a valuable, yet untapped (or untappable!) resource for digital twin development. These datasets contain historical data that can provide insights into long-term trends and patterns, which are crucial for predictive modeling and simulation. To leverage these datasets effectively, research investments are needed for data cleaning and preprocessing techniques to address issues such as missing values, inconsistencies, and noise. Advanced AI and machine learning algorithms can be employed to extract meaningful information from archival datasets, enhancing the accuracy and robustness of digital twin models. By incorporating archival data, digital twins can benefit from a richer and more comprehensive dataset, leading to improved performance and reliability.

Standards:

Ontology and Data Exchange Protocols:

Developing standardized ontologies and data exchange protocols is crucial for ensuring interoperability and seamless integration of digital twin components. Ontologies provide a structured framework for representing knowledge and relationships within a specific domain, enabling consistent interpretation and communication of data. Data exchange protocols facilitate the efficient and secure transfer of information between different systems and platforms. By establishing common ontologies and protocols, organizations can ensure that digital twin components can interact and share data effectively, regardless of the underlying technologies. This standardization is key to building scalable and interoperable digital twin solutions that can be easily integrated into existing workflows and systems.

Encryption Standards:

Encryption standards are vital for protecting the integrity and confidentiality of data used in digital twin applications. As digital twins often involve the collection and analysis of sensitive information, robust encryption methods are necessary to safeguard against unauthorized access and data breaches. Developing and adopting industry-wide encryption standards ensures that data is securely transmitted and stored, maintaining the trust and confidence of stakeholders. These standards should be regularly updated to address emerging security threats and vulnerabilities, ensuring that digital twin systems remain resilient and secure over time. Research in this area is largely limited to mature and/or commercial digital twin systems; however, solutions can be derived from academic groups as well with targeting funding calls.

Evaluation of Data-Driven Digital Twin Components:

Evaluating the performance and reliability of data-driven digital twin components is a critical challenge that requires the development of robust methodologies and tools. These evaluation methods should consider various factors, such as accuracy, scalability, and robustness, to ensure that digital twin models can effectively represent and predict the behavior of physical systems. By establishing standardized evaluation criteria and benchmarks, organizations can systematically assess the quality and performance of digital twin components, facilitating continuous improvement and innovation. This rigorous evaluation process is essential for building trust and confidence in digital twin technologies.

Verification, Validation, and Uncertainty Quantification (VVUQ):

Foundational and Cross-Cutting Methods:

Developing foundational and cross-cutting methods for Verification, Validation, and Uncertainty Quantification (VVUQ) is essential for ensuring the reliability and accuracy of digital twins. Foundational methods provide the basic principles and frameworks that can be applied across various domains, ensuring a consistent approach to VVUQ. Cross-cutting methods, on the other hand, address the common challenges and requirements that span multiple applications and industries. By establishing these core methodologies, organizations can create a robust foundation for VVUQ that supports the development of high-quality digital twin models. These methods should be adaptable and scalable, allowing them to be applied to different types of digital twins and evolving as the technology advances.

Integration of VVUQ into the Full Digital Twin Ecosystem:

Integrating VVUQ into all elements of the full digital twin ecosystem is critical for maintaining the integrity and trustworthiness of digital twin models throughout their lifecycle. This integration involves embedding VVUQ processes into the design, development, deployment, and maintenance stages of digital twins. By incorporating VVUQ from the outset, organizations can identify and address potential issues early, ensuring that digital twins are built on a solid foundation of verified and validated data. Continuous VVUQ practices during the operational phase help monitor and maintain the performance of digital twins, adapting to changes and uncertainties in real-time. This holistic approach ensures that VVUQ is not an afterthought but a fundamental component of the digital twin ecosystem.

Sincerely,

Brian Giera, PhD
Director, Data Science Institute
Lawrence Livermore National Laboratory

[redacted]

Federal Register Notice: 89 FR 51554, Federal Register :: Networking and Information Technology Research and Development Request for Information on Digital Twins Research and Development, June 18, 2024.

Request for Information on the National Digital Twins R&D Strategic Plan

Joshua Zev Levin, Ph.D.

Chief Creative Officer, LeviCar Unlimited

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Interactive Digital-Twins Generator using Artificial Intelligence

by Joshua Zev Levin, Ph.D.
Chief Creative Officer, LeviCar Unlimited
[redacted]

This paper describes a concept for an Interactive-Environment Program Suite to utilize Artificial Intelligence (AI) to generate Digital Twins. This is in response to the request for comments as specified in an RFI (Request for Information) from the National Science Foundation.[1]

Topic Keywords: **Artificial Intelligence (AI)**, **Data**, **Trustworthy**, **LLMs (Large Language Models)**, **SMLs (Small Language Models)**

AI Front End

Assume we have several companies that don't want to share their secrets. Each company has one or more teams of engineers, that may or may not want to share secrets. Each team may work on one or more projects. Some of the projects will use AI and start with LLMs, and the following discussion pertains to such projects, and what the "Generator" would do for them. Other projects that don't use AI are not affected by this discussion.

As each team of engineers commences each project, they would use Large Language Models (LLMs) to fish for ideas and concepts, and then refine things using custom Small Language Models (SLMs). This would be done according to the article by Kane Simms.[2]

It is desirable to make a custom LLM based on juried material, mostly derived from what is already on-line on the internet, but also peer-reviewed journals and respected books. The Chatbot might be based on the Proximity[3] chatbot, either by trying to reverse engineer Proximity, or licensing it from its owners. Proximity lists source materials, which is very useful to engineers. Other chatbots might be used, instead.

The database would be *juried*, that is, selected by professionals for accuracy. The database could be privately-owned and users would pay a fee, or it could be government-owned. In the latter case, I suggest that the National Institute of Standards and Technology (NIST) own and run it, as NIST already has considerable expertise with AI. This is in-line with the tradition of government aiding developing technologies.

Also, the owners of the LLM would also take care of the IP rights, compensating the owners of the source material for the use of said source material. Bear in mind that, here in the United States, the rationale for granting so-called "Intellectual-Property" (IP) rights is based on "to promote … useful arts …" [4], and any attempt to obstruct that would exceed the authority that Congress has the power to give. However, rights holders are entitled to some reasonable compensation.

According to Simms[2] once the engineers have reached the limits of what they can do with the LLM, they need to switch to a customized SML. He states specifically:

> "Once you've proven that the task is doable, you can then start working down in model sizes to figure out whether the same task can be done using a smaller model. When you reach a model size where your results start to change, get less accurate or slightly more unpredictable, you've reached your potential model size."

He also states:

> "With LLMs, you're in the hands of the model builders. If the model changes, you'll have drift or worse, catastrophic forgetting. With SLMs, anyone can literally run them on your own servers, tune them, then freeze them in time, so that they never change."

I myself disagree with the last phrase, "… then freeze them in time, so that they never change." The main purpose of DT is to allow changes, and then virtually test them before committing them to extensive hardware or software development investments.

Each team could implement SMLs on their own firewalled servers, or the operators of the LLMs could established firewalled application within the LLMs to perform this. The question of which to use is beyond my own knowledge of computer security.

In the case of several SMLs coexisting on one LLM server, it is possible to have a supervisor application that can look beyond the firewalls, and, using AI, determine if there is a possibility of two or more teams coöperating. It is an open question as to how it would inform the teams that they have commonality, and for what they guidelines should be for sharing such information.

It is also possible to have different teams have prior arrangements to share some (but maybe not all) of their private data.

DT Back End

You might ask why, if the Front End and the Back End have two different functions, why not simply use two separate programs, instead of have one program suite?

The first reason is that the output of the Front End and the input of the Back End should use exactly the same format, so there is no miscommunication, and no need to have yet another program to "translate" the Front End's output into the Back End's input. Conventionally, once the AI Front End has been used to establish the engineering goals, then the Back End can be used to seamlessly model the finished product, giving the engineering teams the opportunity to "edit" the result and see if such modifications improve performance, longevity, efficiency, costs, and other factors, as outlined below. Once real models are built, measurements from those can be included in the DT, and this iterative enrichment of the DT content can result in a better product, which, after all, is the reason to use and maintain the DT.

However, there is yet a second, more-subtle, reason to keep the two functions together in one overall program suite. The Front End establishes engineering goals (AI, LMs), and the Back End provides a way to realize these goals. However, sometimes the Front End will miss something, and, which may be due to human error, or just simply the complexity of the particular project. Sometimes this might not be apparent until the Back-End output is examined. Perhaps the Digital Twin shows that the project does not (yet) live up to its goals. This might be detected by the engineering team (humans), or might be detected automatically by AI.

In either case, we can have recommendations on how to change the initial input parameters to the Front End. Perhaps the original questions were wrong. Perhaps a new tool or new technology has become available. By having a unified program suite, the two halves can work together to indicate what changes might be needed to the initial input. In other words, not only would the engineers have opportunities to change things and iterate within the Front End and within the Back End, they'd also have the opportunity to iterate between both parts, using errors detected at the output of the Back End to refine the inputs to the Front End.

Getting back to the functionality of the DT Back End: the Digital Twin of an engineered product can be used to make predictions, even before it is built or deployed, about its initial cost, performance, longevity, efficiency, continuing costs, ecological impact, human interface, and even human reactions to it. After the initial design, DTs can be use to continually model each instance of the product, as it is serviced and deployed. This can be aided by feedback from onboard sensors from each instance back to the DT. Details are in the Wikipedia article.[5]

Since DTs can include post-production data from servicing records and onboard sensors, feedback can be used within the Back End, and even between the Back End and the Front End, based upon how the engineered product works in the real world.

Conclusion

The suggested Program Suite can carry a proposed engineering product from the initial idea through several layers of design and implementation by harnessing Artificial Intelligence (AI) in the form of Large and Small Language Models (LLMs and SLMs), and by utilizing the power of Digital Twins (DTs), with feedback possible between different layers. Even post-deployment, feedback from servicing and sensors can lead the Program Suite to suggest modifications based on real-world experience.

The Program Suite can mitigate some of the problems associated with AI, such as using juried source material to reduce "hallucinations", and compensate owners of source material for their use.

References

(1) *National Science Foundation: Networking and Information Technology Research and Development Request for Information on Digital Twins Research and Development*. Federal Register / Vol. 89, No. 118 / Tuesday, June 18, 2024 / Notices pp. 51554-51555

(2) "10 differences between small language models (SLM) and large language models (LLMs) for enterprise AI" by Kane Simms (https://www.linkedin.com/pulse/10-differences-between-small-language-models-slm-large-kane-simms-edvee/) paywalled.

(3) Proximity Chatbot: Website: https://www.perplexity.ai/;
Wikipedia: https://en.wikipedia.org/wiki/Perplexity.ai

(4) U.S. Constitution, Article I, Section 8, Clause 8, "To promote the progress of science and useful arts, by securing for limited times to authors and inventors the exclusive right to their respective writings and discoveries."

(5) Wikipedia article: https://en.wikipedia.org/wiki/Digital_twin

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Request for Information on the National Digital Twins R&D Strategic Plan

Luzay Literatur Pilinci

- Subject: 30 and some articles grouped in 4 sections as follows:

1. ARTICLES ON CIVILIZATION, EDUCATION, PHILOSOPHY, POLITICS, METAPHYSICS.

2. CYCLE OF AESTHETIC ESSAY POEMS.

3. FRAGMENTS FROM DIARY.

4. OTHERS FOR ISUF LUZAJ.

5. NOTES.

6. BIBLIOGRAPHY

Summary,

I am titling it: "The Moment of Freedom in European Thought"

The moment when freedom reveals the foundation of her in Reason, her condition law, even its history in the world. Fragment of honor ‘’when President Ronald Reagan honors him with the title "Professor of America", described by the professor himself the day of honor at Indiana University.

In a class of mine at Indiana University, President Ronald Reagan, a friend of the Professor Award, said, "A good ruler shows the way to the blind; just as a good disciple gives eyes and light to the blind. I believe the world would be better, more excellent as if our disciples were as devoted to the task of happiness as to the happiness of the task".

This was said at the University ceremony, the day that President Ronald Reagan, the guest of honor, had the modesty to come, to present the Honorary Award for the performance of duty. I would like this medal to be hung on a wall nail in the museum of Tirana.

"I have had, I have, and I will intend to publish all my books, although I fear this dream will remain a dream until the beginning of the 21st century, when I believe that the Albanian people will build a democracy indeed, in the sense of the idea that this ideal is close to the democracies of Central Europe, even as close as possible to American democracy.

Some of us, educators of philosophy who by chance can be poets, believe that the freedom to realize the personality, in a cooperative society, is a valid ideal to live, to fight for it. It is a matter of values, Individuality is not enough. At the Philosophy Congress in San Francisco, California, I introduced this topic "Freedom to perfect the personality is an ideal that values the thoughts of life", Isuf LUZAJ.

1. EXISTENCE AND FREEDOM

Existence and freedom is one of the philosophical topics he has attracted the remark of the philosophers of our century. I chose Sartre as the prototype of atheistic existentialism, for my leader in this study for three reasons:

A) The first is that in the vast majority of more than a thousand US universities Sartre is taken as the basis of study and class texts when the course belongs to atheistic Existentialism.

B) The second reason is that Sartre is the most widely read existentialist in the world, in nearly 87 different languages, and this success owes much to his style and the academic classification he chose: the novel, the most compelling and inspiring to understand spiritual analysis.

C) The third reason, less important is because fortunately or unfortunately, a coincidence brought me closer to him and an admiration that ended in friendship, fascinated me.

For Sartre, freedom conceives at its roots with NON-BEING, which is in the human heart. For a human being, since it means to choose himself, nothing comes to man either externally or internally, which coming he will expect or accept. This heavy thought in meaning is also broad in its consequences.

Man is much and without any hope, the mother of the dominion and mercy of unmerciful needs, to make himself good, even down to the smallest detail of his existence. so freedom is not as good as being, it is the being of man, which means his non-being. If we fail to conceive of man as a whole-wholeness, it becomes absurd for us to have in him (man) psychic moments or areas of freedom; we will look for an empty place, inside a box full of water. Man can not be sometimes free and sometimes slave (slave); either he is always and he is not free, or he is.

Unfortunately in this moment of dialogue, the American Minister of Education intervened with American arrogance, who took Sartre by the arm to take him to the University theater where the students were playing the comedy The Mentally Ill (Le malade imaginaire), leaving me with the students who were gathered around us. But man will do this act without giving up his freedom and his clarity, of his mind. So, Sartre concludes, IN SELF to OURSELF can not be realized in reality, but the man continues his project with an imaginary reality, he projects his exterior, the empirical world, and calls this God. So there is no difference in what we are talking about man as his project or as God's project.

Sartre made as his own the old theory of Feuerbach that God is nothing but the projection of man's unattainable ambition.

It is, therefore, a surprise that man, having this clear and free sovereignty for himself, seeks to choose him as a master and to worship him as God, the God he created. This is clear, says Sartre, if we know, we accept that choice and freedom are two words that express an opinion.

Freedom, he wrote in Being and Nothingness, is the human being and nothingness is, say, the nothingness of being. It should come as no surprise to us because he makes the absurd choice effected, affected by the nothingness of being.

I have noticed that Sartre speaks the language of the great mystics: man is nothing. The enlightened doctor of the 14th century Taule said that for the Christian mystic, man, of course, is nothing, but a capable nothing of God, because it is God who fills the nothingness of man in man. The "self" of Sartre's man is a radical void, a void which can not be filled, nor transformed in any way. Sartre is to this day in France and in Europe and the USA, the first atheist philosopher who annihilates a man. In the case I had, as a professor of philosophy at Indiana University, to translate his conferences from French into English, I asked the French philosopher, in front of the professors and students in the auditorium.

Believing in the cosmogony, in the structure and laws of the Universe, in the structures of the microcosm and the macrocosm, and in their laws, have you thought of approaching the idea of the existence of a thinking God?

-No, - he said, - all you claim are human hypotheses and creatures; there is no God of thought. You want to tell me if I have repented of atheism. On the contrary, I am convinced that my philosophy will be better understood and believed in the next century onwards, when Christianity will overthrow false idols with their hypocritical comedians, from the Popes to their soldiers. Man must be perfected until he becomes his Lord. In his conference, Sartre accuses people of being cowardly, hard-working people who take advantage of their vain freedom and live in harmony with that freedom. To deny this freedom cowardly people are convinced that their lives have a lot of meaning and that they are doing something worthwhile in this world. One will manage to be a great man, the other a moral leader, a third claims to be happy. All of these projections are just a camouflage of projects or projections. Heaven is inhabited by an illusory ghost god. The only honest attitude in the face of this absurdity of life is to have the courage to accept a radical divorce with everything that exists between man and the world, between the goal that each of us expects from life and what life can now offer us. This bright view requires the renunciation of an eternal ambition. Sartre thinks that the main reason for our misfortunes and disillusionments in life is the mortal spirit (which makes us suffer), of seriousness.

Nietzsche blamed Christianity, which destroys human life from serious and tragic dimensions by promoting happiness and heavenly comfort.

Sartre blames Christianity that takes life very seriously, giving it meaning. Since man is nothing by nature, what can he do to bring him out of nothingness? The abolition of the thought of seriousness is one of the most essential and urgent tasks of action, an act that replaces Sartre's existing morality. We must overthrow all today's values towards the homeland, faith, and any social revolution if we want to be true existentialists.

Man condemns himself in despair, precisely because he takes, both himself and the world, very seriously. Man's misfortunes are seriousness, hope, faith, dogma, homeland, and religious morality, concepts which hold the human conscience slave of EMPTY.

Atheists believe in moral values, but reject Christianity, because it blinds people with a yoke of spiritual anxiety, but these atheists do not agree with each other. Some denounce Christianity as too authoritarian, disrespecting the spiritual autonomy of the individual, while others atheists who believe in the same values, following Nice, find Christianity too democratic and hold it responsible for the vulgar egalitarianism that characterizes the modern world. I have noticed that close people of thought and peoples of Christian-Muslim and Hindu faiths, in their places, in their shrines: Constantinople-Mecca-Baghdad and in some provinces of the cities of India, sometimes alone, sometimes with Sister or Mother Teresa of Kosovo. With UN chief Perez de Cuéllar, I had the opportunity, as an official of UNESCO and UNICEF, to get a closer look at the people of the Buddha faith. The problem of the existence of God turned to me in a spiritual change and when I had favorable opportunities I even tried to study it through European and Asian philosophers. During my stay at the Vatican, 1945 - 1948, charged with cataloging the Giant Library, according to the English system: subject, language, author, and title, I had the opportunity to study the problem of my anxiety from St. Thomas of Acquina to our century. Isuf LUZAJ "Egzistenca and Boshësia" page17.

3. FRENCH REVOLUTIONS

The peoples of Europe began to wake up sleeping the centuries-old lethargic sleep in captivity. Unfortunately, however, the French Revolution went bankrupt precisely because of the exaggeration of its dimensions, because it did not set the exact goal of where freedom ends and where tasks begin. That freedom brought to the throne the emperor a Corsican, the Kachaku race that filled Europe with graves, both of his sons and the boys of the world as far as Moscow, that finally France ended up in a comedy gym of the English and Germans and the French people remained more enslaved than he was before his famous revolution. That freedom, which died out in the early 19th century, brought into the 20th century the ugliest dictatorships known to history: Nazism, communism, culminating in the Russian dictatorship. The Nazi dictatorship darkened the atmosphere with the smoke of crematoriums, where nearly seven million people were burned to life, according to Franco-German statistics. The Marxist dictatorship, the pupil of French freedom, gave mankind the bloodiest and most shameful example history has ever seen: 219 areas of concentration; forced labor were 45 to 50 million Russians worked and died during 70 years of torture. The Russian statistics of 1995 show with exact numbers that in those areas of concentration approximately 70 million people passed, generation after generation, since their creation with Stalin and their closure with Gorbachev. This freedom of classless peoples ignited fires around the planet, up to their small homeland. Sociologists, statisticians, and writers on the spirit of the peoples estimate that approximately 110 million spirits have died in warfare throughout the planet to date, and in the concentration camps (408 areas in China) live as related animals. Approximately 18 million people work 12-14 hours a day and die before the age of 50 until today in 1996. Isuf LUZAJ ‘’Festimi i Yjeve" page 50.

4. FREEDOM IS THE OXYGEN OF THE SOUL.

We only appreciate it when we miss it.

A man, or a society, who does not feel the need for freedom, does not deserve the gift of life. Freedom begins in our soul when we come out of the water and begin to breathe, and it ends when we no longer breathe. No one is free unless he is the master of his stock the cause of freedom is identified with the fates of humanity. The most valuable freedom is that which gives peoples magnification of their energy, intellect, and virtue. Free is the people who manage to transmit the feeling of freedom to future generations. If we look for the origin of the feeling and the need for freedom, we will find in the ability of knowledge transmitted in historical conditions and in the character of a race that makes possible and intelligent the use of experience for progress Any other self-called FREEDOM, which does not meet the conditions of the mission of civilization, is a false FREEDOM that, when saturated with abuses, burns "Isuf LUZAJ," "Filozofia e Bukurisë ", page 124.

5. WHAT IS COMMUNISM?

Communism is a philosophy of unnatural life, against the laws of nature, doomed to bankruptcy because it is false with logical premises, wrong, and without foundation in the architecture of ideas and fiction sick imagination. Epistemology teaches us that the laws of nature are not equal to the laws of the sciences and are never put in tune with these; it also teaches us that the laws of science are not true, but relatively: 2 + 2 does not make 4 in either physics or chemistry. There is no absolute equality in any law of life and nature (think human and animal mental intelligence). But this inequality gives the harmonious equality of every organic life. If we upset this balance, we are in for sure. Communism, Marxism, Leninism are condemned as a utopia by all the heroes of thought of the 19th and 20th centuries. Epistemology, which comes as a measuring critique: weighing distance in the four dimensions of the essence and existence of the philosophy of science, proves that communism, including Marxism, Angels, Leninism, does not have the necessary basis to be called "philosophy", because it represents no original apparatus structure of constructive thought, but is merely speculation of sophisticated ideas derived from false, subjective bases, and from inaccurate and uninterpreted statistics at a given time, place, function. Thus, communism remains only a political campaign for the time when it was conceived, written, and spread to a backward people: anachronistic to Western civilization and modern technology. If one understands well Soren Kierkegaard, Martin Heidegger, Jean-Paul Sartre, Gabriel Markel, Benedetto Croce (to name just a few heroes of thought), one well discovers and clearly explains the weakness, superficiality, eloquence, integral falsity of communism, which, going through the sieve of free logic, it is reduced to him and remains nothing but a fiction novel of a weak imagination, which does not respect even the simplest laws of natural thought (senso commune), pale the laws of scientific logic. The statistics of communism, which concludes in surplus-value, is one-sided (unilateral - of one side of interest), it is superficial, general, which looks at things in general and not in analysis and in particular, as are the virtues of epistemology, therefore not is scientific in genetic interpretation, not to mention that it is not even mathematically accurate. Materialism is itself a half-hearted philosophy, because it denies or forgets, or does not see as blinded by appearance and mirages at all the values of instinct, intuition, imagination, creative evolution of female neurotransmitters, which in a word, in a theological term, are called SPIRIT, values, mental life mental activities (creative sensibility) that civilizations have created (21 according to Toynbee) and especially the 21st Euro-American civilization. If we go down from erroneous materialism to the materialist interpretation of history, then the errors of communism are magnified many times in theory, until they reach mental aberrations in practice, like a snow-rock, which, falling from the mountain, rolling, collects snow cloud and becomes so great, the more distance travels downhill. To prove this truth, one does not need to be either a philosopher or an epistemologist, it is enough to look at the History of Science to see and understand that civilization was not created by the proletarian masses, but by individual geniuses. with brain light above normal. This is one of the injustices of Nature, which in the function of dynamics, such as neutropenia in the physics of irreversible heat, which is the Holy Justice, which forms the balance and harmony of progress. Bring a million proletarians together for a hundred imaginary years in study barracks, and expect them to express a philosophical system or a scientific creation such as Belle's telephone, Fleming's penicillin, or Einstein's electromagnetic laws. Expect the proletarian masses to advance (not to create) modern technology. Expect them to write a poem together; poetry, not hymns to dictators, resembling the cackling of geese at night when they feel the fox around the hut, Isuf LUZAJ.

6. SCIENTISTS HAVE DONE MIRACLES WITH THEIR STUDIES.

The great historian of Philosophy (HEGELI) did not feel or did not understand, how progress would be made. He explained that the power of Ethics owes it's natural antithetical and revolutionary powers against the laws of nature. Herein lies one of the reasons they took him by the neck, magnifying the error to the utopia of Karl Marx. In simple words we summarize the result of that error thus: Nature is unjust and produces injustice in mankind: the beautiful from the ugly, the wise from fool; agile by clumsy; the healthy from the sick; the simplest of the devilish. Marxism will eradicate these injustices by making everyone equal, like philosophy with the bearer; as the poet with the bloodthirsty; as a saint with the devil; as the beautiful with the ugly will live alike without social classes. So far went the absurdity of the destruction of the privileged products of nature as the Zhen Cui, the poet, the philosopher, the scientist, the artists that in the twentieth century those peoples who were beheaded like a mother ox chose to dream of building the ideal society; but those peoples remained for about seventy years, counting in place without tearing a piece, forward, until they ended up in hunger, darkness, wickedness, bloodshed; areas of concentration, until the definitive destruction of that civilization that existed in the nineteenth century , Isuf LUZAJ “Kujdesjet E Bletës" Volume X.

7. "PHILOSOPHY CREATES NEW THOUGHT"

The philosopher creates the new thought, as an architect of weight, balance, depth, multidimensional height; he unleashes the new hypothesis, which will be transformed into scientific laws to materialize in revolutionary technology. By time and nature, we have Averroe, Aristotle, Leonardo, Fermat, Cartesian, Spinoza, Leibniz, Newton, Kepler, Copernicus, Planck, Einstein, and legions behind them. Their hypotheses created revolutions in all human knowledge, for example, Einstein said that only the speed of light is absolute, all knowledge is relative; there is neither Time nor Space; everybody that gives energy will die; everything that has a beginning has an end. I leave the reader to think about the consequences of these apothegms.

2. The poet creates an imaginary world and ennobles the consciousness with new feelings of beauty, harmony, truth, softening the millennial beast inherited in blood and hidden under the deep layers of the barbaric consciousness, to make it a civilized man: thoughtful, sentimental, lovers.

Poetry translates into all the known arts, in the way that most easily enters the soul, even when that soul is not a thinker - music, paintings, sculptures. The poet is called: Sadiu, Shiraziu, Homer, Shakespeare, Goethe, Hugo, Lamartine, Dante, Pascali, with legions behind them.

The Saint practices by making living things the thoughts of the philosopher combined with the feelings of the poet to create a new world of love, harmony, equality, brotherhood, freedom, which makes this life easier for man and prepares us. peace, to more easily lay the path of overcoming for a happy immortal life. It does not matter to find justification whether or not that life exists beyond the grave; it is important to believe by faith, for thus the living are not terrified before death, as is the case with Sartre. Isuf LUZAJ "Beyond the Good and the League", page 50. "Philosophy is not empirical science but it is a non-empirical science of the empirical. thus help to define the position of the real sciences as a whole (in conguinto generale - Italian) "I. Luzaj

8. STUDYING PHILOSOPHERS

Studying the leading philosophers of Western thought, over 50 years to prepare my university courses, I found myself several times troubled in the face of some PROPHETGMS, which my judgment did not accept, and which by scientific logic seem to me only as hypotheses. . The great architects of the universal study of their systems from Aristotle, Thomas of Aquino, African Agotim to Barth, Dostoevsky and the French and Italian Catholics of our century, on the one hand, and Leibntz Spinoza-Sooren, Heidegger-Sartre, and others on the other hand in their radical objections seemed to be insecure in their theses. The first to fall out of the statute was Bergson, my former master at the Sorbonne. The last one that disillusioned me was SARTRE, I apologize for the friendship he gave me. I suffered greatly spiritually for their contradictions and for the conflicts that were growing in my mind because it seemed too much of a pretense to overturn some of their theories and because I felt guilty of teaching them honestly in that one that I believed in those thousands of young souls, who expected the truth from me, and I was not in tune with my mind and the stars of thought if I was teaching them the truth. A big question arose in my mind: am I right to be just a learner, or are the giant heroes of thought right?

At the International Conference of Heads of Philosophy I attended as a representative of Indiana University at the University of California at Berkley, at that of LOS ANGELES, at Columbia University in New York - at HARWARD BOSTON, IN PITSBURG Penytvanis, in AKRON, OHIO, at the University of WISCONSIN at NORTHWESTERN University, IL, in these discussions with colleagues unknown to me and of course eminent subjects, I found my salvation from my spiritual conflict. Everywhere, by a majority of votes, my presentation was accepted, to criticize the great thinkers.

3) Discussions of the Philosophy and Metaphysics head committees at the Department of Education Illinois, In - New York, SAN FRANCISCO, and their findings referred to and submitted to the USA Secretary of Education in WASHINGTON D.S. These papers are the summary of 28 years in the USA in the above-mentioned Universities. Isuf LUZAJ " Kujdesjet e Bletës " Volume I, page 26.

9. EDUCATION

Education is the art that enables man for social life. His methods must converge in the development of all individual abilities to form a harmonious and fertile personality, intense, striving, calm (seren) in satisfaction, and worthy of living in a society that has as its ideal justice. The cooperation of all members of human society is essential for the well-being of all. He who does not know how to give this union is a parasite. To educate man means by this in conditions to be eternal for society, acquiring the habits of mental work, applied to economic, scientific, aesthetic, or moral production. All possibilities should be taken as being in each. Education should be integral to developing, care, physical, moral and intellectual energy. By enabling man for the life of life, he will not neglect me, he does not say from the tendencies that he expresses as taste and desire. Everything she learns must be learned to the limit of her quantity and time, which she will learn first. The more one learns, the more it will become for society. There is a general basis that they are for everyone, setting aside the skills that they process through talent. Any exclusive specialization without general features is impaired for the specialty. Boundary recognition is less effective when ignoring changes in etiquette. Education must be done complexly and seriously controlled by good masters. Isuf LUZAJ "Reconstruction of Spiritual Powers", page 156.

10. RULE

"It is true that a tree should be known by its fruits." But we ask what is a RULE?

Maybe peeling, ugliness, war, war, crime, and fate are part of the RULE. Maybe evil is an evolution of the order that reaches the RULE? But they see the world that exists more than happy; Therefore PLURALITY and without plurality and war - we achieved this action you would not be to have a world. Well, what about the fruitless war as well as the evil in life? What about the millions of seeds with which millions of lives can be produced that only a fraction show? What about the madness of selfishness and the end of power, like the accumulation of capital, but that all create misery? A real thing that has been created grows, travels together, so far seems real.

What a mysterious law empowers the wicked to annihilate the human race, in worldwide strife, where millions of innocent human beings lost their lives! What a mysterious law of nature is that which twenty civilizations are born and die and that one day our civilization will die and be buried like its ancestors; oriental - Hindu, Arabic, Babylonian, Egyptian, and Greek?

The only ideal left to humanity, to find the path of peace, love, kindness, and working in order like the organs of a concert that produce a symphony can build a better satisfying world, to worth the effort to live. Only in this poetic truth do I believe (1) this position of mine was accepted, not as a philosophical truth, but as an ideal desire poetic-religious, to be instructed to the peoples, of countries and the United Nations, Isuf LUZAJ "Bee Care" ,Volume I.

11. "TRUTH WILL SCIENTIFIC CRITERIA"

The only limit to their spread should be the ability to understand them. The only fate of their applications should be: to increase the overall happiness of the people and to promise them a more dignified life. Fearing the social consequences of cultural diffusion, some privileged once preached: SCIENCE FOR EXACT SCIENCE, claiming to reduce science to a solitary pastime. New times have called for "SCIENCE FOR LIFE", a platform for well-being and progress. When knowledge ceases to be a sport of the Epicureans, then that knowledge can be converted into the moral power of human exaltation, a power that is the only spiritual value. The scientific investigative spirit excludes any principle of authority, Isuf LUZAJ "Reconstruction of Spiritual powers", page 137.

EMPEROR

Emperor Vespasian one day asked Senator Helvidius Priscus not to go to the senate so that his harsh words would not thwart his plans.

- You have it in your hand to remove my task, but until I am a senator, I will never be absent from the senate. -If you will wear in the senate, said the emperor, you will shut up and do not speak, do not give your opinion. -Do not ask my opinion and I will not open it. -When you will be present, I can not stay without asking. -Neither can I stand without saying what I believe to be right. -If you were right, you would die. -We will both do what we have in our conscience and that depends on us. I will tell the truth and the people will despise and despise you. You will make me die and I will die without making a sound. Have I ever told you that I am immortal, Isuf LUZAJ "Reconstruction of Spiritual Powers", page 92.

WHAT IS DEMOCRACY?

Is it a natural phenomenon brought about by any comet?

Any island that came out of the volcano overnight?

Or is it an idea given to us by the Ancient Greeks and adopted by social conditions, with its qualities (and its flaws) that differ from its cultivation?

Democracy is undoubtedly an IDE, which we hold, a concept that we develop in the minds of some privileged persons from certain groups of society, from some nations of advanced and incorporated and grafted into several institutions, *Isuf LUZAJ "Bee Care" Volume I, page 358.*

Uprising of Ideas

The uprising, with Rebelue, is to affirm a new ideal. The three yokes are imposed by the soul

1. rule in ideas.

2. hypocrisy in morality.

3. domesticity in action.

Vacationer - Quietist youth of any nation:

Any attempt to free oneself from these captives is an expression of the rebellious or rebellious spirit, in the best sense of the word. Human society is the enemy of those who blurs. her vital lies." In the face of people who drop a new message, society's first gesture is hostile, forgetting the need for these great souls who from time to time reject the rot of society, preaching vital truths. All those who renew and create are fighters against political privileges, against economic injustices, against dogmatic superstitions. For them the evolution of ideas and habits would be inconceivable; there would be no possibility of progress.

Rebellious souls, accused of heresy, can be comforted by thinking that even Christ from here against the routine, against the law, against the dogma of his people, just as Socrates was before him, as Bruno was behind him. Rebellion is the highest discipline of character, it temples the faith, nurtures power, teaches suffering, placing it in an ideal world, rewards, which is the general great persecuted destiny. Mankind worships their names but does not remember their persecuted names. There has always been a tendency not to doubt a moral conscience of mankind, which gives its sanction. it is sometimes delayed when it is followed by its contemporaries, but it achieves, no doubt, always, increased in power by the perfection of the time, when it is distinguished by posterity.

"Insurgents"

Beliefs, which time has transformed into superstitions, continue to form a dusty atmosphere, which stops the development of human culture. Isuf LUZAJ "Reconstruction of Spiritual Powers", page 81.

12. PEOPLE AND THE UNIVERSITY

In the 17th and 18th centuries, much scientific progress was made by people unrelated to Universities. Scientific societies were the first institutions in the processing of scientific claims and discoveries. Universities began to play a larger role in the 19th and 20th centuries and it has happened that in these times they gave impetus to scientific demands in LABORATORY institutes.

The natural sciences are usually divided into abstract sciences such as mathematics which adds and defines values in other branches of science, and the concrete sciences which summarize the physical sciences:

Astronomy-geology-physics and chemistry; and biological sciences. The growth and enlargement of the body of knowledge have come from the subdivision (SUBDIVISION) of sciences in specialized branches. The inter-relation, relationship of the subdivision of sciences emerged in the evidence (clear picture) from the stabilization of the branches that were related to the field of observation, such as biochemistry-biophysics-chemical geology and psychophysics.

So, we summarize in an objective synthesis that, the term science, identifies, a critical activity of discovery as well as the systematic knowledge established in the exam, Isuf LUZAJ "Bee Care" Volume I, page 284.

12. "PEOPLE WANT CHANGE"

People want change, combinations, progress, but if they have not reached a level of culture, they do not know the way to salvation. The poverty that is exhausting the peoples of India, China, Latin America, Africa, has remained on the scale of RESICHATION - giving up any elementary, progressive idea. peoples explode like atomic bombs. The example of this apothegm we have fresh in the elimination of peoples from Marxist tyranny from Russia to Europe. Two ideas create civilization: The fall of the old fake idols. The disintegration of new ideals, these two factors have characterized every historical crisis. Ideas that shake the foundations of an old society, create reactions in the ruling classes. Here are the changes in people's desires, especially during the crisis, they grow so dramatic. It is clear in those moments that the history of mankind is a ruthless struggle between invention and convention. These concepts have moved the axis of History: The divine right of kings; the sovereignty of the people; dictatorships of any color: black, current, red or white, absolutism all against the sovereignty of peoples, the abolition of tyrants, the abolition of slavery; class warfare; The right of speech; imperialisms, colonization, are the sad examples that characterize the change of concepts between nations. History surgery resembles Medical surgery ‘’Cancer must be removed from the brains of tyrants to bring people's life, freedom, justice, equality, brotherhood’’ , Isuf LUZAJ "Bee Care" Volume I, page 360.

RULED CLASS

Equality of humanity in a classless society, reforming the economy, surrendering to power; dividing the land with agrarian reforms; putting a politician in place of a technician; channeling creative activities; disappearing in death and freedom of thought; power thus creates a privileged class, not thinking, but obedient; an automated bureaucratic class of labor and people: does what it demands free. The healthy part of society seeks to react.

Power imposes its will, based on an organized minority with power: police, army, corruption. But when the will of power begins to waver, it has no other way of escape than TERROR, with prison, concentration camps, forced labor, rope, and bullet. The fate and end of all dictatorships of every color are known. Most politicians are sophists in the service of demagoguery.

The allegory of sophistry is like a screw that enters the soul of the masses twisting and, only when it dies, does it stretch straight and we see all its emptiness.

Throughout history, demagogues have known how to seize power, but they have not known how to govern with democracy, justice, equality, fraternity. The state is converted into secret police. Cops, landlords, and tyrant chief of the Terrorist Police.

Anger or resentment begins with madness and ends with repentance; he is the most impotent passion. It can not operate anywhere; it hurts the man who has it in his soul, more than the one he hates. History is full of unforgivable examples of these people blinded by resentment: it's enough to study, Isuf LUZAJ "Philosophy of Beauty", page 114.

13. I AM A PRODUCT OF FREE EURO-AMERICAN THOUGHT, LATE 20TH CENTURY.

To be free, I can get from the three schools of Existentialism the real ones, those criteria that it accepts one hundred percent, not only EPISTEMOLOGY but also modern TECHNOLOGY of ASTRONOMICAL and BIOLOGICAL miracles. Therefore these writings tend from time to time from one school to another to stay in a completely free field of thought, reasoning, reasoning but also of Metaphysics, Metallurgy, and somewhere even of Theology. I am sure that even Kierkegaard, Thomas of Acquina or Socrates, Plato, Aristotle as well as Pascal - Montaigne and Prust if they were alive today, would make changes in their philosophy. I also think that the reader, you will ask me: Who are you, who dares to oppose one or the other of the giants of thought? Will answer: I can not write to please both thought giants, like my readers.

I write to say a sure word in Her Majesty the Wisdom because I think that each of us spirits should put a pinch of sand-lime and cement to the castles that others will finish. Another reason for my originality, sometimes at odds with the giants of thought, is because all those who have wanted to discover something new have been at odds with the old schools and are called Revolutionaries. Finally, I am Illyrian-Thracian, the only people in the world who called themselves ILIRIS, ie warriors of all information. Only Time will prove if in my writings there will be any clue to the real Revolutionary reality with Revolutionary purpose. Isuf LUZAJ "Bee Care" Volume I, page 14.

Note: To have a clear idea of some of these dark-looking ESSAIS, it would be good for the reader to use Andrè LALANDE's Technical Dictionary of Philosophy French Academy.

14. EURO-AMERICAN CIVILIZATION

Libraries should be cleaned of leukemia that covers them and by replenishing Libraries with books of Euro-American civilization: Philosophy-sociology-epistemology- with courses on the philosophy of history, diplomacy-science. With interpretations of beliefs, for example, Gabriel Marcel - Metaphysque Journal. For natural continuation with then-science-technology.

All these factors can be imposed by the sound civilizations that have given for the result-happiness of man. The Albanian people must sincerely acknowledge their mistakes and, as a conclusion, acknowledge themselves; to place himself at the point of the trajectory of his existence; to rebuild his conscience, to chemically recognize his microbes, to kill them and take a new path, with a new ideal, for a sincere democracy, for a new life, faith in God, faith in the glorious history his, faith in moral values, faith in himself, to open the new path to national history, as soon as, otherwise, he will lose another 50 years, in a swing away from you; one cap front, two cap back.

If he was still able, the sick man to stand up (not as an ambulatory corpse, but as a hero), when the hope that soon he can take the place he likes, as a historical people, in European Civilization and the society of Nations. Let's pray to God for this miracle.

The Argentine and American poet Jorge Luis Borges suggested that I write a study on Albanian Morality, Ethics, and Aesthetics. Modern thought, intellectuals came as they heard journalists, writers, poets, painters, musicians, and a world-famous sculptor.

On that occasion and for that reason, I became a close friend of the great poet, the friend and not companion, because he was a giant, and I a minor, and because he was a Marxist spiritually and an oligarch practically. We sailed in different waters, Isuf Luzaj "Philosophy of Beauty" , page 106. Intellectual personality is a function, it is not balanced, it tends to a permanent integration without rest from an experience, which is added. Another critical meaning, which rectifies, Isuf LUZAJ "Reconstruction of Spiritual Powers".

15. READERS OF THE 21ST CENTURY

So, reader, I send you, to fly like a bird bee, flower by flower, to suck the nectar that will be converted into honey. that will ignite in your soul a desire for knowledge in thoughts that are the fruit of half a century of experience, BUT READ AND THINK!

Make desire habit and habit, not as a curious walk of the Epicureans, but as a methodical school study, delve into thought systematically, roughly, logically by analyzing each subject and depositing it in your memory chambers regularly, so that when to want to open its doors and find you fresh for every purpose, Isuf LUZAJ "Teacher Diary" Volume IV.

End of part 1

2. CYCLE OF AESTHETIC ESSAY POEMS

16. "Literature imposes its magic such as the novel. But our time belongs to thought, truth, beauty, and sadness, not caring about impressionism".

Let us divide it into two distinctions, what we mean when we say good poetry: It means ither, that poetry is good art, or that poetry is good for you; and they are certainly not the same thing. For many reasons we can agree that Dante's poetry has value because it is moral in the soul of the poet, but also because it is expressed with such noble height of art, that it makes us friends to read it all our lives. We must share the judgment critical in ambiguity: aesthetic value and moral value, either in judgment as tra, considered especially by the subject matter, or in judgment in agreement with the subject matter. Poetry is good in the aesthetic sense, it is good as ART when it is expressive and it grabs us, readers, it makes us its clothes. When the poet, looking at an experience, has succeeded = winner, finding equivalent expression to reflect it, which helps the reader to construct a personal experience of his own, to be in quality, like that of the poet, and not much inferior (lower) in intensity. Expression is greater than goodness. A true word can be expressive and in this case, it is moral poetry, and poetry from such a thing is a special expression, or in this case, it can not be an admirable morality it is not poetry. Moral depth can add value to what is being said, but it cannot escape the weakness of expression. Romantic aesthetics made poetry the activity of the human mind, higher than all other activities. Poetry was thought to be the noble endeavor to find the truth, as the apex of the pyramid of thought. We will find many things that can be overcome, if we are obsessed with this esoteric (supported) concept of art, to identify poetry with the language itself, and this opens our eyes to ubiquity (Omnipresenca = almost present) and its primitive nature.

To reverse the judgment: Poetry is not the highest degree of reason, it is the first degree of the experience in question, before logic, before morality. Our mind imposes the human form on this subject, grabs it intuitively. The mind expresses its intuitions in dictionary symbols and what expression is poetry, Isuf LUZAJ.

End part 2

17. MERCY SHELF

The dust of sorrow falls from loom,
Tired of all that travel,
Whoever plants a tree expects the fruits of hope.
Most of the time, fate is unreliable
Sleep like a mountain hotel in winter,
Bitter mistakes go to the parade.
The Idea was shared with the Idol
the green olives are fallen.
The sacred love of bitter times
Resurrected in faking an old dream.
Toss the feather and notebook into eternal rest,
I turn from your shelf, classmate,
And you abandoned, serious and feverish
Loneliness upset you, patience tired you out.
To me, you are a city, a day of celebration,
The old temple, but new in splendor,
He embraces the orphan like a mother,
Ribs for ribs, heroes of thought.
Cut, polished into walnut trunks,
Hard to enter a forest full of giants;
In you, I find believing hope.
Give me generously what I do not have,

The keys to barbaric life.

I believe in you that you will see me on the other side,
The last hope hanging on the mandala
In your pillars an unnamed sculptor
Carve a figure, a faceless God
Gives luck and spreads both mind and heart.

I see Patriarchs clearly as mirrors
Looking forward to kissing a female conscience,
Sow their wheat seed

Your faithful friend, I come and thank you
As the monk of Christ, we are heart in hand.
I ask you, you answer me, I renew myself, I rise again.
I flee from this world, this cruel life,
I leave with you for the snowy mountains
Along with the Patriarchs I worship as saints,
I renew, I get rich, I enjoy.
In you, I find hope, comfort, and peace.
When night comes to beautify the moon,
Giants walk like shadows on the wall,

THE STARS COME DOWN, HUG ME AS A MOTHER

In ancient times when the glory of the flag
Revived the nation with the dawn of freedom.

Dark silhouettes of a world of thought
They travel through the eyes like ships of exile.
A silence comes like in summer when the sea sleeps,
It piles up the thoughts I gathered from the sheets.
Keep memories and nights faithful,
My heart is filled with gold like the king's treasure.
I hear the old man traveling and the river,
Embrace those civilization parents
Enjoying that learning happiness.
The old man lowers his eyelids, so he falls asleep.
Isuf LUZAJ " Lamtumira e Yjeve ", page 164

18. NEGLIGENCE

Let them pave my way with thorns and thistles,
Let me plot mediocrity circles
Born crooks born of curds,
The corpse ambushed the prickly soul.
Linda in the mountains dies standing like oaks.

Never in my life have I mentioned rabbits.
I will drink the water with my clean fist,
Everywhere they asked me, I left the message,
Those farther away approached me,
I taught them the lesson with harsh examples,
Prepare for the battle of lifelike fire,
By faith, I denied every power to the devil.
The laws of life never had a hearth
Nor in the lost farm equation.

Evil can take anything from me,
Values are stolen as History is stolen,
The tyrant stole the path of fate.
One thing they can not take away from me:
‘’The Mysticism of the Church’’,
Patriotism and battles of fire,
The trust I had in the Father,
Nor the pleasing shade under the pine branches,
No matter how much the swamp frogs how.
Isuf LUZAJ " Lamtumira e Yjeve ", page 172

19. INSPIRATION

Trees of silence, shake in the shade
Sheets of that of memories
From a river frenzy to a sea beach
The same forest that did not know the time,
So it did not change from snow or fire.

As he was born, he ascends to heaven.

It's not true that stars are born at night,
It is the darkness that strips them naked,
So they give light to the centuries,
Written will without. But for whom do I know

Color has traces of what without their appearance, He meteorologist, predicts History.
When they disappear Tragedy begins.
Reads the unwritten testament History,
Somewhere rarely do civilizations arise;
Where female minds are born virgins.
The meteorologist had predicted it.
When you're silent, like a dumb born,
I hear the voice saying
What your tongue would never have said,
For between your word and your silence
There is the same geometric distance that is in the middle of the idea that forms the blind
For light and light is never heard.

When the meteorologist catches you, he speaks to you without fear, he sings loudly
Everything that the thought knows about you, But be silent without saying what you are, What you have been and what you will be
But every day dawn means your mysterious essence. Although you get angry with a whim of joy.
Isuf LUZAJ " Lamtumira e Yjeve ", page 256.

20. JOHANN STEBASTIAN BACH

Thank you, O heavenly mind, You have made me very sad times from sadness, so great that I suffered, so much misery.
I called the witch to come with kosor.
I am a stranger in your Paradise
Where you have accepted the wicked and the good
Of all races, nations, and countries;
You saved mankind from the anxieties of emptiness.

You give me expression, peace, tranquility.
I followed the devil who gave me the temptation,
With my breath, I extinguished the candle.
The wounds of the soul defeated the spirit.

You restored harmony to my mind,
Thought drains when you play the symphony.
He escapes the mystery, the emptiness of the slave
The resurrected faith takes flight to GOD.

You snatched the LIFE effort again.

With the imagination of a thousand fantasies
I continued the journey of traces of truth, I created for myself many mythologies with your sounds I recognized the beauty, which I desperately needed to touch with courage.
With it I built my Cosmogony

TO LIVE ALIVE AND WHEN I AM DEAD.

With you, I will dance, hymns of loving your servant in heavenly faith.
I will build a temple of poetry for you,
With your mysticism, you took me by the hand.

Your music, Religion of Purity, Mirror symbol, crystal clarity;
gives me hope the courage of harmonious language, gives me a wealth flight of inspiration, Unwavering faith your mystical power, your flight in the heavens Revelation.
I prepare quietly over the bridge,
To live clean centuries across the river.
Your art, the splendor of Architecture,
It gave me dimensions in sleep dreams.

All peoples understand your language.
All mankind sends thanks
For light in the soul, in the senses, in the mind.
The temple of the peoples for a thousand faiths.

Isuf LUZAJ " Festimi i Yjeve ", page 70.
My note; The professor wrote the verses with his sounds because he liked Bach.

21. MARIA BELLONCI

Italian Senator

The time has come like a sea wave,
Like molten silver in flag celebration,
When it resembles gold and wood
Green, more rhyming than the sky
When it lacks the moon and the sun.
The eye of light, the heart like fury.

Dumb mouth, stingy in question
Feeling sincere, distinguished, alive,
Promise and doubt trigger like eels,
Concentrated on virtue with the stars,
Here and there when it comes and goes
Like the silence of the lazy moon in the woods,
As the ascent-descent goat valley,
In the branches that burned like fireplaces, fury.

Our pain a diamond silence,
Tranquility like the night of Kumi,
On the beaches, you have long slept
Si pertesa ne koke elefanti.
The time has come in May for the fingers.
Iku time as a fantasy creature
Deep green, like the light of your eyes,
Express a heart in magic magnets,
Merciful nun, when she breaks one knee

The chain that connected me to you
That love found the limit,

On the one hand, a lawyer with a mind and a heart,
Hope for my place in captivity,
With a giant side like a church and a glass,

The other side of the devil in a woman,
Hem's nuns with Calvary's faith, Marx's faithful veil, and weep for the plight of my homeland.
That was the question, this was the despair that forced me into exile.
I never read in your brave soul:
Were you with God, were you with the devil,
A man, a barbarian?
Your enigma will lead to the funeral.

YES HERS

Once upon a time after months of rage
Reading your emotions,
I was seized by indefinite doubt,
Your very confused thoughts:
How not decide on the path you have taken.
I looked for the purpose in your oratory of indiosmicrosis that you hide with two minds, but I could not find the way to appetite
Both with Saint Paul and with Lenin,
Here uses the mind, here use the goods,
With one hand the cross, with the other the devil. I could not find a scale to weigh your heart, so I turned it in the fall of memory.
I have two reins in my feelings and my mind Because the flowers that sprout after summer Give only a mystical perfume. Even the devil could not find the intentions, if I had been a little hypocrite, To nurture your intentions and hope I would have silenced all sadness. Yes, my mother gave birth to a steel block.

Isuf LUZAJ "Farewell to the Stars" Pages 184,185,186, book published in Albanian 2001.
Note Professor Luzaj called Mrs. Maria Belloncin an Italian Senator because she influenced culture.

22. THE MOON THAT MY DEAR

She kissed me when she slept over the logs
It has comforted me from the anxieties of life
He caressed me when I was in despair

She cooked me last night bread
When they hit me hard it gives me inspiration
She learned the law of the bee.

My obsession with the six oceans
That despite me as a baby in the cradle
Wait and follow the continents by land
Welcome! Goodbye taste of life.

I cooked the joys with fierce anxieties
I forgot the present, I lived for tomorrow
I saw the ideals with a different prism

I was convinced that ideas do not die
With my arms, I hugged the giants
The most religious, the most pagan.
Books make me the roofs of castles
When sleep did not come age-old enemy.

Isuf LUZAJ " Vallja e Luleve " Page 62.

23. TIME OF SHAME CONFESSIONS

Poor my verses,
He burned the robber's hand,
Poor shame in history,
Police time, gendarme time ...

Silent time, time of hunger
Time of shame, time of mourning,
From head to toe;
Dead fairy, dead watch,
Dead nation, when Vlora dies,
Deaf, dumb, and blind;
Men for hours bag
Bent back, broken knee,
Poison on the head and claws,
Destroyed through the mud,
People, more river and stream -
The first shame in History!
Poor my verses
Dream Hive Ideal,
I believed in the healing
In the state of the baraka,
Around the cone of snakes
Fate dice toy nation,
Tirana, Switzerland, Italy
Fly suitcases of gold.
The people died of starvation
Stuffed grass-clover mouth,
Further on in Labëri
Vdisnin si mizat beharit,
When the storm catches them and it rains.
Poor my verses
The stoves burned them.

The arrest took place in Lice
In class, I was teaching.

Decourville does wonders
"What will this young boy have done,
very strict doggie-
Why did the arrest take place?
For some verses brave words
That lalagjoni cried,
Eavesdropping on young spies:
The book speaks with irony
Figure allegory
Very vivid, allusion
He speaks of His Majesty,
In the Serpent and Nero
Narrow bins in the ministry
Ninety days in the dark,
With two barbaric tortures
That the Albanian is ashamed to say.

My poor Albania
When will you remember the type,
Learning in history

HOW IS FAQEBARDHI HONORED?

Crucified soul in sludge,
God is the bayraktar.
A black trial was opened in Korça
Ceremonia Prap Goxha,

Journalism is not allowed,
Gjergj Bubani protested:
"This is not a producer
A young boy is tried,
Why did he write poetry
Innocent, without wickedness
It was a dream come true! "
Judge Shkodrani happens to be there
Noble blood, noble uncle,
Trim posi Selam Musai
Arberian blood Arberori,
He denied what the witness said,
He played his fate,
Albanian "INNOCENCE".
The book that was written the most
With troubles, poverty,
It crumbled and was crushed,
Labi soul, how to endure!
Confessions make their ashes.
Woe to you, my Albania,
When will a new generation come:
Make time with me ?!
Isuf LUZAJ "Stories published in 1937".

Note: 1.DECOURVILLE- French director of the Lyceum of Korça. 2. Snake and Nero, two poems in Confessions. 3. Ndoc Çoba presided over the trial of Vasil Xhaçka, Sotir Kozma, a mathematics professor from Gjirokastra, aprosecutor from Vlora, constitutes the trial of I. Luzaj.

24. MY LIGHT

Throughout the centuries
Every tyrant has threatened me
Beaten, imprisoned,
I thought they buried me.
They caught my shadow.

The hand of the slave never disappeared from me
That I am a slave of God
I teach, I teach,
Wherever tyranny disappears,

He raises the ghost from the grave,
Just as Lazarus was raised.

MY PEOPLE LIGHT LIGHT

Woe unto him that heareth not me!
Knowledge is not borrowed.

Existence makes sense
From the essence of my heart.
Experience teaches lessons,
Corrects when he makes mistakes.
Isuf LUZAJ

25. ETHE EMPTY

Ask him out well if he is no longer absorbed in the connection.
What he intends to do with my future, would be folly.
No one deserves this miracle.

Nor can I ask my deeds to
They look with search and understanding, without Anger, as jealousy would be as if forgiven, without guilt.
Forgiveness cleanses the offended, not the offender,
Which I do not love.

The freedom of my thought to discuss with Time is illusory
for those who have not fought against it.
I am determined to have the courage I have left through the millstones, If this is not enough, I give hope and
My dreams, let the cynical Lady hear me.
I do not claim to be treated by that poet,
Which is an alms exaggeration, yes as a friend,
As a counseling elder, as a schoolteacher
Primary, for those who accept advice.

Forgetfulness is knocking on my door; it
It gives me hope because I will not
I do most of the Mystery fever.
Isuf LUZAJ "Farewell to the Stars" page 123.

End of part 2

3. EXCERPTS FROM HIS DIARY

January 30, 1940

Today Hitler delivered a speech at SPORT PALAST in Berlin celebrating the seventh anniversary of his coming to power.

He announced that those who wanted the war would have it now. The Führer applauded deliriously when he articulated with ironic exaltation the information of the Allied war preparations: "We have not slept for the last five years." People jumped for joy and ecstasy that electrified them, who were sure that there were many bombs in military depots.

Crazy world. How is it possible for an entire German people to be mesmerized to such an extent that they think with the brain of a single man?

How is it possible that all that culture is lost and has no value in the face of the folly of a foolish ladder, sick selfishness, a manic ambition, to be laid out for a strong medical visit? How is it possible that all that civilized Germany does not have an external scientific statistical service to recognize the productive power of North American heavy industry? How is it possible for a civilized people, of 100,000,000, to go all crazy? To drive a civilized nation crazy to exchange for madness? In our country, when one plays with the mind, he is tied with rope and locked in a dark room; in Germany, they wear it with ranks placed at the head of the state, *Isuf Luzaj "Philosophy of Beauty", Page 46.*

June 1941

Today I received the transfer order to Cortona d'Arezzo. I greeted all Albanians. The communists also came to wish me well. I saw some tears in the pages of friends. They cried because they felt sorry for us; they cried, for it seemed to them that they were left alone and less; they wept because they remembered the day on which they could all come out; weeping with tears of joy or sorrow? God knows. Most cried. With suitcases in hand, a policeman in front and two behind, we went down the stairs and boarded the small steamer in the direction of Gaeta.

On the steamer, my hands untied. After three and a half hours of the sea voyage, we arrived in Gaeta. We got the liturgy for Foggia and from there the train to Rome. We arrived in Urbe at 9 p.m at the termini station, we were met by other police officers who picked me up.

I parted with a thank you for the effort they received from both police officers and one who remained accompanied me along with 4 others to the general police station, Via nazionale. From there we returned to Termini station and took the train to Arezzo. Darkness. Rome looked more like a prison, sacramento- war, danger, death.

These were the words that were heard everywhere. Trains full of soldiers; an extraordinary movement, a turmoil, a Babylon. We arrived in Arrezo at 7 a.m only the fifth, with 4 policemen, went to the square of the prefecture palace, to wait for the police station to open. At the police station, I had a terrible fever with a severe headache. I was angry because tears came from the fire and the police did not see me because they were crying from weakness. I have a fever, 40 temperature. I was pulled out of the cramped closet where I was put and put in a large crate of more than 50 people. He had last year's watermelon skins on the ground, never cleaned, it looked like a pigsty.

June 27, 1941 CORTONA D'AREEZZO

Cortona is a medieval Mediterranean castle, some 35 m high above Lake Trasumen. A small town of about 2000 inhabitants, on a wooded hill. There is a main street called VIA PIANA, a gymnasium, two congregations of Jesuits and Franciscans, a cemetery, two primary schools; a museum, a library, a carabinieri office, 7 carabinieri, and some 5-6 fascists. Here are the great malarial and cavalier hospitals. It is a beautiful town and climatic center for the poor of nearby cities. A small annex police office of an office with an Arezzo quest representative and two secretaries. The police commissioner, a man some 50 years old, welcomed me well, i.e. as a human being, as opposed to those to date to treat like animals. After registering me in his register of internees, he showed me a pension where I could live more freely (cacciatore pensions). The owners of this pension also had an anonymous restaurant. There I settled as a pensioner with 15 lire per day, accommodation, food, cleaning and all that is left and of course. The retired lady was a strong young woman, male type. She ran the entire interior and exterior administration of the house, where her ex-husband was just gossipy, sweetly submissive to the spontaneous will of the Florentine lady.

Here I began to enjoy a little peace and rest. A neighbor named Arnetta Tribioli, a 35-year-old single girl came to me on good days of illness and accompanied me carelessly throughout my stay in Cortona. Anetta was a sincere, healthy, beautiful, blonde, blue-eyed, round-faced girl, very agile and quite smart.

He had graduated from a classical high school and spoke two or three foreign languages. She had been a teacher and a postal clerk. Now she stayed at her house and lived with private lessons.

She sang quite well, played the piano like a virtuoso, felt and knew classical and modern music, danced very beautifully all the modern and classical balls of Europe, even the Russian ones, and was a perfect ballerina as if strong muscles did not hinder her of the untapped youth who had remained virgins to this day by a disillusionment of love so strong that not even the grave pays for it.

I knew her because she sent me students for lessons to get some free. She then retired herself to bring me students and their parents to get to know me. It helped me a lot to recover materially and morally. Former superior woman, therefore former anti-fascist and democrat. The great pain that had kept her a virgin until that age had isolated her from all the social environments there for the fact that she hated them and called them ‘’Contadinaci’’.

We went from an hour of rest with a long walk from via Piana to the tennis court near the forest. Usually, she always spoke. Our themes were literary, artistic, philosophical. When I wanted to talk about fascism and war, she summed it up with these words: let's not talk about canaglie; ladri, trufatori, criminali, ignoranti, megallomani dell tre clicbe: il mignolo (king), il pazzo (Duçja) ed il ladron (Papa).

She was well acquainted with modern Italian culture. He had spent almost 20 years of his life in solitude, reading, and had a discreet (secret) library of eight. He had an only brother, a militia officer in Florence.

This woman treated me very well. It gave me a job to live independently of home and government; gave me the courage to recover strongly after so many imprisonments and internments; gave me moral nourishment because it was my only spiritual fellowship. Respect respected me and, although we loved each other spiritually, I physically left him as I found him. That is why friendship lived, *Isuf Luzaj "Philosophy of Beauty", page 79.*

ENTOTENE 1 November 1940

I presented this draft program of the Social Democratic Party Ventotene central committee.

1. The Social Democratic Party is revolutionary, militant, reformist.

2. The Social Democratic Party goes to war against the occupying Italian fascist enemy or any political color; goes to war against any external enemy that violates our integrity and any external and internal enemy that restricts political freedom and social justice.

3. The binomial of the Social Democratic Party is political freedom, social justice.

4. The Social Democratic Party fights for a free Ethnic Albania, with its natural borders that include the five vilayets that were part of the Ottoman Empire, i.e. Old Albania, Kosovo, and Chameria.

5. The Social Democratic Party will seek to take over the executive power of the government, but always in a democratic way, with direct elections for universal direct suffrage.

6. The Social Democratic Party will fight for the liberation and unification of the homeland, leaving it in the hands of a plebiscite or direct voting for the people to choose the form of their government.

7. The Social Democratic Party cooperates with every Albanian party that aims at the liberation of Albania and that does not violate territorial integrity, political freedom, or social justice.

8. The Social Democratic Party has in its program social, agrarian, financial, cultural reforms with a western spirit.

9. The Social Democratic Party fights for perfect social justice regardless of classes, beliefs, provinces.

10. The Social Democratic Party is popular, it is born from the people, towards the people, it consists of the people, it works with the people, for its ideals.

The decalogue was followed by a three-page minute, which included a motion for cooperation with the Communist and Socialist Party. After the minutes, a program of internal administration and the skeleton of the party, with a general congress of the Albanian people, from which the party hierarchy emerged d.m.th. the 7-member central committee, the national defense committee, would be a kind of executive power according to the program voted by the congress. Each prefecture a provincial committee, each sub-prefecture a provincial sub-prefecture; each village a committee, an armed gang, a political commissar, an administrative commissar, a financial commissar. The Central Committee appointed the central executive committee, which was a kind of general command of the armed forces.

It named three commands of the armed forces: one in the south, one in the north, one in Kosovo with one headquarters each. The three deputy commanders-in-chief were subordinate to the executive committee. The sections of the central committee would be:

1. Press propaganda. 2. Politics. 3. Military. 4. Administrative. 5. Disciplinary 6.Financial. this escalation would continue for the provincial committees as well.

Later I presented in a decree a revolutionary law for the regulation and administration with a strong martial basis of the civil and military rights and duties of the people, of the revolutionaries, of the armies during the revolution until the day of national freedom, *Isuf Luzaj "Philosophy of Beauty" page 73.*

My note; continues but I'm interrupting it here.

March 17, 1940

Went a week in prison in Vlora, with questions to students. Finally, 12 high school students were arrested. The others released them. This morning, at 4 o'clock, the prison guard woke me up, notifying me that we were leaving. Handcuffed, together with the 12 students, they transported us (took us) to the Durrës prison, from where they put us in the steam barn in the direction of Barin. The steamer was called Barletta, the commander was called Broggi; the commander of the police squad was called Meschino; the cops were all poor. They chained us, like horses or cows, so that they would not be killed with each other. What about us, why? I asked Commander Meschino, who answered meekly: - Because here the Fascist Roman Empire rules. -Aha, -I said, it is a form of adequate behavior with you and your Empire. No reason. "Tel maitre tel valet - tel grani tel pani" I translated into his language. The students slept all night because they were tired, and I could not sleep for the first, second, or third night at sea. On the fourth morning, we arrived at the port of Bari. After 6 hours on foot, hand in hand in the corridor of the port, we were taken to the police station of the mall. A marshal sat down at the table and wrote: ‘’Ordine of Carcerazone’’, *Isuf Luzaj "Philosophy of Beauty", page 49. "Filozofia e Bukurisë"*

Today at noon the little steamer landed us at Ventotene. The small island of Pandatori near Ponza and St. Stephen in the Tyrrhenian Sea, five hours from Naples, three hours from Gaeta with a slow journey. The place is wild and without plants, with some rare trees and sea figs. It is inhabited by families of fishermen, police guards, militia, carabinieri, financial guards who serve to maintain a strong, disciplined order of internees. The houses are all ground floor, Gothic-Byzantine style, domes like mountain caves, where animals sleep or rest. The strong wind here is more lady than the human hand and therefore no tall houses can be built, nor can they be tiled. Legend has it that the first prison was set up here to send the first victim of society, the sister of the emperor of Rome, who shamed the honor of her family because there was blessing and curse in her soul, boy and worry. Legend does not define which emperor and what was called the bandille girl. As soon as we got off the steamer we climbed the zigzag path consisting of 387 steps, we found ourselves in a beautiful square that has a free view of the sea, and in the middle in the direction of the colony of internees, a vaulted hut with a half-floor; to the left is a small church and to the right is the residence of the principal and deputy principal. About 67 people were handcuffed because from the prison of Bari they accompanied us together with Dibra and Bajraktars and simple workers, among whom was noted for generosity and nobility of all Aziz Kaloshi, the uncle of Murat Agë Kaloshi. After being ushered into the small courtyard surrounded by an iron fence and lots of guards of the popular fascist security, they untied our hands and feet and allowed us to sit in the square, *Isuf Luzaj "Philosophy of Beauty", page 55.*

25. AUTUMN MORNING PARIS 1933

One autumn morning in 1933, with torrential rain that cooled even the bones, with fog that did not see man on the street, as happens in Paris, at the Sorbonne, in the Des Carte's amphitheater, my professor of Philosophy, Andre Lalande, distributed the themes of drafts. After handing it to one by one, approximately 100 pupils, he removed the halves, wiped the sweat from the eyelids and the wrinkled cheeks like elephant skin, and taking a deep breath, said: - I have the best topic, but also the most difficult one because it requires work, will, and nervous calm, which I do not owe to any of you who do not know you, but the volunteer is welcome.

The topic is: "*Philosophical parallelism from Des Cartes to my genius colleague Henry Bergson."*

I raised my hand as a volunteer. - What ethnic group do you come from? -Iliro-Thracian, Albanian, The Mediterranean. With a smile of pity and an expression of the Patriarch, the old professor said:

-Today's Mediterranean nationalities do not have a cold scientific temperament. They are more imaginative than logical, therefore, you, young man, think well, that, if you did not develop the average acceptable, you may lose the right to the oral exam in December I want four to six thousand words. Think again. I begged him to give it to me. He extended his arm without looking at me and I took it from his hand. I worked on the topic, studying not only books selected from his bibliography but also translations of Kant, Hume, Libnitz, Nietzsche, Spinoza, Heidegger.

I wrote about 8000 words, over three months, devoted to religious faith. At the end of December, when he returned the drafts to us, he kept mine last, which made me experience cold sweat of fear. Finally, when the handover was over, tired of the many comments, he again removed his vestments, wiped his eyes, and with a smile the saint said: ‘’Here is an exception that confirms the rule. I wish you to continue with this enthusiasm. Give the draft to be printed at the Sorbonne Philosophy Society. Whenever you have impediments, come to my office. I can not describe my joy when I saw that he had given me 18 out of 20, which was the best grade given by the Sorbonne "pig", *Isuf LUZAJ "Philosophy of Beauty" page 157.*

Note Andre Lalande: Professor of Logic and Methodology at the Sorbonne; Professor of Educational Psychology and Logic at NORMAL SUPERIOR ECOLE, preparing (assistant) professors University; the author of the Dictionary of Philosophy used to this day in all the universities of the world, the most prominent personality of the University of Paris, visiting professor-friend of the Universities of London and Berlin. The former was so stingy on the grade that he passed no more than 15 to 20 percent of pupils (students) in the annual exams. For this habit or virtue (from which prism you look at it), the students of the Sorbonne had baptized him with the surname "le cochon" de la Sorbonne = Sorbonne pig.

SOLIDARITY

Justice does not consist in eradicating inequalities, but in reaping the benefits of using them to harmonize the whole world. It is incumbent on everyone to intensify their efforts by the characteristics of the environment in which it takes place.

Losing those features would be detrimental. Solidarity must be thought of as a balance by increasingly diverse parties, capable of better fulfilling their functions for the benefit of others. When a people lose the notion of interdependence between other peoples, it tends to break the balance in its favor, sparking war to the detriment of all.

Promoting solidarity

It is characterized in the future by the development of legal, economic, and moral bodies that regulate the relations of peoples. An unstable and imperfect balance would promise the co-occurrence of parts, harmonizing the well-being of the family, the country, the provinces, and the states. Some dreamers, forgetting that humanity is not a homogeneous myth but a heterogeneous reality, nurture the illusory desire of an international ideology or conglomerate of universal world peoples. It is fairer to imagine that above the current political states, without moral unity, to attempt to constitute nationalities capable of producing new types of civilization, confederating peoples similar in blood, tribe, and race.

Solidarity will be natural, based on similarities of origins and interests, languages, customs, and aspirations. The present ideal of political perfection is the federal coordination of close sociological groups that respect its characteristics and harmonize them into a strong and general nationality, *Isuf LUZAJ "Philosophy of Beauty"(Filozofia e Bukurisë) , page 181.*

End of part 3

4. OTHERS FOR ISUF LUZAJ

27. The prominent German albanologist Mr. Robert Elsie who when he died was buried in Albania, out of the love he had for Albania, to whom the Albanian people owe a lot said these words: - Isuf Luzaj raises the role of true moral poetry in life. According to Luzaj, Dante's poetry is good because it is moral. It includes the nobility of art. "Poetry exists as art when the poem read makes us cry, laugh, repent, correct ourselves".

Milton's "Paradise Lost" sums up all the qualities of the poem: "Virtue, ecstasy, spiritual purity education and above all heavenly music." The author rightly raises Homer, Hygo, Geta, Schiller, Milton, Mycenae, etc., but also Confucius, Buddha, Christ, Muhammad, because they also have in their works the true poetry, because they strongly touch the mind and soul of man. For the author, pure poetry is what tries to express as sincerely, as truly as possible the thoughts and feelings. The spiritual world of Professor Isuf Luzaj appears in the books, very rich, pure, sincere because it is the world of culture, education, and all the many human qualities and values, *Robert Elsie, "History of Albanian Literature", 1997.*

28. DEDICATION FOR ISUF LUZAJ

Temple of knowledge, Coryphaeus of patriotism, for the liberation of the Eagles enslaved in the cage of dictatorship, worked tirelessly.

It was your undeserved reward the sad curve and the Animal Internment of woman and children, But from the grapes of misfortune, you produced a sweet wine By illuminating American Universities With your ingenuity.

In the meadow of your mind, Your verses blossomed. In the pantheon of scholars, In the constellation of philosophers Thunder Your immortal name, *Carrie Hooper "Pictures in Words", Page 96.*

Note: Carrie Hooper is an American professor, poet, and even speaker of several foreign languages. Ronald Reagan at the occasional ceremony attended by the Governor of Indiana; Minister of Education and President Reagan. When President Reagan would hang the decoration of honor around his neck, it is a very interesting moment, because Reagan, while placing the decoration, tells Prof. Luzaj jokingly, because Reagan was a President who had *subtle humor, but also used many popular words. and says to Luzaj: "I have learned who you are and I have learned from you." Luzaj interrupts him, like Luzaj who was an explosive bit, and says: "I pray to God that what I think is not true because the truth is that I have learned from you and not you from me." Reagan likes this laconic expression, Isuf Luzaj smiles and applauds.*

MESSAGE:

"The love of truth compels us to never believe what can not be formed and never to accept what can not be proved. It must be clearly understood that dogmas, which are considered true, whether revived by religion or accepted by metaphysics , whether Learned from the social, political theories of this century, are all dogmas, because they do not allow critics to express their logic. Youth must open their eyes and nurture all other feelings, of every dimension, In order not to fall into the traps of new, served dogmas by demagogy ”It is one of the supreme needs of the world and I firmly believe that one of the great contributions that the United States of America has made to the world is the science of governance, how the life of a nation can intelligently evolve, inspire ideals of new, to rebuild the universal structures of the Spiritual architectures of the peoples, cleansing and divorcing them from all the folly of dogmas, superstitions and emotionalist fears, which have blinded and blinded, even today, three-quarters of the planet's population, Isuf LUZAJ.

MY NOTES:

1. Professor Luzaj had correspondence with Starter and Gabriela Mistral, but this correspondence is lost or I was not able to see that at that time, the professor did not have a stable residence and because of this they lost some manuscripts even the letters of those perhaps.
2. He is known as an existential philosopher who in international congresses, has defended God's view against atheism. He also says that the inspiration for dictatorships came precisely from the atheism that caused the uprising, and you vehemently opposed beliefs in God.
3. Has helped Mother Teresa in Calcutta for 3 years, with the former UN chief Prez de Cuelar has collaborated to overthrow dictatorships, in several different countries, She was a functionary of Unesco and Unicef.

4. The former US Secretary of State in the Truman Presidency Mr. Dean Acheson will present Professor Isuf LUZAJ his book with a dedication phrase that was - "Desihtegration of the Secular Faith" after his 205-page speech entitled "Captive Peoples" from the tyrannies and duty of the US and the European community.
5. Dean Acheson as United States Secretary of State in the administration of President Harry S. Truman from 1949 to 1953, he played a central role in shaping American foreign policy during the Cold War.
6. The President of France Charles de Gaulle during his historic visit to Argentina, also visited the French Institute of Higher Studies there, whose director was Professor Isuf Luzaj and De Gaulle broke the protocol and the two talked for about two hours drinking tea together.
7. If the European Union will formalize the contribution of Professor Luzaj, something I strongly believe, because he had cooperation with almost all European leaders after World War II, and he should be considered a European personality as he is, I think that there is a major interest in European Union policy, Western culture, and EU objectives in the Balkans, Argentina, and other countries. Because his contribution consists in the perfection of individual freedom of thought, the prosperity of peace, the development of human values, even for the quality of democracy.

From what I have read so far, I do not believe that anyone knows the Balkan issues better than Professor Isuf Luzaj, where it is worth noting that his father also studied at the Berlin academy precisely for the diversion of German culture in the Balkans, so values of western culture. Whereas it is known that culture, education, history, give us better results than sanction. At the same time, he is well aware of the anti-democratic, anti-Western influences that today threaten the EU.

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Note; The book "Bee Care" is 12 volumes organized in two books, with 6 volumes and goes to 1 thousand pages.

Federal Register Notice: 89 FR 51554, Federal Register :: Networking and Information Technology Research and Development Request for Information on Digital Twins Research and Development, June 18, 2024.

Request for Information on the National Digital Twins R&D Strategic Plan

Michael Dediu

Via FDMS

Michael Dediu, 7/17/2024

[redacted]

Yes, Digital Twins R&D are necessary for medical applications, and other similar areas - the sooner, the better.

Federal Register Notice: 89 FR 51554, Federal Register :: Networking and Information Technology Research and Development Request for Information on Digital Twins Research and Development, June 18, 2024.

Request for Information on the National Digital Twins R&D Strategic Plan

Michael Kennerly

One area for consideration os the use of Digital Twins for transportation networks. This is an area already receiving a lot of attention and would benefit from this effort:

- *Artificial Intelligence (AI):* The growth of AI in the transportation sector presents enormous potential to improve our ability to maximize our investment in reconstruction and rehabilitation. In addition, it has the potential to allow more precise identification of safety issues and mitigation strategies. AI can be deployed to assist or perform real-time traffic management functions reducing congestions and delays on our networks. Combined with advances in computer aided design software AI can be used to evaluate the effectiveness of design alternatives to ensure the selected alternate will address the transportation issue in question.
- *Business: Business Case Analysis:* Transportation agencies like the Iowa DOT are developing processes to that require development of a Business case for investment decisions. Transportation agencies the create Digital Twins of their network, that is combined with additional meta-data including, pavement condition, traffic volumes, crash statistics and other key evaluation data can more effectively develop the Business Case Analysis for investment strategies. This has the potential to maximize limited funds for highway improvements, potentially resulting in a safer more efficient highway system. Depending on how far this was taken it could allow for multi-state analysis for the interstate system.
- *Data:* With the move toward digital delivery and enterprise wide at most transportation agencies there is a much greater emphasis on data management best practices, data stewardship, and data governance that at any point it the past. The creation of digital twins of the network and the corresponding use of digital models that incorporate data from construction projects that can be utilized to update the digital twin makes the creation of data standards critical in order to be successful. Those standards need to be based in national standards to facilitate data transfer as well as maximize efficiency. Again, the ability to use real time data on traffic conditions that can be shared with the public through direct vehicle communication enhaces mobility and allows drivers to make better decisions.
- *Ecosystem:* The case has been made that the use of digital models in design has the potential to make significant improvement in our carbon footprint, and minimize our impact on the natural and human environment. This is accomplished by not only maximizing the design as noted above, but also providing the contractor with a tool that allows them to make better decisions on how to construct the project. These decisions will result in more effective staging of the project resulting in reduced construction time, resulting in lower emissions associated with delays from congestion. It allows designers to review and evaluate more alternatives to minimize the impact on the human and natural environment. When you take the project level benefits and multiply that over the network through the use of Digital Twins the potential impact is far more profound.
- *International:* Transportation agencies are already working to collaborate with international partners on digital delivery and the use of international standards to leverage what is being done n the global transportation market. The growth and use of Digital Twins expands that and creates new opportunities for collaboration.
- *Long Term:* Long term research in how to better utilize vehicle to vehicle communication to provide real time traffic and road condition information. How to utilize AI to make better system wide infrastructure investment decisions. Connecting Highway Digital Twins with those created in other areas to enhance the concept of smart cities. There are a number of avenues that could be explored.
- *Regulatory:* Regulatory Science Challenges associated with the use of Digital Twins

- *Responsible:*
- *Standards:*
- *Sustainability:*
- *Trustworthy:*
- *VVUQ:* Develop Rigorous Methods for Verification, Validation, and Uncertainty Quantification for Digital Twins:
- *Workforce:*

I apologize, there is so much more I could add in each of the areas where time did not permit me to comment or expand. However; I hope this will at least merit consif-deration as this project modves forward. Feel free to contact me if you have any questions.

Mike

Federal Register Notice: 89 FR 51554, Federal Register :: Networking and Information Technology Research and Development Request for Information on Digital Twins Research and Development, June 18, 2024.

Request for Information on the National Digital Twins R&D Strategic Plan

Dr. Mina Sarpi, UTC Professor and Director of the UTC Research Institute

Mr. Charlie Brock, President and CEO of the Chattanooga Quantum Collaborative

The University of Tennessee at Chattanooga (UTC) Response

Ecosystem, International, Artificial Intelligence, Data

The Research Institute at UTC - https://www.utc.edu/research/research-institute - manages and continues to develop a large urban testbed (100+ signalized, instrumented and connected intersections) for connected and automated vehicles. An expanding Digital Twin (DT) for a 2km corridor is part of the infrastructure.

The US DOE, DOT, DOC, NSF and other agencies have been supporting R&D in Chattanooga performed by UTC, by Oak Ridge National Laboratory, and by the Electric Power Board (EPB) the City owned electric utility and communications company.

In the course of this work, several accomplishments involved the development of DTs of key infrastructure assets, such as transportation and energy. The research team is the expanding Digital Twin (DT) for a 2km corridor, a key piece of infrastructure through advanced simulation technologies like VISSIM and CARLA. VISSIM, a sophisticated traffic simulation software, models detailed traffic dynamics, signal operations, and vehicular interactions. When combined with Unreal Engine, these simulations are visualized within a high-fidelity, immersive 3D environment. Unreal Engine's realistic mapping and visualization capabilities enhance the user experience, making it easier for planners and stakeholders to comprehend and interact with complex traffic scenarios.

CARLA, an open-source autonomous driving simulator, adds another supportive layer to digital twin models. It focuses on simulating autonomous vehicle behavior and processing sensor data, enabling detailed testing and validation of autonomous driving algorithms. CARLA's co-simulation capability with both VISSIM and Unreal Engine to create realistic driving scenarios that include interactions between autonomous and human-driven vehicles. Together, these developed tools enable the creation of dynamic and accurate digital twins that reflect real-world conditions, supporting research, development, and deployment of advanced transportation solutions.

Similar efforts have been done for the energy sector. Majority of these efforts have been on pseudo digital twin that uses historical data. The future efforts need to include several enhancements: 1) integrated digital twin that includes transportation and energy; 2) real-time and adaptable such digital twins. Making these interconnected digital twins will enable to address the challenges from a system-of-system approach and enabling them to adapt to real-time real-world data enhances their accuracy and reliability. Furthermore, these enhancements will allow for real-time decision making that will effectively bridge the physical and digital worlds.

Chattanooga has been a paradigm for urban renewal, and is recognized widely as the first US city deploying a fiber optic communications network, which generated $2.7B in economic value over a decade (https://cities-today.com/chattanoogas-municipal-broadband-pays-off-with-2-69-billion-in-benefits/). These efforts have also resulted in the deployment of phase I of a commercial quantum network - https://quantum.epb.com/. This ecosystem is now working to create a quantum-ready environment (https://www.chattanoogaquantum.com/).

Developments of dynamic, adaptable, and interconnected digital twins are becoming an integral part of these activities. The expertise, capabilities and infrastructure assets in Chattanooga can be leveraged to inform the development of the National Digital Twins R&D Strategic Plan.

Chattanooga Points of Contact:
Dr. Mina Sartipi, UTC Professor and Director of the UTC Research Institute
Mr. Charlie Brock, President and CEO of the Chattanooga Quantum Collaborative

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Request for Information on the National Digital Twins R&D Strategic Plan

Nikunj C. Oza, Jacqueline Le Moigne, Michael Little, Robert A. Morris, Nipa Phojanamongkolkij, K. Jon Ranson, Haris Riris, Laura J. Rogers, Benjamin D. Smith
NASA, Earth Science Technology Office (ESTO), Advanced Information Systems Technology (AIST) Program

Response to "Networking and Information Technology Research and Development Request for Information on Digital Twins Research and Development"

Nikunj C. Oza, Jacqueline Le Moigne, Michael Little, Robert A. Morris, Nipa Phojanamongkolkij, K. Jon Ranson, Haris Riris, Laura J. Rogers, Benjamin D. Smith.

NASA, Earth Science Technology Office (ESTO), Advanced Information Systems Technology (AIST) Program

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Who We Are

This response to the NITRD RFI for Digital Twins is from NASA's Advanced Information Systems Technology (AIST) program. As part of NASA Earth Science Technology Office, the Advanced Information Systems Technology (AIST) Program identifies, develops, and supports the adoption of software and information systems, as well as novel computer science technologies expected to be needed by NASA's Earth Science Division in the 5-10-year timeframe. Projects under this Program start at a Technology Readiness Level (TRL, [1]) from 1 to 3 and usually advance one or two TRLs before completion. AIST information systems and software technologies contribute to the entire data lifecycle, as represented in Figure 1, from the acquisition of new measurements and the design of new observing systems to onboard intelligent data understanding and decision making and all the way to data analytics and extraction of the "science data intelligence" needed to create actionable information. Within that framework, AIST focuses on three thrusts:

(1) The first one, *Novel Observing Strategies (NOS)*, enables new observation measurements and new observing systems design and operations through intelligent, timely, dynamic, and coordinated distributed sensing. This contributes to the first part of the data lifecycle.

(2) The second thrust, *Analytic Collaborative Frameworks (ACF)*, enables agile science investigations that fully utilize the large range of diverse observations using advanced analytic tools, visualizations, and computing environments. This addresses the second part of the data lifecycle.

(3) The third thrust, *Earth System Digital Twins (ESDT)*, enables the development of integrated Earth Science frameworks that mirror the Earth with state-of-the-art models (Earth system models and others), timely and relevant observations, and analytic tools. These information systems can be used for supporting near- and long-term science and policy decisions. Here "science decisions" include planning for the acquisition of new measurements, development of new models or science analysis,

integration of Earth observations in novel ways as well as various applications to inform choices, support decisions, and guide actions, e.g., related to climate change or for societal benefit. ESDT frameworks will build upon NOS and ACF technologies to integrate a continuous stream of observations, interconnected models, data analytics, data assimilation, simulations, advanced visualizations and the ability to conduct "what-if" scenarios, for example to assess the impact of human activity on natural phenomena. Therefore, technologies associated with ESDT contribute to the entire data lifecycle, as shown in Figure 1.

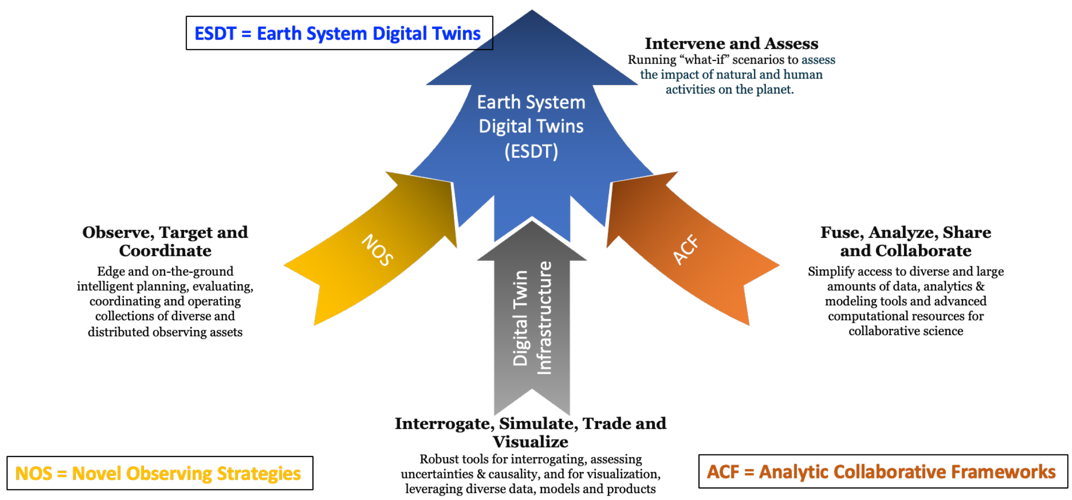

Figure 1 – ***The AIST Program Spans the Entire Earth Science Data Lifecycle***

This response document addresses several topics of interest stated in the RFI: **Artificial Intelligence, Data, Ecosystem, Long Term, Standards, and VVUQ.**

What is a Digital Twin?

The National Academies report "Foundational Research Gaps and Future Directions for Digital Twins (2023)" defines digital twins as follows:

> *A digital twin is a set of virtual information constructs that mimics the structure, context, and behavior of a natural, engineered, or social system (or system-of-systems), is dynamically updated with data from its physical twin, has a predictive capability, and informs decisions that realize value. The bidirectional interaction between the virtual and the physical is central to the digital twin.*

A key omission from this definition is within the predictive capability. The digital twin should not only allow for prediction given the current and past states and actions and planned future actions, but also given **alternative** current and past states and actions and various future actions – What-if scenarios. The AIST program conducted a workshop on Earth System Digital Twins (ESDT) October 26-28, 2022 in Washington, D.C., USA. The workshop report [2] defines ESDTs, but the definition can be easily generalized to digital twins:

> *An Earth System Digital Twin or ESDT is a dynamic and interactive information system that first provides a digital replica of the past and current states of the Earth or Earth system as accurately and timely as possible; second, allows for computing forecasts of future states under nominal assumptions and based on the current replica; and third, offers the capability to investigate many hypothetical scenarios under varying impact assumptions. In other words, an ESDT provides the integrated "What-Now, What-Next, and What-If" pictures of the Earth or Earth system, by continuously ingesting newly observed data and by leveraging multiple interconnected models, machine learning as well as advanced computing and visualization capabilities.*

In particular, our definition of Earth System Digital Twin **distinguishes *what-next* from *what-if***. The what-if capability enables predictions of the outcomes of different decisions to enable exploration of new ideas and their benefits and drawbacks (e.g., how much the average temperature in a city decreases as a function of the density of trees planted). This what-if capability is likely helpful in many other domains as well, such as engineered systems, where changes in maintenance strategies (time between maintenance, conditions under which maintenance is performed, specific tasks conducted during maintenance) can be explored for short-term and long-term impact.

Core components of digital twins

1. *Sources of Data*

The Novel Observing Strategies (NOS) AIST thrust described above illustrates the need for not only different sensors and platforms as sources of raw data, but also the need for coordinated, distributed, timely sensing. The data lifecycle in figure 1 is a true cycle---in many cases, data collected in the past is run through data analytics and visualization to produce not only useful insights, but suggestions for additional data to be collected in the future. Such a sensing system is necessary for digital twins, as they must be able to assimilate the latest data and request additional data in some cases to help improve the twin's accuracy. The types of data needed will vary across domains. However, in general, the data required may relate to the system for which the digital twin is produced, the environment in which the system operates, and the actions of people who interact with the system, and possibly others.

Earth System Digital Twins will fuse data from multiple sensors to build a digital replica and to drive forecasts and what-if scenarios. Calibration (geometric and radiometric) has a big impact on data fusion quality and uncertainty. Well-calibrated instruments have a higher effective data value due to smaller errors propagating through the data processing, fusion, and analysis chain. Vicarious calibration against a network of reference sites can provide frequent, accurate calibration.

2. Domain Knowledge

The knowledge of domain experts who know the system for which the digital twin is being produced is important and should be codified for use within the digital twin. In some cases, the knowledge is in the form of physics-based mathematical models (e.g., global climate models), while in other cases, the knowledge may be a set of rules. In some cases, the experts themselves may serve as direct sources of knowledge during the operation of the digital twin. For example, there are human in the loop (HITL) simulations of the National Air Space (NAS) in which human air traffic controllers issue instructions to simulated aircraft.

3. Data-Driven Models

Data-Driven Models are models developed to fit past data. Machine Learning is a discipline within Artificial Intelligence that develops such methods. There is much press currently around generative models, which are a class of Machine Learning models that learn to model the process that generated the data or could have generated the data. Machine Learning models are a critical component of digital twins. These would be used in cases where the domain knowledge is limited (e.g., physics-based models are inaccurate) or the mathematical models are too slow to run in a real-time simulation. Machine Learning models that quickly provide approximations to physics-based models are often referred to as surrogate models. In many cases, both physics-based models and data-driven models may be used, with each one being used where most appropriate, for example, trading off accuracy and speed, or different models being more accurate in different situations (e.g., physics-based models may not work well in off-nominal situations), or output of physics-based models being used to train data-driven models. Data may be an important part of this tradeoff between accuracy and speed. For example, in Earth Science, data of different spatial and temporal resolutions is available, where lower resolution data enables rapid calculations but yields lower accuracy while higher resolution data enables greater accuracy but requires greater running time. Machine Learning models that provide predictions plus measures of confidence (e.g., an error bar), such as Gaussian Processes, can be particularly helpful, as they can quickly provide an answer which may be deemed good enough if the error bar is small, or which can prompt running a physics-based model if the error bar is too high. Overall, one may obtain comparable accuracy to running a physics-based model every time, but at much lower computational cost.

4. Computational Systems

All of the digital twin components described earlier require computer systems. One or more systems ranging from desktop computers to traditional on-prem supercomputers, cloud-based systems, and edge computers may be used. Within these, there may be different types, such as traditional CPUs, GPUs, TPUs, and FPGAs may be used. Of course, significant data storage is also needed. Whenever multiple computer systems are used, the communications infrastructure will be critical. In some domains, such as Earth Science, the digital twin may span a vast geographic area, so the computer and communications infrastructure will span a large area. The communications reliability will be relatively low over a large geographic area, therefore, having more compute power closer to the data required is preferred. There are several architectural models that can be considered for providing high-end computing needed for digital twin tools and services. Conventional High-Performance Computing (HPC) batch processing is perhaps the most obvious, and other architectures include interactive HPC environments, Jupyter Notebook Orchestration, Dedicated Project Environments, edge computing, and Software-Defined Systems and Networks.

5. Visualization

Domain experts and others must be able to understand the insights produced by the digital twin. In some domains, traditional simple plots may be sufficient or even preferred. However, in data-intensive areas such as Earth Science, immersive visualization, such as Virtual Reality (VR), Augmented Reality (AR), and eXtended Reality (XR), is a potentially disruptive paradigm that would allow users to explore complex data in intuitive ways to obtain insights. Immersive visualization can overcome limitations of two-dimensional (2D) displays, such as constrained screen size. Immersive visualizations also provide interactions that are more natural to our senses, which can improve understanding and retention. For example, studies have shown that people are better at remembering items they experienced in an immersive visualization than a 2D display.

Technology gaps include:

- Human factors for improving ergonomics and productivity.
- High-level software Application Programming Interfaces (APIs) for streaming digital twin data for ingestion into extended reality systems.
- If needed, headsets that are lightweight with high-resolution and wide field-of-view.

And some of the major challenges include:

- Development of algorithms for analyzing, visualizing, and deriving insights from large scale, multi-modal streaming datasets.
- Advances in visualization, Artificial Intelligence (AI), ML, human factors, and digital twin general domain expertise.
- Development of a workforce that intuitively understands and leverages the power of VR, AR, and XR.

6. Data Science and Interactive Data Analysis

One of the important uses of a digital twin will be analysis of data, models, and projections to better understand processes and their trends and impacts. AI and Data Science technologies can address challenges in developing interactive data analysis and modeling capabilities, such as:

- Interactive analytics
- Automated multi-scale, multi-temporal event detection
- Integrated workflow management
- Understanding and Reduction of uncertainties, i.e., uncertainty quantification (UQ)
- Multi-disciplinary science applications of ML

Some of the relevant AI and Data Science capabilities include anomaly detection, data assimilation, ML, uncertainty quantification, and computational workflows, among others.

Data science technologies, in addition to aiding in analysis, could also be used to identify supplemental observations that would improve models or provide important data about ongoing events. Data-driven observing systems are an emerging concept in which observations are requested based on an analysis of models and other data. The digital twin could request supplemental observations that would reduce its forecast uncertainty, for example, high-resolution images in areas where events like floods or fires are forecasted.

7. Federation

For some systems, a single digital twin will be sufficient. However, for larger systems, such as the Earth, a single twin will not be practical. Multiple twins representing smaller local/regional or thematic Earth systems will be developed, likely by different groups of people with different expertise, and they will need to be connected in some ways.

Some of the challenges related to federation are the following:

- Sharing the same needs and definitions would be a catalyst for federation
- Ongoing standards and collaboration efforts that would contribute to federating Earth System Digital Twins are:
    - Findable Accessible Interoperable Reusable (FAIR)
    - OGC APIs: Maps/Tiles/Routes/Styles.
    - Processes and Environmental Data Retrieval (EDR).
    - Cloud-native geospatial standards (COG, COPC, STAC, ZARR, GeoParquet, etc.)
    - Proposal for joint OGC-ISO standard with framework and Analysis Ready Data for land, ocean, atmosphere, earth system, etc.
    - Standard for training and validating data for ML
    - Standard for assessing data quality, data fitness for use, etc.
    - OGC pilot and testbed programs for developing and evaluating standards.
- Where to start federating efforts? In addition to federation, the community could develop specific reusable building blocks.
- As a community, there could be prioritization of a common outcome with public value, e.g., forecasting water flow, or land level change, or subsurface hazards and resources;
- Agree on how to promote and federate with each other’s digital twins and/or source data to enter a cycle of improvement
- Interoperability of data layers, models, services will be needed.

- Another opportunity would be to develop the capability to systematically generate local, thematic and dated Digital Twins to address specific territorial needs/usages, to support decision making (a “Digital Twin Factory” [5])
- Creation of software and information layers that interoperate by exchanging well defined geophysical variables and services, rather than by tight coupling of software, models, and information.

8. Other Technologies

Depending on the application domain, other technologies are also needed. For example, Verification, Validation, and Uncertainty Quantification (VVUQ) are important at various points throughout the digital twin to provide confidence in the results, especially if they will be used to inform decision making, and to quantify the uncertainty in the results. In Earth Science, modeling the effects of calibration and fusion errors could provide a basis for deriving traceable error bars and uncertainty distributions for digital twin state variables. Vicarious calibration could be performed “on demand” to minimize uncertainties, rather than only up front when sensors are first deployed. This might be particularly useful for fusing data from constellations of small satellites and CubeSats within an ESDT observing framework. Assessing the uncertainty in data-driven models and in running what-if scenarios will also be very important, especially in giving users metrics that will ensure confidence and trust in these digital twins.

Reinforcement Learning (RL) is a branch of Machine Learning that we have not mentioned so far. RL enables agents to learn how to behave by providing rewards (positive or negative) in response to its actions. RL can be used to learn agents that operate within the digital twin but that can be implemented in the form of real systems once there is sufficient confidence that the agent has learned how to behave. Causal models and reasoning technologies are necessary to enable the digital twins to truly model the behavior of the target system. This is especially difficult in areas like Earth Science where there are feedback loops of causes.

Foundation Models is another branch of Machine Learning that might also have a strong impact on the way Earth System Digital Replicas will be computed as well as on increasing the speed and the accuracy of forecast models. This past year has already seen tremendous progress using Foundation Models for medium-range weather forecasting, e.g. with NVIDIA FourCastNet, Google GraphCast, European Centre for Medium-Range Weather Forecasts (ECMWF) Artificial Intelligence/Integrated Forecast System (AIFS), and Microsoft Aurora.

Standards are important and necessary for the development of digital twins to enable the community to develop them and connect them. This will require standards for both software and data. The current hodge-podge of non-conforming outputs and unique formats slows their use and increases the computational requirements to translate the data products into something usable in a digital twin. This becomes more important as scientific investigations create more data products to be preserved (for transparency and reproducibility) through fusion of elements from multiple datasets.

Culture change is needed to encourage both collaboration and competition. Some specific changes include:

- Digital Twins are not owned by an individual organization or community but have structured means to encourage inclusive contribution, including modular design, plug-and-play architectures, federation, etc.
- Access to diverse inputs and a guide to help discover unrecognized assets.
- Permitting others to contribute to a shared Digital Twin
- Leverage developments from multiple agencies and organizations
- Current concepts of intellectual property block openness
- A new model to give credit for intellectual advances earlier than publication.

Confidence in the validity of the digital twin will be essential to its usability. Confidence in the validity is distinctly different than validation. What is required to establish credibility in the digital twin and confidence in using it varies widely across communities but is important to all, and digital twins will be used and will need to be trusted by a wide range of users, such as the general public, non-scientific decision makers, as well as research scientists.

Examples

Over the past 4 years, the AIST Program has funded multiple projects in the area of Earth System Digital Twins [2,6] focusing on:

- Underlying analytic capabilities needed to build Digital Replicas, such as domain-focused Analytic Collaborative Frameworks (e.g., for Air Quality or Wildfires)
- Novel infrastructure technologies such as reproducible containers and virtual reality
- Surrogate modeling and Machine Learning-based emulators
- Preliminary prototypes including the interconnection of several models, e.g., for agriculture, for wildfires, for hydrometeorology, for assessing the impact of climate change on urban environment, and for floods and their impacts on coastal populations and their health.

Two specific examples are:

a. The Integrated Digital Earth Analysis System (IDEAS), developed by several NASA Centers and in collaboration with the French Space Agency (CNES), is a Digital Twin for Water Cycle and Flood Detection and Monitoring, It interconnects several models for river discharge, for Land and Hydrology Information and for predicting worldwide energy resources as well as for flood prediction. It is being federated with the digital twin being developed in parallel at CNES, called FloodDAM-DT, with the goal of investigating, developing and promoting common interoperable standards.
b. A Coastal Zone Digital Twin (CZ-DT) is now being developed as a collaborative project between NASA, NOAA and CNES under the umbrella of the Space Climate Observatory (SCO) [7]. The overall goal is to build a multi-organization CZ-DT around relevant Earth system models and simulations related to coastal zone change (e.g., sea level rise, increasing hazardous storms, pollution, and land cover/land use dynamics) and both observed or potential impacts now and into the future. The breadth of the topic is immense and covers coastal, terrestrial and

marine water quality, lagoon and estuary ecosystems, human lives and livelihood, agriculture, infrastructure and socioeconomic factors. This will address many questions of growing interest such as those related to assess: 1) the current state of coastal zones, 2) what can we expect under climate change and 3) how can we mitigate current impact and prepare for future impacts?

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Request for Information on the National Digital Twins R&D Strategic Plan

Natalia Trayanova

HeartRhythm
The Official Journal of the Heart Rhythm Society, The Cardiac Electrophysiology Society, and The Pediatric & Congenital Electrophysiology Society

Moe Lecture

Up digital and personal: How heart digital twins can transform heart patient care

Natalia A. Trayanova, PhD,[1,2] Adityo Prakosa, PhD[1]

ABSTRACT

Precision medicine is the vision of health care where therapy is tailored to each patient. As part of this vision, digital twinning technology promises to deliver a digital representation of organs or even patients by using tools capable of simulating personal health conditions and predicting patient or disease trajectories on the basis of relationships learned both from data and from biophysics knowledge. Such virtual replicas would update themselves with data from monitoring devices and medical tests and assessments, reflecting dynamically the changes in our health conditions and the responses to treatment. In precision cardiology, the concepts and initial applications of heart digital twins have slowly been gaining popularity and the trust of the clinical community. In this article, we review the advancement in heart digital twinning and its initial translation to the management of heart rhythm disorders.

KEYWORDS Heart digital twins; Arrhythmia; Atrial fibrillation; Sudden cardiac death risk prediction; Ablation

(Heart Rhythm 2024;21:89–99)

Precision medicine is envisioned to provide therapy tailored to each patient. The rapidly increasing ability to capture extensive patient data, coupled with machine learning, a powerful tool for processing massive amounts of data and identifying correlations in it, is a pathway to achieve this vision. A different pathway toward precision medicine is the increasing ability to encode known physics laws and physiology knowledge within mathematical equations and to adapt such mechanistic models to represent the behavior of a specific patient.

The expectation is that it will be highly beneficial to have a digital representation of ourselves. A digital doppelgänger that is tailored to represent our own unique physiology, structure, biophysical processes and even diseases could allow health care professionals to simulate our personal medical history and health conditions using relationships learned both from data and from biophysics knowledge. That virtual replica of ourselves would integrate data-driven learning and multiscale physics-based modeling and will update itself, either continuously with data from monitoring devices, or intermittently with data from health care provider (hospital or physician) visits and tests. It will thus reflect the changes in our health conditions because of interactions with the environment, changes in lifestyle, and changes in response to medical interventions These *digital twins* (DTs) would forecast the trajectory of a patient's disease, estimate the risk of adverse events, and predict treatment response so that the potential outcome would inform treatment decision.

A DT is a virtual replica of a physical object, person, or process that can be used to simulate its behavior. This dynamic model represents both the components of a system and their ongoing interaction. Digital twinning is not a new concept—DTs have been used to replicate many real-world entities, from equipment life cycles through to entire manufacturing processes,[1] as they allow one to oversee the performance of an asset, identify potential faults, and make well-informed decisions about maintenance and global performance. In health care, the DT represents the vision of a virtual tool that integrates dynamically clinical and/or tracked data acquired over time for an individual and predicts behavior using comprehensive multiscale mechanistic simulations based on physiology knowledge and physics laws.

In precision cardiology, over the last decade, the concepts and initial applications of heart DTs have slowly been gaining popularity and the trust of the clinical community. Pathways forward have been charted,[2,3] and current developments[4–7]

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have been assessed. Figure 1 presents a flowchart of the clinical workflow using heart DTs and their envisioned applications for clinical decision support in the diagnosis and prognostication of the patient's disease trajectory as well as for guiding treatment that is optimized by considering the patient's response to the potential therapy.

One of the most advanced heart DT applications is in the management of heart rhythm disorders, with major developments in the field reviewed in this article. The present article is the review of the body of work of each year's recipient of the Gordon Moe lectureship presented by the Cardiac Electrophysiology Society. Dr Trayanova was this year's recipient, and this review article summarizes her work and that of her team at Johns Hopkins University on the development and application of heart DTs for the management of atrial and ventricular arrhythmias (VAs).

DTs for atrial arrhythmia management

Atrial fibrillation (AF) is the most common heart rhythm disorder, having a prevalence of 1%–2% worldwide. It is associated with embolic stroke, heart failure, and cardiovascular hospitalization and death.[8] Patients with AF have increased rates of cognitive impairment and a diminished quality of life.[9] The growing burden of AF and the high rate of health care expenditures associated with its management have led to a large body of basic and clinical research aimed at uncovering both a permanent cure of AF and an improved AF management strategy. Computational modeling of the atria and personalized atrial DT technologies have been and continue to be an integral part of these developments.

An important focal point in these efforts, including ours, has been the representation, in personalized DTs, of fibrotic remodeling that takes place in the atria of (aging) patients, and particularly in those experiencing the persistent form of AF (PsAF). In these patients, the mechanisms giving rise to AF shift from electrical abnormality in the pulmonary veins (PVs) to recirculating electrical waves (reentries) perpetuated by the fibrotic substrate. Personalized DT technologies have provided understanding of how fibrotic remodeling results in the turbulent propagation associated with AF and have suggested management strategies, some of which have been tested in prospective studies. Before this review, we and others have reviewed different aspects of computational modeling of the human atria.[6,10–12]

In developing a personalized atrial DT that represents the patient-specific fibrosis remodeling, the process commences with the assessment of the patient's clinical contrast enhanced (late gadolinium enhancement [LGE])–magnetic resonance imaging (MRI) scan, typically a 3-dimensional scan of higher resolution to resolve the thin atrial walls.[13,14] In addition to providing information on atrial shape, MRI imparts excellent heart tissue characterization, as gadolinium-based contrast agents accumulate in scar and fibrotic tissue.[15] Areas on LGE-MRI scans correspond to areas of scar and fibrotic remodeling, with the high image intensity corresponding to deep scar. Reconstruction of atrial geometry requires segmenting the chambers and the remodeled tissue from the LGE-MRI scan; the study by McDowell et al[16] was the first to reconstruct a personalized DT incorporating fibrotic remodeling. The threshold for fibrosis segmentation is not well established and remains controversial. We have used a version of the image intensity ratio since it uses ratiometric values instead of raw voxel intensities. Our team also reconstructed, for the first time, the personalized fibrotic remodeling in the right atrium (RA) of patients; we adapted the image intensity ratio for RA fibrosis.[17] Figure 2A presents a number of reconstructed biatrial models of patients with PsAF and fibrosis. In addition, atrial DTs incorporate fiber orientations to ensure realistic conduction patterns. Reconstruction of personalized atrial DTs in our translational research has involved the use of atlas human fiber orientations,[18] acquired from explanted human hearts using diffusion-tensor MRI[19] (Figure 2B), which visualize the fiber tracts in the myocardium. These are then assigned in the patient-specific geometric model with the use of a universal atrial coordinate system.[20]

In our translational work aimed at improving AF management, personalization of atrial DTs was done predominantly on the basis of patient-specific disease remodeling, where distinct electrophysiological (EP) properties are assigned in different regions on the basis of image intensity. This has been a deliberate choice, as our intention has been strategically down the road, to develop noninvasive technologies for the prognostication and treatment of AF. Several research groups have instead chosen to personalize the EP properties from invasive intraprocedural measurements.[21,22] Instead, we developed, on the basis of clinical measurements in patients with AF, a set of baseline EP properties[23] that could be modified, when needed, to explore different arrhythmogenic mechanisms. These included, but were not limited to, exploration of the effect of potential myocyte-fibroblast interactions[24,25] and arrhythmogenesis related to calcium-driven alternans in AF.[26,27] For instance, in the latter study, we found that elevated Ca^{2+} alternans propensity due to decreased ryanodine receptor inactivation, and development of repolarization alternans at slower heart rates, resulted in increased ectopy-induced arrhythmia vulnerability, complexity, and persistence because of increased repolarization heterogeneity and wavebreak.

Our atrial modeling studies strongly support the notion that the extent and distribution of atrial fibrosis are critical determinants of AF initiation, maintenance, and reentrant driver dynamics during AF. Although presence of a certain amount of fibrosis is sufficient for the initiation of AF in simulations, we found that patient-specific fibrosis distribution determines

Abbreviations

AF: atrial fibrillation

ARVC: arrhythmogenic right ventricular cardiomyopathy

CT: computed tomography

DT: digital twin

Geno-DT: genotype-specific heart digital twin

inFAT: penetrating adipose tissue

MRI: magnetic resonance imaging

OPTIMA: OPtimal Target Identification via Modelling of Arrhythmogenesis

SCD: sudden cardiac death

VT: ventricular tachycardia

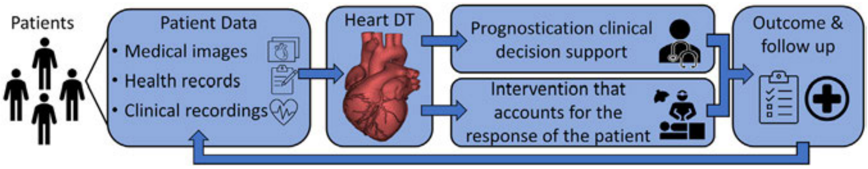

Figure 1
Flowchart of the clinical workflow using heart digital twins (DTs).

reentrant driver dynamics.[28] The study by Zahid et al[29] took this understanding further, demonstrating, in a cohort of 20 patients, that reentrant drivers induced in the fibrotic substrate by rapid pacing persist only in areas with highly specific spatial patterns of fibrosis. The study was the first to construct atrial DTs of both the left atrium (LA) and the RA. Fibrotic spatial patterns were characterized by calculating, from the 3-dimensional LGE-MRI scans, maps of fibrosis density and fibrosis entropy. Local fibrosis density indicates the proportion of fibrotic elements among all elements surrounding the given location, while local fibrotic entropy quantifies the degree of disorganization between fibrotic and nonfibrotic elements in the local neighborhood. All the reentrant drivers that could be induced in each remodeled substrate persisted in the zone of fibrotic boundaries characterized by high fibrotic density and fibrotic entropy. Fibrotic patterns with such specific regional fibrosis metrics correspond to atrial areas with a high degree of intermingling between fibrotic and nonfibrotic tissue. The findings of this atrial DT study were subsequently validated[30] with clinical data (electrocardiographic imaging).

Potentially the most transformative clinical application of atrial digital twinning is the development of personalized PsAF ablation strategies, tailored to each patient's unique (fibrotic) atrial substrate. While PV isolation (PVI), the electrical isolation of PV arrhythmia triggers, is the standard of care for patients with symptomatic AF,[31,32] in patients with PsAF and atrial fibrosis, AF recurrence rates after PVI are high,[33,34] resulting in freedom from AF of only 40%–50% 1-year postprocedure. The presence of regions of fibrosis that extend beyond the traditional wide-area PVI and have arrhythmogenic propensity could explain PVI's ineffectiveness in patients with atrial fibrosis. Establishing noninvasively whether PVI will result in subsequent AF recurrence in a patient with atrial fibrosis, and if so, determining before the ablation procedure the custom-tailored extra-PVI ablation targets that will deliver long-term freedom from AF could result in dramatically improved treatment efficacy and reduce the need for

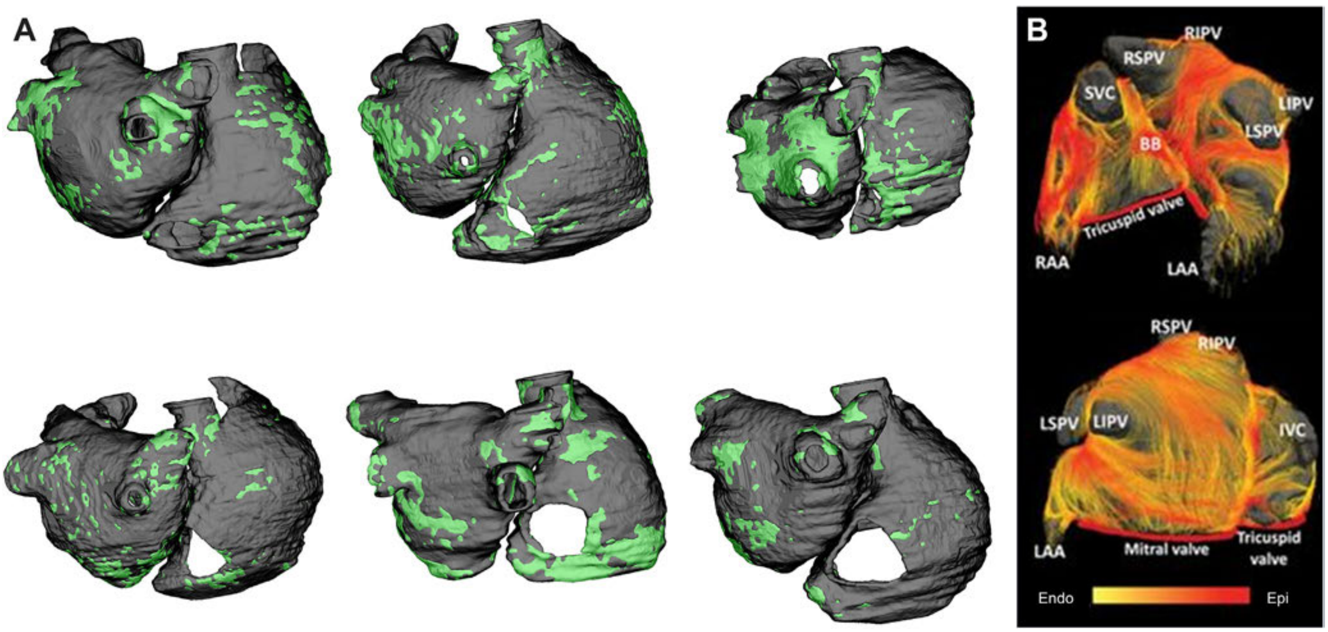

Figure 2
Developing personalized atrial digital twins (DTs). **A:** Reconstructed biatrial geometries from 6 patients with persistent atrial fibrillation. Fibrosis distribution is in *green*. **B:** Human fiber orientation acquired from explanted human hearts and used as fiber atlas for DT construction. BB = Bachman bundle; Endo = endocardium; Epi = epicardium; IVC = inferior vena cava; LAA = left atrial appendage; LIPV = left inferior pulmonary vein; LSPV = left superior pulmonary vein; RAA = right atrial appendage; RIPV = right inferior pulmonary vein; RSPV = right superior pulmonary vein; SVC = superior vena cava. Modified with permission from Pashakhanloo et al.[19]

repeated ablation procedures. In this, atrial digital twinning has found its calling.

McDowell et al[28] was the first study to demonstrate, as a proof of concept, that LA DTs reconstructed from the patient's LGE-MRI scans (n = 4) can be used to predict ablation targets in the fibrotic substrate. The targets were the locations in the fibrotic substrate where reentrant drivers (rotors) form after rapid pacing from locations in the substrate. Executing this virtual ablation strategy in the LA DTs rendered the atrial model noninducible for reentry. Having demonstrated the potential utility of atrial DTs in predicting ablation targets, we also assessed whether the predicted targets would be affected by different baseline cellular EP properties. In a sensitivity analysis,[35] we varied atrial action potential duration or conduction velocity to address this question. These changes resulted in different likelihoods that a location in the fibrotic substrate would sustain a reentrant driver. However, Hakim et al[36] demonstrated that this uncertainty was mitigated by first executing reentrant driver ablation procedures followed by repeat inducibility tests to evaluate the occurrence of any emergent reentrant drivers postablation. In other words, depending on the baseline EP properties in the patient's atria, locations in the fibrotic substrate will give rise to rotors either on the first inducibility test or on the subsequent inducibility tests probing for emergent rotors postinitial ablation, with the sequence determined by the patient's EP properties. Thus, as long as both initial and emergent drivers were captured, the DT with the baseline AF EP properties would be a useful clinical tool to provide personalized guidance in AF ablation.

Boyle et al[17] pioneered a prospective ablation study for patients with PsAF and fibrosis entirely guided by personalized atrial DTs. In this landmark study termed OPTIMA (OPtimal Target Identification via Modelling of Arrhythmogenesis), 10 patients were enrolled. The locations of reentrant drivers were determined following a reentrant driver inducibility test. These locations in the DT atrial substrate were then ablated virtually. In essence, the OPTIMA DT approach for guiding AF ablation is a targeted substrate ablation approach, where locations in the fibrotic substrate capable of sustaining reentrant drivers are discerned and ablated to eliminate that capability. After ablation, the DT inducibility test was repeated, and if there were aroused new locations that were capable of sustaining reentrant activity in the new (fibrosis plus initial ablation) substrate, then these emergent activities were also targeted with ablation until a set of optimal ablation targets was found that results in a complete arrhythmia noninducibility of the substrate. The proposed ablation targets were then used to steer patient treatment during the procedure, eliminating not only the clinically manifested AF but also any potential emergent AF drivers. Figure 3 shows the OPTIMA flowchart, illustrated with one of the patients in the prospective clinical study. While very

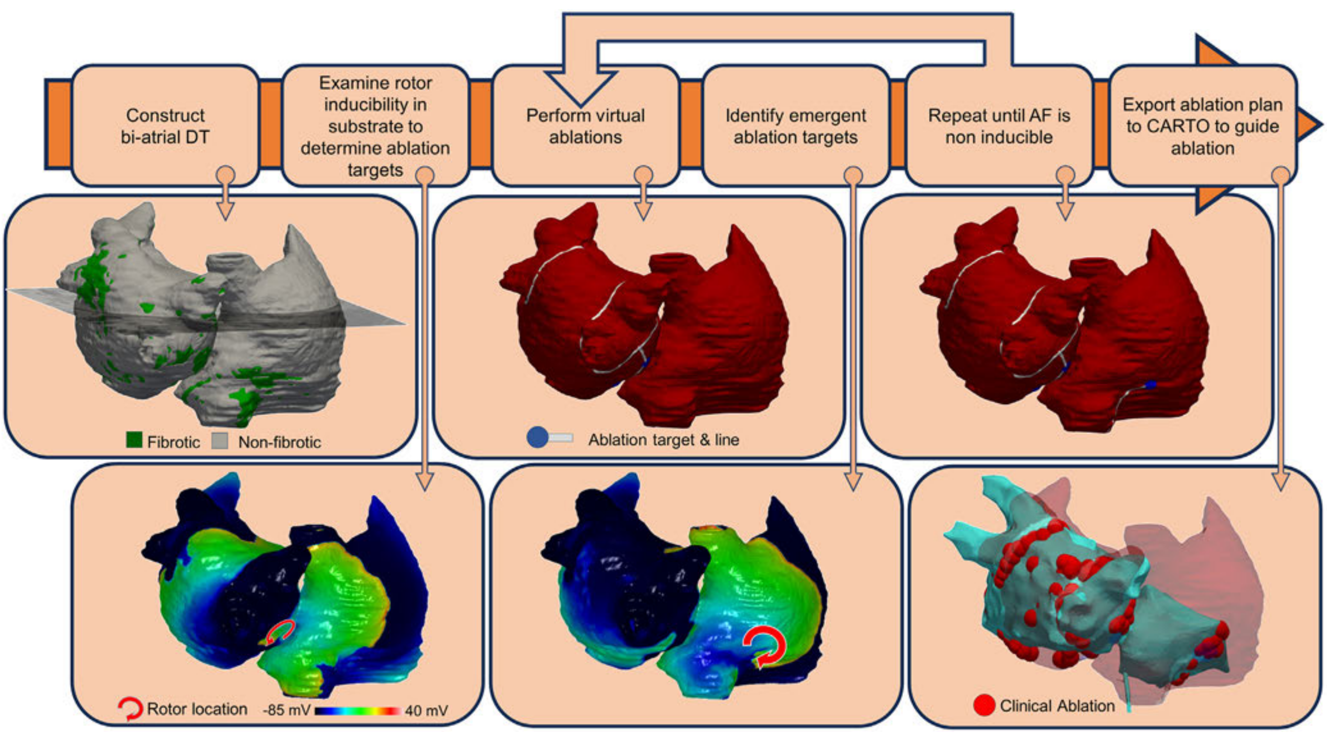

Figure 3
Flowchart of the OPtimal Target Identification via Modelling of Arrhythmogenesis approach using personalized heart digital twins (DTs). The individual steps are illustrated with the DTs of one of the participants in the study. Late gadolinium enhancement–magnetic resonance imaging scans were used to construct the patient's biatrial geometry and fibrosis distribution. After a baseline inducibility test, one location at the left atrial anterior septal wall was determined to have a high likelihood of sustaining a rotor (**bottom left**). After virtual ablation procedures targeting the detected location, a repeat inducibility test identified an emergent rotor location at the right atrial posterior region (**bottom middle**), which was then ablated. The final optimal ablation targets resulted in a complete arrhythmia noninducibility of the substrate. The proposed targets were imported to the CARTO system to guide the ablation procedure. AF = atrial fibrillation.

successful, the efficacy of this study is now being tested in a Food and Drug Administration–approved randomized controlled clinical trial (ClinicalTrials.gov identifier NCT04101539). Atrial DTs have also been used to determine how to ablate patients with atypical flutter.[37] The use of atrial DT-driven ablation has also been compared to other approaches, such as focal impulse and rotor mapping or electrocardiographic imaging.[38–40]

Inadequate modification of the atrial rotor-sustaining fibrotic substrate may explain AF recurrence after failed PVI. In a retrospective longitudinal study of 12 patients with AF who underwent pre- and postablation LGE-MRI, Ali et al[41] aimed to evaluate, using LA DTs, the postablation changes in arrhythmogenic substrate and to establish whether failure of AF ablation resulted from inadequate termination of preablation rotors or emergence of new rotors postablation. The research demonstrated that recurrent AF after PVI in the fibrotic atria may be attributable to both the existence of locations in the substrate capable of sustaining rotors that were not modified/eliminated by ablation and the emergence of new rotor-sustaining locations after ablation. The same levels of fibrosis entropy and density that underlie propensity to rotor formation in the preablation substrate hold true for the postablation substrate as well, providing a uniform framework to understand fibrosis-induced arrhythmogenesis. These conclusions led to the development of a strategy to predict, preprocedure before PVI, which patients are most likely to experience AF recurrence after PVI. To achieve that, Shade et al[42] combined LGE-based atrial digital twinning with machine learning in a proof-of-concept study of 32 patients. The algorithm used as input results of rotor induction simulations in the fibrotic substrate with imaging features derived from pre-PVI LGE scans (Figure 4). The machine learning classifier to predict the probability of AF recurrence post-PVI achieved an average validation sensitivity and specificity of 82% and 89%, respectively, and a validation area under the curve of 0.82. The study presented a highly generalizable AF recurrence predictor, despite the small training data set.

With the further development of the DT technology, the hope is that outstanding questions pertaining to AF

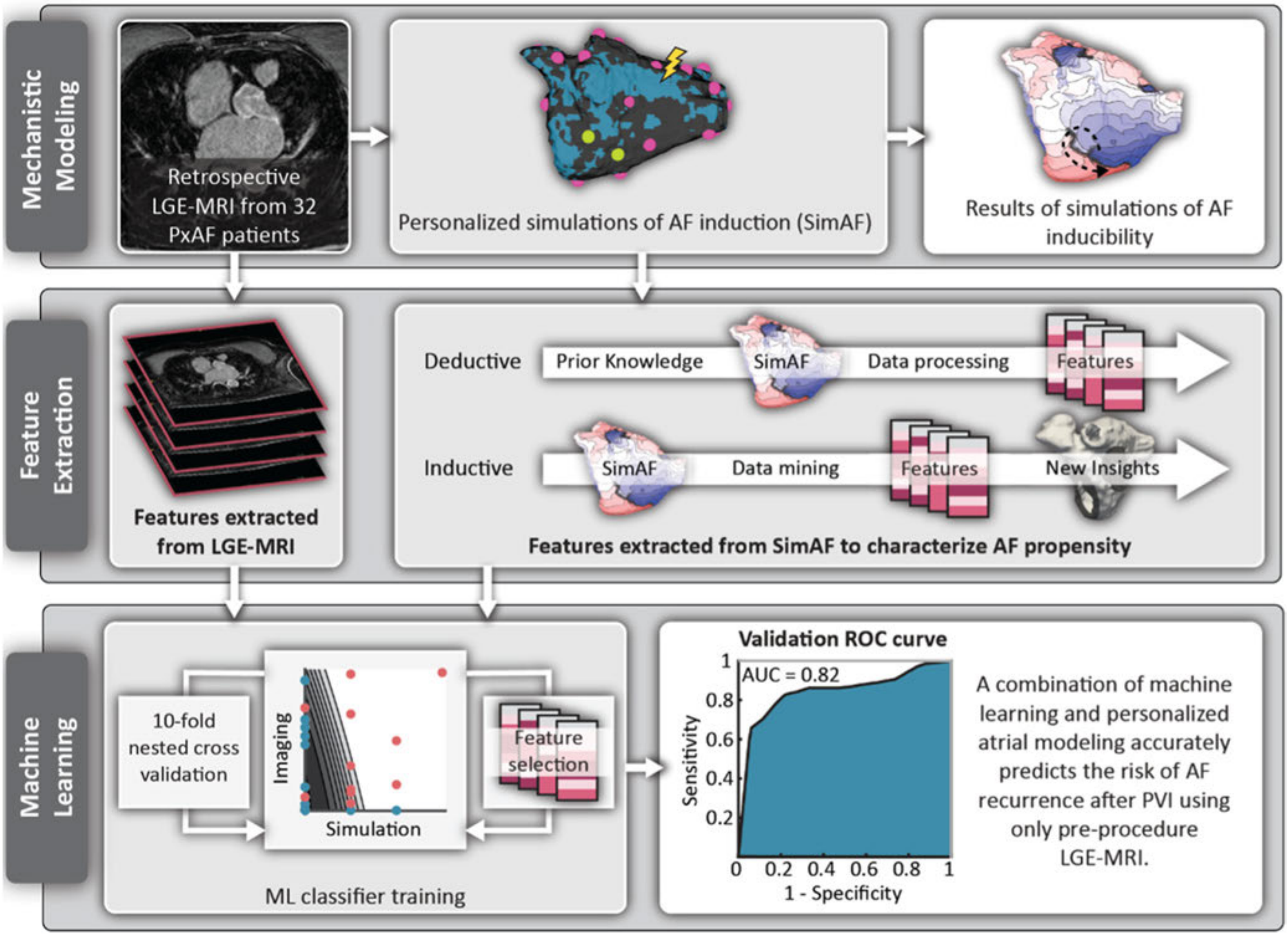

Figure 4

Predicting atrial fibrillation (AF) recurrence post–pulmonary vein isolation (PVI) by using the results of simulations with atrial digital twins (DTs), and training a machine learning (ML) classifier to predict, preprocedurally, clinical outcome. Features in DT simulation results can be extracted in 2 ways: deductively and inductively. AUC = area under the curve; LGE-MRI = late gadolinium enhancement–magnetic resonance imaging; PxAF = paroxysmal atrial fibrillation; ROC = receiver operating characteristic. Modified with permission from Shade et al.[42]

management will also be addressed. These include why some patients with fibrosis never develop AF, whether PVI will be the required strategy if ablation lesions in the fibrotic substrate eliminate its ability to sustain reentrant activity, or what are the important characteristics of the substrate that render it arrhythmogenic in patients with AF.

DTs for VA management

Personalized ventricular DTs have also made significant contributions toward being part of the clinical management of VAs. Such DTs have been constructed and used for a number of cardiomyopathies, both ischemic and nonischemic. Construction of ventricular DTs follows the general steps as outlined for atrial DTs, with the difference that in addition to using LGE-MRI for model construction, other imaging modalities have been used, often developing a personalized DT by fusing the different clinical images to represent different types of structural remodeling and functional remodeling (eg, inflammation). Figure 5A shows ventricular DTs reconstructed from various imaging modalities.[43–46] Frequently, before being used to suggest clinically relevant decisions, personalized DTs have been validated with clinical data (Figure 5B). Below we review 2 major clinical applications of computational modeling: the prediction of sudden cardiac death (SCD) due to arrhythmias in various diseases and the use of computational modeling to advance and ultimately provide guidance in arrhythmia treatment by catheter ablation.

Personalized ventricular DT studies have been compelled to address the issue of predicting the risk of SCD. It is an important clinical issue, as worldwide the prevalence of SCD, already high, is on the rise; it results predominantly from VAs, particularly in patients with prior heart disease. Accurate SCD risk assessment is thus crucial to enable primary prevention of SCD via the deployment of implantable cardioverter-defibrillators (ICDs).[48] Currently, the decision is based on a single clinical metric, which is not sensitive.[49] Thus, many patients receive ICDs without deriving any health benefit[50] (90%–95% of implanted ICDs are never used), whereas others are not protected, dying suddenly in the prime of their life. The conventional approach to SCD risk stratification has been to search for biomarkers that correlate with increased SCD risk. However, thus far, no biomarkers have enabled an accurate SCD risk assessment. Thus, inadequate SCD risk assessment poses a large public health and socioeconomic burden and remains a major unmet clinical need.

The study by Arevalo et al[51] demonstrated the first use of DTs of a cohort of patients with ischemic cardiomyopathy (n =

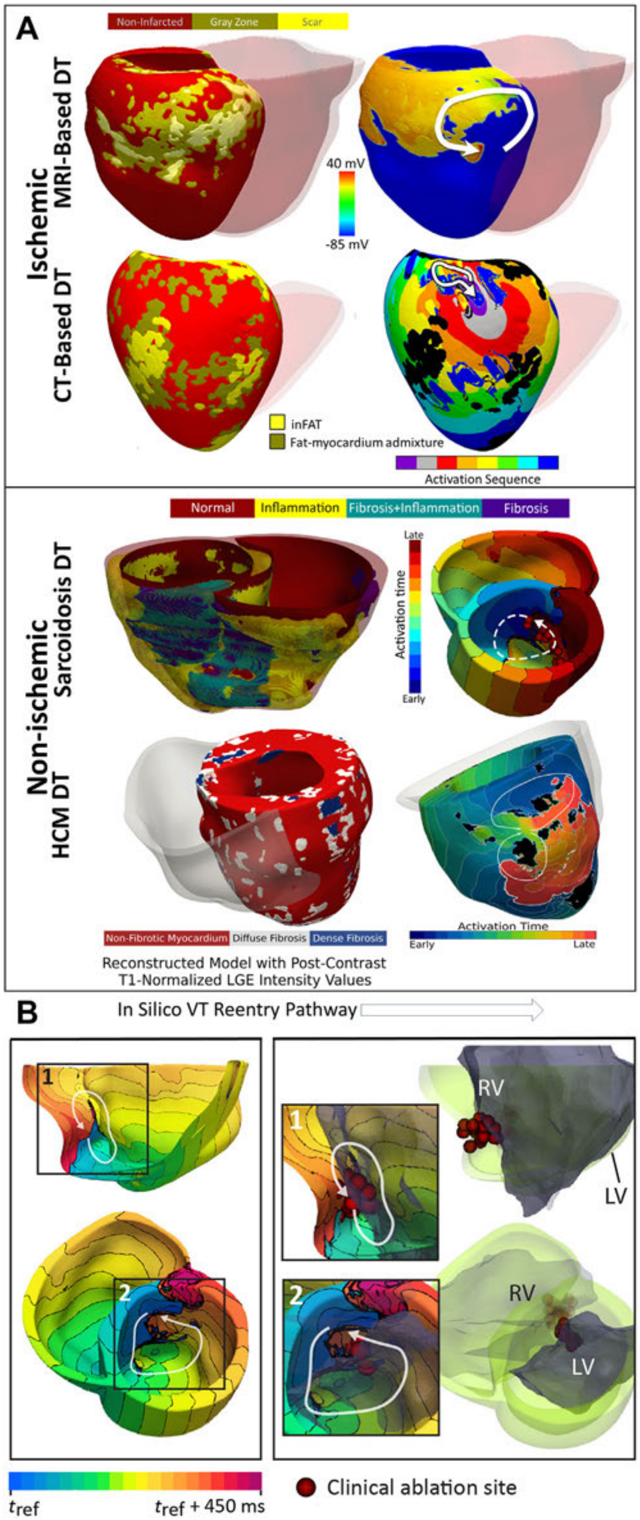

Figure 5

A: Personalized ventricular digital twins (DTs) with the corresponding predicted ventricular tachycardias (VTs). Shown here are the DTs of patients with ischemic cardiomyopathy (**upper box**) reconstructed from late gadolinium enhancement–magnetic resonance imaging (LGE-MRI) (**top**)[43] and computed tomography (CT) (**bottom**)[44] scans. The **lower box** shows the DT of a patient with sarcoidosis, which incorporates the region with inflammation detected from the positron emission tomography scan (**top**). Modified with permission from Shade et al.[45] Post-contrast T1 mapping scans were used to personalize the detection of diffuse and dense fibrosis in the DT reconstruction of a patient with hypertrophic cardiomyopathy (HCM; **bottom of the lower box**). Modified from O'Hara et al[46] (permission exempt per https://elifesciences.org/terms). **B:** Validation of the personalized DT of a patient with sarcoidosis with clinical ablation data. Two in silico VTs were induced in the DT (*white arrows*). The *red spheres* show the location of the clinical ablation lesions recorded in the patient electroanatomic mapping (EAM) data during the procedure. The EAM data co-registered to the DT show the correspondence between the predicted VTs and the clinical ablation lesions. inFAT = penetrating adipose tissue; LV = left ventricle; RV = right ventricle; t_{ref} = reference time point. Modified from Shade et al[47] (permission exempt per https://creativecommons.org/licenses/by-nc/4.0/).

41) to determine the patients' propensity to develop infarct-related VAs and SCD. All patients were with reduced left ventricular (LV) ejection fraction (<35%), thus deemed of high SCD risk, and all underwent ICD deployment. The patient's risk was assessed on the basis of whether arrhythmia was inducible from any of the numerous pacing sites tested in the DT; if it did, the patient was deemed at high risk. The comparison of the predictive capabilities of this DT approach with those of other clinical risk assessment metrics, including left ventricular ejection fraction and other imaging variables, revealed that only the outcome of the heart DT was significantly associated with arrhythmic risk in this patient cohort. The study demonstrated that DTs of patients with prior infarction can be used to determine which patients should have prophylactic ICD implantation for primary prevention. In addition, in a small proof-of-concept study, SCD risk was investigated in a small cohort of patients with myocardial infarction and preserved ejection fraction with the DT results matching clinical outcome.[52] A more complex approach to the development of DTs of patients with prior infarcts was recently presented,[53] where the patient heart DT also incorporated the distribution of penetrating adipose tissue (inFAT), which develops in infarcts >3 years old. This was a 2-center prospective clinical computational study, where enrolled patients underwent both LGE-MRI and CT (n = 24). inFAT was reconstructed in the DT from the patient computed tomography (CT) scans. The hybrid CT-MRI heart DTs, combined with electroanatomic map (EAM) data, revealed that for these infarcts inFAT exhibits greater proarrhythmic EP abnormalities than does scar and that it is the primary driver of substrate arrhythmogenic propensity. Subsequent clinical studies confirmed these DT predictions.[54–56] Finally, in addition to further developing heart DTs that are based on mechanistic considerations, recently new deep learning on different types (multimodality) of data has been proposed.[57] The deep learning analysis (termed survival study of cardiac arrhythmia risk) combined learning unprocessed (raw) patient LGE-MRI scans and clinical covariates of patients with ischemic cardiomyopathy and was imbedded in survival analysis to predict time to SCD over a period of 10 years; it performed well on the external validation data set, demonstrating generalizability. Algorithms such as survival study of cardiac arrhythmia risk are paving the way for multimodal prediction of patient outcome, but they will become particularly powerful when combined with DT for interpretability and mechanistic insight.

For SCD risk prediction in patients with nonischemic cardiomyopathies, several heart DT studies have demonstrated the clinical utility of the approach. The first 2 applications of personalized DTs in nonischemic cardiomyopathy were in pediatric patients. The first assessed VA risk in acute pediatric myocarditis.[58] In the second study, DTs were constructed from patients with repaired tetralogy of Fallot[59]; the childhood surgical intervention in these patients led to potential arrhythmogenic scarring in the heart. DT risk assessments in repaired tetralogy of Fallot predicted high risk, later validated by clinical outcome, in those patients in whom an ECG-based clinical algorithm predicted low risk. In hypertrophic cardiomyopathy, a common genetic disease characterized by thickening of heart muscle, high SCD risk arises from the proliferation of fibrosis in the heart. The study by O'Hara et al[46] used DT technology to analyze how disease-specific remodeling promotes arrhythmogenesis and to develop a personalized strategy to forecast the risk of arrhythmias in these patients (n = 26). The authors combined LGE-MRI and T1 mapping data to construct fusion DTs that represented the patient-specific distribution not only of dense scar but also of diffuse fibrosis; the latter was reconstructed from T1 maps.[60] The analysis demonstrated that the presence of diffuse fibrosis, which is rarely assessed in these patients, increases VA propensity. In forecasting future arrhythmic events in these patients, the DT approach significantly outperformed current clinical risk predictors; both the American College of Cardiology Foundation/American Heart Association and the European Society of Cardiology risk models offered prognoses that were inferior in accuracy, sensitivity, and specificity than the LGE-T1 DT prognosis. Another nonischemic cardiomyopathy associated with high SCD risk and difficult risk prediction is cardiac sarcoidosis. Shade et al[47] developed a 2-step prediction approach, combining digital twinning with machine learning in a study of 45 patients. The patient's arrhythmogenic propensity was assessed using a novel hybrid DT, reconstructed from the fusion of LGE-MRI and positron emission tomography scans. The results of DT simulation were fed, together with a set of clinical biomarkers, into a supervised classifier—and the technology outperformed current clinical decision making.

Finally, a genotype-specific heart DT (Geno-DT) approach was recently developed to investigate the role of pathophysiological remodeling in sustaining arrhythmia and to predict the arrhythmia circuits in patients with arrhythmogenic right ventricular cardiomyopathy (ARVC) and different genotypes.[61] This approach integrated the patient's disease-induced structural remodeling and genotype-specific cellular EP properties and revealed that the underlying arrhythmia mechanisms differ among ARVC genotypes. In a retrospective study of 16 patients with ARVC and 2 genotypes—plakophilin-2 (*PKP2*; $n = 8$) and gene-elusive (GE; $n = 8$)—Zhang et al[61] found that Geno-DT accurately and noninvasively predicted the ventricular tachycardia (VT) circuit locations for both genotypes with very high accuracy, sensitivity, and specificity in both the GE and *PKP2* patient groups when compared with VT circuit locations identified during clinical EP studies. Importantly, the results revealed that the underlying VT mechanisms differ among ARVC genotypes: in GE patients, fibrotic remodeling is the primary contributor to VT circuits, while in *PKP2* patients, slowed conduction velocity and altered restitution properties of cardiac tissue, in addition to the structural substrate, are directly responsible for the formation of VT circuits. Figure 6 shows an interesting result: when the genotype in DTs was mismatched, VT circuits could no longer be predicted correctly. With its incorporation of genetic EP information, Geno-DT is the latest development in heart DT applications. The Geno-DT approach demonstrated the potential to augment therapeutic precision in the clinical setting and lead to more personalized treatment strategies in ARVC.

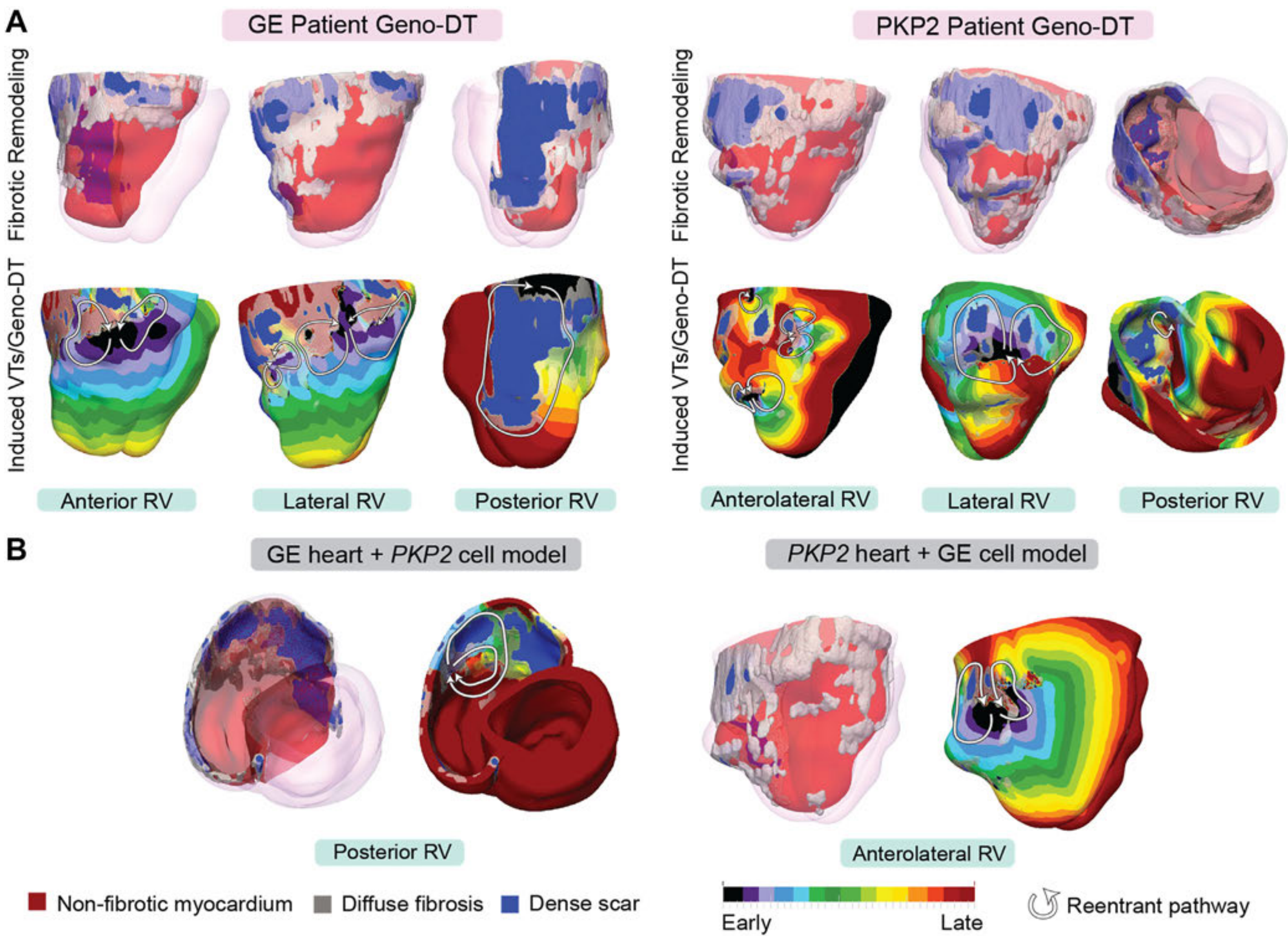

Figure 6
Ventricular tachycardia (VT) prediction using genotype-specific heart digital twin (DT; Geno-DT) of patients with arrhythmogenic right ventricular cardiomyopathy. Reconstructed DTs from 2 patients of gene-elusive (GE) and plakophilin-2 (*PKP2*) genotypes along with the simulated VTs with (**A**) genotype-matched condition and (**B**) genotype-mismatched condition. The mismatched condition led to an incorrect prediction of VT circuits. RV = right ventricle. Modified from Zhang et al[61] (permission exempt per https://elifesciences.org/terms).

Like the management of AF, catheter ablation plays a major role in the contemporary management of VAs. Eliminating VAs with ablation has achieved, however, modest success, 50%–88%.[62,63] Similar to AF ablation, a number of patients, for whom the initial procedure fails, are repeatedly ablated, further extending adverse structural remodeling in the ventricles. Discovering new strategies that result in accurate identification of the optimal ablation targets for VAs in patients with different heart diseases, and which also deliver long-term freedom from VAs, is a quest of paramount clinical significance. Personalized DT technology has made major strides in improving ablation precision by providing noninvasive localization of ablation targets. A study using DTs from 13 postinfarct patients who underwent ablation showed that ablation targets from DTs were consistent with the targets executed in the clinic.[64] The landmark study by Prakosa et al[43] was demonstrated for the first time the clinical utility of personalized DTs in determining noninvasively the optimal (ie, minimum lesion size) VT ablation targets and guiding the clinical procedure of VT ablation. The capability of the approach was first assessed in a retrospective study (n = 21), where predicted targets were compared with clinical data. This included patients in whom image construction was done from clinical images with device artifacts. Furthermore, the feasibility of using DTs to guide clinical VT ablation was demonstrated in a proof-of-concept prospective study (n = 5) in 2 clinical centers (Figure 7A). This work highlighted the potential of DT technology to impact the clinical management of VAs. The sensitivity of DT ablation targets to EP parameter variability has also been assessed.[65] Using DTs based on the CT scans of patients has also been shown, in a retrospective cohort of 29 postinfarct patients, to be able to provide guidance in ventricular ablation.[44] DTs predicted not only the targets on index ablation but also the ablation targets on a redo procedure several years later (Figure 7B). Overall, the ablation targets predicted by the heart DTs consistently encompassed much less lesion volumes. Since CT is accessible across a broad range of clinical centers, DTs could be readily deployed prospectively to improve ventricular ablation.

DTs have also been used to improve ablation by better understanding VT circuit morphology. Sung et al[66] demonstrated that inclusion of repolarization gradients, both

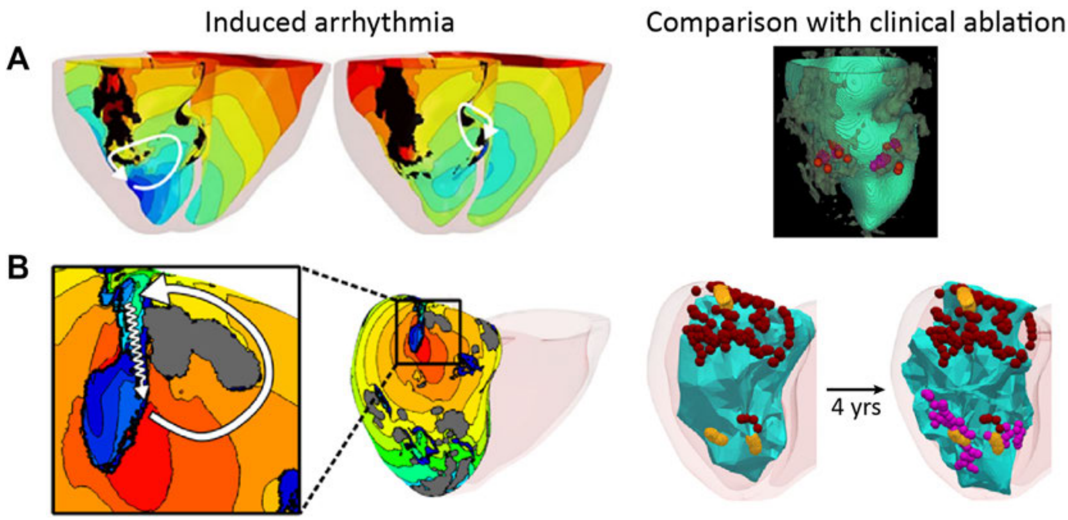

Figure 7
Digital twins (DTs) guiding ventricular ablation. **A:** Ablation in a prospective patient with ischemic cardiomyopathy guided by magnetic resonance imaging–based DT. Shown are the 2 predicted VT circuits, and intraprocedural electroanatomic mapping (CARTO) with the predicted (*purple*) and actual (*red*) lesions. Modified from Prakosa et al[43] (permission exempt per https://www.nature.com/nature-research/reprints-and-permissions/permissions-requests). **B:** Using a computed tomography–based DT in a postinfarction patient with infiltrating fat to predict VT circuits (**left**; the *inset* presents the detail of activation; *white arrows* denote the reentrant pathway; *zigzag arrows* denote the conduction channels) and ablation targets retrospectively, where predicted ablation targets and clinical ablation lesions colocalize in a patient who underwent redo ablation ≈4 years after the index procedure. Modified with permission from Sung et al.[44]

transmural and apicobasal, altered VT circuit morphologies, with minimal change in ablation targets. DT simulations of VT circuits have also been combined with automated ECG-based localization algorithm to predict VT exit sites,[67] highlighting a potential synergy between the 2 methodologies. A recent study further developed and validated a technique called reentry vulnerability index, demonstrating that the technique allows localization of ablation targets.[68] In the clinic, multiple wavefront pacing (MWP) and decremental pacing are 2 EAM strategies that have emerged to characterize[62,63] the VT substrate and determine ablation targets. A recent DT study in 48 patients assessed how well MWP, decremental pacing, as well as other techniques used in clinical studies improve identification of EP abnormalities at critical VT sites.[69] The study found that EAM with MWP is more advantageous for the characterization of substrate for ablation in hearts with less remodeling.

Concluding remarks

The development and examples of applications of heart DTs in arrhythmia management by our team presented in this review highlight the significant advancements that cardiac computational modeling has made in bringing such tools closer to the patient point of care. Heart DTs could potentially become a disruptive approach, fully embodying the expectations of precision medicine in cardiology, as these virtual tools leverage robust physics and physiology-based mechanistic insights, are capable of encoding pathophysiological complexity across multiple spatial scales, and can be continuously updated with the individual patient's clinical and lifestyle data.

The pathway to accelerate the clinical impact of heart DTs is to continuously work on increasing the trust in the technology among researchers, clinicians, and health care professionals; to emphasize its benefits to patients; and to educate the society at large. An important aspect in this endeavor is to always recognize and account for the limitations of the technology. DTs of organs and patients will likely never represent all aspects of physiological reality. Thus, focus should be steadily on DT performance and the resulting patient outcome, both becoming increasingly important. To cite George Box, "all models are wrong, some are useful"—it is this usefulness that we will strive to enhance in the years to come.

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Federal Register Notice: 89 FR 51554, Federal Register :: Networking and Information Technology Research and Development Request for Information on Digital Twins Research and Development, June 18, 2024.

Request for Information on the National Digital Twins R&D Strategic Plan

National Institute of Building Sciences (NIBS)

Digital Twins Research and Development Comments for NITRD NCO

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Submitting Organization: National Institute of Building Sciences (NIBS)
NIBS representative: Roger Grant, Vice President Building Technology; Johnny Fortune, Executive Director, US National BIM Program

The National Science Foundation's (NSF) Request for Information (RFI) on Digital Twins Research and Development (R&D) underscores the growing recognition of digital twins as transformative tools across various sectors. Recognizing the potential of digital twins to accelerate innovation, enhance decision-making, and address complex societal challenges, the NSF seeks to develop a National Digital Twins R&D Strategic Plan. The National Institute of Building Sciences (NIBS) is pleased to respond to the Networking and Information Technology Research and Development (NITRD) National Coordination Office (NCO) and National Science Foundation Request for Information (RFI) on the topic of Digital Twins. NIBS provides comments specifically to address the topic of Digital Twins through the lens of **engineered systems of systems** for the **built environment** with an emphasis on **buildings and infrastructure** as integral components of **smart cities**. The built environment is impacted by and in turn impacts **natural systems**. Digital Twins support this relationship. NIBS is uniquely positioned to offer insights on interoperability, standardization, data management, long-term research priorities, and other critical aspects of digital twin development and deployment. Our goal is to contribute to a comprehensive national strategy that fosters a robust, collaborative, and responsible digital twin ecosystem, ultimately benefiting society. This response is structured to provide general information from our existing work and initiatives and communicate our efforts in alignment with the RFI's key topic areas.

NIBS is a crucial nexus for individuals and organizations from the public and private sectors involved in the creation and management of the built environment. NIBS was established by the U.S. Congress in the Housing and Community Development Act of 1974, Public Law 93-383. Congress recognized the need for an organization to serve as an interface between government and the private sector. NIBS convenes experts from throughout the built environment including designers, architects, engineers, constructors, owners, operators/users, technology and service providers, and academia and government representatives. Our work includes public events and publications along with contracted project work with federal and state agencies. NIBS is committed to fostering collaboration on critical topics such as Digital Twins and a unified approach, involving diverse stakeholders, is essential to unlocking the full potential of this technology. We are enthusiastic about facilitating such partnerships and providing a platform for knowledge exchange and innovation. In our role as convener we work closely with industry associations and standards development organizations; examples include AIA, ASHRAE, bSI, bSUS, CSI, DBIA, DTC, ICC, Global BIM Network, NHBA, SAME, and many more. Digital transformation is addressed with industry stakeholders through our U.S. National BIM Program and our Digital Technology Council. In 2023, NIBS formed a Digital Twin Integration Subcommittee (DTI-S) with support from the Digital Twin Consortium to specifically address Digital Twins for the built environment.

NIBS recently published the DTI-S position paper titled "Digital Twins for the Built World" (DTI-S, 2024), which was the result of over a year of rigorous collaboration among experts in architecture, engineering, construction, and technology. The position paper reflects a thorough understanding and commitment to advancing Digital Twin technology. The position paper emphasizes that Digital Twins are a system of systems, necessitating a collaborative approach that no single entity can achieve alone.

NIBS brings together a diverse array of stakeholders, fostering interdisciplinary collaboration and integration across various systems and domains. This collective effort is essential for understanding and harnessing the full potential of Digital Twins, ensuring that advancements in one area are effectively connected and aligned with developments in other areas. By providing a platform for such comprehensive engagement, NIBS plays an indispensable role in driving innovation and efficiency in the Architecture, Engineering, Construction, Owner (AECO) industry. NIBS sees the effort of NSF to develop a Digital Twin R&D strategic plan as an opportunity for our organizations to collaborate further on advancing this technology into the AECO industry.

The DTI-S position paper provides a structured exploration of Digital Twins, segmented into major portions including Definitions, Public Perception, Foundations, Data Standards, Use Cases, and Calls to Action. Each section delves into critical aspects necessary for the successful understanding, implementation, and adoption of Digital Twins:

1. **Foundational Information:** The paper clarifies the concept of Digital Twin and establishes a common language for AECO stakeholders. Further, it outlines the foundational technologies and methodologies underpinning Digital Twin development and use in the built environment and highlights the importance of standardized data practices to ensure interoperability and accuracy.
2. **The Importance of Integration:** The paper emphasizes the significance of integrating BIM and Digital Twins to drive innovation, efficiency, and collaboration within the AECO industry. It seeks to address the existing confusion and uncertainty surrounding the interchangeability of these terms.
3. **Target Audience:** The paper caters to a diverse audience within the AECO industry, including executive leaders, technologists, and practitioners. It offers insights into the transformative potential of BIM and Digital Twins, technological intricacies, and the impact on the evolving landscape.

4. **Top-Level Position:** The paper posits that the relationship between BIM and Digital Twins is integrative rather than duplicative, commonly misunderstood, and uniquely suited for solving substantial AECO issues. It advocates for the symbiotic adoption of both technologies in accordance with standards.
5. **Public Perception:** The paper underscores the often-overlooked influence of public perception on the integration of BIM and Digital Twins. It argues that the general public, though not directly involved in technical discussions, significantly impacts the adoption and perception of these technologies.
6. **Use Cases:** The paper explores the practical applications of BIM and Digital Twins, demonstrating how they revolutionize the life cycle of built spaces and the natural environment. It emphasizes the importance of clear and well-defined use cases for successful implementation.
7. **Execution:** The paper delves into how BIM and Digital Twins can be executed by harnessing their differences. It highlights that BIM Models provide detailed and static asset representations, which Digital Twins can animate and operationalize, suggesting a strategy where BIM serves as a foundation for AECO digital twins.
8. **Data Frameworks:** The paper outlines a dynamic approach to managing and harnessing data vital for the evolution of BIM and Digital Twins. It presents strategies for immediate implementation and future growth, emphasizing adaptability and responsiveness to the changing landscape.
9. **Conclusion and Call to Action:** The paper concludes by emphasizing the integrative nature of BIM and Digital Twins and calls for action from industry leaders, technologists, and practitioners. It urges engagement with NIBS and the adoption of interoperability standards, data management optimization, and the refinement of use cases.

The development and publication of the paper resulted in the identification of logical next steps for the NIBS DTI-S as outlined below.

Stakeholder Engagement for National Digital Twin Implementation

- **Reason:** To define Digital Twin in a cross-industry fashion and address the need for liaising and collaboration within the AECO industry.
- **Desired Outcome(s):** Engage stakeholders to discuss BIM-DT relationship, current state of Digital Twins, and requirements for enhancing deployment. Collect insights to develop a comprehensive Digital Twin standard.
- **Resources Needed:** Contracted design facilitation expertise, NIBS staff input.
- **Budget:** Roughly $25k for contracted design facilitation.
- **Timeline:** 1 year recommended.

Agile Testbed for Digital Twin & BIM

- **Reason:** To counter industry trends towards siloed advancements by fostering open collaboration and sharing of innovations.

- **Desired Outcome(s):** Implement and refine use cases within a live testbed, demonstrating practical applications and filling gaps in existing standards.
- **Resources Needed:** Advanced simulation software, real-time data processing tools, user interface technologies, industry-aligned consultant.
- **Budget:** Roughly $100k for contracted design facilitation.
- **Timeline:** Initial effort of 1 year, reassessed annually.

A Technical Approach for Advancing BIM and Digital Twin

- Reason: To transform valuable ideas and insights from DTI-S working groups into actionable knowledge and share it with the community.
- Desired Outcome(s): Provide a technical whitepaper on policy, technical, and organizational requirements for successful Digital Twin adoption. Address action items identified in the DTI-S position paper.
- Resources Needed: Part-time industry-aligned consultant, NIBS staff input.
- **Budget:** Roughly $100k for contracted design facilitation.
- **Timeline:** Generally, 1 year, but depends on topics and format (single vs. modular documents).

Implement a Modern Foundation for Digital Collaboration

- **Reason:** To overcome inefficiencies of traditional file-based systems and support dynamic, interconnected environments for effective Digital Twin operations.
- **Desired Outcome(s):** Establish interconnected digital tools embodying Digital Twin principles, enhancing communication and data accessibility. Develop leadership training materials.
- **Resources Needed:** Acquisition of software licenses, standards, and training programs. Integration of legacy systems with advanced web-based tools.
- **Budget:** Amount unknown without further study.
- **Timeline:** Immediate initiation with rapid deployment. Initial 3-month review phase for feasibility.

Identify Use Cases for Digital Twin & BIM

- **Reason:** To extend Digital Twin applications beyond architectural models to encompass environmental interactions and foster sustainable urban planning.
- **Desired Outcome(s):** Develop integrative use cases adhering to existing standards and create new standards where needed. Highlight practical benefits and facilitate deployment across sectors.
- **Resources Needed:** BIM, GIS, and collaborative platforms for stakeholder engagement, part-time industry-aligned consultant, NIBS staff input.
- **Budget:** Roughly $25k for contracted design facilitation.
- **Timeline:** One-time effort of 3 months, with annual review for updates.

NIBS welcomes the opportunity to collaborate with NSF on executing these next steps.

Topic Areas

NSF requested comments on various topic areas. Below are aligned responses to the topic areas suggested.

- **Artificial Intelligence (AI):**
  - Generative AI applications have the potential to effectively align with and enhance the physical counterparts of digital twins. NIBS' has begun to look into this potential working with our network of experts in Building Information Management, digital twin, and simulation, coupled with their understanding of the built environment. For example, we have started an AI in the Built Environment Interest Group and recently hosted a workshop on Digital Twins and AI at our annual conference.

- **Business: Business Case Analysis:**
  - The are numerous potential use cases for BIM and Digital Twins, use cases are the cornerstone of successful integration. Here are some key business cases that could be explored:
    - **Enhancing Efficiency and Sustainability:** BIM and Digital Twins can optimize energy use, benefiting individual buildings and the broader community. For instance, a digital twin of an electrical utility system could interact with a facility's mechanical system to improve efficiency.
    - **Streamlining Asset and Project Management:** BIM and Digital Twins offer capabilities for effective asset lifecycle management. This includes tasks such as asset maintenance scheduling, space utilization planning, design development, generative design, value engineering, construction sequencing, and quality control.
    - **Monitoring and Control:** Digital Twins can monitor building systems and occupant patterns in real-time. This can be used to optimize performance, ensure loaned asset value, and foster trust between stakeholders.
    - **Data-Driven Decision Making:** Integrating BIM and Digital Twins provides a comprehensive view of an asset, enabling informed decision-making. This is particularly valuable for complex systems where real-time data and predictive analytics can drive efficiency and innovation.
  - These use cases can be applied across different phases of an asset's lifecycle, from design and construction to operation and maintenance. Clearly defining use cases before implementing BIM and Digital Twin technologies is an important first step to ensure that the solutions are tailored to specific needs and deliver maximum value.
  - Evaluating the foundational research costs and return on investment for Digital Twins requires expertise and understanding of the built world, infrastructure, and smart cities. NIBS and our community of AECO organizations can provide invaluable insights into the cost and time required for implementation, ensuring

that NSF's efforts are informed, strategic, and impactful in advancing smart city initiatives and infrastructure development.

- **Data**:
  - Data quality, management, and accessibility are critical for the success of digital twin initiatives:
    - **Data Quality Assurance:** Emphasize the need for high-quality, reliable, and timely data to ensure the accuracy and effectiveness of digital twin models. Establish guidelines and best practices for data collection, curation, and management to maintain data integrity and reliability. A roadmap of how to transition from a low level of maturity to the level of maturity needed to leverage a digital twin.
    - **Data Sharing & Accessibility:** Advocate for the creation of shared public datasets and repositories to facilitate research, development, and innovation in the digital twin space. Encourage data sharing across different domains and sectors while adhering to privacy and security regulations.
    - **Privacy & Security:** Address privacy and security concerns related to data collection, storage, and sharing in digital twin applications. Implement robust security measures and adhere to relevant data protection regulations to safeguard user privacy.
  - See the position paper (DTI-S, 2024) for more information on this topic. The position paper highlights the importance of a **dynamic approach to managing and harnessing data** vital for the evolution of BIM and Digital Twins. This aligns with the RFI's emphasis on **encouraging the adoption of data management best practices**. The DTI-S's expertise in data frameworks can inform the development of **governance methods for data collection, curation, sharing, and usage**, as well as the establishment of **shared public datasets and repositories**.
  - NIBS can support NSF in establishing effective governance methods for data collection, curation, sharing, and real-time integration, thereby enhancing the efficiency and resilience of smart city and infrastructure projects.

- **Ecosystem**:
  - To establish a thriving national digital twin ecosystem, it is crucial to prioritize:
    - **Interoperability:** Develop and adopt standardized frameworks, ontologies, and protocols for seamless data exchange and integration between diverse digital twin platforms. This will enable the creation of a unified ecosystem where digital twins from various domains can interact, share information, and collaborate effectively.
    - **Collaboration & Knowledge Sharing:** Establish platforms (e.g., online forums, workshops) and mechanisms for collaboration between researchers, industry stakeholders, and government agencies to share

knowledge, best practices, and lessons learned in digital twin development and deployment.

    - **Open Innovation:** Encourage the development and adoption of open-source tools, platforms, and datasets to accelerate innovation, reduce barriers to entry for new players, and democratize access to digital twin technologies.

  - See the position paper (DTI-S, 2024) for more information on this topic. The position paper emphasizes the need for **clarity and guidance** in the AECO industry regarding BIM and Digital Twin integration. This aligns with the RFI's focus on establishing a **national digital twin R&D ecosystem** and addressing **foundational research gaps and opportunities**. The DTI-S's expertise in integrating these technologies can provide valuable insights into **collaborations across agencies** and the development of **common mathematical, statistical, and computational foundations**.
  - NIBS' expertise in the built world, infrastructure, and smart cities, combined with its ongoing effort to create an inventory and collaborate with nearly 50 Digital Twin public and private organizations, uniquely positions it to contribute significantly to establishing a National Digital Twin R&D Ecosystem. By leveraging its deep understanding of interdisciplinary collaboration and data integration, NIBS can help NSF identify and address foundational research gaps, facilitating advancements in areas such as sustainability, climate change, and smart and connected communities in the built environment.

- **International:**
  Along with Building Information Modeling and Management (BIM) there is extensive activity around the world on Digital Twins. Because many large private sector service and technology companies operate globally and several federal agencies (Department of Defense and Department of State Overseas Buildings Operations) also operate globally, it is important to look at what others outside our borders are doing. Also, other countries such as the UK and many EU countries have advanced further in adopting common BIM processes and standards that form a solid foundation for Digital Twins. This has allowed them to advance their focus to innovation which has included establishing national Digital Twin programs (UK Digital Twin Centre) and several EU initiatives. In the same way NIBS is involved with global BIM efforts, we also have connections with Digital Twin work in other countries such as the UK and EU countries through membership in the Global BIM Network and buildingSMART International and can leverage these connections to assess and potentially connect for what can be shared to advance efforts here.

- **Long Term**:
  - To ensure the continued advancement of digital twin technology, it is essential to prioritize long-term research investments in the following areas:

- **Novel Modeling & Simulation:** Invest in research to develop novel modeling and simulation techniques, including integrating AI and machine learning algorithms, to enhance the predictive capabilities and accuracy of digital twins.
- **Bidirectional Data Flow:** Research and develop technologies to enable seamless bidirectional data flow between virtual and physical assets, ensuring that digital twins are continuously updated with real-time data and can effectively inform decision-making in the physical world.
- **Sustainable High-Performance Computing:** Invest in developing sustainable high-performance computing infrastructure and energy-efficient algorithms to support the computational demands of large-scale digital twin implementations.

- **Standards**:
  - A robust standardization framework is essential for the widespread adoption and integration of digital twins:
    - **Comprehensive Standards:** Advocate for developing comprehensive standards covering data formats, communication protocols, security measures, evaluation methodologies, and AI integration for digital twin development, testing, and interoperability.
    - **Active Participation:** Encourage active participation of all stakeholders in relevant standardization bodies and initiatives to ensure diverse perspectives and expertise are incorporated into the development process.
    - **Widespread Adoption:** Promote the adoption of these standards by industry stakeholders and government agencies to ensure consistency, compatibility, and interoperability across different digital twin implementations.
  - See the position paper (DTI-S, 2024) for more information on this topic. The paper advocates for the **symbiotic adoption** of BIM and Digital Twin technologies **in accordance with established standards**. This directly addresses the RFI's call to **promote the development of evaluation tools, methodologies, and consensus standards** for digital twin development, testing, and interoperability. The DTI-S's focus on standards can contribute to the creation of a **community of practice** and the development of **ontology and data exchange protocols**.

- **Trustworthy**: Data integrity is foundational to the implementation of Digital Twins. To address cybersecurity challenges and data integrity. NIBS has several initiatives that relate to this topic area. NIBS' Digital Technology Council produced a series of events addressing cybersecurity of AECO data. See website links below for the resource. NSF and NIBS can work collaboratively to continue to convene experts to help strike the balance between security and innovation.

- **Workforce**: To take advantage of using digital twins to improve the operations of buildings and infrastructure requires a workforce that knows how to use digital processes to visualize, monitor and optimize operations. Digital Twins is a topic that is in high demand currently as the industry is grappling with the concept and implementation. NIBS produces various educational webinars, podcasts, and training material for the AECO industry. NSF and NIBS could collaborate on educational materials to advance workforce development. NIBS also manages the Whole Building Design Guide (WBDG), which includes a wide range of criteria as well as training and educational material. The WBDG can be used as an outlet to advance the work of educating the industry on Digital Twins.

Additionally, the position paper's (DTI-S, 2024) emphasis on the **integrative relationship between BIM and Digital Twin** and its exploration of **practical use cases** can further contribute to the RFI's topics on **AI integration, long-term research investments**, and **responsible development and use of digital twins**. The paper's focus on the **execution and implementation** of BIM and Digital Twin can also inform the RFI's discussion on **sustainability and the design and development of systems and architectures**.

Conclusion

NIBS believes that a unified approach, involving diverse stakeholders, is essential to unlocking the full potential of Digital Twin technology. We are enthusiastic about facilitating such partnerships and providing a platform for knowledge exchange and innovation. NIBS welcomes the opportunity to engage in deeper discussions and collaborate closely with the NSF to accelerate the widespread adoption of Digital Twins across diverse sectors of the built environment. NIBS can help expand the reach of strategic development and together, we can drive the creation of smarter, more efficient, and resilient built environments. Collaborating with NSF on this effort and partnering with others is crucial in transforming findings into impactful, real-world applications. Please contact NIBS representatives Roger Grant (rgrant@nibs.org) and Johnny Fortune (jfortune@nibs.org) for additional engagement and support.

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References:

Digital Twin Integration Subcommittee. (2024). Digital Twins for the Built Environment: A Position Paper on Integrating BIM and Digital Twin. National Institute of Building Sciences, Digital Technology Council. https://www.nibs.org/files/pdfs/DigitalTwinsBuiltEnvironment.pdf

Website links:

National Institute of Building Sciences: https://www.nibs.org/
NIBS U.S. National BIM Program: https://www.nibs.org/usbimprogram
NIBS Digital Technology Council: https://www.nibs.org/bimc
Introduction to DTI-S Paper: https://qrco.de/bfECJL or https://www.nibs.org/blog/new-paper-bim-and-digital-twins-coexist-drive-sustainability
NIBS report: Collaborative Digital Delivery in the Age of Information Privacy and Cybersecurity: https://www.nibs.org/reports/collaborative-digital-delivery-age-information-privacy-and-cybersecurity
Whole Building Design Guide: https://wbdg.org/

Additional Resources:

Digital Twin categories paper: Ghorbani, Zahra, and John I. Messner. “A Categorical Approach for Defining Digital Twins in the AECO Industry.” Journal of Information Technology in Construction (ITcon), vol. 29, no. 10, Mar. 2024, pp. 198–218, https://doi.org/10.36680/j.itcon.2024.010.

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Request for Information on the National Digital Twins R&D Strategic Plan

Nature Computational Science

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Perspective

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Digital twins in medicine

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Check for updates

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Medical digital twins, which are potentially vital for personalized medicine, have become a recent focus in medical research. Here we present an overview of the state of the art in medical digital twin development, especially in oncology and cardiology, where it is most advanced. We discuss major challenges, such as data integration and privacy, and provide an outlook on future advancements. Emphasizing the importance of this technology in healthcare, we highlight the potential for substantial improvements in patient-specific treatments and diagnostics.

A 52-year-old man was found confused in his prison cell by the staff and brought to a hospital emergency department (ED). He had a remote history of a stroke and consequent hemiplegia. In the ED, his initial blood pressure was low and responded to volume resuscitation. His laboratory studies showed a mildly elevated peripheral leukocyte count and a mild renal insufficiency, and his chest X-ray showed bilateral airspace disease. He was diagnosed with pneumonia and started on empiric antibiotics aimed at pathogens that cause severe community-acquired pneumonia. Six hours later, he became more confused, developed hypotension again (requiring initiation of intravenous pressor drugs) and required increasing supplemental oxygen. His chest X-ray also showed worsening airspace disease. Three hours later, he required endotracheal intubation and lung-protective mechanical ventilation for worsening hypoxic respiratory failure due to acute respiratory distress syndrome. Over the following day, he developed refractory septic shock, requiring multiple intravenous pressors, acute kidney injury, and escalating ventilator requirements. His blood cultures, obtained on admission, showed *Klebsiella pneumoniae*, an organism that was sensitive to the antibiotics he had received. The patient's condition continued to deteriorate, and he died of multi-organ failure 32 hours after his initial presentation.

In this case (encountered by B.M. in the medical intensive care unit (ICU)) and others like it, existing illness severity scoring systems provide quite accurate data on the likelihood of acute mortality, and are hence helpful in determining, for example, whether the patient can be treated at home, in the hospital or in the intensive care unit. Their main shortcoming, highlighted by this case, is that the information they provide is not otherwise actionable, for example, by identifying interventions that may have altered the course of the illness. This represents the biggest promise and challenge in applying computational modeling at the level of individual patients: given that biological heterogeneity leads to a wide range of responses to illness and treatments, can computational models, together with the right kinds of data, help the medical team intervene with more effective and better-timed interventions, tailored to an individual patient and resulting in better outcomes?

When President Obama announced his precision medicine initiative during the 2015 State of the Union address and established a working group to implement it[1], he called for an unprecedented effort to collect data on a million patients to bring the United States closer to an era where medical treatment can be tailored to each individual patient. The digital twin paradigm, as initially formulated and developed in industry and engineering, has a compelling analog in medicine as a powerful tool for truly personalizing medical care. The first attempts at medical digital twin (MDT) technology were made decades ago, including the very comprehensive pioneering Archimedes project on diabetes[2]. The literature has grown substantially over the past several years. A PubMed search for 'digital twin' retrieves over 1,400 citations, with an exponential increase since 2020. Three developments have probably contributed to this trend: an increased focus on precision (or personalized) medicine, the increasing availability of data characterizing human biology[3,4] and electronic health record (EHR) data for large patient cohorts, as well as the emergence of powerful modeling and simulation capabilities, such as machine learning (ML) algorithms and artificial intelligence (AI) models.

In this Perspective, we review the current state of development of MDTs and the challenges that need to be met to move forward with the development of an MDT industry, similar to what currently exists in the industrial sphere. These challenges are (1) technological, such as appropriate modeling technologies, (2) medical, such as our understanding of the biological determinants of health and disease, as well as the availability of appropriate data-generation technologies and (3) administrative, such as standards for regulatory approval of MDT-based devices and data-sharing standards. We will also highlight developments in two

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medical fields in which MDTs have made substantial progress already. We describe some approaches to MDTs in oncology, and we give a detailed description of the use of MDTs in cardiology, in particular heart arrhythmias.

Here, we will focus primarily on mechanistic modeling as the basis for MDTs. A plethora of ML/AI modeling methods have been applied, such as causal AI and physic-informed neural networks. We refer the reader to two review articles that focus on the integration of mechanistic modeling and machine learning techniques[5,6], which we believe will be one of the most promising approaches to MDT technology.

Industrial and medical digital twins

Industrial digital twins are characterized by two features: (1) they are built on a mechanistic model of the physical system to be twinned and (2) they are dynamically calibrated to the system for the purpose of forecasting system performance and identifying interventions, such as preventive maintenance. In other words, the digital twin evolves with the physical system over time. This definition conforms to the vision of personalized medicine, either curative or preventive. However, there are only a few tools currently in use in medicine that completely fit this definition, and we give some examples later. Although the industrial paradigm represents the gold standard for personalized medicine, digital twins that fall short of this can still serve as valuable tools that improve on the standard of care in many cases.

There are three main challenges that distinguish medicine from industry when it comes to digital twins. First, for many medical applications, the relevant underlying biology is partially or completely unknown. For example, it is known that some diseases have an important microbiome component. However, in most cases, little is known about the mechanisms involved. Having said that, microbiome data are easy to collect and are abundant, so there are opportunities to apply data-driven approaches to patient stratification and potential actionable insights for targeting treatments to patient subpopulations identified through ML algorithms. Second, even if there are mechanistic dynamic models of the requisite human biology available that could be personalized, the needed data are often not available or are difficult to collect. Third, human biology is often not easily describable with deterministic models based on physical principles, such as systems of ordinary differential equations based on physical laws. In these cases, other modeling platforms need to be used, such as agent-based models. The resulting computational models can be multi-scale, hybrid and stochastic. However, the theoretical and computational infrastructure to analyze and control such models is not yet developed to a degree that is needed for medical applications.

It is worth mentioning that there is no broad consensus as to what constitutes a digital twin in medicine[7,8]. Candidates range from simply a computational model relevant to disease to a full digital replica of all or part of a patient that is continually or periodically updated with patient-derived measurements (this is the full analog of an industrial digital twin). For different applications, all of these can be effective. The comprehensive report *Foundational Research Gaps and Future Directions for Digital Twins* by the National Academies[9] proposes, as a general definition, a computational model of the system to be twinned (in our case all or part of a human patient) that is connected to the system in a bidirectional fashion over time, periodically recalibrated with patient data, and provides patient predictions over time. This definition is closely related to the one widely used in industry.

Applications for medical digital twins

There are three main types of application for MDTs (hypothetical scenarios are depicted in Fig. 1): keeping healthy patients healthy, restoring health in ill patients, and developing novel therapeutics, such as drugs and medical devices. We describe each of these applications later in this section.

It is worth noting that, in addition to these, there are also other important applications not discussed in depth here. For example, MDTs could be used to reduce the use of animals in drug and product development, a priority of the US Food and Drug Administration (FDA)[9]. In addition, MDTs could be used to address health inequalities. One of the important sources of inequality in healthcare arises from clinical trials that are not representative of certain parts of the population, such as women or people of color, or different geographic regions of the globe. Another source of health inequities is the scant attention paid to rare diseases, for which it is often a challenge to recruit large enough cohorts for clinical trials with sufficient statistical power. Computational models are used now in different contexts to create virtual patient cohorts or enlarge existing cohorts through virtual patients. If, for a given trial, a digital twin is available that can be customized to specific patient groups, then clinical trials could be run with more representative patient cohorts. Finally, a further potential impact of MDT technology is on the reduction of health disparities. Incorporating a model-driven decision support system into treatment decisions can help alleviate the healthcare disparities that patients face, where social sources of bias (race or ethnicity, sex and sexuality, body weight, socioeconomic status and so forth) can influence medical decisions.

Keeping healthy patients healthy

MDTs can be an important tool as we transition from curative to preventive medicine. Risk score calculators have been in use for some time, and they might use genetic data, data collected from wearables, such as heart rate and rhythm or sleep patterns, or exercise patterns from fitness trackers. A major obstacle is our lack of knowledge about how to define health in the presence of the great biological variability between patients and, consequently, our inability to build predictive models that can be used for this purpose. At the same time, this application of the digital twin concept is the most impactful one in the long run and comes closest to a major use of digital twins in industry, namely preventive maintenance. It is important to note that, for industrial applications, the use of AI/ML techniques face several challenges[10,11]. Mechanistic models are generally preferred because they provide the means to forecast the effect of specific interventions and can be used to identify optimal control interventions.

Restoring health in ill patients

The most progress in MDT technology has been made for the purpose of treating patients with a health condition. A successful example of this is the development of automated subcutaneous insulin delivery for patients with type I diabetes. There are now several US FDA-approved devices on the market for this purpose. One of these[12] has been approved for all age ranges, most recently for young children[13]. It is based on an ordinary differential equations model of human glucose metabolism, coupled with a closed-loop control algorithm. The model receives near-streaming glucose measurements from a subcutaneous sensor in the patient and calculates the appropriate amount of insulin required, and the control algorithm drives an insulin pump that automatically injects it under the patient's skin. The model is recalibrated to the patient every few minutes. Currently, the algorithm still requires some input from the patient about food intake and activity level.

Another application area where MDTs hold considerable promise is in critical care, such as ICUs. In a fast-paced environment where healthcare personnel are typically confronted with a continuous stream of large volumes of data, MDTs can be valuable as decision support tools or data integration devices. At the same time, an ICU is a comparatively data-rich environment where patient measurements are collected routinely. Many of the MDTs in this field are blackbox ML models. Some of these are scoring systems[14] that provide risk scores as output, such as mortality risk for a given patient as described above. An example of an alternate approach that is more likely to produce

 https://doi.org/10.1038/s43588-024-00607-6

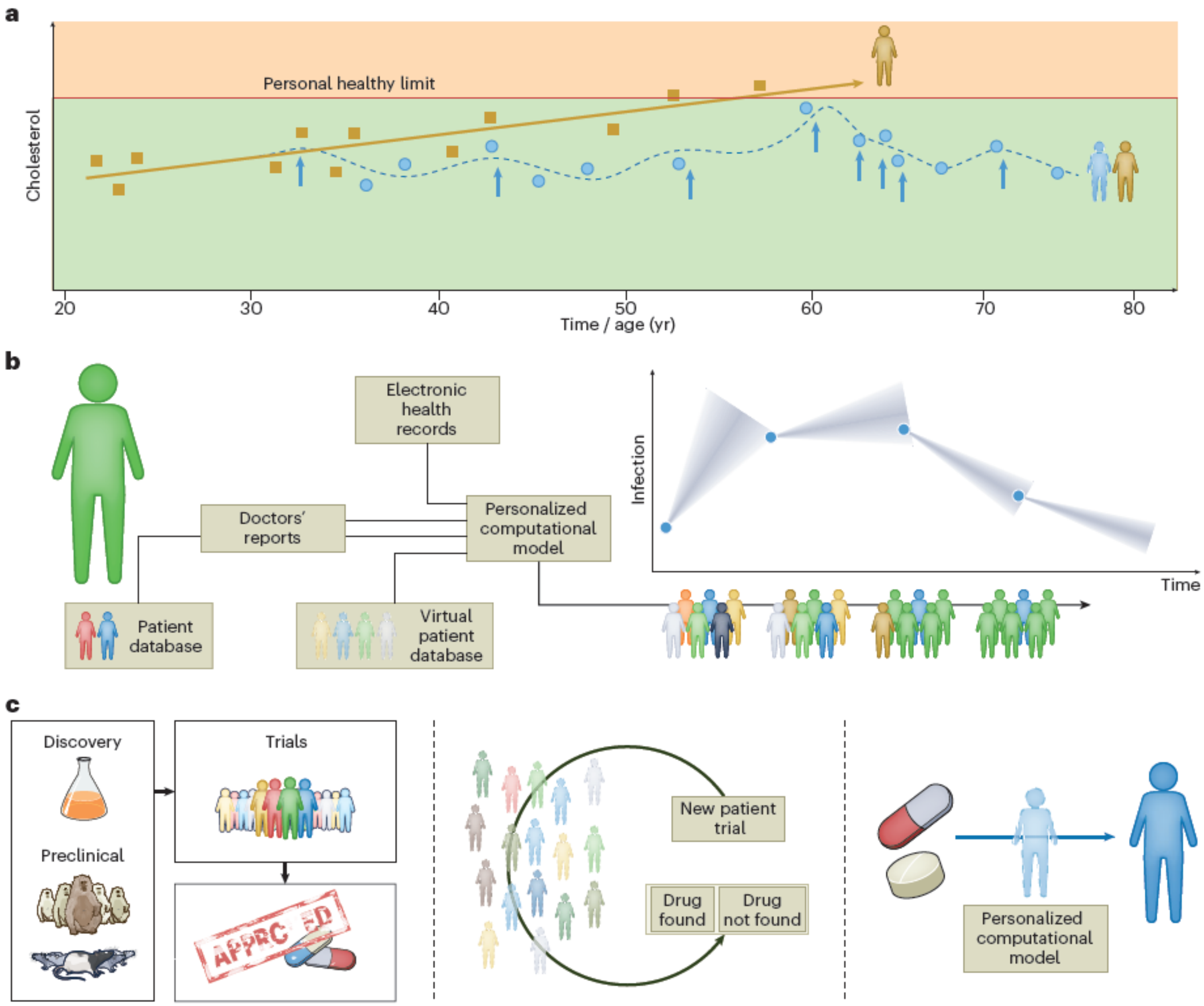

Fig. 1 | Applications for medical digital twins. a, Keeping healthy patients healthy. For a given patient (in yellow), a safe cholesterol level is determined, using genetic information, family history and other data. The yellow line indicates the trend of the patient's cholesterol levels over time, if untreated. Yellow boxes represent measurements. The patient's digital twin (blue), on the other hand, forecasts the trajectory and recommends periodic preventive interventions (blue arrows), resulting in cholesterol levels following the blue curve. **b**, Restoring health in ill patients. Upon admission to the ICU, the patient (green) is evaluated and receives initial treatment for an infection. A computer algorithm personalizes an appropriate computational disease model, together with information from a database of reference patients to recommend optimal interventions. As more repeated measurements are taken from the patient, the reference population is refined, the model is recalibrated to the patient at later time points, and the recommendations for optimal treatment are refined. The cones represent the likely trajectory of the infection as determined by the digital twin. With time and a larger number of patient data points, the uncertainty in the predictions decreases (the cone becomes narrower) and subsequent patient time points fall closer to the center of the previous prediction cone. The improvement in the parameter ensemble that describes the patient is reflected by the corresponding virtual cohort that describes the patient at each time point, which is depicted as increasingly containing more green subjects, like the patient being treated. **c**, Development of novel therapeutics. Currently, clinical trials typically involve the use of animals and patient cohorts (left panel). With the advent of MDTs, it will be possible to reduce the number of animals used in preclinical trials and to optimize patient trials using virtual patients. They can be used to screen large numbers of drug targets and drug candidates, and to perform initial optimization studies using large numbers of patient MDTs and virtual patients (middle panel). Optimal drug regimes, doses and combinations can also be inferred by MDT before administering drugs to patients, thus minimizing side effects (right panel).

such actionable information combines a causal AI model with expert rules for clinical decision making, in which a digital twin is introduced for acute stroke care[15]. The basic structure is a directed acyclic graph, built from expert-curated statements, such as 'ischemic stroke leads to cerebral edema' or 'timely administration of thrombolytics can lead to improvement of outcomes in ischemic stroke', together with likelihood scores obtained from consensus levels among a group of experts. The graph with associated probabilities is fashioned into a Bayesian network that is then further trained with patient data. Once sufficiently trained and validated, the model can be used for decision making for individual patients. A similar digital twin has been developed for the critical care of sepsis patients[16].

As mentioned earlier, one of the biggest challenges for MDTs is accounting for the biological heterogeneity of patients, which manifests itself in a highly variable response to therapeutic interventions. Higher-resolution models that take account of a patient's disease-relevant biology could help with more accurate predictions. A possible roadmap for such an approach in the case of sepsis[17,18] is to use a detailed mechanistic model of systemic inflammation and then create variability in the parametrization of this model through ML algorithms trained on large sets of patient data; a particular patient can then be matched to an appropriate parametrized model that can be used for forecasting of intervention outcomes and choice of optimal ones. Another early-stage project to develop a digital twin for pneumonia also uses a mechanistic model of the early immune response to respiratory infections[19].

Developing novel therapeutics

Virtual clinical trials are a third application area for MDT technology[20–22]. The basic approach here is to begin with a computational model—often mechanistic, in the form of a system of ordinary differential equations or an agent-based model—that captures the human biology relevant to the compound or intervention to be tested. In the case of a mechanistic model, the model parameters will typically have biological meaning, such as immune cell counts, or relate to a patient's physiology, such as heart rate or glucose levels (as opposed to parameters in many ML models). Based on expert knowledge or published information, one can determine physiologically reasonable ranges for these parameters and create a virtual patient population by sampling the parameter space of the model within these intervals. Available clinical data might provide information about the distributions of parameter values across these ranges. Each specific parametrization represents an individual virtual patient. If there is already an existing patient population that one desires to enlarge through virtual patients, then one can determine ranges for the model parameters based on measurements from this existing population. This could be useful, for instance, for drug development focused on relatively rare conditions, where recruitment of a sufficiently large patient cohort is difficult (as described before). Finally, one might aim to create a digital replica of a real patient population by creating a digital twin of each individual patient and assembling them to an exact digital replica of the patient population. This would be required to create a digital twin that fits the industrial paradigm. Currently, we do not know of any published instantiations of this last approach.

In the following, we provide a more detailed discussion of two domain areas for which MDT technology development has been very encouraging: oncology and cardiology.

Medical digital twins in oncology

Digital twins for patients with cancer are emerging as a transformative tool in oncology, enabling a highly personalized and dynamic approach to cancer treatment and research. These digital replicas facilitate a comprehensive understanding of individual cancer cases, allowing for the simulation, analysis and prediction of cancer progression and treatment outcomes in a virtual environment. This technology is poised to make substantial contributions to clinical practice by enhancing the precision and effectiveness of cancer care[23,24]. The development of such a digital twin involves the meticulous integration of diverse patient data, such as genetic information about the patient and the tumor, clinical history and detailed imaging data. This rich dataset forms the foundation for the digital twin, enabling the simulation of tumor behavior and the assessment of potential treatment strategies.

Advanced ML algorithms and computational modeling techniques, such as multi-scale models that span molecular, multicellular and organismal scales, are integral to this process. These modeling techniques may include systems of ordinary differential equations or agent-based models, as well as other dynamical systems models. The latter are crucial for modeling molecular interactions within cancer cells that ultimately determine cellular phenotypes. Moreover, ML algorithms contribute by identifying patterns and correlations in large datasets, helping to predict tumor behavior and response to treatments with greater accuracy and efficiency.

In addition to enhancing treatment planning and assessment, digital twins for patients with cancer can play an important role in monitoring cancer progression and evaluating treatment responses. This continuous assessment allows healthcare professionals to make real-time, data-driven adjustments to the treatment plan, ensuring the delivery of the most effective and personalized care. This adaptability is pivotal in enhancing the likelihood of positive treatment outcomes and improving the overall quality of life for patients.

The multifaceted nature of these digital twins also enables the bridging of various biological scales, from molecular changes to physiological responses. Cancer digital twins incorporate data about the patient's pre-existing health, cancer type, size and location of tumors, their metabolic activity, and molecular markers expressed by the tumor. The model will then learn and adapt to the evolving patient data (for example, timing and type of chemotherapy, effect on tumor size, development of adverse effects, occurrence of metastases), ensuring that the models remain up to date and reflective of the patient's current condition. This periodic updating enhances the predictive accuracy of the digital twins, ensuring that healthcare professionals have access to the most relevant and current information for making clinical decisions. The integration of real-time data enhances the responsiveness and adaptability of cancer digital twins, ensuring that they remain a reliable and effective tool for guiding cancer treatment and management.

The application of digital twins also holds promise for addressing issues of equity in cancer care. By providing a platform for the exploration and assessment of diverse treatment options, digital twins enable the delivery of personalized and effective cancer care to a broader patient population. This inclusivity ensures that individuals from various demographic backgrounds have equitable access to advanced and innovative cancer treatments, promoting fairness and equality in healthcare delivery.

There are now several MDT projects under way that can realize this promise and become effective tools in the clinic. For example, Wu and colleagues have developed an MDT project[25] that is designed to predict the progression of breast tumors using a partial differential equations model of breast tissue, calibrated with patient-specific images from both magnetic resonance imaging (MRI) and quantitative positron emission tomography. The images are used to derive model parameters that capture the cell-migration and tumor-cell proliferation properties of the specific tumor. The model can be used to forecast the effect of drug treatments or predict the efficacy of immunotherapy[26].

A similar approach has proven effective when using a digital twin for patients with glioblastoma, a highly aggressive type of brain tumor with poor prognosis, which is part of the growing field of mathematical neuro-oncology[27]. This MDT, developed by Swanson and colleagues, also uses MRI images, in this case of the brains of glioblastoma patients[28]. A time course of such images allows the estimation of two parameters in the partial differential equation, one that captures the proliferation rate of the tumor and another that captures the rate of cell migration. These two parameters are independent of each other, as it has been observed that tumor cells either migrate through tissue or divide, but do not do both at the same time. With these patient-specific parameters, one can predict the actual extent of the tumor, informing surgery planning. The reason this cannot be done accurately simply from the MRI image is that tumor cells invade adjacent brain matter in a diffuse fashion that is not captured accurately by imaging, so the actual dimensions of the part of the brain containing tumor cells cannot be determined from MRI images alone. Modified versions of the digital twin can also predict the effect of different treatments[29].

Although there has been much progress in this field, there are still big challenges ahead, including a lack of sufficient patient data and a lack of sufficient mechanistic understanding underlying the many subtypes of different cancers and of the effectiveness of an ever-growing supply of cancer drugs, impeding model-based prediction of appropriate interventions at a given stage of the disease.

Medical digital twins in cardiology

MDTs are transforming the field of cardiology by providing tools for patient care, treatment planning and healthcare delivery. These virtual representations of the heart and its functions hold immense potential to improve the diagnosis, management and outcomes of cardiovascular diseases. A cardiac digital twin is typically composed of three main components: (1) data acquisition (imaging, EHR, genetic data and wearables), (2) modeling and simulation (based on anatomy and physiology) and (3) clinical decision making. Here, we showcase the pivotal role that heart MDTs can play in decision support and patient care, and we focus on one of the most important aspects of cardiology: arrhythmia care management. We present two of the clinical applications of heart MDTs: the prediction of sudden cardiac death due to arrhythmias in various diseases and the use of MDTs to provide guidance in arrhythmia treatment by catheter ablation.

The incidence of sudden cardiac death due to arrhythmias is increasing globally, and accurate individualized risk assessment of death remains a major unmet clinical need. Heart MDTs have made major strides in predicting a patient's risk of sudden death, for patients with ischemic (that is, caused by coronary atherosclerosis) and non-ischemic cardiomyopathies. The study by Arevalo and colleagues[30] demonstrated the first utilization of MDTs created from contrast-enhanced MRIs of a cohort of patients (n = 41) after myocardial infarction (scarring in the heart) to determine the patients' likelihood of developing infarct-related ventricular arrhythmias and sudden death. The MDT prediction outperformed all current clinical risk assessment metrics, indicating that MDTs can be used to determine the need for a prophylactic implantation of defibrillator devices to prevent sudden death. A more complex approach to the assessment of the arrhythmia propensity of patients with previous infarcts using MDTs involves the additional incorporation of penetrating adipose tissue (fat)[31].

In relation to predicting the risk of sudden cardiac death in patients with non-ischemic cardiomyopathies, heart MDT studies have demonstrated the clinical utility of the approach in pediatric patients, such as those with acute myocarditis[32] and with repaired tetralogy of Fallot[33]. MDT technology has also been used[34] to predict arrhythmia risk in hypertrophic cardiomyopathy, a common genetic disease characterized by a thickening of heart muscle, substantially outperforming current clinical risk predictors. Another non-ischemic cardiomyopathy associated with high risk of sudden death and difficult risk prediction is cardiac sarcoidosis, an inflammatory disease. Shade and colleagues have developed a two-step prediction approach, combining MDT with ML in a study of 45 patients[35]. The results from MDT simulation were fed, together with a set of clinical biomarkers, into a supervised classifier. Finally, a genotype-specific heart MDT (Geno-DT) approach was recently developed to predict the arrhythmia circuits in patients with arrhythmogenic right ventricular cardiomyopathy (ARVC) of different genotypes[36]. This approach revealed that the underlying arrhythmia mechanisms differ among ARVC genotypes. The Geno-DT approach demonstrated the potential to augment therapeutic precision in the clinical setting, which can lead to more personalized treatment strategies in ARVC.

Catheter ablation plays a major role in the contemporary management of arrhythmias. This procedure involves the use of catheters that are maneuvered into the cardiac chambers and deliver radiofrequency energy to specific locations to terminate the perpetrator of arrhythmia. Identification of these specific locations in the heart is, however, difficult, and ablation targets are often inaccurate, with new (emergent) arrhythmias occurring post-ablation and necessitating repeat procedures and re-hospitalization. Personalized MDT technology has made major strides in improving ablation precision by providing non-invasive localization of ablation targets. Following a validation study[37], MDTs were used to predict the ablation targets and guide the ablation in post-infarction patients[38,39]. This work highlighted the enormous potential for MDT technology to impact the clinical management of ventricular arrhythmias. The MDTs predicted not only the targets for initial ablation, but also the ablation targets for re-do procedures several years later.

Another exciting aspect of personalized MDTs is the ability to plan different atrial fibrillation management strategies, and even predict a patient's risk of recurrence. Atrial fibrillation occurs in the upper chamber of the heart and is the most common human arrhythmia, affecting 1–2% of the population. Although not as dangerous as ventricular arrhythmias, it is associated with a high probability of stroke and a high burden of healthcare expenditures due predominantly to patient re-hospitalization. Several atrial MDT studies have tested the effectiveness of different ablation strategies in patients with a persistent form of the arrhythmia. The discovery of atrial fibrosis as a substrate for atrial arrhythmias resulted in the development of atrial MDTs reflecting the patient-specific atrial fibrosis distribution[40–44]. Boyle and colleagues pioneered a prospective ablation study for patients with persistent atrial fibrillation and fibrosis entirely with personalized atrial MDTs[45]. In that study, the MDT-proposed ablation targets were used to steer patient treatment. Finally, atrial MDTs have been used, often in combination with ML or other technologies, to predict atrial fibrillation recurrence[46,47].

The initial successes with heart MDTs constructed from imaging and other health data described above have opened new pathways for the development and application of MDTs in cardiology. Of particular importance will be the ability to incorporate continuous data from various streams, thus ensuring that the patients' MDT continuously reflects the state of the patient's heart.

Opportunities and challenges

MDT research has largely been scattered across individual laboratories and companies, often without explicitly using the MDT label. In recent years, there has been an emphasis on research funding for MDT projects in Europe, through the Horizon Europe grant program of the European Commission. Possibly the most ambitious project is the Ecosystem Digital Twins in Health (EDITH)[48], a comprehensive initiative to develop a roadmap for digital twin technology in healthcare in Europe, funded by the European Commission. The Virtual Physiological Human (VPH) is a European initiative to lay the groundwork for a collaborative framework to investigate the human body as a complex system[49]. Other examples of a large-scale MDT project include the Swedish Digital Twin Consortium[50,51], aiming to create MDTs for the entire Swedish population. In the United States, the National Institutes of Health and the US Department of Energy have partnered to support the development of digital twins for cancer patients[24]. These and other community- and agency-driven MDT efforts provide a wide range of opportunities for research collaborations, funding and community infrastructure.

One application area that is particularly promising and urgently needed is the response to infectious diseases. The SARS-CoV-2 pandemic was marked by the major challenge of the highly heterogeneous response to infection and treatment. The availability of MDTs that capture certain features of the immune system, even in rudimentary ways, could have provided additional decision support for healthcare providers[52]. Subsequent efforts to advance MDT technology focusing on the immune system were developed[53–55]. These and other efforts have begun to catalyze a research community focused on the immune system, as a major contributor to infectious-disease outcomes, as well as other diseases such as cancer, autoimmune diseases and diabetes.

As mentioned previously, the main three factors limiting MDT development are our incomplete knowledge of human biology, the availability of patient data in sufficient quantity and quality (and at all scales) and the lack of a well-developed modeling technology that can form the basis of an MDT industry comparable to that existing for industrial applications. Furthermore, to bring digital twin technology into the clinic, we need to solve a range of problems related to patient privacy, security, ethics, standards for models and data, and regulatory requirements. For the latter, we refer the reader to the strategic plan[56] released by the EDITH project. This plan addresses a comprehensive range of regulatory and business aspects for developing and implementing digital twin technology in healthcare at scale.

In particular, the plan addresses issues of data collection, privacy concerns and ethics guidelines. A plethora of different data types and sources are potentially valuable for MDT applications, collected from wearables and other types of mobile sensor, patient charts, a wide range of imaging data, as well as data collected from samples, such as blood or tissue samples from biopsies. Some of these are subject to patient protection regulations under the HIPAA law, whereas others are unprotected, such as data from fitness trackers or genetic sequence information generated by private companies. A particular concern, as with other personal data, is that an MDT is a vehicle for systematic data integration—one of its strengths as a medical tool—but potentially damaging to patient privacy. Issues such as who controls the MDT of a patient, who it belongs to, and what can be done with it, are not currently settled and will likely require regulatory actions.

Another challenge that must be addressed in the future is related to the models underlying MDTs, which in many cases will be multi-scale. Most drugs, for example, have mechanisms of action at the intracellular scale, but have organ- or organism-level effects. Models will probably be hybrid, combining for instance blood flow through an artery, modeled by a partial differential equation, with intracellular signaling in the endothelial cells lining the artery, modeled by a system of ordinary differential equations or a Boolean network. The models will probably be stochastic too, reflecting, for example, features of the immune system or gradient-based movement of cells in a tissue. These characteristics pose challenges to most of the established model building and analysis tools available, as well as mathematical control approaches. There are no formal methods available for this type of model, and tools that are standard for differential equations models, such as global sensitivity analysis, identifiability, forecasting and optimal control, are not directly applicable. New approaches to model validation are required too. Furthermore, MDT models will need to be updated and expanded over time, as our knowledge of biology or the application type changes. Standard model implementation methods do not result in models that are robust with respect to these operations. To provide the basis for a large-scale standardized MDT industry, extensive research in this area is required.

The future

Over the past two decades, digital twin technology has evolved to become an increasingly mature and rapidly growing industry, projected to reach US$183 billion by 2031[57]. Fitzgerald and colleagues[58] provide a discussion of the most important opportunities and challenges for the further development of digital twin technology for industrial applications, including the following central research questions:

1. What are the specifications that are necessary for a dependable digital twin?
2. What are the key specifications for usability and credibility that are required for a digital twin?
3. How accurate does a digital twin have to be to be useful?
4. What benefits does a digital twin have to provide to justify constructing one?

These same open questions need to be answered for MDTs. Industrial digital twin technology is benefiting from a more highly developed infrastructure, including standards for computational model specification, standard operating procedures and physics-based models for many of the systems to be twinned, to name a few. In biomedicine, in contrast, existing MDTs and MDT projects are still early in their development, without broadly available infrastructure, standards and templates for the successful development of commercial products. Successful strategies for commercialization remain largely unexplored, and the regulatory requirements and hurdles are formidable.

A special challenge MDT technology faces is a very complex regulatory environment for the use of computational models in medicine. These challenges need to be addressed before the technology can be broadly adopted. The FDA has encouraged the use of modeling and simulation in the development and approval process of drugs and medical devices, and has issued guidance on this topic[59,60]. A comprehensive set of standards in relation to the credibility of computational modeling for medical devices is also available[61], as well as a summary of all regulatory efforts and guidelines[62]. Unfortunately, there are currently no standards available for models that are not physics-based and use modeling platforms other than systems of differential equations. As mentioned earlier, in many cases, MDTs will have to rely on other model types, and additional standards and requirements will need to be developed for approval.

One of the biggest challenges to precision medicine and the use of MDTs is the biological heterogeneity of patients. To account for this, we will probably need to develop higher-resolution models than the ones that are currently available, given our knowledge of human biology and the data to capture it. By analogy, the accuracy of numerical weather prediction models over longer forecasting windows provides a good paradigm. Accuracy has increased dramatically over the past two decades, largely due to the higher-resolution models that have been made possible by higher-resolution data (and more powerful computation resources). This reflects the fact that both humans and the atmosphere are truly complex systems in which microscopic perturbations can result in macroscopic effects, the proverbial butterfly effect. Once we make progress on these challenges, medical digital twins will change healthcare fundamentally, helping us to transition from curative to preventive medicine.

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Author contributions

The authors are listed in alphabetical order in the author list. R.L. conceived the Perspective and drafted the first outline. N.T. wrote the section on digital twins in cardiology. B.M. and I.S. contributed to the other sections. All authors reviewed and edited the final version.

Competing interests

The authors declare no competing interests.

Additional information

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Request for Information on the National Digital Twins R&D Strategic Plan

Salvatore D'Oro
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The Institute for the Wireless Internet of Things (WIoT) at Northeastern University

Before the

Networking and Information Technology Research and Development (NITRD)

National Coordination Office (NCO), National Science Foundation

Alexandria, VA 22314

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COMMENTS OF THE INSTITUTE FOR THE WIRELESS INTERNET OF THINGS AT NORTHEASTERN UNIVERSITY

The Institute for the Wireless Internet of Things (WIoT) at Northeastern University respectfully files these comments on the NITRD Request for Information (RFI) on digital twins research and development. WIoT commends NITRD for seeking comments on this topic. This document aims to provide comments on a specific subset of matters raised by the RFI, as outlined below.

Regulatory:

Regulatory Science Challenges associated with the use of Digital Twins

Digital twins can significantly enhance spectrum management by providing spectrum regulators like the FCC with detailed insights into the dynamic needs of modern wireless communication. By simulating various scenarios and use cases, digital twins can help regulators evaluate, revisit and update existing spectrum regulations. For example, they can aid in extending spectrum coexistence principles beyond the Citizens Broadband Radio Service (CBRS) and Industrial, Scientific, and Medical (ISM) bands. With most spectrum allocated exclusively but rarely utilized, digital twins can model and optimize spectrum sharing, making better use of this valuable resource. They can be instrumental in reassessing exclusion zones, refining tiered spectrum access policies, and improving the deployment of cognitive radios, which can dynamically adapt to real-time spectrum availability and conditions. These insights can drive more efficient and flexible spectrum management practices, ensuring that regulatory frameworks keep pace with technological advancements and evolving usage patterns.

Furthermore, digital twins can also support the Federal Aviation Administration (FAA) in enhancing regulations for beyond line of sight (BLOS) UAVs and drone operations. By creating accurate virtual environments that replicate real-world conditions, digital twins can simulate UAV and drone activities in various scenarios, helping to identify potential risks and optimize safety protocols. This capability allows the FAA to evaluate and refine regulations related to BLOS operations, ensuring that they are robust and adaptable to emerging drone technologies and applications. For instance, digital twins can be used to test and validate new flight paths, assess the impact of UAVs on existing air traffic, and develop advanced collision avoidance systems. By leveraging digital twins, the FAA can create a more responsive and effective regulatory framework that supports the safe and efficient integration of UAVs into the national airspace, fostering innovation while maintaining high safety standards.

Ecosystem:

Establish a National Digital Twin R&D Ecosystem: Possible focus areas: smart and connected communities

The development of intelligent connectivity with robust and reliable algorithmic components and seamless multi-vendor integration requires addressing several challenges at the architectural, algorithmic, and system-level design. In this context, digital twins for smart and connected communities can serve as a safe digital playground to address the following challenges:

- **Need for Datasets.** To develop robust and scalable Artificial Intelligence (AI) and Machine Learning (ML) solutions, which generalize well across a variety of real-world deployment scenarios, it is necessary to leverage rich datasets of Radio Access Network (RAN) telemetry, data, and performance indicators [1]. While network operators are in a unique position to collect such datasets, it is often impractical or impossible to use them for research and development due to privacy and security concerns. Wireless testbeds represent a feasible path to overcome this limitation [2–6]. However, they are often limited to the Radio Frequency (RF) characteristics and topology of their deployment area.

- **End-to-end AI and ML Testing.** Once trained, AI/ML-based control solutions need to be validated and tested in controlled environments to avoid disruption in production networks. At the same time, the testing conditions need to be realistic to obtain meaningful results that consider, for instance, the user load, traffic patterns, and RF characteristics of real-world deployments the models will be used to control.

- **Continuous Software Validation.** While softwarization introduces flexibility and programmability of the stack, it also comes with concerns around software quality, reliability, security, and performance [7]. Therefore, integrating, validating, testing, and profiling software for wireless in a continuous fashion is key to the Open RAN vision. Additionally, this validation needs to consider various compute platforms and hardware acceleration solutions for physical layer processing.

- **Automated Integration and Testing of Disaggregated Components.** Disaggregation comes with a more robust supply chain, but also a need for the validation of interoperability across vendors and devices. This is a labor-intensive and often manual process that calls for the development of automated techniques [8].
- **Bidirectional Interaction Between the Virtual and Physical Media.** Incorporating Digital Twins (DTs) into wireless communication can enhance predictive maintenance, resource allocation, and troubleshooting, thus bolstering network reliability. To unleash these capabilities, it is essential for DTs to integrate real-time data when mirroring their real-world counterparts. This enables precise monitoring, planning and optimization of a pre-deployed wireless networks, which requires bidirectional and near real-time links between real-world deployment and their DT replicas. Lightweight publish-subscribe, machine to machine network protocols such as MQTT can be utilized to enable such bidirectional data transfer between the twin media [9].

To this end, a digital twin infrastructure that complements real-world wireless testbeds can play a unique role in addressing these challenges and advancing smart and connected communities. To this end, we have been developing digital twin capabilities in the Colosseum network emulator—the world's largest wireless network emulator with hardware in the loop [10]—thanks to support from the O-RAN ALLIANCE, the NTIA Innovation Fund, OUSD R&E, and NSF. A the Open RAN digital twin, Colosseum can be leveraged to address these challenges and to develop end-to-end, fully integrated, and reliable solutions for Open RAN, as shown in Figure 1, from [11]. Through its channel and traffic emulation capabilities, Colosseum can replicate countless real-world scenarios representative of real-world cellular deployments, and generate datasets that can be used to train AI/ML models robust to network changes [12]. A combination of generic compute nodes, Software-defined Radios (SDRs), and the possibility of integrating Commercial Off-the-Shelf (COTS) devices, allows for the digital replica of Open RAN and 5G-and-beyond protocol stacks [13, 14], which we manage through automation and Continuous Integration (CI) and Continuous Deployment (CD) pipelines [15]. This enables repeatable experiments, where different network configurations and protocol stacks can be tested against the same

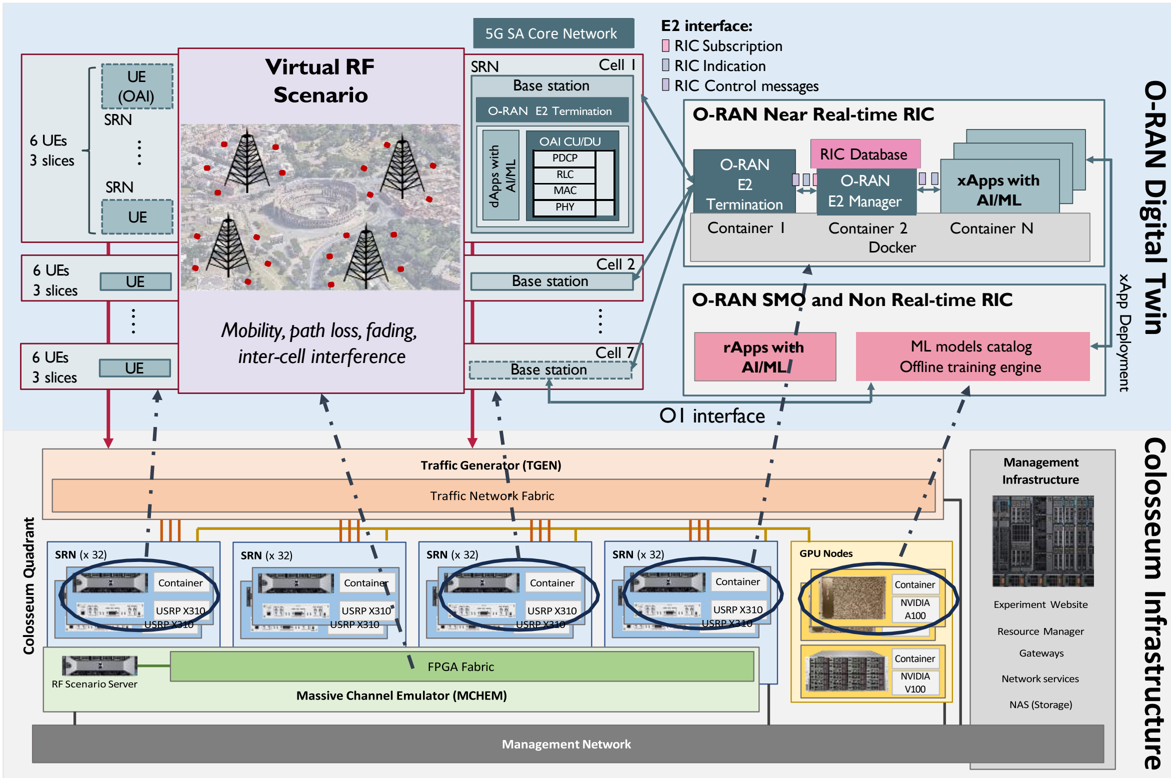

Figure 1: Open RAN twinning capabilities in Colosseum.

channel and traffic conditions, as well as a safe playground for testing of AI/ML solutions. The CI/CD and automation also enable continuous validation, as the same software can be tested over time for regression in a realistic environment, and against various other stacks for integration.

We argue that to further the development of smart and connected communities it is fundamental to coalesce resources across government, industry, and academia to advance the capabilities of digital twin solutions such as Colosseum, toward 6G and next-generation wireless systems.

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Request for Information on the National Digital Twins R&D Strategic Plan

Oak Ridge National Laboratory (ORNL)

Oak Ridge National Laboratory's Strategic Research and Development Insights for Digital Twins*

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Introduction

Oak Ridge National Laboratory (ORNL) is pleased to provide our response to the NITRD RFI on Digital Twins Research and Development. Digital twins are virtual representations of physical systems, leveraging real-time data to simulate and predict behaviors. ORNL is advancing digital twin technology across various disciplines, including neutron scattering, networking, science ecosystems, supercomputing, secure facilities, mobility technologies, materials design and discovery, power systems, fusion reactors, biological sciences, and earth observation. These efforts aim to enhance scientific research, operational efficiency, and decision-making processes. ORNL facilities, such as the High Flux Isotope Reactor (HFIR), Grid-C, Spallation Neutron Source (SNS), and Oak Ridge Leadership Computing Facility (OLCF), provide the infrastructure to develop and demonstrate these digital twin technologies. In this document, we lay out key challenges, research gaps, and future opportunities based on our experience with digital twins that aim to serve as useful contributions towards a National Digital Twins R&D Strategic Plan. In the remaining document, we address nine of the thirteen topic areas specified in the RFI.

1 Artificial Intelligence (AI)

Prior R&D at ORNL has utilized AI/ML to advance digital twin development for various applications. This strategy involves integrating simulations with real-time data, enabling continuous learning and optimization. For nuclear and energy systems, digital twins can enhance design, safety, and operational efficiency. In

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fusion reactors, they provide insights into plasma behavior and material interactions, informed by experimental data. Neutron scattering experiments benefit from autonomous measurement and experimental steering. Inverse materials design uses AI to generate optimized material structures. Mobility technologies are enhanced through realistic traffic scenario generation and AI-driven control systems. Cellular modeling and earth system simulations require multimodal data integration and advanced computational models. ORNL's supercomputing resources enable real-time data processing, supporting these digital twins' continuous learning and application across various domains. However, developing robust digital twins requires overcoming numerous challenges:

- Data Quality and Reliability: Ensuring accurate and reliable sensor data is crucial, as digital twins rely on real-time data, which can be noisy or compromised.
- Legacy Data Management Systems: Outdated systems limit the scalability and efficiency of digital twin deployment.
- Data Privacy: In critical infrastructure applications data sharing is restricted due to proprietary concerns.
- Continuous Updating: Digital twins must continuously be updated with new data, which can be challenging given the systems' complexity.
- Security Concerns: Robust measures are necessary to protect against cyber-attacks on digital twin systems.
- Standard Protocols: Establishing standard protocols for digital twin design, deployment, and maintenance is necessary for safety and efficiency.
- Integration of Multi-Physics Models: Developing comprehensive models that integrate different physical domains (e.g., plasmas, materials) remains a significant gap.
- High-Throughput Virtual Representation: Creating robust and high-throughput virtual representations of complex systems is challenging, requiring further AI model development.
- Scalability of Inversion Algorithms: Solving inverse problems with non-linear physics models at scale is an ongoing challenge.
- Trustworthy AI Models: Ensuring AI models are reliable and transparent is essential, especially in critical applications like nuclear safety and weather prediction.
- Simulation and Data Analytics: High-quality simulations and real-time data analytics are expensive, requiring significant computational resources.
- Model Trustworthiness and Manufacturability: Addressing trustworthiness and feasibility in manufacturing remains crucial for materials design.

ORNL's interdisciplinary approach, leveraging its extensive facilities and expertise, aims to address these challenges, advancing the state-of-the-art in digital twin technologies for diverse applications.

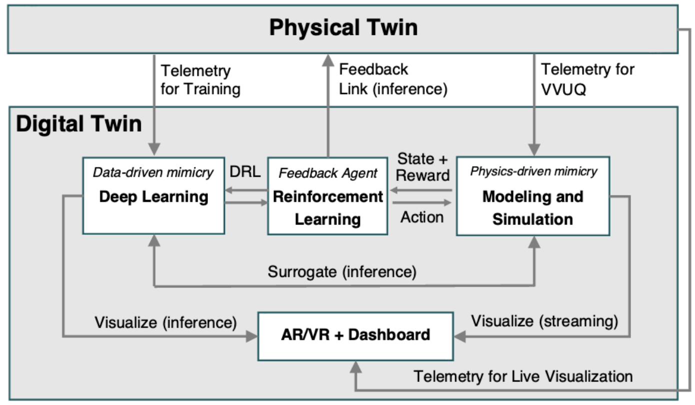

Figure 1: Typical DT component interaction patterns [11]

1.1 Digital Twin Model Integration and Real-time Performance

Topic: AI, Focus area: Integration of Digital Twins with AI

Digital Twins (DT) typically consist of a collection of various models (AI/ML, simulation), control agents, system telemetry data, and AR/VR components, all inter-communicating to create a virtual replica of their physical counterparts. Figure 1 illustrates typical interaction patterns between AI/ML and different components of digital twins. For example, telemetry data may be used to train data-driven AI/ML models to "mimic the structure, context, and behavior of a physical counterpart" [21].

AI/ML models may be deployed in several ways. They can serve as surrogate models to replicate specific aspects of the digital twin. Frameworks such as HPE SmartSim can integrate simulations for either online inference [23] or online training [4]. Reinforcement learning (RL) uses a simulated environment to train an agent to make optimal decisions for the physical twin. Typically, simulations act as the training environment.

Studies have identified at least six different execution motifs or patterns for deploying AI with traditional simulations, along with the middleware that may be used and performance implications [10]. Performance is influenced by various factors and scenarios. For instance, inferencing can be conducted online, offline in batches, or by streaming [8].

Challenges and Gaps: Real-time inference remains a significant challenge in integrating simulations with AI models. Achieving real-time performance may involve several strategies, including reduced precision, scaling across computational resources, or implementing AI surrogates. Numerous studies have investigated scaling up computational resources to achieve real-time performance (e.g., [6, 7, 9]).

Despite recent progress in coupling simulations with AI models, more complex digital twin workflows, encompassing all components shown in Figure 1, still require robust ecosystems for development and benchmarks to assess performance. These ecosystems may integrate existing frameworks such as SmartSim [23] for AI-Sim coupling and benchmarks such as XRBench [18] for assessing AI-VR coupling and SimAI-Bench [3] for assessing AI-Sim coupling performance.

1.2 Enhancing Cognitive and Generative Digital Twin Interaction

Topic: AI, Focus area: Leverage generative AI for digital twin modeling & simulation with the consideration of the potential impact on a digital twins' physical counterpart

Motivation The advancement of generative AI models, including Large Language Models (LLMs) and physics-based generative models, has revolutionized Digital Twins (DTs) in scientific research. These models enhance DTs' ability to interact with their physical counterparts [20] by analyzing vast amounts of unstructured and structured data. This integration allows DTs to provide detailed responses [30], enhance data synthesis [19], improve decision-making [27], facilitate accurate simulations [29], and support intelligent operations [13]. The synergy between generative AI and DTs promotes citizen science and informed

decision-making through Human-AI partnerships, making scientific research more efficient and impactful.
Challenges Despite their successes, generative AI models face significant challenges. LLMs, for instance, suffer from hallucinations, generating plausible-sounding but incorrect information [16]. This issue is pronounced in specialized domains due to training on static datasets that lack depth in these fields [5]. Additionally, physics-based generative models can struggle with the computational complexity and accuracy required for realistic simulations. The inability to access dynamic, up-to-date, and comprehensive specialized knowledge results in inaccuracies and a failure to provide reliable answers in scientific contexts [12]. Establishing trustworthiness and reliability in these models is crucial, particularly in high-stakes applications. Integrating dynamic, domain-specific data and continuous training is essential to improve precision and relevance.
Vision Addressing these limitations involves integrating Retrieval-Augmented Generation (RAG) into DTs and extending the scope to include physics-based generative models. Cognitive Digital Twins (CDTs) incorporate advanced AI for learning, reasoning, and decision-making [22]. Embedding RAG enables the dynamic retrieval of relevant information, providing accurate insights and accelerating research processes. Physics-based generative models can simulate complex systems with high fidelity, enhancing the realism and applicability of DTs. Establishing robust validation and verification frameworks will be critical for advancing the trustworthiness of these models. This might include incorporating systematic and continuous feedback loops from domain experts and deploying advanced evaluation metrics to assess accuracy and relevance.
Examples Autonomous Decision Optimization uses LLMs for optimizing intermodal freight transportation by gathering requirements, automating decision strategies, and conducting data analytics [27]. Autonomous Scientific Discovery utilizes RAG for process conformance in healthcare, dynamically retrieving up-to-date information to improve process models [17]. There is a wide range of LLM evaluation frameworks, however, there are not specifically focused on digital twins.
Implementation Strategy Create a comprehensive scientific database, evaluation frameworks, integrate it with a generative language model, and fine-tune it with domain-specific data to enhance responses and reliability. Create and refine physics-based generative models tailored to specific applications within DTs. Establish robust validation and verification frameworks involving domain experts and advanced evaluation metrics.
Conclusion Integrating trustworthy LLMs with DTs advances scientific research by enabling sophisticated analysis and interaction with vast unstructured data. Addressing LLM challenges through RAG integration enhances DTs' capabilities, supporting various research scenarios and continuous learning. This integration promises to make scientific research more efficient, comprehensive, and impactful.

2 Is it fit for purpose? Understanding valid use and its relation to the value of information

Topic: Business, Focus: Evaluate value/return on investment
The recent report on Foundational Research and Future Directions for Digital Twins [21] underscores the importance of validation for specific purposes, emphasizing that the success of a digital twin hinges on models that accurately represent the physical counterpart, provide predictions with known confidence, and meet computational constraints. Critical yet under-investigated aspects include the quality and quantity of information the digital twin provides and its value. The model must deliver necessary and accurate information to be useful, and the value of this information must exceed the costs of data, construction, and integration. Balancing value relative to cost and the scope of valid use is essential for successful and economical digital twin efforts. Research is needed to provide a robust framework for considering problems of model validation alongside questions of cost and value. While the problem of model validation has been studied extensively, research seeking to understand and quantify the relationship between validation, cost, and value is relatively new.

We envision a research and development program with at least three distinct, but nonetheless intertwined, topics. First, what is the return on investment for simulation? Some of the investment challenges faced by organizations that make extensive use of modeling and simulation are described in a 2011 report "Calculating Return on Investment for U.S. Department of Defense Modeling and Simulation" (Defense Acquisition University (DAU), Defense Acquisition Research Journal, April 2011). Second, when is a digital twin good enough? Distinct from how accurate or precise the model is when providing information, we ask the question of how accurate or precise does it need to be for a specific purpose? Moreover, how can we decide when the necessary accuracy and precision have been satisfactorily demonstrated? Answers to these questions will involve issues of risk incurred by the possibility of insufficient or inaccurate information; statistical questions underlaying a quantifiable approach to risk assessment; and other topics concerning the use of information within the intended context. Third, how much should be invested in a digital twin? What should its scope of use be? Questions of cost, value, and risk are expected to motivate the creation of digital twins that have a more or less narrow scope of use. How broad or narrow a scope is economical while offering an acceptable level of risk?

3 Advanced Data Management for Digital Twins

Topic: Data, Focus: Governance methods for data collection, curation, sharing, and usage
Motivation: Integrating digital twin-based development into experimental, design, and manufacturing processes necessitates combining traditional high-performance computing (HPC) (scale-up) modeling and simulation with distributed (scale-out) machine learning/AI analysis. These workflows demand advanced data management beyond the current capabilities of DOE's leadership computing facilities. Data will be shared between HPC systems and local clouds, and its computation and transfer need to be managed for workflow correctness and performance. Ensuring FAIR (Findable, Accessible, Interoperable, Reusable) compliance will enhance scientific discovery by making digital twin processes more transparent and verifiable.
Strategy: Implementing advanced data management in digital twins requires innovations in several areas. Lifecycle metadata must be attached to data throughout its lifecycle, making it discoverable, queryable, and accessible even in archival storage, with repositories functioning as active computational elements rather than static storage. Automated curation is necessary due to the growing size and complexity of data, necessitating AI-based tools to detect anomalies and manage metadata, ensuring data is ready for digital twin integration. Federated operation is essential for interdisciplinary research, requiring cross-organizational data and metadata management to support large-scale digital twins. Additionally, consistent policies and governance across organizations are needed to guide data access, use, and sharing, supporting the other strategy components.
Current Gaps and Challenges: Current tools capture limited metadata, resulting in fragmented and incompatible data management services. Ad hoc approaches and siloed metadata formats make it difficult to query relationships between data artifacts. The volume, velocity, and variety of data exceed the capacity of human curators, necessitating automated tools to adequately appraise and describe datasets. Establishing federated data management mechanisms is challenging due to the involvement of multiple policy and infrastructure organizations. Additionally, defining and agreeing on cross-organizational policies often pose a barrier to implementing technical solutions.

4 A Digital Twin of Science Ecosystem

Topic: Ecosystem, Focus: Integrated Research Infrastructure
Motivation Developing science workflows across distributed instruments and high-performance computing platforms is complex and time-consuming, requiring resource allocation for development, debugging, and testing, especially in the early stages. Digital twins of science ecosystems facilitate the development and testing of workflows with minimal or no need for physical resources. These twins emulate physical components, supporting remote instrument control, measurement transfer, integration of simulation and analytics mod-

els, ecosystem messaging, and AI applications for autonomous workflow orchestration. Examples include microscopy workflows, beam-line instrument control, and ecosystem and network profile estimation [1,2].

Current gaps and challenges Developing digital twins for science ecosystems requires addressing the ecosystem infrastructure counterparts of instruments, computing, and network elements to match the physical ecosystem representation. In addition, the software environment of workflow and ecosystem modules, including instrument simulators and network emulators, should be available for integration in the emulated ecosystems utilized for science workflow developments. This type of digital twin also requires powerful computing resources to support high-performance distributed computing and GPU computations.

5 A Global Consortium for Supercomputer Digital Twins

Topic: International, Focus: Opportunities for International Collaborations

The ExaDigiT international community is a grassroots effort to develop an open-source framework for developing digital twins for supercomputers. ExaDigiT has multiple modules for modeling energy consumption, cooling dynamics, system workloads, and visual analytics – including a web dashboard for performing "what-if" experiments and an augmented reality module for interacting with the digital twin [11]. Formed by numerous supercomputing centers and universities globally, ExaDigiT also includes industry partners such as HPE and NVIDIA. It features workgroups on various topics, including AI/ML, power and cooling, and visual analytics. The community hosts events and provides resources for modeling data centers, having developed digital twins of several supercomputers already. For more information, visit https://exadigit.github.io.

6 Process Twins for Decision-Support and Dynamic Energy/Cost Prediction in Water Reuse Processes

Topic: Long Term Research, Focus: Research enabling the bidirectional flow between the virtual and the physical assets

Water treatment systems offer significant opportunities for efficiency optimization, which can minimize energy and chemical usage, reduce waste products, and maximize output, thereby lowering the cost of water for potable, industrial, and agricultural uses. These systems are complex and nonlinear, making them ideal testbeds for evaluating the effectiveness of digital twin technology beyond linear approximations. A digital twin must integrate various disciplines, including physics, chemistry, fluid dynamics, economics, and material science, while adapting to data from the physical asset to optimize processes such as energy expenditure for softened cooling water and preventing scaling in heat exchangers.

The evolution of flight simulators from physical twins to advanced digital models highlights the potential of digital twins in other industries. Historically, obtaining experimental data for flight models involved significant safety risks and costs. Modern digital models, like those used in Formula One, allow for rapid design modifications through virtual experiments, reducing the need for physical prototypes. Applying this to water treatment, a small-scale pilot system can safely generate data to train digital twins, allowing for exploration of operational regimes that would be unsafe in full-scale industrial systems. This approach enhances the accuracy of data-driven methods such as AI/ML, statistical regression, and multi-physics models, addressing the current limitations in predicting behavior outside the data's scope.

The project's collaborative nature, involving universities, software companies, and national laboratories, emphasizes significant advancements in data integration, experimental design, data transmission, and techno-economic analysis. This research aligns with the National Science Foundation's focus areas, providing a comprehensive approach to improving water treatment efficiency through advanced digital twin technology and interdisciplinary collaboration.

This project is designed for secure data flow over a wide-area network between the testbed and infrastructure. It is also a highly complex nonlinear system with unpredictable stochastic variation in the physical system that is challenging to model accurately using the most common general digital models. Accuracy requires real-time digital twin calibration using physical data. The project is designed to enable long-term digital twin research by providing a physical system that is not easy to model but easy to perform experiments on and obtain data from. It can also be manipulated with minimal safety concerns compared to an industrial system.

7 The Challenge of Data Privacy

Topic: Responsible, Focus: Intellectual property and privacy

Context In the era of digital transformation, digital twins have become essential in various areas, including manufacturing, healthcare, and urban planning. Digital twins are virtual replicas of physical objects, processes, systems, or environments, facilitating data analysis and system monitoring to enhance decision-making. But how can data be leveraged to save energy or foster synergies in medical research without experimenting on animals or people? Digital twins might be a solution. By accurately replicating real-world entities, they allow us to predict consequences, identify obstacles, and devise strategies to overcome them and maximize benefits. However, despite their vast potential, digital twins raise significant data privacy concerns that research institutions, businesses, and regulators must carefully address.

Challenges Scientists and engineers need real-world data to create accurate systems, which often involves gathering personal information. Data sensitivity and accessibility are significant concerns, as the data used in digital twins can be highly sensitive, containing personal identifiers that trace back to individuals. For instance, in healthcare, patient-specific data used for personalized treatments can reveal deeply private information. Ensuring that only authorized entities can access sensitive data is crucial but challenging due to the multiple vectors of potential exposure in digital ecosystems. Data integrity is another major concern, as there is potential for data tampering or misuse. Inaccurate or manipulated data could lead to faulty predictions about critical infrastructure, endangering public safety or causing financial losses. Additionally, there is a risk of data being used for purposes other than originally intended. For example, data collected to optimize building energy efficiency might be used to infer the behavior patterns of residents without their consent, leading to privacy violations.

Mitigating the Privacy Risks To mitigate privacy risks, incorporate privacy by design into the development and deployment of digital twins, addressing privacy concerns proactively by integrating privacy and data protection principles from the outset of technology design. Enhanced data protection measures should be utilized, including state-of-the-art cybersecurity technologies such as encryption and blockchain to secure data transmission and storage. Implement strong access control and identity verification systems to ensure that only authorized personnel can access sensitive data.

8 Surrogate and generative models for trustworthy digital twins of complex physical and engineering systems

Topic: Trustworthy, Focus: Trustworthiness of digital twins

Digital twins (DTs) for complex systems require advanced AI to handle multi-source, multi-fidelity data, ensuring precision across diverse scenarios. High-dimensional spaces pose challenges, stressing experimental and HPC facilities. AI accelerates both forward and inverse problem-solving in various applications, including materials modeling, fluid dynamics, and engineering.

Challenges Surrogate deep learning (DL) models must be (1) generalizable to different physical scenarios, (2) transferable across system sizes for scale bridging, and (3) confident in predictions to maintain DT quality. These properties define trustworthy surrogate models. However, stable training with multi-source, multi-fidelity, imbalanced data remains challenging. Reinforcement learning (RL) and generative models (GM) algorithms must propose realistic scenarios for DL models to assess DT component responses. Ensuring feasibility constraints in these scenarios is critical but challenging, especially for complex systems without clear mathematical models.

Proposed solutions Trustworthy DL surrogate models should integrate physics to maintain self-consistency in target properties, either through physical correlations or additional physics laws. Multi-modal learning in GMs can uncover hidden correlations, enhancing realistic scenario generation and scientific discovery. These correlations help efficiently sample new parameters, improving modeling accuracy.

Expected outcome Integrating DL surrogate models with RL and GM in a unified AI workflow will create DTs that offer trustworthy virtual descriptions of complex engineering/physical systems.

9 High Performance Probabilistic Ensemble Digital Twins for Time Dependent Problems

Topic: VVUQ, Focus: Foundational and cross-cutting methods

Understanding and harnessing non-equilibrium physical and engineering systems rely heavily on computing. Mathematically rigorous methods that integrate physics, observations, AI/ML parameterizations, and expert knowledge offer the greatest promise. Probabilistic estimation methods, particularly those leveraging Bayesian techniques, can handle non-Gaussian/nonlinear processes and provide a framework for digital twins. These methods, established since the 1960s in stochastic control and data assimilation, enable interaction between the physical and in-silico worlds, producing results with bounded uncertainty and interpretability [14].

Current Challenges Framework adaptability involves creating a general framework that can balance constructs like meta-stable, Markovian, Bayesian, and frequentist approaches to various problems [25]. Computational challenges include developing stable and efficient probabilistic digital twins that manage evolving probabilities and epistemic errors while ensuring statistically convergent results [15]. Sampling techniques need to define sampling stability and develop efficient methods for high-dimensional problems to generate explainable results [26]. Ensuring interpretability in complex, non-equilibrium problems requires addressing multi-modal and multi-scale statistical challenges [28]. Tackling the curse of dimensionality involves employing dimension reduction techniques for models, data, and observations. Additionally, managing pervasive biases and unknowns necessitates achieving convergence for fidelity exchange [24].

10 Uncertainty Quantification and High-performance Computing

Topic: VVUQ, Focus: Foundational and cross-cutting methods

Motivation Physical systems inherently exhibit randomness and uncertainty, complicating simulation-based or data-driven predictions. Robust and scalable Uncertainty Quantification (UQ) techniques are essential, particularly in HPC environments, to bridge the "predictive/validated HPC" gap. This is crucial for national priorities like fusion energy and drug discovery in digital twins. Automated UQ tools can connect the needs of engineers and scientists using supercomputing platforms, creating reliable digital twins that incorporate simulation and real-time data with reduced risk.

Digital Twins and UQ Digital twins use existing tools to create future models that evolve the domain. Success in digital twins varies across applications, but reliability and robustness depend on UQ methods. Coupling digital twins with UQ builds confidence through multiscale, multi-physics simulations, improving VVUQ performance and prediction fidelity. HPC is vital for these calculations, balancing edge and supercomputer computations for precision.

Challenges and Requirements Massive computing power, mathematical modeling expertise, and scientific domain knowledge are needed to develop problem-solving digital twins. An interdisciplinary approach ensures successful uncertainty assessment and informed decision-making. Long-term investment in reproducible codes is crucial.

Specific HPC Challenges Current HPC practices lack clear paths for coupling diverse CPU/GPU usage across platforms. Opportunities lie in developing interfaces for physics and engineering code coupling, such as in-memory coupling and standardized file formats. Implementing UQ methods builds confidence in error estimation and design under uncertainty, identifying impactful variables and using influential computations strategically. Addressing experiment variability and minimizing downtime, such as in fusion modeling, are key goals.

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Federal Register Notice: 89 FR 51554, Federal Register :: Networking and Information Technology Research and Development Request for Information on Digital Twins Research and Development, June 18, 2024.

Request for Information on the National Digital Twins R&D Strategic Plan

Plato Systems

Plato Systems in Response to the Networking and Information Technology Research and Development Request for Information on Digital Twin Research and Development

Plato Systems Inc.
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Digital Twins in Manufacturing

Since the turn of the millennium U.S. share of global manufacturing has declined, with one-third of manufacturing jobs disappearing in just the first ten years. By 2030, it is projected that 2 million manufacturing jobs will be unfilled in the U.S., including 150,000 in the semiconductor industry alone. Without urgent and tactical action to bridge the talent gap, the U.S. risks minimal return on an over $300B investment to build manufacturing infrastructure through the CHIPS and Science Act and the Bipartisan Infrastructure Law. Technology is a key part of the solution, with digital twins emerging as frontrunners for rapidly scaling capacity and driving efficiency in labor-constrained environments.

Digital twins are part of a larger smart manufacturing trend, which has collectively garnered more than $50B in annual investment, but has yet to realize significant returns. According to Forbes, only 14% of smart factory installations are considered successful. Industry must examine why these initiatives are unsuccessful and how new technologies can leverage existing investments to realize the promised productivity gains.

A critical shortcoming of current digital twins in manufacturing is that they were designed prior to the age of big data analytics and AI, thereby rendering these tools less effective and inefficient in addressing systemic operational productivity gaps that lead to higher production costs, lower production capacity, and lower quality. More specifically, manufacturing data is stored across several disparate and disconnected digital twins, each producing a lot of the “what” data (i.e. “when” did “what” happen) but they don’t enable or help with understanding the “why” data; Additionally, manufacturing is a complex ecosystem, and the data that is currently available lacks critical context that would disentangle the complex interactions that lead to poor productivity. This combination results in overburdensome and costly root cause analysis which is beyond the resources of most companies. Presently, an analyst must manually review siloed, fragmented, and often incomplete machine data to determine the root causes of anomalous adverse events. To address these challenges, a new modular digital twin is needed that is purpose-built to provide actionable insights and enable rapid scalable root-causing of productivity issues. This new platform should be able to ingest existing data streams as well as new sources of data that add critical contextual information, provide a replica of all physical operations (including crucially the operator-machine interactions), and be paired with a set of AI copilot tools that can help objectively measure, identify, root-cause, and predict systemic issues automatically at scale.

Plato has developed a streamlined method to contextualize manufacturing operations data using novel approaches of spatial data and spatial intelligence, unlocking rapid AI-assisted root cause analysis and corrective action that enables the digital twins to have proven impact on real world operations. In Plato's solution, proprietary sensors and cameras digitize operator-machine interactions. This missing piece of data is critical for both facilities that haven't undergone digital transformation (by digitizing their physical operations) and those that have (by complementing and contextualizing their data), giving the model the necessary context to identify *why* an anomalous event occurred. Plato has deployed this system in multiple global electronics manufacturing and semiconductor fabs, demonstrating 20% productivity increases over manufacturing execution systems and machine data collection schemes alone.

Therefore, Plato recommends that:

1. Manufacturing should be considered a critical domain across R&D topic areas. The manufacturing sector provides a necessary real-world deployment environment for digital twin learnings to demonstrate measurable productivity improvements.
2. An R&D topic should be focused on identifying the data gaps preventing current digital twin efforts from realizing productivity gains, as these learning will extend beyond the manufacturing domain to areas such as smart cities and energy, which resemble complex factory environments, with many actors, subsystems, and interactions.
3. An R&D topic focused on developing complete digital twin solutions that use spatial data and AI to determine the root causes of failures and provide recommendations on mitigating these failures in the future by leveraging AI.

Data: Expanding Data Collection to Enable Digital Twin Development

Success of AI and big data analytics relies on having access to data that is both high volume and has high quality in terms of its completeness and correctness. Relying solely on machine data to construct digital twins poses a problem to manufacturers. Machine data provides an abundance of data on what happened, but little insight into why. This makes employing analytical tools challenging, as models do not contain the information required to diagnose the cause of an anomalous event. As a result, data analysts must manually investigate across disconnected and incomplete data sources to determine root causes and the corresponding corrective actions, wasting time and resources.

The inclusion of spatial data in manufacturing digital twins is critical to extracting actionable insights from these models. Spatial data is required to accurately capture machine-operator interactions, as self-reporting and other mechanisms have proven unreliable. With spatial data, digital twins can determine the operator's relation to the machines and other operationally critical areas (such as inspection stations, warehouse, etc) during an anomalous event. With this context, AI can analyze how an ideal operator minimizes machine downtime in a digital twin. These insights can be incorporated into training material for workers to increase their productivity, and resolve systemic issues such as those related to facility layout planning, scheduling, capacity planning, staffing, material preparation, and standard operating procedures. While machine data enables part of a plant's story, spatial data is imperative for developing comprehensive and reliable digital twins that enable effective root cause analysis for anomalous events.

The Digital Twins R&D Strategic Plan (The Plan) should include a robust data collection system that includes spatial intelligence. The Plan should seek to incorporate a variety of data streams including machine operations data, scheduling, material data, and other organizational data consolidated into one platform, with the goal of establishing a complete digital twin able to explain *why* anomalous events occurred. Digital twins of this nature are the key to demonstrating the business value of smart manufacturing initiatives.

Plato's Expertise in Data Collection: Plato captures data continuously on a 24/7 operative basis and uses AI-enabled sensor technology to digitize operator activity onto Plato's cloud platform. The Plato Cloud further integrates into and ingests manufacturers existing operations, MES, or ERP data to create a highly contextualized Operations Digital Twin with a demonstrated 20% productivity improvement in electronics and semiconductor manufacturing facilities.

AI and Digital Twins:

In modern manufacturing, data and technology play a crucial role in driving productivity. With the increasing reliance on automation, there is a near infinite amount of machine and other factory operations data available to manufacturers. The challenge is extracting actionable insights and trends from a vast amount of data. This is where AI thrives.

AI models can detect and identify patterns between data and incidents, identifying the biggest causes of inefficiency at greater speed than previous analytical methods. While machines can make parts, they cannot solve problems autonomously. When equipment is down or needs maintenance, human interventions are critical to optimizing uptime. Digital twin environments that leverage AI allow managers to proactively receive insights into how machines and operators are interacting to better respond to problems in real-time and plan for future operations.

The Plan should prioritize the use of AI within digital twins technology in manufacturing processes to focus on technologies that can proactively deliver actionable insights on the data collected and thus efficiently deliver productivity gains. Moreover, conversational AI models that allow the user to interact and analyze data using conversational prompts can further contribute to the utility of these tools by removing the need for end users to have advanced data science skills. The Plan should prioritize R&D efforts that effectively collect data that can be easily integrated into ML and AI systems for digital twin environments, and provide interactive AI insights in a streamlined manner.

Plato's Expertise in AI with Digital Twins: Plato's AI assistant allows the production facility to identify root causes of manufacturing efficiencies across shifts, lines, and plants, with the promise to deliver actionable data for productivity improvement within 8 weeks of deployment.

The incorporation of AI with digital twins in manufacturing sites is critical to helping plant management address efficiencies with speed and simulate future environments. Rather than spending hours every week to root-cause a single adverse event such as a downtime, AI-assisted Digital Twins allow managers to quickly identify where issues are stemming from and access insights immediately and at scale.

AI enables the ability to quickly collect insights from the data and facilitate the future modeling and simulation of facilities for long-term and strategic planning.

Long Term

Forward-looking digital twins allow for thorough validation of designs before actual construction begins, identifying potential flaws and bottlenecks early in the design phase where they can be ameliorated at a fraction of the cost compared to during or post construction. By including spatial data in forward-looking digital twins, manufacturers can reap several impactful benefits:

1. Optimized performance: digital twins can simulate how different designs will perform under various conditions. With the inclusion of spatial data, the manufacturer can understand where the operator will have challenges maximizing machine effectiveness. Through modeling, designs can be optimized for the operators, ensuring that the factory and workers operate at their best from day one.
2. Enhanced Training: digital twins can simulate the optimal workflow for each individual operator before a factory is built. Training materials would be developed based on the optimal workflows, and used to educate staff *before* the factory is built. The workforce will be able to hit the ground running on day one, reducing ramp time and enhancing productivity from the outset.
3. Continuous improvement: insights gained from simulating designs, optimizing performance, constructing the optimized designs, and then analyzing how well the optimizations performed in the real world can inform future projects, leading to constant improvement in industrial design. Long term, this practice enhances innovation and competitiveness within the U.S. manufacturing sector.

Workforce

Significant workforce challenges are expected in the U.S. manufacturing sector due to high turnover rates and projected talent shortages. According to the U.S. Bureau of Labor Statistics, there is over a 40% turnover rate in manufacturing and the industry is projected to face 85 million unfilled jobs globally by 2030, leaving a significant gap for the sector to fill over the next 5 years.

To truly overcome the aforementioned labor challenges, digital twins should enable a more productive workforce in two ways. First, the workforce of tomorrow should be empowered by providing them the ability to take advantage of feedback loops from an AI-assisted digital twin that allow the operator to access and analyze data and retrieve best practices using simple conversational prompts. Second, by leveraging spatial data, an AI-enabled digital twin can identify root causes of inefficiencies and directly lead to improved standards of operation and training material that address any missing procedural or skills gaps. With these insights, managers can tailor training programs to address specific needs, enhancing the overall skill set of the workforce.

The Plan should include a key topic for workforce demonstrating how digital twins can enhance workforce development efforts to fill the manufacturing talent gap. The Plan should consider how digital twins can be used as an effective training tool for upskilling talent and understanding the operations of the existing workforce to plan for future talent.

<u>Plato's Expertise in Digital Twins for Workforce Development:</u> Plato Systems is an expert in this area, offering proven monitoring and proactive solutions for manufacturing plants. Plato's unique spatial-based solution unlocks an understanding of human-machine interactions that helps companies upskill their operators. Plato has developed training materials for multiple multinational electronics and semiconductors companies based on their spatial digital twin, resulting in an average 20% increase in worker productivity. Additionally, Plato's software provides insights that allow plants to plan future facilities with better layouts for employees that streamline workflows. The system also constructs training materials for future operators, who may lack experience, enabling accelerated on-boarding and training.

<u>International: Digital Twins for International Collaboration and Insights</u>

Southeast Asia has over 50 years of advanced electronics manufacturing experience and is continuing to attract global investment, rapidly extending its integration of automation to meet growing demands. Modern day technology involves complex manufacturing processes made up of specialized tooling and well-trained operators, forcing manufacturers to constantly improve operationally in order to remain competitive.

Digital twins are an effective solution for the enhanced productivity and observability of manufacturing processes onshore and for cases where they do need to be observed overseas. Incorporating machine and spatial data into a digital twin monitoring system, companies can remotely solve for inefficiencies and understand how operations are being conducted overseas. This remote monitoring can help U.S. companies learn from operator's best practices and plan for replicated, optimized processes in manufacturing facilities on U.S. soil, while developing a playbook of best operating strategies for manufacturers.

The Plan should incorporate methods for integrating digital twins for the remote monitoring and replication of international facilities, to gain insights that will enable the U.S. to improve its manufacturing methods and effectiveness onshore.

<u>Plato's Expertise in Remote Data Collection:</u> Plato's solution offers a valuable solution for remotely monitoring factories through the ability to collect, track, and monitor a database of historical and real-time machine and operations data of the factory floors.

About Plato Systems

Plato Systems has developed an AI-Powered spatial intelligence platform to optimize manufacturing processes and productivity. Plato has developed the first ever tagless Spatial Intelligence Platform (SIP) to track spatial activity patterns of operators and machines. Founded in 2019, the team consists of experts from industry and academia with deep expertise in machine perception, multimodal AI and analytics, software reliability, and manufacturing processes.

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Request for Information on the National Digital Twins R&D Strategic Plan

Polybiomics

RFI Response: Digital Twins R&D Plan

Mandana Veiseh I Polybiomics, Inc & Lawrence Berkeley National Lab

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Submitter agrees with proposed plans from the Artificial Intelligence (AI) to Standards outlines. Below please find revisions in brackets on:

***Sustainability:** ...develop approaches for the design, development, and deployment of Digital Twins; the ability to create interoperable Digital Twins with evolving technology and standards [towards an accurate, predictive scale-up and a sustainable, flexible economy. Establish innovation hubs and consortia to facilitate knowledge sharing, enhancing collective effectiveness, and forming joint public-private ventures across various sectors].

***VVUQ:** Develop Rigorous Methods for Verification, Validation, and Uncertainty Quantification for Digital Twins: Possible focus areas: foundational and cross-cutting methods as well as domain specific; integration of VVUQ into all elements of the full digital twin ecosystem. [Digital twin ecosystem of living organisms, require abundant, often heterogeneous, and dynamic data for proper adaptation, thus VVUQ for such ecosystems highly depends on data sources, stepwise optimizations, and resilience of the training environment for accurate outcome predictions].

***Workforce:** Cultivate Workforce and Training to Advance Digital Twin Research and Development: Possible focus areas: diverse talent recruitment; incentivize cross-disciplinary STEM research programs across educational institutions, [accelerate the new science of hybrid DT-human teaming by developing new metrics for human-DT teamwork performance evaluation, and encourage talented individuals by offering national cross-disciplinary fellowships on topics of substantial user need].

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Request for Information on the National Digital Twins R&D Strategic Plan

R. Rodulfo

Via FDMS

R. Rodulfo, 7/6/2024

[redacted]

Digital Twin Smart City Case Study City of Coral Gables, FL Digital Twin smart city public platform - strategic planning, engineering, design, community impact: The Coral Gables smart city Digital Twin platform (https://www.coralgables.com/digitaltwin) was engineered in house by the City of Coral Gables Innovation & Technology team (CGIT), as part of our strategic plans and ongoing R&D and innovation operations. The first version (v1) went live in 2021. There was no additional funding requested/required for this project. The CDT project is aligned with our strategic action plans, specifically with our Innovation & Technology Strategic Action Plan 4.1-1 (City Goal 4) – Citywide Horizontal Integration of Enterprise Systems and Dashboards: https://issuu.com/cgit/docs/cgitstrategicplan/26 The homegrown digital twin platform (Smart City OS) merges the Coral Gables Smart City Hub public platform (https://www.coralgables.com/smartcityhub) launched in 2018, the City's Urban Analytics Artificial Intelligence (AI) Internet of Things (IoT) platform, citywide enterprise systems and open data, and a 3D horizontal integration spatial computing platform. This architecture fosters interoperability in real time and connects the dots between all the city's enterprise systems and data domains to improve operational efficiencies and citizen access to digital services. It also allows for integration with building information models and immersive virtual reality user experience navigation for operations, inspections, monitoring, and control. The platform is widely used by city departments (Innovation & Technology, Public Works, Public Safety, Police, Fire, Emergency Management and EOC, Historical Resources & Cultural Arts, Development Services / Building/Planning & Zoning), by traffic engineers, environmental analysts, urban planners, city officials and decisionmakers, etc., and by university and school researchers and students (UM, FIU, MDC, UC Berkeley, and others), and referenced by scientific research institutions (NIST, PNNL, CDG, CTI, and others.) Our smart city digital twin started as a concept around 2013 when we published a paper to help our team to identify the urban computing knowledge foundations and engineering standards that we could leverage at that time to embark on a smart city roadmap, aggregating research from IEEE, academia, and the industry. This was the last update of that early document: https://issuu.com/cgit/docs/cgitsmartstories/202 - https://drive.google.com/file/d/1gn2vUx0VLBZGjBoiIo3HhEitcgFao0oH/view Our digital twin concept matured into a systems engineering horizontal integration interoperability model paradigm and a smart city engineering framework presentation layer in our innovation and technology strategic plan, first published in 2016: https://www.coralgables.com/itstrategicplan In our strategic plan, the digital twin is a subset of the Smart City Hub layer of the Coral Gables Smart City Engineering Framework (https://issuu.com/cgit/docs/cgitstrategicplan/47), and its topology is defined by Framework # 5 of our Smart City Engineering Framework Architecture, also introduced in the strategic plan: https://issuu.com/cgit/docs/cgitstrategicplan/42 - https://issuu.com/cgit/docs/cgitstrategicplan/48 All those documents and public platforms are available in our Smart City Digital Library: https://www.coralgables.com/itdocs Additionally, these stories in our innovation & technology bulletin explain more about our smart city digital twin platform: First time we presented the prototype version to the public, at a smart city conference in University of Miami: https://issuu.com/cgit/docs/cgitsmartstories/92 Digital Twin Public Launch (v1): https://issuu.com/cgit/docs/cgitsmartstories/87 Digital Twin Presentation with NIST: https://issuu.com/cgit/docs/cgitsmartstories/79 Digital Twin Presentation to City Commission and city officials and residents: https://issuu.com/cgit/docs/cgitsmartstories/71 Media article: https://issuu.com/cgit/docs/cgitsmartstories/59 Harvard library publication: https://issuu.com/cgit/docs/cgitsmartstories/56 Digital Twin Project Award: https://issuu.com/cgit/docs/cgitsmartstories/41 Digital Twin Platform Redesign (v2) launch with advanced photogrammetry and IoT integrations: https://issuu.com/cgit/docs/cgitsmartstories/25

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Request for Information on the National Digital Twins R&D Strategic Plan

Readiness Resource Group (RRG)

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Digital Twins R&D Strategic Plan: National Use Case
Digital Engineering the Defense Maglev Network

by

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26 July 2024

Response to NITRD National Coordination Office Request for Information (RFI) 89 FR 51554
Topics: **Artificial Intelligence**; **Business Case Analysis; Ecosystem; Standards; Sustainability**

Abstract

We address the importance of a) developing national use cases in formulating the National Science Foundation (NSF) Digital Twin Research and Development Strategic Plan, and b) including a priority use case for the emerging industrial sector of superconducting magnetic levitation technologies, and the concept of digital engineering a national Defense Maglev Network (DMN).

A Defense Maglev Network is a national security and economic benefit, the precursor to an Interstate Maglev Network, and a stimulus for a new industrial ecosystem and supply chain. The network offers cross-cutting benefits to the defense industrial base (DIB), transportation and logistics infrastructure competitiveness, and restoration of U.S. technological superiority.

Digital Engineering (DE) is now underpinning large systems design, development, implementation and sustainability with anticipated productivity, rapid transition to manufacturing, accelerated test and systems validation, and dramatically reduced lifecycle costs. Transformations in digital engineering will dramatically reduce the time from concept to full-scale production-ready systems.

The Recommendation

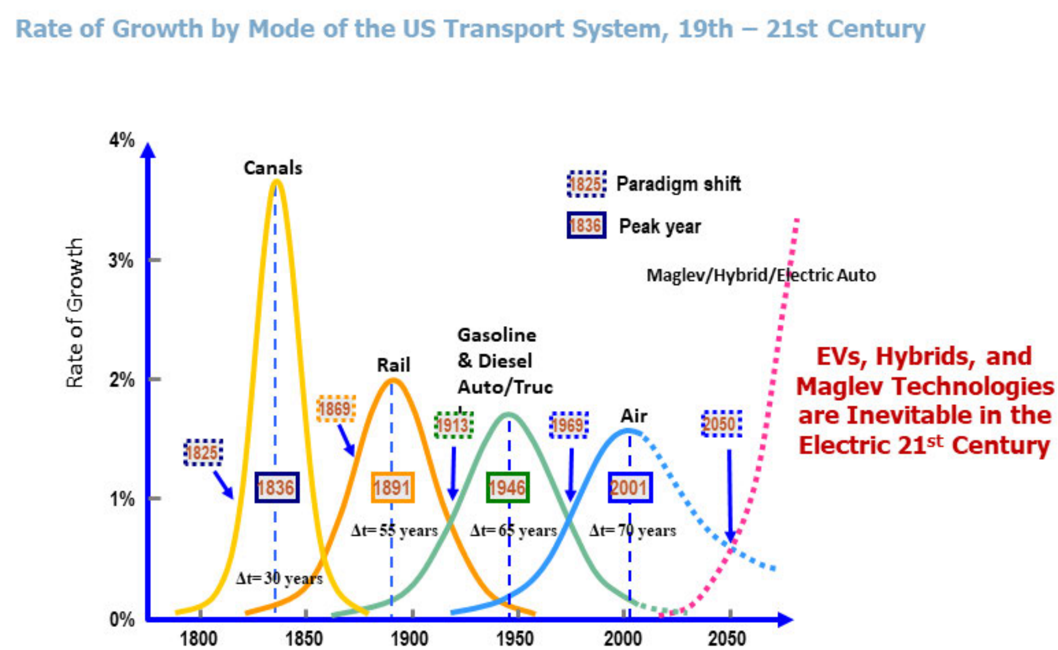
An extraordinarily rare opportunity exists to leapfrog our international competitors by investment in a comprehensive Digital Twins (DT) program initiative focused on multiple national use cases. As a priority use case, we seek to advance our transportation infrastructure because it is foundational to national security, economic competitiveness, and societal resilience.

We recommend undertaking a digital engineering development effort to enable implementation of the first transcontinental ultra-high-speed, environmentally benign, and energy conserving logistics network based on U.S. designed and manufactured superconducting maglev technologies. The initial implementation of such a network should support priority defense and homeland security needs to connect critical nodes for readiness, response, and recovery from a spectrum of threats and hazards, to enhance mobilization and deployment options, and to validate the operational competitiveness and resilience for what could become a more extensive national interstate maglev network serving all Americans.

Background

America led the world in transportation. In the 1800s we developed canals like the Erie, Robert Fulton invented the steamboat, and we built the Transcontinental Railroad. In the 20th Century, we led the way with Henry Ford's automobiles, Wright Brothers airplane, Panama Canal, jet airliners, Eisenhower's 45,000-mile Interstate Highways, our Space Program, and the Internet. Existing modes of transportation have reached their practical, cost-effective limits. Railroads have changed little in over a century. Highways are increasingly costly to maintain, congested and unsafe in metropolitan areas. Sustaining the Highway Trust Fund is a well-known challenge.

Exhibit 1 portrays the rate of growth of various modes of transport within the United States.



Source: adapted from J.H. Ausubel, C. Marchetti, and P. Meyer (1998) "Toward Green Mobility: the Evolution of Transport", European Review, Vol. 6, No. 2, pp. 137-156.

Exhibit 1 The Dynamic Evolution of U.S. Transportation

America's adversaries and near-peer competitors are investing in superconducting magnetic levitation (SCM) technologies for logistics, surface transportation, and grid-scale energy storage. This idea was first introduced by two American scientists in the 1960s and has largely been ignored by the United States. Following the model of previous American technology successes, we propose the creation of a DMN to support the nation's homeland security and defense requirements with a continent-wide advanced logistics infrastructure.

Superconducting Maglev was invented in 1966 by Gordon Danby, Ph.D. and James Powell, Sc.D. at Brookhaven National Laboratory. Learning of their inventions, scientists and engineers from Japan and other countries visited them to obtain details. Other governments implemented Maglev systems, and these are now operational in China, South Korea, and Japan.

We face grand challenges in modernizing critical infrastructure. Facing those challenges without considering the benefits of SCM runs the risk of hobbling the U.S. economy for decades to come, especially as competitors in China, Japan, South Korea, India, and the European Union build out their maglev infrastructures. Danby and Powell's first-generation SCM has been demonstrated by Japan and holds the world's speed record of 375 miles per hour (mph) for guided surface transport.

Military logisticians are aware of the history of the Interstate Highway System (IHS), starting with Dwight Eisenhower accompanying a 1919 Army expedition of trucks and tanks across the continental United States. It took 62 days to travel 3,200 miles, with roads in the west described by Eisenhower as a "succession of dust, ruts, pits, and holes." During World War II, the future president also perceived the utility of the German Reich's autobahn for Nazi military supplies movement. There was opposition in Congress as to the cost of modernizing the nation's road infrastructure but use for defense helped justify the passage of the Federal Aid Highway Act of 1956 and the start of IHS construction in the same year.

The already obtained rights-of-way (ROW) of the IHS strongly influenced the vision of the late Drs. Powell and Danby for the development of a continent-wide (to include some Canadian destinations) high-speed elevated freight and passenger surface transportation network based on their invention of second-generation superconducting magnetic levitation (SCM), known as Maglev 2000. Many stations on this envisaged 29,000-mile network would be essential for military and disaster evacuation movements, which would be made at speeds exceeding 300 mph.

Concerning rail travel, the United States is in a position akin to telecommunications in (so-called) Third World nations a few decades ago. Rather than slowly advance from not even having telephones to setting up the typical telephone infrastructure, people even in remote areas received cell phone infrastructure and joined the developed world in individual communications. For the U.S., there is no need to advance from its current state—with few trains even traveling 100 mph—to European steel-on-steel systems that can reach 200 mph. It is time to "leapfrog" steel-on-steel and move directly to an elevated maglev system and its 325 mph cruising speed.

The DMN, which will become an essential element of the Defense Industrial Base (DIB), must be protected as an asset under the Defense Industrial Base Critical Infrastructure Sector Security Plan. Just as military bases and the nation's airports and seaports are heavily protected, the DMN network must have strong security, (some) redundancy, avoidance of a single point of failure (with alternate routing), and an assured supply of critical raw materials along with back-up sources for those materials. IHS primarily serves civilian passenger and freight vehicle purposes; the maglev network will do the same caveated for emergency appropriation by military authorities.

It is difficult to perceive future threats within and along the borders of CONUS. What if a situation, for example, on the southern border requires a response the size of an Army division (i.e., 10,000-15,000 soldiers) from Fort Riley, Kansas or a Marine division (i.e., 22,000 Marines) from Camp

Pendleton, California—and their associated ground attack equipment assets? Military convoys on the IHS typically average 40 mph. DMN can move troops and cargo at EIGHT times that speed.

Defense Maglev Network would support:

- Rapid mobilization of troops and equipment at eight times the current speed.
- Much faster supply container movement from and to sea, air, and land ports in an all-weather resilient infrastructure.
- Expedited distribution of materiel from Defense Logistics Agency depots, with military command and control exercised by the U.S. Transportation Command.
- Implementation of a Medical Response Disaster Train for large-scale patient evacuation away from mass casualty incidents to higher levels of care.

Exhibit 2 illustrates the concept for construction of the national maglev network. Three Waves of Construction Blue, Green, and Red to be completed in about 20 years.

Inside a given metropolitan area, Maglev will access existing rail networks, by adapting existing railroad trackage for Maglev travel. The adaptation consists of attaching thin polymer concrete panels encapsulating loops of aluminum to the crossties.

Maglev Network	States In Network	Population of States in Network (millions)	Population Living Within 15 Miles of Stations (millions)	Route Miles in Network
First, Second and Third Waves Completed	48 plus Toronto, Montreal & Vancouver	315 includes Toronto, Montreal & Vancouver	232 includes Toronto, Montreal & Vancouver	29,000
74% of the population in States live within 15 Miles of a Station				

Exhibit 2 Notional Implementation Timeline

The Challenge and Opportunity

The evolution of maglev technology reaches back to the pioneering work of Michael Faraday, Heike Onnes, Nikola Tesla, Robert Goddard, and Emile Bachelet. The invention of *superconducting* maglev for transport rests with the tireless work of James Powell, Sc.D., and Gordon Danby, Ph.D., both distinguished scientists from the Brookhaven National Laboratory. The Japanese government invested in developing Powell and Danby's first-generation design and built the full-scale system at their Yamanashi Test Facility. The United States failed to seize the opportunity to take global leadership in this technology and now we have competitive solutions emerging from China, India, Korea, Germany, Poland, Italy, and Japan. Powell and Danby's work continued, enabling development of the 2nd generation maglev system. Powell and Danby were awarded the Franklin Medal of Engineering for their contributions to transportation. They share this honor with Albert Einstein, Niels Bohr, Alexander Graham Bell, Thomas Edison, Pierre and Marie Curie, Nikola Tesla, Wernher Von Braun, and Stephen Hawking.

Full-scale components for the Defense Maglev Network – superconducting magnets, guideway panels, guideway beams, vehicle concepts, etc. – have been successfully fabricated and tested and their costs validated. The next step is to assemble the components into operating vehicles and test them on a guideway track to demonstrate third-generation SCM's unique capability to electronically switch (vice mechanical guideway switching), levitate heavy freight (loaded long-haul trucks), and switch between the high-speed mainline guideway to Maglev-adapted conventional railroad tracks for accessing densely built population centers and using existing rail tunnels, bridges, and terminals.

Maglev Architecture

Maglev vehicles are magnetically levitated above and propelled along guideways at hundreds of mph, without mechanical contact. They do not emit pollutants or greenhouse gases, are noticeably quiet, comfortable, and safe. The fundamental design innovations underlying all SCM systems present today were invented by Powell and Danby between the years 1966 and 1971 during their service to the Brookhaven National Laboratory. These innovations include electric dynamic stabilization (EDS), null-flux loop geometry (NFLG), and linear synchronous motors (LSM).

Between 1966 and 1996, Japan conducted a multi-billion dollar R&D program to develop SC maglev into a workable system. Between 1997 and 2015, at the Yamanashi test track, Japan entered into a testing phase for the vehicle and guideway configurations that would become their final commercial maglev system. During testing the commercial test vehicles travelled with a 100% safety record over 100,000 miles, carrying more than 10,000 passengers, at speeds up to 375 mph. In 2015, Central Japan Railways began construction of their Chūō Shinkansen maglev line between Tokyo and Nagoya.

The DMN DT should describe the design of a North American logistics network that maximizes elevated, narrow-beam guideways, minimizing at-grade disruptions enhancing speed of delivery and reducing safety hazards. Reliability is enhanced by a design that has almost no moving parts, making operation and maintenance a small component of the life cycle system cost.

New supply chains and manufacturing opportunities defined in the DMN Digital Twin will strengthen the Defense Industrial Base (DIB):

- Manufacturing
  - Manufacture of Third-Generation Magnet Assemblies (leveraging high-temperature superconductors and Cryocooler technologies applicable to other defense applications)
  - Manufacture of Superconducting Wire & Cable Materials (renaissance of a production capability that has been offshored for decades)
  - Manufacture of Roll-on/Roll-off Freight Ferry Vehicles (reinforcing aerodynamics and aviation engineering expertise)
  - Additive Manufacturing Solutions.

- Construction
  - Green Concrete within prefabricated piers, stanchions, and guideway beams
  - Passive Maglev Loop Panels within advanced polymer concrete casings
  - Architect and Engineering (A&E) Design and Build for Intermodal Operations, On-Site Pier Footings, and Transfer Stations.

- Integration
  - Command, Control and Communications, e.g., position and speed control, switching, emergency response, failure management, artificial intelligence (AI)/machine learning (ML) for network optimization and route planning
  - Integration with Steel Wheel Railroad Operations (Maglev Emplacement on Railroad Infrastructure)
  - Advanced Safety and Security Management (intrusion detection systems; AI-enabled security surveillance and monitoring; perimeter protection; safe escape provisions; ballistics protective measures; cybersecurity).

Key Benefits of Digital Engineering (DE)

Ecosystem: The NSF initiative driving the Digital Twins R&D recognizes the long-term benefits of adopting the digital engineering best practices:

- Improves the quality and the speed of system and system-of-system (SoS) mission capability deliveries.
- Enhances understanding of engineering designs and improves decision making, including all hardware and software configuration, system test and evaluation.
- Collapses the cycle time by moving the right side of the Systems Integration V to the left, enabling early system understanding, architecture design trades, and detecting defects early in the design phase.
- Reduces lifecycle cost through systematic design reuse and lowering transaction cost.
- Improves the ability of "owning the technical baseline," configuration and change management, better requirement definition and traceability, and rapid engineering responses.
- Enables knowledge management and communication and across stakeholder communities and acquirer-supplier teams.

A Reference Model or Framework under the auspices of a government-wide DT R&D portfolio would validate commercial and government developed databases and software applications used to generate, visualize, analyze, and validate designs. This approach would incentivize the building of a common architecture unlike the incremental development designs and build programs of past decades.

Standards: The excellent standards development expertise of the National Institute of Standards and Technology (NIST) within the U.S. Department of Commerce, to include its cybersecurity guidance, in partnership with DOT on system requirements, feasibility, route planning and NASA on other technical challenges would be value added. Coordination with the Environmental Protection Agency (EPA) and Occupational Safety & Health Administration (OSHA) would validate the benign environmental, health and safety (EH&S) aspects of the proposed maglev transport for both logistics and passengers. A panoply of federal departments and agencies all have important contributions to make to a DMN Digital Twin prototype in cooperation with industry and the academic research community. Standards for guideway, control systems, and emplacement over conventional railroad trackage each require novel standards development.

Digital engineering approaches also support rapid implementation of innovations within a connected digital end-to-end enterprise. Models can provide a precise and versatile representation of a system, phenomenon, entity, or process. In early phases of the lifecycle, models enable virtual exploration of solutions before actually instantiating them. Over a solution's lifecycle, models mature and become useful replicates to physical counterparts for virtual testing and sustainment.

Models will be used as the basis for defining, evaluating, comparing, and optimizing alternatives and making decisions. This paradigm shift will fundamentally change the current practice of accepting documents to accepting models and provides the technical underpinnings for acquisition domains and functional areas. Users can generate various views using a shared network of models and data to offer coherent digital artifacts, while reducing time-consuming effort and rework.

The fundamental tools for the DE endeavor include:

- Model-Based Systems Engineering (MBSE): The use of a modeling and simulation approach as theprimary means of information exchange and to create digital threads.
- Integrated Product Lifecycle Management and Supply Chain Management: Streamlining the lifecycle process of design, build, integration, and testing to connect the desktop to the testing laboratory and the manufacturing floor.
- Cloud Services: Implementing secure cloud services, providing a multi-security enterprise cloudenvironment, and driving cloud migration.
- AI/ML: The use of large language models (LLMs) and other algorithmic models in route planning and network optimization, and structural monitoring.
- VR/AR/MR: State-of-the-art Virtual Reality (VR)/Augmented Reality (AR)/Mixed Reality (MR)technology for immersive and collaborative digital engineering, design reviews, training, and application of digital twins technology.

Business Case Analysis: Freight on highway trucks transported by Maglev roll-on/roll-off ("Ro-Ro") vehicles is projected to cost 10 cents per ton-mile, compared to 30 cents a ton-mile by highway.

Passengers travel on Maglev vehicles will cost 4 cents per passenger mile, compared to 15 cents per mile by air, and 40 cents per mile by highway.

Transporting trucks by maglev will also reduce:

- Highway deaths, injuries, and accidents
- Highway congestion
- Emissions of toxic pollutants and greenhouse gasses
- Cost of transporting goods
- Cost of repairing highway surfaces and infrastructure.

Sustainability: Benefits of an Interstate Maglev Network include:

- Decrease of transportation-related exhaust emissions by 50% from current levels by 2050
- Decrease of transport and logistics costs in the U.S. and the world, economically accelerating both developed and emerging economies by substantially lowering the price of goods and travel
- Fostering of smart growth by using the network infrastructure to serve as a low-cost means for distributing electric power and protected, secure broadband communications
- Beginning a sustainable global transportation infrastructure boom to attract tens of trillions of dollars of investment in both developed and emerging economies in electric transport for both logistics and passenger travel, with America setting the technical standards for global expansion of the network.

Conclusion

Defining a national network requires coordinated governmental, industrial, and academic leadership presenting a once in a century opportunity to mobilize technical expertise in partnership to implement the largest infrastructure system design endeavor in the nation's history.

Using the Defense Maglev Network as the case study advances U.S. leadership in both digital engineering practices and the infrastructure development. Today this nascent industrial opportunity is aggressively being pursued by the European Union (especially Poland), China, Japan, Korea, and India. Failure to undertake this effort assures the loss of this critical infrastructure domain and market opportunity to our near peer competitors and adversaries.

The preliminary DMN would have collateral benefits for the transportation, energy, and communications infrastructure sectors. A resilient design of prefabricated guideway can support secure conduit for fiber optic cables and power for widely distributed EV charger stations along the network route. This will extend high-speed broadband service to thousands of locations in the dark today and will add integrated transportation services for EV mobility. Thus, the DMN will provide additional resilience to our communications and power distribution architecture.

Ignoring key technologies such as Superconducting Maglev underscores the growing deficit in our logistics and technology preeminence and the gulf between our applied research and that of our adversaries and competitors who are implementing these systems in plain view. It is noteworthy that applied research in maglev for logistics will enable breakthroughs for its future use in grid-scale energy storage and in extremely low-cost electromagnetic space launch infrastructure. America's failure to develop its inventions reduces our competitiveness in science, engineering, and logistics.

The Digital Twins R&D Strategic Plan should highlight multiple national use cases within which the value of digital engineering can create a resilient repository of knowledge that will accelerate the testing and implementation of new systems and services, dramatically reducing time from concept to operational cutover. Those use cases that are cross-cutting in terms of advancing emerging technologies, supply chains, and research domains should be prioritized. We propose that the Defense Maglev Network is a viable, priority national use case of merit and should be highlighted within the NSF Digital Twins R&D Strategic Plan.

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Federal Register Notice: 89 FR 51554, Federal Register :: Networking and Information Technology Research and Development Request for Information on Digital Twins Research and Development, June 18, 2024.

Request for Information on the National Digital Twins R&D Strategic Plan

Sandia National Laboratories

Sandia National Laboratories' Response to the Networking and Information Technology Research and Development Request for Information on Digital Twins Research and Development

Date: July 26, 2024
Organization Name: Sandia National Laboratories, [redacted]
POC: Anna Wakeland; Technical Business Development Specialist; [redacted]

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Executive Summary:

Sandia recommends emphasis on the following R&D topic areas for strategic planning:

- AI, as it pertains to the construction of digital twins, data analysis, fast-running surrogate models, and real-time feedback control of manufacturing processes,
- Data management practices related to data collected from physical systems or physical systems augmented with machine learned models,
- Establish ecosystems founded on interagency collaboration and composed of public-private consortia that develop and promote standards, and fund interdisciplinary work that addresses identified gaps,
- International collaborations like the Digital Twin Consortium and the Omniverse for Microelectronics Fabrication,
- Long-term research investments in the bidirectional flow of information needed to construct digital twins, bringing together experimental and digital computing technologies, and combining models of various fidelity,
- Methods for creating safe and secure digital twins based on rigorous model-based engineering concepts,
- And verification and validation methods stemming from complex systems analysis

Artificial Intelligence (AI): AI and Digital Twins:

The Office of the Secretary of Defense in 2016 defined a future Digital Engineering Ecosystem for the Department of Defense as "the interconnected infrastructure, environment, and methodology (process, methods, and tools) used to store, access, analyze, and visualize evolving systems/data and models to address the needs of the stakeholder." Similarly, we are constructing a Digital Engineering Ecosystem for Nuclear Deterrence (ND) at Sandia that enables advanced model-centric workflows and applications across engineering domains and the lifecycle of weapon systems. Moving away from static document-based processes towards a dynamic model-based ecosystem will enable the creation of an authoritative digital source of truth for each weapon program. This will ensure the right information is always available for accelerated decision making and accurate and appropriate assessment across the weapon lifecycle. This model is applicable to other high consequence areas such as satellites, global security and other energy related areas.

Digital twins (DTs) are real-time virtual renderings of the physical world. A primary capability offered by a DT is rapid access to - and communication around - data and information. With the high consequence complex systems within the national security enterprise, most teams are challenged to manage large volumes of technical documentation, often in multiple formats and duplicated throughout the organization, over multiple decades leading to fragmentation and degradation of information integrity. This leads to significant financial and safety risks during operations. DTs can help ensure that information is easy to find when it is needed as well as serving as a single source of truth that supports communication and collaboration by presenting information in context or data pedigree. An effective DT is based on the inherent data structure and governance that maintains the validity and accuracy of the twin. AI connects the digital and physical worlds transforming science and engineering. Enabling real-time virtual representations of the manufacturing process provides production teams with the ability to support faster, smarter, and more cost-effective decision making. Accurately captured models in AI can deepen manufacturers' understanding of complex physical systems and production operations, optimize production scheduling, or simulate "what-if" scenarios to understand the impact of new product introductions, which are critical for responsive national security needs.

AI connects the digital and the physical worlds transforming science and engineering. AI understood methods have the potential to revolutionize the formulation and use of DTs. For example, graphical models like dynamic Bayesian networks can be used to augment equations of physical systems to enable robust updates of DTs at scale [Kapteyn, 2021]. Similarly, AI models can be used to entirely replace physical system models in applications where either the physical system is poorly or where such models are not practical (e.g. modeling human behavior). E.g., Sandia has explored the use of process models and hidden Markov models as DTs to model and analyze human behavior in physical [SAND2023-14702, SAND2024-00219] and cyber systems [KTR-2024-003, SAND2023-06726C]. Many research questions remain concerning the use of AI models as DTs. For example:

- How do we develop trustworthy AI models from sparse, noisy data sources?
- How can domain information, including subject matter expertise, be effectively integrated into AI models?
- How can AI models capture both statistical and logical relationships in physical systems?

Machine-learning and AI will play an integral part in the successful construction of DTs. This need arises from two separate issues. DTs will need to be continuously calibrated to measurements streaming from the physical twin. Continuous data assimilation algorithms e.g., Ensemble Kalman Filters exist, but require the DT to execute quickly on a computer – but for complex systems, this is hardly feasible. Fast-running AI proxies of computationally expensive models will be necessary to make DTs a success; indeed, such DTs are already being used to design inertial confinement fusion targets [Wang et al, 2024] and could be used to design processes to allow fusion power generation. The second use arises from needing the DT to be of a fidelity sufficiently high such that it can successfully exploit and assimilate the information content in the continuous measurements of the DT. All DTs will likely contain phenomenological models / closures that are "curve fits" to historical data; they can (and should) be replaced by AI models trained on data from high-fidelity models that already exist (the feasibility of this process has been widely demonstrated [Duraisamy, 2021]). In many cases, a dense observation of the physical twin may be impossible (due to size/power/weight/accessibility restrictions on the sensors), and it may be necessary to “fill in” the gaps in observational data, for visualization, interpretability, fast anomaly detection and classification of the observed phenomena and perhaps also for decision-making and control of the physical twin. “Filling in the blanks” (or conditional generation) is a prototypical generative AI problem, and efforts have already begun to address scientific problems via the construction of generative (or “super-resolution”) models [Deng et al, 2019, Fukami et al, 2021]

At Sandia, we have demonstrated that by using a machine learned anomaly detection approach, it is possible to detect voids and other defects in materials DT. This paves the way for future research in integrating materials DT with its physical counterpart. Detecting anomalies in fatigued and fractured experimental materials is an interesting yet challenging topic. The reasons are threefold. First, the anomalous microstructure feature that gives rise to structural failure is small, sometimes in the order of 10^{-7} of the interrogated volume. This, in turn, results in a highly imbalanced classification problem in machine learning (ML). Second, the consequence is high, in the sense that the test specimen is destructed in such case. Third, the convolution between microstructure stochasticity and the small probability of void nucleation, growth, and coalescence makes failure and fracture a hard-to-predict and challenging problem in materials science due to its irreproducibility, even experimentally. In [Tran, 2024] we developed a materials DT and applied anomaly detection methods to detect voids and anomaly in additive manufacturing (AM). The materials DT is driven by two integrated computational materials engineering (ICME) models, which are kinetic Monte Carlo (kMC) and crystal plasticity finite element method (CPFEM).

Investigate Task Suitability and Sustainment of AI Tools: This action will involve locating potential case studies that examine the suitability of AI tools for use in DT application. The objective is to identify and gather information on real-world examples of AI applications, focusing on both successful and unsuccessful implementations. The objective is to distinguish operations currently identified as benefitting from AI augmentation from those that should remain under human control, considering factors such as complexity, ethical implications, decision-making requirements, and the potential for AI to enhance or detract from the task. Exercises will also be undertaken to evaluate hypothetical near-future operations and AI capabilities in the same manner. Through this investigation, a clear framework will be established to guide the desired use levels and roles of AI in supporting human operators. It aims to define the tasks that are appropriate for AI facilitation as determined by human systems researchers and the DoD and to highlight areas where the current limitations of AI technology and practical challenges make its application inadvisable.

Develop Requirements for High-Consequence Human-AI Decision-Making: Extending the activities of #1, this proposed action will evaluate the tasks deemed suitable for AI use from a risk standpoint. These tasks will be assessed across the spectrum of error consequence severity. Our objective will be to more fully characterize how consequence severity should be accounted for in deciding when and how to utilize AI tools in DTs. We will use formal methods such as failure modes and effects analyses (FMEAs) and less formal “what-if” scenario case studies to explore the consequence gradient with respect to potential AI-assisted decision-making activities.

Data: Encourage Adoption of Data Management Best Practices:

Digitals Twins will likely be purely data-driven or hybrid (a combination of approximate physics models augmented with machine-learned corrections). This is because the DT will need to be computationally efficient so that it can be kept calibrated to observations from the physical twin. This, in turn, implies that a DT will be associated with two data corpora – a training dataset (TD) for its machine-learned components and a calibration dataset (CD) gathered from the physical twin. Their (potentially real-time) integration with a DT demands new interoperability standards that enable seamless data exchange across models, systems, and platforms.

Strategic challenges: There are enormous challenges in assembling the TD, as the data must be informative about the physical processes that are of concern to the physical twin (e.g., aging, failures, tampering/sabotage etc.) *and* can be observed via sensors. While one can generate the TD using high-fidelity models, there are no automated means to detect whether a proposed dataset has the correct physics, in the operational regimes of interest. There have been attempts to gauge the physics-content of TDs, but these efforts are in their infancy [Barone et al, 2022]; without a well-developed capability to do so, assembling TDs for realistic systems, especially for rare phenomena like failures (i.e., the data will be largely model-generated), seem to be infeasible. A second, but related challenge lies in making such datasets FAIR (Findable, Accessible, Interoperable and Reusable). Finding datasets implies being able to index them in some fashion, and to date, only textual (and perhaps pictorial) descriptions of a dataset can be indexed. For quantitative modeling purposes, these are insufficient; instead, one needs summaries of the dataset that not only provide the physics content of latent information in the TD, but also (summaries of) features of the data – spatiotemporal autocorrelations, coherent structures, etc., that can be checked for correctness and interpreted via the laws of physics. Prototypes [Bien et al, 2011], which are elements of the TD selected from physically interpretable clustering of the TD [Barone et al, 2022] are one way of summarizing a dataset in this fashion; reducing the dataset into a simplified, machine-learned dynamical system e.g., Universal Differential Equations [Rackauckas et al, 2020] is an another. These methods, rooted in machine-learning, are far from being mature, but are necessary for FAIR datasets. Integrating these representational techniques for TDs into a searchable storage system remains a distant vision.

Tactical challenges: Before TDs can be assembled, they must be generated and contributed to a repository for checking, indexing, and archiving. This implies the need for massive *fast* storage in the computational centers where they are generated and where the DTs are learned. Cloud storage is sufficiently large but too slow to be coupled to supercomputing centers. In addition, a dataset, once accepted into a TD, needs to be described in text and "logged" into a metadata directory for easy perusal. There are efforts to design an appropriate scheme [Gebru et al, 2021] but it is debatable whether these schemata are complete for scientific TD. Further, there does not seem to be any effort to develop such summary textual descriptions for TD for DTs, let alone archive them and make them searchable. Such a capability would not be difficult to construct (i.e., would not require much research), but would need concerted (implementation) effort.

Ecosystem: Establish a National Digital Twin R&D Ecosystem:

To establish a National Digital Twin R&D Ecosystem, we recommend the following:

- Encourage interagency (federal agencies, national labs, industry and academia) collaboration & task force to coordinate DT R&D efforts and organize regular interagency workshops and conferences to share progress, challenges, and best practices.
- Identify the critical research gaps & fund interdisciplinary research projects that address these gaps, focusing on areas such as data integration, real-time analytics, and predictive modeling.

- Develop public-private consortia to collaborate on high-impact DT projects where industry and academia can collaborate on developing and testing DT solutions.
- Develop and promote standards to ensure interoperability and scalability of DT systems.
- Biomedical sciences: Develop DTs of (i) virtual patient model for better decision making / decision support system; (ii) monitor chronic disease to predict future conditions in advance and treat patient on time; (iii) surgical instruments and procedure to enhance preoperative planning and train surgeons, bio-surveillance to monitor public health; (iv) biological systems to simulate drug interactions, efficacy of drug, and identify side effects.
- Common mathematical, statistical, and computational foundations: (i) develop a framework that support multiscale modeling (enabling the integration of models at different spatial and temporal scales); (ii) combine deterministic and stochastic modeling techniques to capture both predictable and random behaviors in complex systems; (iii) use Bayesian inference methods to update DT models in real-time based new data; (iv) deep learning techniques to create highly accurate and scalable DT models; (v) integrate cloud computing technologies with HPC resources to provide flexible, on-demand access to computational power.

International: International Collaborations on Digital Twins:

By bringing together expertise from different countries and sectors, these initiatives are driving innovation and setting the stage for the widespread adoption of DT technology across various domains.

Digital Twin Consortium (https://www.digitaltwinconsortium.org/)

An international consortium including companies including Microsoft, Dell, and GE Digital, along with academic and governmental organizations. The Digital Twin Consortium aims to accelerate the adoption of DT technology across industries by developing standards, guidelines, and best practices. The consortium includes members from around the world, fostering global collaboration and knowledge sharing.

Horizon Europe Digital Twins (https://research-and-innovation.ec.europa.eu/funding/funding-opportunities/funding-programmes-and-open-calls/horizon-europe_en)

The European Union's Horizon Europe Program is investing in multiple DT activities. These include ocean and earth models as well as models focused on infrastructure and manufacturing.

The International Data Spaces Association (IDSA) (https://internationaldataspaces.org)

IDSA includes members from various countries, including Germany, the USA, Japan, and others. IDSA develops standards and architectures for secure data exchange in DT applications, particularly in manufacturing and logistics. The association's global membership fosters international collaboration on data standards and interoperability.

Omniverse for Microelectronics Fabrication (https://resources.nvidia.com/en-us-industrial-sector-resources-mc/en-us-industrial-sector-resources/gtc24-s62610?ncid=no-ncid)

This is an industrial collaboration Nvidia, Siemens, TSMC, Samsung and others. Nvidia's Omniverse capability for digital twinning is being specifically developed to support twins of microelectronics fabs. There is a potential for this to become a standardized tool within this space although there will be competing technologies. This is a capability that could be highly aligned with the CHIPS and Science Act as well as facilitating the incorporation of AI technologies through Nvidia's other products.

Long Term: Identify Long Term Research Investments:

The bidirectional flows of information required to build functional DTs require a commitment by all parties involved to incorporate a high degree of digital cooperation. The continuous integration and continuous deployment (CI/CD) technologies of software development (e.g. GitHub/GitLab/runners, etc.) are good examples of how such processes are currently developed and maintained. However, DTs require communication between many distinct software and data repositories with proper information protections in place that are both sufficiently secure but yet open to all appropriate entities and containing access to sufficient meta-data that automated processes can be built and maintained. A significant challenge to such a broad based and usable information environment is to provide overarching and broad-based data availability requirements so that the needed data and associated personnel expertise can realistically be supported. Combining experimental software and digital simulations requires a great degree of commitment to cross-disciplinary cooperation.

From a research point of view the main challenges to the development of DTs are the inherent roadblocks arising from scientific and engineering funding structures and culture that are misaligned with the DT ecological viewpoint. Research should be funded to demonstrate specific instances of DT systems that bring together experimental and digital computing technologies and be required to show measurable benefits or failures so as to expose the essential issues needing improvement. Proposals that provide for delivery of multi-domain cross-cutting glue code that could be open sourced should be carefully considered. At this early stage working demonstrations of real systems that expose the essential requirements of DTs should be funded and the results presented as widely as possible. The development of systems and processes that enable easier maintenance and evolution are essential since the whole idea of a DT is a continuous monitoring and improvement.

Rudimentary DTs (per the NITRD definition), with bi-directional coupling, already exist – a common example would be a model of an oil/gas reservoir that is kept calibrated to monitoring wells' data and periodic seismic surveys and which are used to make decisions e.g., enhanced oil recovery, that significantly impact the nature and response of the physical twin. The primary challenge has been the steady improvement in the density, quality and modalities by which measurements of the physical twin are made, as they require a concomitant improvement in the sophistication of the model – one cannot assimilate measurements of a physical process unless it is included in the DT. It is never very clear which processes should be included in the model, and their inclusion invariably increases the computational cost and numerical pathologies of the model (including the embedding of machine-learned phenomenological models / closures for higher fidelity); despite these complexities, the DT must be subjected to sequential data assimilation / calibration to streaming observations. The continuously assimilation of multiscale measurements has been achieved, to some degree, in Earth system models, but employing a hierarchy of model of variable fidelities, but what this hierarchy may be for an arbitrary physical twin is unknown and has not been attempted. Successful sequential data assimilation will require robust calibration techniques that adapt to increasing complex models, or their hierarchies, and these simply do not exist today.

Trustworthy: Realize Secure and Trustworthy Digital Twins:

A key opportunity for DTs is that they can enable comprehensive analyses of security and cyber resilience that are not practical on the physical counterpart. Sandia has previously explored the use of process models as DTs to model and analyze activities in physical [SAND2023-14702, SAND2024-00219] and cyber systems [KTR-2024-003]. A process model is a graphical or logical representation of an operational process or workflow, including events or activities that occur in the workflow, how they are executed, and their logical relationship to other activities and resources. Although there is a robust literature on the use of process models in both the business and engineering applications, many research questions remain concerning their use as DTs. For example:

- How do we develop trustworthy process models from sparse, noisy data sources?
- How can domain information, including subject matter expertise, be effectively integrated into process models?
- How can process models capture both statistical and logical relationships in physical systems?

Ongoing research at Sandia is starting to consider research questions like these (e.g. [SAND2023-06726C]).

DTs seek to represent the behavior of complex cyber-physical systems, thereby inheriting the complexity of the systems themselves. Due to their nonlinearity and vast state spaces, establishing trust in DTs is generically very difficult, especially if they are constructed as monolithic, fully detailed models. R&D is needed to discover appropriate multi-fidelity modeling abstractions and decompositions that make DTs tractable and scalable for analysis and verification.

Trustworthy DTs should ideally be the result of rigorous model-based engineering. That is, models should be constructed iteratively throughout the engineering process and be used to guide *design for analyzability*. This will improve robustness of both the DT and the system itself. It is much easier to establish trust when starting from simpler high-level models and incrementally refining them, in a way that generates mathematical evidence (such as formal verification) of their consistency and conformance.

When the iterative engineering process is complete, the collection of these interrelated models constitutes a more useful DT for the system because it captures the decisions and reasoning that tie the system's components together, and tie the fully detailed behavior to the higher-level requirements and functional models. This allows particular questions about the system to be addressed using DT models of an appropriate scope and detail for the task, providing an improved basis for trust.

VVUQ: Develop Rigorous Methods for Verification, Validation, and Uncertainty Quantification for Digital Twins:

VVUQ represents a foundational commitment to quality and continuous improvement. This means that the DT ecosystems will be continuously changing, improving and evolving. A healthy VVUQ ethos should be expected and funded from the beginning, and embedded into all stages of the DT life cycle, e.g., following the ASME VVUQ Standards.

Complex systems are ubiquitous across all of science and engineering and beyond. Historically, improving understanding of complex systems has involved building models of these systems and using these models to develop a simulation framework; that is, a virtual representation of the system. These simulation frameworks have evolved over the past decade into the concept of a DT [National Academies, 2023], which involves bridging the virtual system and the physical system it represents. The recent SIAM Report on the Future of Computational Science [Hendrickson, 2024] notes that while DTs present enormous opportunities, their development faces great mathematical, statistical, and computational challenges. Models of complex systems are subject to a wide variety of sources of both epistemic and aleatory uncertainty that must be quantified to enable robust and informed decision making. The accurate prediction of the behavior of complex systems, utilizing DTs, are necessary to inform critical decisions that can enhance national security and/or avoid substantial human and financial losses. Moreover, risk assessment is needed to quantify the effect of uncertainties on the severity of predicted outcomes. Rational decision making requires robust, accurate, and computationally efficient methods that can compute quantitative metrics on actionable time scales.

However, as noted in [National Academies, 2023], “verification, validation, and uncertainty quantification as essential tasks for the responsible development, implementation, monitoring, and sustainability of digital twins", however, “a gap exists between the class of problems that has been considered in traditional modeling and simulation settings and the UQ problems that will arise for digital twins." Thus, the integration of robust metrics in decision making workflows faces several critical challenges. First, probabilities must be conditioned on available observational data. While numerous advances have been made in Bayesian inference to characterize epistemic uncertainty, far less attention has been paid to aleatoric uncertainty. Moreover, almost no attention has been given to conditioning both epistemic and aleatoric uncertainty on data in a unified framework. Second, quantifying metrics from the push-forward of posterior distributions is computationally demanding for existing methods that rely solely on high-fidelity simulations. Techniques such as Markov Chain Monte Carlo (MCMC) require numerous evaluations of the simulation model, which are often intractable even on leadership-class computing resources. Third, there is a need for more efficient methodologies for optimal experimental design (OED) to guide data acquisition efforts that will optimally improve model parameter characterization and the subsequent reliability of the predictions made using the computational model. All of these challenges are amplified when models are parameterized by large numbers of uncertain variables and risk-assessment must be executed on actionable time-scales.

Addressing these challenges will require advances on multiple fronts and combining concepts from different fields. Enabling fast and credible predictions for decision making using models of complex systems requires the integration of state-of-the-art UQ methods and Scientific Machine Learning (SciML) approaches. SciML is well positioned to address the high-dimensionality of parameterizations and the computational cost of coupled models that currently limits the complete adoption of UQ in scientific workflows. To serve as the basis for decision-making, new AI/ML approaches must be developed that respect the data, respect the physics and their well-developed numerical treatments, and be able to quantify the uncertainty in their outcomes.

For DTs of complex systems to be truly useful, a holistic UQ framework that addresses both epistemic and aleatoric sources of uncertainty is required. Moreover, such a framework should be replete with computational diagnostics that allow for AI-enabled inferences and decision making in the presence of such uncertainties. Recent work indicates that leveraging information from a population of assets through the solution of an aleatoric stochastic inverse problem to build population-informed priors can significantly reduce the uncertainty in asset-specific Bayesian (epistemic) inferences [White, 2024].

AI system security capability (EXCALIBUR) provides methods to examine (attack and measure) the security of systems that use data-driven models. EXCALIBUR examines broader perspectives beyond the data-driven model and data focusing on (1) the reliability and robustness of the system and how it will behave in novel conditions, (2) the vulnerability of the system to adversarial attacks, and (3) the vulnerability of the data driven model to being affected through cyber-means. EXCALIBUR bridges the gap between established capabilities in machine learning, adversarial machine learning, and cyber-security to focus on AI systems. We provide real-world insights and lessons learned through assessments on actual AI systems including a DT cyber defense technology for process modeling (PROM) that utilized subspace identification techniques to model dynamic behavior in industrial processes. With this "digital twin" of the physical industrial process plant, PROM can operate as a cyberphysical intrusion detection system to detect anomalous behavior. EXCALIBUR evaluated adversarial threats to this DT system and identified weaknesses that may be exploited to compromise system performance and trustworthiness.

Workforce: Cultivate Workforce and Training to Advance Digital Twin R&D:

Integration of AI and DTs in high consequence applications required a specialized workforce with a diverse set of skills. The skills can be broadly categorized into technical expertise, domain expertise, multi-disciplinary skills, and maturity involving awareness including soft skills such as communication. With regard to technical expertise AI and machine learning skills are required for developing the algorithms that drive the predictive and analytical capabilities of DTs. Individuals proficient in data analysis, model training and algorithm optimization will play a crucial role. Further staff will be required to efficiently handle large volumes of data processing, visualizing and managing simultaneously. Fundamental understand of the data structures and governance would be key to enable the workforce. Domain expertise would be addressed by industry specific experts with deep insights and knowledge of the specific high consequence fields such as nuclear deterrence (design and manufacturing) or global security or satellite systems. Individuals who understand the operational aspects of the complex systems being modeled; play a foundational role as they bring the physical connection to help validate the DT models. System engineers and project managers with multi-disciplinary skills who can take a holistic view of the entire system, ensuring that all aspects (hardware, software, data, and processes) work together effectively. Systems engineers play a crucial role in managing and maintaining a complex interconnected physical system which would apply to the DT model as well. Continuous learning and training for the workforce will enable to team to stay updated with the latest advancements which would be both on the job training as well as formal education. Staff supporting environments where workforce can experiment and learn about DT and AI systems without impacting critical path tasks adversely. Workforce knowledgeable in topics such as safety, security, and other regulations and guidelines as applied to DT and AI systems will be integrated into teams.

Sandia's FORGE ND program aims to revolutionize the onboarding and training process for new employees at Sandia National Labs by integrating artificial intelligence (AI), large language models (LLMs), and the digital environment into an apprenticeship-based learning model. This initiative addresses the lag time between theoretical knowledge and practical application, ensuring that new hires become productive more quickly and efficiently.

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Request for Information on the National Digital Twins R&D Strategic Plan

Scott McClure

Via FDMS

Scott McClure, 7/28/2024

[redacted]

My colleagues and the NIBS team I work with are submitting a separate comment to make recommendations for the National Digital Twins R&D Strategic Plan. Unlike that submission though, this comment is one perspective regarding a separate, often overlooked area for these complex sociotechnical systems. The below recommendation to promote grant funding for research into culturally sensitive change management is applicable to the topics of Business, Ecosystem, Regulatory, Responsible, Standards, and Workforce. Through my efforts leading the Digital Twin Integration Subcommittee and co-authoring two papers on the subject of Digital Twin (with a focus on the general public), I've come to realize that the interdisciplinary social challenges of bringing an organization to work with a Digital Twin are most often oversimplified in a subtle regard: though there is a tendency to rightly say that the technical requirements are complex, advocates generally assume that once the system is developed the workforce will simply want to use it. This "field of dreams" approach risks neglecting the "socio" component of the sociotechnical system, and my experience has been that it very often results in mistrust, delayed adoption, and inefficient/ineffective implementation. Evidence of this often shows in the struggles to transition Digital Twins from R&D into operations (i.e. “crossing the chasm”). I think it can be said that dynamic organizations need effective change management, but this can and should begin well before investments are made to develop a Digital Twin. Clearly, the organizational culture must be understood so that the tool can be effectively designed to better promote a healthy shift into this future reality. But unfortunately, few organizations - particularly in the federal government - have change-practices that address the subtle cultural sensitivities around digital transformation. Stated plainly, the problem is that many folks in the workforce do not trust this type of change. Worse, framing this skeptical population as the "late majority” or "laggards" (a popular innovation framework) creates a cross-cutting adversary rather than a resource. They tend to be disregarded even though their insights do have value. As a result of this negligence, their disaffected narratives drive resistance and degrade quality in transformation efforts. But few recognize that, in some ways, this fierce independence is a hallmark in the identity of the American People, something that must be well considered! And once researched, any effective, scientifically derived change management strategy must be authoritatively communicated throughout organizations facing this sort of disruptive change. Therefore, I propose that the FTAC on Digital Twins recommend in the national strategy "grant funded research into optimized and scientifically derived strategies for culturally sensitive change management in the Digital Twin domain". This type of research can affect responsible innovation throughout the US economy, particularly if it is implemented as a whole of government effort across key federal industries (because federal contract language drives many topics of discussion within organizations and trade venues, and research findings in this area will be attractive to many businesses). In support of this proposal, consider the following NITRD request statement: "a Digital Twin is a set of virtual information constructs that mimic the structure, context, and behavior of a natural, engineered, or social system." Though a Digital Twin may not be of the social system (implied by the use of "or"), the social component of a Digital Twin cannot be disregarded because Digital Twins change the tools used by the American workforce and these tools are a part of the identities Americans live by. This makes Digital Twin a social issue! Implemented poorly - even when guided by the right motivations and the best technologies - this risks harming cultural identities and undermining our best efforts to change. In closing, it should be noted that the industry I've spent my career in (the Architecture, Engineering, Construction, and Owner/Operator industry) is the single greatest industry for suicides in the United States. Based on 15 years of experience, I believe much of that comes from the difficulty in transitioning blue collar workforces through a series of maligned and haphazard "identity changing" management efforts. Grant funding "culturally sensitive change management" can address key national priorities such as suicide prevention and is highly likely to develop methods that fast-track agency missions through responsible, informed, and compassionate change practices. And thank you. I appreciate the NSF providing the public with the ability to submit individual comments for equal consideration on merit even though these comments may not be as refined as many of the submissions you're otherwise receiving.

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Request for Information on the National Digital Twins R&D Strategic Plan

SLAC National Accelerator Laboratory

Digital Twins for Enhanced Modeling and Control of Light Sources and Neutron Sources [1]

SLAC National Accelerator Laboratory

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1 Introduction

Light sources and neutron sources play a key role in understanding the fundamental properties of complex matter at different time and length scales by capturing their structural and electromagnetic dynamics. These scientific facilities rely on some of the most complex machines humans build. For example, X-Ray Free Electron Lasers (XFELs) are driven by particle accelerators and produce highly coherent light for detailed imaging of samples, and their operation requires close integration of many subsystems: high-performance particle accelerators, sensitive magnetic undulators to produce X-rays, high-power X-ray optics, and sophisticated detectors and complex sample environments (e.g. synchronized pumping with ultrafast lasers). Comprehensively exploiting the capabilities of light sources and beamlines can lead to new scientific discoveries in a wide range of fields, such as biology, chemistry, physics, and material science. Increasingly more complex instruments and light source capabilities can enable unprecedented measurements to unravel the fundamental properties of matter. However, the scarcity of neutron and light sources relative to the large experimental demands leads to a shortage of allocated beam times. Consequently, there is a pressing need to develop real-time data analysis and experimental guiding capabilities in order to make efficient use of limited experimental time and maximize the scientific value of the collected data. Additionally, there is a need to reduce the large amount of time that is currently spent setting up facilities for delivery to different experiments.

Experiments at light sources can benefit greatly from **digital twin (DT)** technology, which can leverage prior measurements, known parameters, and theory to guide sampling strategies during an experiment and to produce unique scientific insights. DTs will be critical for streamlining operation of user facilities, which involves complex system control. Light sources are also ideal test beds for the development and deployment of DT technology. They are highly dynamic systems with many deliberate and unintended changes in conditions over time, they are made of multiple complex interacting sub-systems that need to operate in concert for optimal performance, they have physics simulations that can be readily leveraged and fused with measured data, they provide a more contained environment in which to explore DT concepts than many other applications (in contrast, for example, to DTs of global climate), and there are many light sources worldwide with shared designs, enabling the exploration of technology that is easily interoperable and exchangeable across systems. Experience with such test beds will be critical for developing reliable, sustainable, interoperable DT infrastructure that can be used across the numerous application areas of US national interest (climate, energy grid, etc.).

A prominent example of a complex light source is the one-of-a-kind, high repetition rate

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1-MHz LCLS-II, which opens a new era for XFEL science and technology. This new superconducting linear accelerator will be delivering photons at unprecedentedly high repetition rate and brightness, with ultrafast time-resolutions to unravel new physical phenomena. The LCLS-II exploits complex instrumentation capabilities to enable unprecedented scientific measurements. To make full use of these capabilities, at SLAC we have begun developing and deploying parts of a facility DT ecosystem and identifying areas of urgent need for current and future R&D. In this response to the NSF request for information [1], we outline challenges for operation of light sources, the role DTs could play in improving operation of light sources and promoting scientific discovery, and R&D needs to bring DT technology to fruition for these systems.

1.1 Challenges and Needs for Operation of Light Sources

Many challenges complicate operation of a light source, including the high dimensionality of available settings and input parameters, numerous sources of uncertainty, and nonlinearity of system responses. These can make it extremely challenging to fulfill specific beam parameter requests within required tolerances for different applications. User experiments also require different experimental parameters (e.g., x-ray parameters, different samples, different acquisition and analysis modes) that need to be delivered on-demand. Because meeting these needs typically requires laborious hand-tuning by expert human operators, the range and number of science experiments that can be performed is significantly reduced. This is both due to the time it takes to set up individual experiments and the challenges in achieving and maintaining the required beam quality. Time-varying changes in the facility conditions (e.g. initial beam characteristics, RF cavity phase calibrations, ambient temperature) complicate the task further.

An increasing suite of experiments also require precise dynamic control over the beam during an experiment. For example, X-ray correlation spectroscopy requires the separation between two electron bunches to be smoothly scanned, which is highly challenging and necessitates joint tuning on accelerator and photon beamline settings to achieve extremely delicate final beam parameters. The demanding level of fine control required by new experiments requires monitoring and adjustment of settings across the entire facility to carefully control the beam evolution from the beam source to the experimental area. Finally, although physics simulations can aid experiment planning and operation, these are also challenging to construct in ways that provide sufficient accuracy relative to the real machine behavior, due to the many nonlinear phenomena and the high dimensionality of these systems (for example, LCLS-II at SLAC will have over 2M variables to monitor). Despite many advances in automated tuning based on artificial intelligence and machine learning (AIML), the majority of adjustments, complicated diagnostic analysis, and assessment of machine behavior still require human operators.

Another aspect of operation is "experiment steering," in which information relevant to the final science outcomes is provided on-the-fly during an experiment and used to suggest next steps in the experiment (e.g. new beam conditions to examine for a particular sample). These approaches can provide insight into how best to maximize information gain for a given experiment. This requires, for example, fitting of many physically relevant model parameters and determining which are most likely given the data. Techniques such as Bayesian Optimal Experiment Design (BOED) can then be used to suggest experimental inputs that would further reduce possible model uncertainty and aid better determination of the physics model. This process requires sophisticated analysis of user experiments (including both diag-

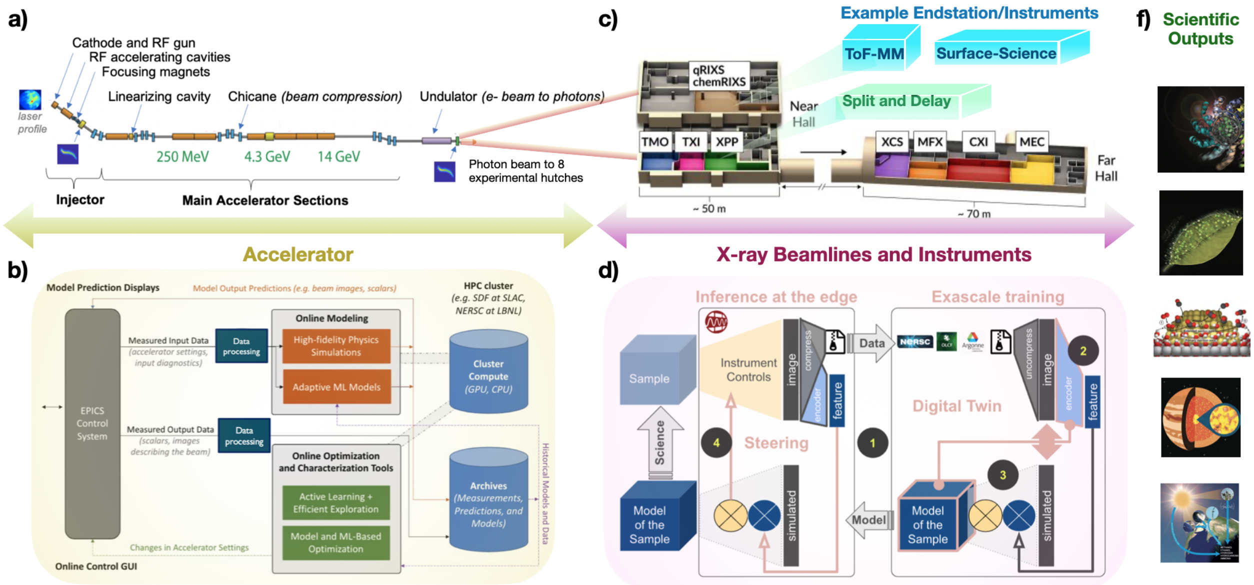

Figure 1: Layout of the LCLS accelerator and X-ray Free Electron Laser (XFEL), which delivers photon beams to myriad scientific users in biology, molecular dynamics, drug discovery, and chemistry. An outline of desired end-to-end alignment spanning from the accelerator to XFEL and scientific user experiments. Schematic diagrams of (a, b) the accelerator and associated DT and ML-based control infrastructure under development. (c) The x-ray free electron laser that delivers photons to different beamlines for user experiments, including gas phase, liquid, material, biological science. (d) Desired DT model and framework for an LCLS beamline and instrument. The flow chart describes the needs and challenges, including (i) framework for timely data and model transfer across data generating and data processing DOE facilities, (ii) large area detector image encoding, (iii) accurate and trustworthy differentiable simulators, (iv) leveraging information flow from sample parameters to instrument parameters for actionable experiment steering. (f) Scientific outcomes of experiments, which will directly benefit from developed end-to-end DTs and machine learning models.

nostic data processing and inclusion into physics modeling/analysis) to be tightly integrated with the optimization of (at minimum) the photon beamline setup. Incorporation of this information into start-to-end DTs to aid joint accelerator optimization and control, photon beamline optimization and control, and experiment analysis, would greatly reduce overall time-to-science, improve efficiency, and aid discovery.

Overall, there is an urgent need to decrease the overall time-to-science, ensure sufficiently high beam quality can be achieved and stably maintained for experiments, and enable new capabilities such as dynamic control over the beam. Coupled to this, there is a need to integrate on-the-fly analysis of user experiments to feed back into the direction of a given user experiment.

1.2 Role of Digital Twins in Meeting Light Source Needs

Accurate fast-to-execute system models that are kept updated as the light source enters new regions of parameter space could substantially improve online monitoring and control of the facility, as well as aid the ability to infer structures and molecular dynamics directly from the data, achieving the demanding performance for experiments that will fuel future discovery.

We take a DT to be a data-informed digital model of a complex physical system in all its aspects [2] that tracks the real inputs to the system and provides feedback to the system. As the RFI notes, the two-way interaction is a key element of a DT. They may leverage both physics information and artificial intelligence / machine learning (AI/ML).

In particle accelerators and light sources, a facility DT can be used to provide insight into global machine behavior during operation (including to identifying anomalous behavior and prompt faster intervention), provide estimates of beam behavior that are not able to be observed at sufficient speed or resolution with conventional methods (i.e. virtual diagnostics), be used directly in online model-informed optimization and control, and be leveraged in experiment steering. This includes optimization for experiment setup, continuous control for stable delivery and correction of unintended time-varying changes, and integration of live feedback from the scientific output of user experiments. Note that in addition, a DT can be copied at a certain point in time and used offline for experiment planning, design of new diagnostics or beam manipulation hardware, and prototyping of software and algorithms for analysis and control. Aside from a DT of the facility, a DT can also span the interaction between the incoming beam, a particular physical/material process under study (including unknown physics parameters), and measurement devices. DTs and ML models can also enable extraction of scientific understanding from new measurements. Combined with accelerated and parallel computation on GPUs, this can enable live-analysis to steer experiments and data collection. By linking facility DTs to DTs for specific experiments, active feedback to both the next steps in the experiment and to the facility controls can be linked to enable highly-efficient, precise experiment guiding.

SLAC has been developing and deploying technology to enable DTs of LCLS instruments, the LCLS-II accelerator, and other particle accelerators it stewards (e.g. FACET-II, MeV-UED, SSRL). These efforts span improvements in the speed of execution of physics models through the use of AI/ML, improvements to the overall accuracy of system models through coupling physics simulations and data, incorporation of deployed system models into improved online optimization of machine setup, development of software infrastructure and workflows for deployment of DTs and feedback control, and approaches for streaming ML-ready data. Work has also been ongoing to integrate new analysis techniques, including based on ML, into fast analysis of user data to aid experiment steering. Below we briefly describe several current and future applications and areas of need for DTs at LCLS-II, including open challenges.

1.2.1 Current Examples and Future Use Cases for LCLS-II

Accelerator Operation: As one example, open-source software developed at SLAC has enabled substantially easier construction of start-to-end simulations that use different physics codes for different parts of the accelerator [3, 4]. These tools are highly inter-operable and have, for example, been used with minimal additional effort to run online physics simulations for the LCLS-II injector and the FACET-II injector. These online physics simulations were used during LCLS-II injector commissioning to aid the intuition of physicists in the control room, which when coupled with automated tuning reached the highest beam quality (measured in terms of the beam emittance) then seen during commissioning. This infrastructure has now been expanded to start-to-end simulations of the accelerator and deployment on the local HPC cluster (the S3DF) using tools such as Prefect and Kubernetes. This enables physics simulations with relatively high fidelity to be computed based on live input in minutes for quasi real-time information in the control room. Surrogate models based on ML enable even greater execution speed. These models have then been used to provide priors to

Bayesian optimization and similar approaches to more efficiently tune the accelerator (e.g. see [5], and [6] for a survey of techniques). Substantial software development and infrastructure is still needed to develop and deploy the system for true facility-scale prediction and control.

Tuning of Complex Photon Instruments and Beamlines: Relevant challenges for XFELs and ultrafast lasers includes stochastic characteristics of input laser and x-ray parameters, constantly changing sample environment, massive data rates and quantity ($\sim$ TeraBytes), live-analysis, and fast feedback for experiment steering. Hence, accelerated computing and computation are required to extract scientific understanding on a reasonable timeline. Trained DTs can enable pre-alignment, optimization of crucial parameters, and auto-alignment during beam times to maintain optical conditions. Efficient and live analyses of the massive incoming data become crucial for steering relevant experiments and data collection. We have been developing DTs for the split and delay, ToF-MM, cyo-EM, and will expand to other complex spectrometers, the RIXS endstation, and the LCLS-II/-HE beamlines.

Split and Delay Lines: Particular challenges include the tuning and control of complex photon optics in a beamline, which consists of perfect crystals to focus and redirect beams. X-ray beams are sensitive to nanoradian-scale mirror misalignments and picometer-scale thermal deformation of crystal optics. The very narrow and highly non-linear acceptance of X-ray optics (especially diffractive single crystal optics), make for isolated, sharp optima in in otherwise vast and mostly featureless search space. As state-of-the-art light sources such as XFELs mature, the complexity of X-ray optical schemes tends to increase to push the boundaries of beam characteristics for enabling new scientific directions. Examples include split and delay systems that enable X-ray pump/X-ray probe and X-ray probe-probe measurements, tunable high resolution monochromators, nanofocusing/nanoimaging systems, pulse shapers, etc, some of which already exist and others that are under development. There are typically > 10 critical motion degrees of freedom for most of these optical system. Extreme sensitivity to changes in thermal loading from absorbed beam power, frequently deforms the system significantly from ideality, making tuning and drift correction by a human operator very challenging if not impossible.

RIXS and Momentum Microscope: The resonant inelastic X-ray scattering (RIXS) and time-of-flight momentum microscopy (ToF-MM) instruments/ end-stations are currently being commissioned and offered to the scientific communities. Developing DTs and ML models can tackle these challenges with the ongoing advancements and innovation on the instrumentation and beamline frontiers. For example, the end-to-end ML model will enable real-time optimization of electron optics to minimize time to alignment and optimization of ToF-MM, which is a momentum imaging electron spectrometer, while incorporating feedback from a DT of the detector systems to increase the feasibility of studying complex matter. ToF-MM consists of 500+ tuning parameters to enable direct momentum or spatial imaging to comprehensively capture the properties of matter. The vast parameter space presents a prohibitively difficult optimization problem during limited time during beam times for complex targets. Automated tuning leveraging a DT could help gather data to further develop analysis of new classes of materials and molecules via photo-induced processes, such as phase change, band transitions, electron-phonon coupling dynamics, and photoinduced isomerization.

Photon Experiment Steering: Analysis of imaging experiments typically entails solving ill-posed inverse problems through iterative methods that cycle through estimating parameters of a forward model mimicking the experiment and updating of the sample of interest. Traditional approaches to the first step suffer from lack of scalability to large datasets while the second step often imposes limits on the complexity of the models used to describe the experiment. Hence, researchers at SLAC have explored the ability of these generative modeling strategies to perform single shot ab initio processing of unfiltered cryoEM datasets, freeing the analysis process of typically tedious and error prone manual intervention, and the ability to tackle heterogeneous datasets that resisted traditional solvers and allowed the discovery of new sample states [7]. They demonstrated a general framework (Fig 1. d.) that can accommodate different representations of the sample and its dynamics by representing them directly at the atomic level [8–10]. They then successfully applied this model to X-ray coherent diffraction images of isolated particles [11]and are actively working on mapping the framework to all the imaging modalities encountered at LCLS, including ptychography [12], inelastic scattering [13] or crystallography.

2 Needs and Challenges in Digital Twin Technology for Light Sources and Neutron Sources

While substantial progress has been made toward development and deployment of DTs for light source facilities and experiments, much work remains to see DTs brought to fruition and put into day-to-day use, especially at the scale of an entire facility. This ranges from fundamental improvements in AI/ML techniques for modeling and analysis, to the need for reliable software ecosystems for deployment of DTs and handling of streaming facility data, to improved physics modeling, to integration with high performance computing (both local systems and the larger DOE HPC ecosystem). We describe these needs in further detail below, loosely following the structure of topics listed in the request for information.

2.1 AI and Digital Twins

AI/ML for Facility System Models and User Experiments: A major challenge in light source facilities and accelerators is the ability to obtain physics models with sufficient accuracy and execution speed to be leveraged in live prediction and control. The as-built system often differs from design due to numerous compounding sources of error and non-idealities that are typically not included in physics simulations (including time-varying behavior). Physics simulations are computationally expensive (e.g. it can take many minutes to hours for a single simulation). ML models can aid automatic determination of likely error sources (and associated uncertainties), even for high-dimensional systems; they can also serve as fast-executing surrogate models for physics simulations. In cases where no physics simulation is available, ML models can be trained on empirical data.

However, there are challenges in reliably using ML for modeling these systems. The time-varying nature means they are both deliberately and unintentionally brought outside of the statistical distribution of the training data, prompting a need for more generalizable modeling methods, improved uncertainty quantification, and the ability to adapt to changes over time (see "continual learning" below). These systems are also very high-dimensional, which in and of itself can be challenging for ML modeling. Further, because a major aim is to use ML system models in online experiment steering and control, it is desirable to have some interpretability in the model.

Light source facilities are also simultaneously data-rich and data-poor: there is usually extensive archived facility and user data, but it can be spread across many different distinct operating modes in ways that are not conducive to easily learning global system models. Physics simulations can be run on HPC systems, but are computationally expensive in ways that limit the ability to make sufficiently large data sets (e.g. tens of thousands of samples).

There is a need for sample-efficient methods for driving data gathering in simulation and measurement, as well as techniques for sorting through and cleaning large amounts of archive data (which may include ML-based approaches to data clustering and tagging).

Physics Informed ML and Differentiable Physics: Various approaches are being investigated to combine ML models and physics information to improve the sample-efficiency, generalizability, and interpretability of learned models. For example, multi-fidelity modeling can capture information from multiple different types of models (coarse analytic representations, detailed numerical physics simulations) and different data sources (e.g. slower detailed diagnostics and faster coarser or noisier diagnostics). Differentiable physics simulations can also be coupled to ML components to enable learning of high-dimensional unknowns in a way that is highly constrained against the physics (e.g. see [14, 15]).

Unfortunately, differentiable physics simulations are challenging to produce. Automatic differentiation (AD) systems are ubiquitous for training traditional AI/ML systems; however, the complexity of physical models can require reaching beyond this typical scope of AD systems. For example, some challenges require novel R&D for their use in differentiable simulators, such as the presence of discontinuities in physical models, especially discontinuities that depend on the parameters of interest, and require the development of novel methods for differentiation. Several strategies are in development for such challenges, such as smoothing, relaxing, or adding randomized perturbations to such systems, to enable differentiation [16–19]. Further R&D on differentiable simulations will greatly expand the our capabilities to develop accurate and more robust differentiable simulations for scientific facilities.

Continual Learning: As ML models are used on data that is outside of the statistical distribution of the training data, they become less accurate in their predictions. A major challenge is thus keeping these models updated over time and quantifying uncertainties in their predictions, alongside trying to develop methods for improved generalization to unseen conditions. For an accelerator setup, this could be due to putting the accelerator in a fundamentally different configuration of settings to enable new beam parameters, or due to slow unintended drift in parameters. The challenges are even more acute for photon beamlines, which are frequently reconfigured for different experiments and examine an ever-changing variety of different types of samples. Software infrastructure to support continual learning is needed in addition to fundamental AI/ML approaches. Constraining learning with physics information can help aid continual learning, as could the development of larger, more comprehensive community data sets, leading toward foundation models. Overall, this is a large area of need for R&D.

AI/ML on the Edge: The re-programmability of emerging EdgeAI accelerators makes it possible to deploy a custom ML inference model for each detector and experiment, and even for individual shifts. This flexibility allows EdgeAI accelerators to deliver actionable information within minutes of source or target conditions changing during active experiments. FPGA and edge devices, however, have severe resource constraints that limit the number of parameters to the order of tens of thousands (in contrast to millions of parameters). The resources available at the edge are also limited in terms of I/O and memory. Developing a methodology to take offline-developed algorithms and adapt them to the constraints of the ASIC or FPGA environment and the streaming environment will be important if DTs are deployed in this hardware. Readout of high rate instruments may also be distributed; any given ASIC/FPGA may only see a fraction of the data, so algorithms must adapt to this distributed data environment. This is a major area of needed R&D.

2.2 Adoption of Data and Model Management Best Practices

ML-Ready Data and Data Cleaning: The BES light sources and neutron sources could generate thousands of petabytes of data per year[20]. DTs have the potential to transform experiment operations at these facilities and significantly reduce the time to science. This will only be possible, however, if BES leverages the totality of the acquired and simulated data and provides resources to ensure the data are FAIR. This includes the acquisition and central registry of data and metadata, curation and access to high-value datasets, the ability to search through the data for key characteristics, and the capture of provenance and context. Tools will need to be built to enable the registry, indexing, and availability of these large and multi-modal datasets. Likewise, the AI/ML products generated also need to be curated, the provenance and context recorded, and the models rendered easily findable by users. In many cases, preparing the data for ingestion to a DT or AI/ML model is vital and time-consuming; data preparation could include reformatting the data, eliminating outliers and missing data, and ensuring that the metadata provided are accurate and have appropriate units.

On-the-fly Data Analysis, Data Logging: Information about the performance of the DT on data in-flight is vital to validate the performance of the DT, train new DTs, and for doing error analysis. A DT is never just one piece of code running in isolation, but a collection of codes running in, potentially, geographically separated environments. We must maintain the ability to benchmark the performance of the end-to-end system and log the results of each individual job.

Data Movement: At LCLS-II data rates and data volumes, required computational resources will scale to hundreds of GPUs. These resources are not locally available, so LCLS will be looking to the DOE Leadership Class Facilities for training. Once the data moves outside of the local lab, and in fact, even when the data must move through local networks within a lab, data movement is a key concern. New methods for doing parallel data transfer on tens to hundreds of files while they are being written will need to be developed in order to accommodate the models and use cases that we are envisioning. Data movement also requires some certainty that data integrity is maintained, the ability to buffer data when there are bottlenecks along the path, and the ability to do data transfer seamlessly with little human intervention. Low latency networking at Tb/s is needed to keep pace with the expected data rate from LCLS in 2028.

Best Practices for Handling of Scientific User Data in Light Source Facilities: In BES, user data belongs to the user. Although individual user groups may extract science from their own data, the scientific community is missing an opportunity to fully leverage the overall data sets for the national good. Collective use of datasets to train DTs will enable a host of experiments, especially as DTs become more sophisticated and adaptable/tunable to new circumstances. However, if data are used to train a common model for the good of all, then there is an additional burden on the trainers and maintainers of that model to publish which data was used for the training and to define appropriate constraints on the use cases for that model. The facility should be able to use data to provide generic algorithms for the general good. The data generated by the BES user facilities is a national resource and models and DTs developed from these data are powerful tools that should also be useable across user facilities. Such data use will significantly enhance facility performance, but data provenance and use will need to be tracked through the system. In a national environment where DTs and models are reused at different facilities, it will become necessary to develop a methodology to understand the applicability of a model to an environment or experiment, or to develop a workflow for rapidly adapting/retraining a model to the new modality. Policy changes coupled to infrastructure improvements will be necessary to make DOE data and models a national resource, available to all with a clear understanding of how to use and adapt models to new modalities. DTs also cannot be a black box to the users. Users must have the ability to validate the performance of the DTs against their specific use case. Without some ability to verify the performance in real time during an experiment, users will be reluctant to use tools provided by the facility no matter how well documented and vetted.

2.3 Software Ecosystems and Computing Infrastructure

For successful deployment, we need to have a robust data path (maintain integrity, low latency, high throughput, with a low-touch interface), the ability to deploy code on remote HPC (many different architectures, environments, and local policy implementations), the ability to control/messaging pathways between distributed infrastructures, and workflow orchestration tools to allow users to deploy desired DTs with the desired parameters (adapted to the data/situation), parallelization, and ability to scale to HPC.

Another aspect is visualization and user interfaces. Even in a fully-autonomous DT environment, it is vital to monitor data analysis progress and measurement results as well as the recommendations from autonomous data analysis during experiments. Depending on the specific aspects of the experiment, it may be advantageous to incorporate a human in the loop, enhancing human insight with autonomously generated information. Development of tools that allow users to monitor status and interact with live data as its being produced to understand the performance of the data pipeline will be necessary to assist in the trustworthy deployment of such models. Similarly, for facility control, human operators typically need to monitor and interpret numerous signals streaming from the facility; having visualization tools coupled to a DT will be essential for aiding monitoring and diagnosis of operational issues, as well as aid decision making for improving or maintaining beam quality being delivered to experiments.

It also essential to develop software ecosystems that can be used across different facilities. For example, accelerator systems (even beyond light source use-cases) share many similar component designs, control challenges, and types of diagnostics. Photon science experiments and beamlines similarly share many characteristics and types of diagnostics. The establishment of a multi-facility framework and/or modular ecosystem of tools that can handle fast data analysis, autonomous experiment steering, and facility monitoring and control is crucial for supporting advanced research.

Computing systems are important to facility operation, data interpretation, and scientific productivity. DTs require computing to run simulations, to analyze experiments, to train new models, to retrain or adapt existing models to new modalities, and coordinate end-to-end workflow execution. As LCLS-II and subsequent upgrades ramp up, the computing needs will exceed available local resources. LCLS plans to make use of DOE Leadership Class Facilities such as NERSC for all aspects of DT workflows. Analyzing data and retraining/adapting models on experimental timescales will require a data path of sufficient bandwidth and integrity, tools for automated network orchestration, as well as the ability to deploy complex workflows deployed across local edge, including ASIC, FPGA and other AI/ML accelerator resources, local compute, and remote HPC resources. Workflow orchestration tools are needed to automate data movement, analysis tasks, and control algorithms to translate actionable information to directives used to steer the accelerator, experiment, or beamline based on the results derived from DTs executing elsewhere.

Seamless connection to Leadership Class Facilities will be vital to successful deployment of DTs at the light sources. The High Performance Data Facility (HPDF) and Integrated Research Infrastructure (IRI) program will be integral components in the overall strategy to harness the tremendous data rates and volumes produced by the light sources and neutron sources. Interoperability and uniform deployment of code on the leadership class facilities and uniform methods for securely transporting data (with integrity and low latency) will be vital to the successful deployment and use of DTs to steer accelerators and experiments and analyze scientific data in the future.

2.4 Other Considerations:

International Collaborations on DTs: There are numerous light sources worldwide that share similar challenges in operation, modeling, and data handling. For example, the layout, component design, and operation of the normal-conducting accelerator for LCLS is very similar to the accelerator for SwissFEL. This presents many opportunities for shared use and development of technology for DTs, ranging from software frameworks for deployment to AIML techniques and even direct transfer of ML models between facilities. Funding support and incentives for shared software development are needed.

Long Term Research Investments: Aside from the topics described earlier, some examples of long-term research topics include foundation models for enabling cross-facility and cross-experiment DTs, methods to appropriately integrate quantum computing (e.g. in cases where it is beneficial to include quantum simulations for physical processes, or solve complex optimization problems suited to quantum computing), and fully integrated co-design of future light source facilities to aid designing machines with the highest efficiency, broadest experimental capabilities, and/or best performance across target experiments. Improvements in operation of present facilities through the use of DTs, alongside the software infrastructure required to create them, can help inform design of future ones.

Workforce Development: DTs can also be used in training and workforce development. Training of beamline scientists and accelerator operators can leverage offline copies of DTs. Facility-agnostic infrastructure for DTs could be used at smaller-scale accelerators, such as those at universities, exposing students to advanced computing workflows, AI/ML, and advanced control in addition to preparing them for careers at light sources.

Business Case Analysis: In 2015, it was estimated that approximately 400 hours were spent on manual tuning by accelerator operators for initial experiment setup at LCLS, corresponding to 9-10 additional user experiments and millions of dollars equivalent value (taking into account the operating budget). ML-based automated tuning algorithms informed by system models have shown substantial improvements in tuning speed (e.g. 20x faster electron injector tuning [21]). Leveraging a DT of the entire facility in online tuning would substantially reduce time-to-delivery.

Going beyond the efficiency of individual facilities, the similar needs and structures across facilities means that critical infrastructure for DTs can be shared across them. Rather than having individual facilities construct their own infrastructure (which is a very large undertaking), ensuring software can be shared and co-developed across facilities will ensure resources are not wasted on duplicative efforts. Joint developments across facilities (including modular, interoperable software developments and standards) will ensure modeling and control technology can be readily transferred between facilities.

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Federal Register Notice: 89 FR 51554, Federal Register :: Networking and Information Technology Research and Development Request for Information on Digital Twins Research and Development, June 18, 2024.

Request for Information on the National Digital Twins R&D Strategic Plan

Spatial Web Foundation

Networking and Information Technology Research and Development Request for Information on Digital Twins Research and Development

Dear Office of Science and Technology Policy,

The full promise of Digital Twins will only be realized when they are deployed as an ecosystem of virtual representations of systems interacting with natural and artificial intelligence agents for decision-making. This multi-directional interplay between Digital Twins, physical systems, and agents requires new R&D activities to achieve trustworthy interactions. Research is needed in providing common interfaces to the variety of Digital Twin modeling methods; in defining robust interoperability between Digital Twins, sensors, actuators, and agents; and in fostering sustainable ecosystems of Digital Twins as sources of knowledge.

The Spatial Web Foundation (SWF) [1] is dedicated to the development and implementation of socio-technical standards that will provide a safe and secure and interoperable foundation for the Spatial Web. SWF is a community of developers, creators, scientists, innovators and ethicists with a shared mission to enable a hyper-connected, contextually aware, ethically-aligned network of humans, machines, and artificial intelligence.

The Spatial Web provides the holistic and coherent technical framework for the implementation of a collaborative, interactive, interoperable ecosystem of Digital Twins. As defined in IEEE P2874 Spatial Web Protocol, Architecture and Governance standard, [2] the Spatial Web is the conceptual and distributed computing system-of-systems for a shared world system of agents and knowledge domains. The Spatial Web depends upon Digital Twins to provide models of the natural, engineered, or social systems as the basis for agents to perform activities that meet the needs of socio-technical stakeholders. It aims to provide the technical framework required to handle the challenging topics of data integration and management, interoperability, verification and validation, and ethical and security concerns.

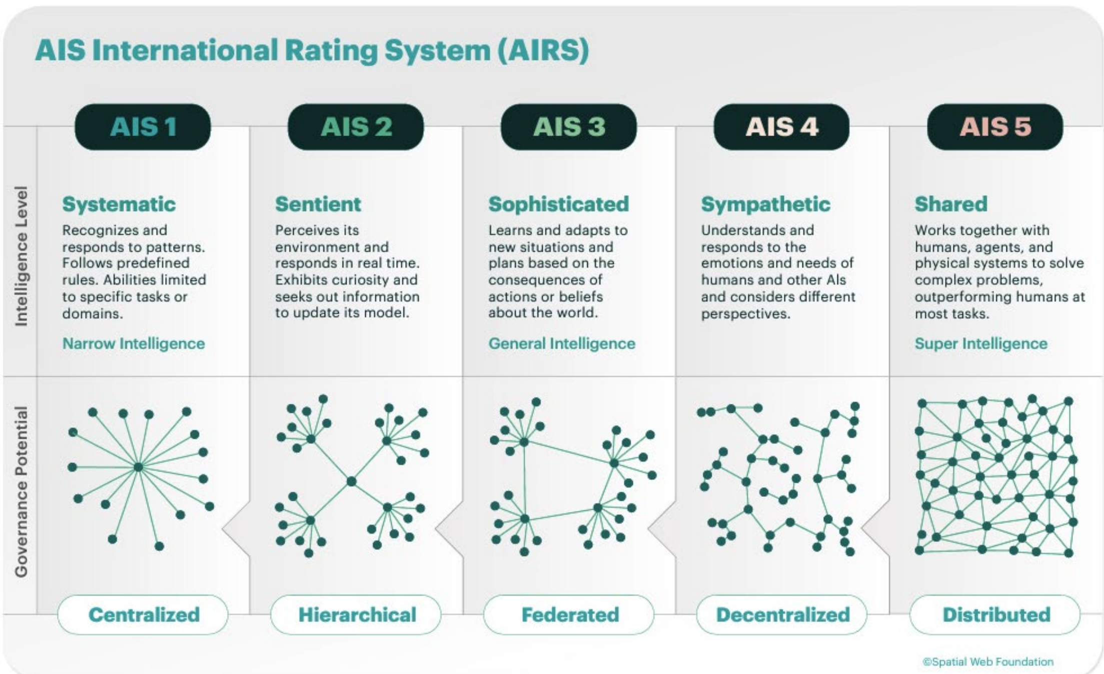
The specification and standards were accepted by the IEEE in July of 2024 and will be made available to the public by the end of the year. We humbly welcome the readers of this RFI to join our working group and would greatly value your guidance and input. See The Spatial Web Protocol, Architecture and Governance Specification Summary [3] for more information.

Trustworthy: Governance of AI and Digital Twins
In 2016, the IEEE launched the Global Initiative on Ethics of Autonomous Intelligent Systems (AIS) [4] to address ethical, legal, and social concerns in AI and autonomous technology design and development. These standards are informed by IEEE's Ethically-Aligned Design P7000 Series [5] of standards that address human rights, well-being, accountability, and transparency for AI and AIS. The IEEE P2874 [2] standards are being developed with SWF to address the following needs as it relates to building a future global AI governance framework:

1. Ensuring digital twins provide a shared understanding of meaning and context between humans and AIs.
2. Ensuring explainability of AI systems, enabled by the explicit modeling of their decision-making processes.
3. Ensuring interoperability of data and models that enable universal interaction and collaboration across organizations, networks, and borders.
4. Ensuring compliance with diverse local, regional, national, and international regulatory demands, cultural norms, and ethics.
5. Ensuring authentication and credentialing, driving compliance and control over critical activities, with privacy, security, and explainability built-in by design.

This new generation of socio-technical standards are being developed to scale at the speed of AI evolution. If adopted globally, these standards could enable us to steer AI systems, even those that exceed human-level intelligence. These standards lay the foundations for the efficient integration and adoption of AI technologies while minimizing the risk inherent in AI.

Such frameworks, if adopted, would enable stakeholders to select the desired level of autonomy they are comfortable granting to an AI system to operate within a particular domain. In addition, to assist regulators and stakeholders in assessing which governance frameworks are appropriate, and to comprehensively evaluate the capabilities and limitations of AIS under these frameworks, we propose the adoption of a multilevel AIS International Rating System (AIRS). Akin to the Society of Automotive Engineers (SAE) levels used for self-driving vehicles, AIRS would apply to any AI-powered system, ranking the levels of intelligence and autonomy exhibited and providing potential corresponding governance frameworks at each level. These levels and governance frameworks could replace the hierarchical ranking system being adopted in many jurisdictions around the globe. Dentons, The Spatial Web Foundation and VERSES Inc have published a report outlining their approach in this Future of AI Governance Executive Summary [6]



This table illustrates the proposed AIS International Rating System (AIRS).

Domains and digital twins can be used to simulate activities within a domain at scale, ensuring they comply with all safety, security and ethical standards before receiving the credentials required to be deployed into the real world.

R&D is needed in order for governments, regulators and industry to leverage these new socio-technical standards and adopt a new, sustainable framework for AI governance.

VVUQ: AI and Digital Twins need a standard language for trustworthy interactions. The Spatial Web has defined an ontology that defines the primary entities needed for a language that allows AI Agents to evaluate relevance of a Digital Twin to the Activity being performed by the Agent. Once a Digital Twin is identified, the AI Agent defines and structures Activities to be executed over time. In some cases Contracts between the AI Agent and Digital Twin will need to be agreed upon in order to establish the basis for reliable execution of the Activity. The Spatial Web Ontology has been encoded in the Hyperspatial ModelingLanguage (HSML). The ontology was developed based on careful examination of several existing ontologies, i.e., IEEE

7007™-2021, ISO/IEC 21838-1:2021, ISO/IEC 21838-1:2021, and the Suggested Upper Merged Ontology (SUMO).
R&D is needed to elaborate, test and confirm that the Spatial Web ontology provides trustworthy interoperability between AI Agents and Digital Twins. Furthermore, research should be conducted to ensure universal, cross domain interoperability and standardization, enabling AI agents to access data and execute activities across a system of systems.

VVUQ: A common interface is needed to uniformly access Digital Twins with varying representations of space and time. Digital Twins represent systems using information constructs that mimic the structure, context, and behavior of the system. The most primary constructs of Space and Time are highly variable. The Spatial Web approach to modeling Digital Twins is based on an abstract definition for hyperspace, i.e., A set of 'points' such that, for every ordered pair of points, there is a set of 'paths' from the first point to the second, This abstract definition includes all classes of hyperspace as shown in figure 5; topological manifolds, vector spaces, graphs, hypergraphs, cellular structures and abstract data types enabling digital twins to model any type of hyperspatial data. The Spatial Web is using Category Theory to define a common interface across all classes of hyperspace [7].

Additional R&D is needed to elaborate, test and confirm a common interface to all hyperspace representations used in Digital Twins based on Category Theory.

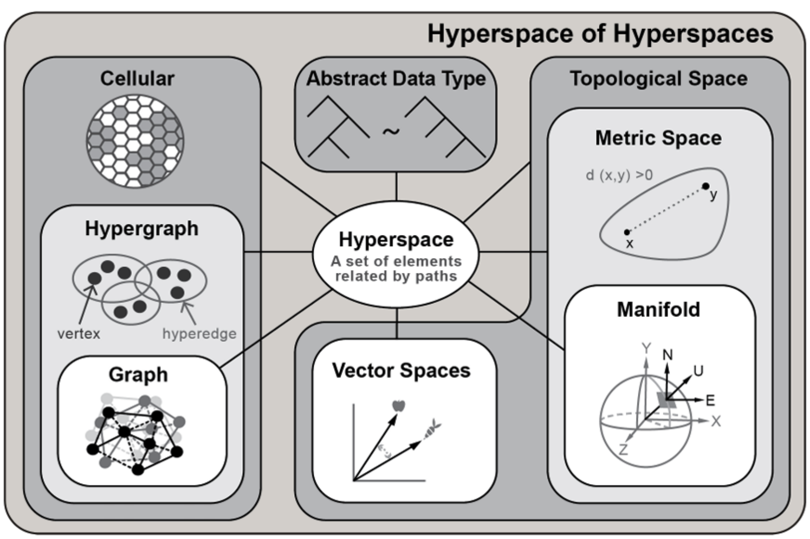


Figure 5 —Basic classes of hyperspace.

VVUQ: Scalable and sustainable ecosystem of Digital Twins as domains of knowledge. Individual Digital Twins mimic the structure, context, and behavior of a natural, engineered, or social system. Collectively, networks of Digital Twins will represent a knowledge structure about domains of the observable world. The Spatial Web provides for a knowledge model of any domain based on graph structure encoded in the HSML. This graph of all domains and their relationships in the Spatial Web is termed the Universal Domain Graph (UDG). Based on current large knowledge graphs and a cellular model of the surface Earth at decimeter-scale, the UDG is estimated to eventually contain approximately 10^{14} nodes. A distributed server instructure is needed to manage distributed storage and performance scalability of the UDG. *Additional R&D is needed to elaborate, test and confirm feasible implementations of the UDG as a basis for the Digital Twin Ecosystem.*

We view the Spatial Web as a cyber-physical ecosystem of natural and synthetic sense-making, in which humans are integral participants -- what we call "shared intelligence". This vision is premised on active inference, a formulation of adaptive behavior that can be read as a physics of intelligence, and which inherits from the physics of self-organization. In this context, we understand intelligence as the capacity to accumulate evidence for a generative model of one's sensed world -- also known as self-evidencing. Formally, this corresponds to maximizing (Bayesian) model evidence, via belief updating over several scales: i.e., inference, learning, and model selection [8].

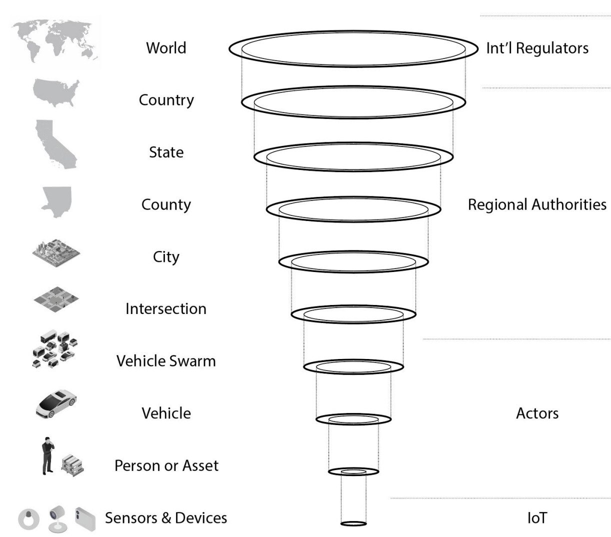
By ensuring data interoperability, AI agents can query data, make informed decisions and execute activities across domains without needing to be retrained or re-coded to operate within a specific domain, greatly accelerating the adoption and deployment of digital twins.

R&D is needed to ensure HSML can support a multitude of intelligence types to reason and plan across any domain and digital twin.

VVUG: HSML and factor graphs document databases as means of quantifying uncertainty. The Spatial Web Foundation in collaboration with VERSES have developed a new technology called factor graph document databases, or FDD. FDD are databases capable of storing data under both vectorised and graph representations, following the ontology of HSML. Crucially, they also have computational capabilities (e.g., Bayesian and approximate Bayesian inference), meaning that they can update the value of their related entities by performing computations over those entities. They can infer and predict change in their stored entities, and importantly, provide an estimate, through probabilistic inference, of the uncertainty over the relation between those entities. Concretely, this means that FDDs, because they use HSML as their modeling language, can be used to produce digital twins of different real world systems, and perform computations over the entities that make up those systems – the kind of computation that allows simulation, but also the kind of computation needed to measure the uncertainty of the aspects of the real world system's modeled by the FDD. *Additional research is needed to validate FDDs as means for probabilistic inference.*

Regulatory Science: Digital Twins need to represent the rules and laws within their domains that can be interpreted by both humans and machines. Existing rules and regulations have been drafted traditionally by humans and for humans, but with little regard for interpretability and executability by a machine. There is tremendous value in seeking to bridge the gap between the traditional way of drafting and publishing regulation (i.e., by humans for humans) and having machine-readable and machine-executable regulation (i.e., by humans, for machines). Translating existing regulation into machine-interpretable and machine-executable code will allow us to properly capture how humans read and interpret the regulation and ensure machines and AI universally follow the same rules and regulations.

In order to accurately represent laws, digital twins need to be hierarchical in a nested architecture that inherit the rules above them and pass their rules to the ones below them. For example, the autonomous car industry needs a national, state and local digital twin registry, including all the laws and ordinances required to safely operate on the roads. These rules then need to be accurately applied to hierarchical scales of actors, agents and IoT devices, from swarms of vehicles to individual sensors. Such a registry would enable regulators to make real time updates to laws so cars are aware of construction, hazards, and adjust laws based on dynamic factors like weather.



AI can be used to ingest the massive amounts of existing legal text and regulations, applying it to digital twins where it can be administered by humans to ensure its accuracy and compliance. Real world scale simulations can then be run to ensure the machine code accurately represents the laws and recommend adjustments to increase safety and efficiency, eventually becoming a self learning and improving system.

R&D is needed to accurately represent laws to digital twins and run them in simulation to ensure their efficacy.

Business: Regulators need a framework to digitally transform the industries they regulate. Over the coming decades, entire industries will become smarter, connected, automated, secure, and more sustainable. This initiative requires the digital transformation of most if not all commercial and public entities including governments, institutions, corporations, customers and their interactions while preserving their privacy and security. Doing so will greatly transform the economy, accelerating growth and innovation while reducing the commercial friction of regulations and bureaucracy.

The Spatial Web Foundation provides the framework and standards necessary for industry leaders and regulators to create, regulate and operate industry specific domains such as transportation, healthcare, energy and space exploration. Further research is needed to design economic ecosystems and frameworks that provide the tools required for regulators and industry stakeholders to deploy, manage and operate within the industry domain. *Additionally, research is needed to ensure ethical deployment of such systems.*

Business: Regulators, lawmakers and industries need an economic simulation model. In order to accelerate the growth of high risk industries that require significant financial and R&D investments, a global scale economic digital twin is needed to simulate potential costs and benefits of various business models. For example, in the case of space and lunar of exploration, aerospace companies and space agencies can model and simulate various kinds of exploration activities, helping to define which organizations will be responsible for specific activities, what the commercial benefits could be and what additional services are needed to be supported by new industry startups or taken on by the government. Such a simulation could also serve as an investment vehicle, enabling companies to help validate their business assumptions and attract investment.

Or in another example, such a system could help lawmakers and researchers craft tax and incentive models to more accurately predict the economic and social benefits of policies before making it law. As economic and tax decisions are put into action, analysts and AI agents should be able to validate how well the simulation reflected the real life deployment of the project, determining where the model should be adjusted for future simulations, creating a self learning and increasingly accurate representation of economic reality. Furthermore, these economic models should feed into one another, enabling it to more accurately represent the economy as a whole.

R&D is needed to take into account the various stakeholders of such a model, ensuring it is flexible and scalable to adapt to any industry and ensures that it can accurately represent the socio-economic principles of the industry it is meant to serve.

Spatial Web scenarios that utilize Digital Twins

Spatial Web Scenario: Cross Platform Simulation and Coordination of Lunar Exploration. In order to autonomously coordinate activities on the moon, rovers and landers must communicate position and planning, however existing maps from previous fly-bys of the moon have insufficient resolution for planning optimal, energy-efficient paths through or around obstacles such as rocks, craters and regulus (moon dust). Simulating and executing these routes requires rovers to digitize the terrain and share real time position and physics dynamics in a shared multi-dimensional world model. However interoperability between systems and organizations is a gating factor to autonomous collaboration on the moon just as it is on Earth.

The Spatial Web Foundation and JLP have completed a research project to demonstrate the sharing of world models and data between a rover and lander.

Spatial Web Scenario: Digital earth / Greenhouse Gas Monitoring

The scenario describes how the multi-level cognitive computing network of the Spatial Web can facilitate the interaction of greenhouse gas (GHG) monitoring with emitters and goals to collectively take action to reduce atmospheric carbon and the resulting impact on the Earth’s climate.

Spatial Web Scenario: Urban digital twin / Smart city

Digital twin technology coupled with AI is improving how cities function, meeting major challenges of human civilization including health, climate change, and sustainability. Urban Digital Twins (UDTs) move us toward the UN goal to make cities and human settlements inclusive, safe, resilient and sustainable.

This scenario shows how the Spatial Web enables digital twin technology for addressing urban sustainability with a focus on energy. Using urban energy system modeling and action plans developed in the Spatial Web multi-scale cognitive computing ecosystem will benefit next generation cities and the globe. Considering climate change it is vital that more cities deploy energy UDTs to address energy consumption and climate sustainability.

Spatial Web Scenario: The Metropolis Energy Model Digital Twin domain

The Metropolis Digital Twin — Energy Model Domain is heterarchially related to the Metropolis Digital Twin Domain and the Regional Energy Grid domain.

To support the Spatial Web Scenario for Urban digital twin several domain models are needed:

- Metropolis geographic domain is a Spatial Web geographic containing the geometry of relevant features that are under the jurisdiction of the Metropolis government.
- The Regional Energy Grid Domain is a model of the grid electrical technology using a conceptual graph for the substations, transmission lines , etc
- Metropolis Digital Twin — Energy Model Domain merges these two domains

R&D is needed to further research the above examples, working with stakeholders to accurately represent the ecosystem of their industry and properly apply digital twins and AI to solving their challenges across all platforms.

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Federal Register Notice: 89 FR 51554, Federal Register :: Networking and Information Technology Research and Development Request for Information on Digital Twins Research and Development, June 18, 2024.

Request for Information on the National Digital Twins R&D Strategic Plan

SRI

SRI Digital Twins Research and Development

SRI is pleased to respond to the National Science Foundation's (NSF) Notice Networking and Information Technology Research and Development Request for Information on Digital Twins Research and Development. As an independent, nonprofit research institute headquartered in Menlo Park, CA with offices across the country, SRI has had the privilege of supporting the federal government for many decades. In the most basic of terms, SRI develops, delivers, and integrates solutions to our society's most pressing problems.

SRI has been working on various aspects of Digital Twins (DTs) in multiple domains, which include engineering design and manufacturing, materials, computer hardware, supply chains, climate modeling, biology, human behavioral modeling, computer human teaming, and social systems. Our history of collaboration across technical and scientific disciplines has provided us unique insights into the broad challenges that need to be addressed by a large government program. The focus of this response is not aimed at narrow or singular ideas but instead at cross cutting technologies.

Terminology: Death of Prototyping

We would like to propose to expand the scope of DTs to include physical systems that do not exist but are in the process of being designed. The focus of *Foundational Research Gaps and Future Directions for DigitalTwins (2024*) and NSF's call is on "operational" use of DTs where the physical artifact already exist. However, the case where the physical product is being designed and built represents a major opportunity that is currently handicapped by our inability to manage complexity. It is also believed that developments in this area will having cross cutting benefits for society in general.

The ultimate goal of DTs in the "design" context is to eliminate physical prototyping and use reasoning over DTs to find unanticipated problems. We realize that this is a far-reaching goal which may never be entirely achieved, but it provides insights in the fundamental technologies that need to be developed that benefit both use cases of DTs. The anticipated impact will be reduced cost and time (>2x) to build first time quality (and qualified) systems. It will also democratize design and manufacturing and put complex products within reach to small and medium sized companies that do not have the expertise or labs to currently compete with the large defense or commercial contractors. Additional motivations described further below.

The "design" DT use case raises two major questions:

a. How do you create a DT when the physical entity does not exist? Typically, a lot is already known about the components that make up a system (e.g., simulation and math models, empirical models, the laws a physics, engineering and scientific principals), the main challenge is how to ingest and compose this information automatically and incrementally. For example, how would you embed the laws of physics in a neural network to reduce training time for neural nets[1]? If you have two DTs representing sub-systems, how would you compose them? This also benefits the "operation" DT use case, because many partial models already exist.

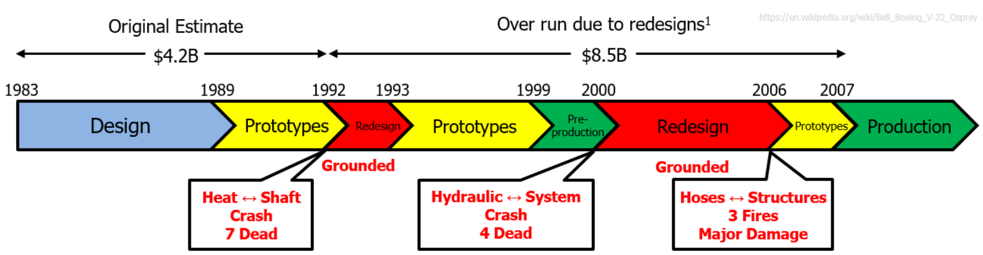
b. How do you find unanticipated problems or emergent behavior in a DT that is composed of multiple subsystems represented as DTs? The aim is to go beyond current uses of DTs that aim to optimize or predict some future state of known quantities. The main reason why we still build physical prototypes is because we lack the computational ability to find unanticipated problems.

The subsequent examples are rooted in design and manufacturing of complex engineered systems. SRI has extensively studied these and gained insights that could be applied to other domains (e.g., medicine, the influence of the biome on the rest of the body). To some degree, engineering design represents the "simplest" case even though it is far from solved despite the claims from certain commercial software vendors.

Example 1. Emergent Behavior: Huygens' synchronizing clocks

In 1665, Dutch clock builder and scientist Christiaan Huygens observed that when two pendulum clocks are mounted on a common beam, their pendulum swings would eventually synchronize. It took roughly 300 years to explain the phenomena mathematically[2]. Suppose you represent the clocks as DTs, and then "compose them", how would you discover this emergent behavior if you did not à priori know about this behavior? How would you structure the DTs so that you can compose the models and then find this behavior? There are several branches of mathematics that may show a way forward such as Algebra of Operads and Sheaf theory, however they quickly breakdown when physics gets involved. A lot more fundamental work is needed.

Example 2. Unanticipated Problems: V-22 case study



V22 Production Timeline

The V-22 Osprey tilt rotor aircraft combines vertical takeoff capabilities with fixed wing horizontal flight. The DoD launched the program in 1983 with an original budget of $4.2B, and first delivery expected a decade later. What followed were a series of failures during prototype and pre-production testing causing multiple fatalities, two major redesigns and a 15 year, $8.5B

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[1] Raissi: Physics Informed Neural Networks, 2019.

[2] https://royalsocietypublishing.org/doi/10.1098/rsos.170777

overrun[3]. The cost of correcting design problems increases exponentially as a product matures in its development cycle[4], which means the earlier a problem can be found the better. The first major unanticipated problem was an engine fire that in turn melted the carbon fiber shaft that connects both rotors to enable single engine operation in case of engine failure. Even though engine failures were anticipated as part of the design, the side effect of melting the shaft was unanticipated. Most of the other major failures were also unanticipated. The V-22 is not unique, most other recent defense programs suffered from similar delays and cost overruns[5]. A RAND[6] report concluded that the growth in complexity and our inability to manage it is one of the main drivers in cost and time overruns.

A way to deal with complex problems is to subdivide them into simpler problems or disciplines. Medicine is subdivided in orthopedics, cardiology, neurology, gastroenterology, and so on. Likewise, airplane design is subdivided into many subdisciplines: aero, structures, propulsion, hydraulics, electrical, stability and controls and many more. Each of the disciplines painstakingly create math or empirical models in 100s of disparate software systems to capture their designs, often representing 10s-1000s of FTEs of effort, each.

Integration, meaning determining whether everything will fit and work together, is predominantly done manually during integration design reviews and by performing limited simulation and bench studies. Combining these disparate models into a full DT representation of the product is currently impossible because the underlying software cannot handle the complexity and scale, while the amount of effort required to combine the models is prohibitive. A Boeing 777 contains about 5M parts, while current geometry Computer Aided Design (CAD) systems can only work with ~250k objects during a session[7]. There are many other challenges, but the consequence is that complex product design is not integrated and heavily relies on physical prototyping and expertise that are only in the hands of a few companies. However, the growth in complexity has outpaced our ability to find unanticipated problems using our current tools and methodologies. Similarly, if an ailment in a human crosses multiple disciplines it often becomes exponentially difficult to diagnose because of lack of "integration" between the disciplines. Medicine by and large lack an integrated approach to diagnostics[8].

The remainder of this RFI response focuses on Artificial Intelligence.

The Vision, Part 1: "DT Compiler"

Creating DTs ab initio is too labor intensive and expensive (current practice). The vision is to develop a "DT compiler" that will automate ingestion of the available information[9], and build

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[3] GAO-09-692T: Published: Jun 23, 2009.
[4] https://www.qualitydigest.com/feb00/html/design.html
[5] Norm Augustine's 16th law
[6] RAND: https://www.rand.org/pubs/monographs/MG696.html
[7] *Conversation with Burhop @ Siemens*
[8] Beauchamp et al, "Integrative diagnostics: the time is now—a report from the International Society for Strategic Studies in Radiology", National Library of Medicine, Dec 2023.
[9] DARPA Perceptual Task Guidance is focused on heterogeneous ingestion and composition of information

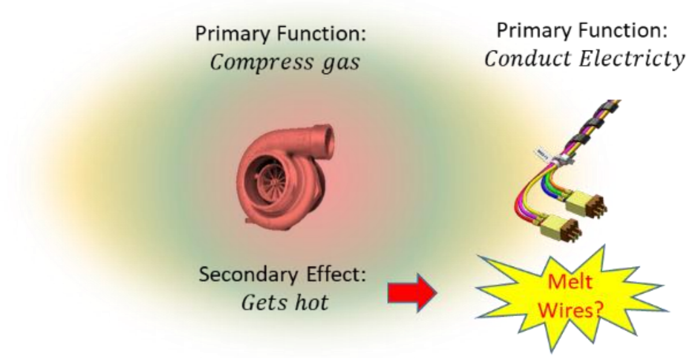
DTs with several orders of magnitude reduction of effort. This vision is inspired by DARPA's Computable Models program which demonstrated a 100-1000x reduction in effort to create physics simulators with equal or better accuracy using the notion of a compiler[10].

The major challenges to be addressed are:

- **Ingestion:** There is lots of data in many forms, how can they be ingested to build DTs? SRI insights: DARPA AI Research Assistant (AIRA); Perceptual Task Guidance (PTG) and Computational Cultural Understanding (CCU) – which ingest and fuse data from heterogenous sources. Other insights: DARPA Big Mechanisms that read cancer texts and generated a system of ordinary differential equations to model cancer pathways, i.e., Large Language Models are not always the answer.
- **Embedding Priors / Small Data:** We know the laws of physics and other scientific principles; how can they be built into the structure of neural nets? This eis specially critical for areas with little data to reduce training effort (e.g., engineering, medicine). SRI insight: DARPA Physics Informed AI (PIA)
- **Composition of DTs:** Physical objects interact with each other in non-intuitive ways across multiple physics. How can DTs' representations encapsulate this? SRI insights: DARPA CompMods with algebra of operads

The vision, part 2: Finding Unanticipated Interactions

The vision is that once you have a DT representation of a system, to search through all the subsystems represented by DTs and find unanticipated problems that would occur during operations. For example, if you route wires too close to a turbo charger, they may melt if they are too close because turbo-chargers get hot. This requires spatial awareness between the DTs, the side effects that each DT has (heat, vibrations, noise, EM fields) and the specifications (e.g., material properties, in this case insulation melting temperature).



Unintended turbocharger interaction due to secondary effects.

[10] Pietrzyk et al., Automated upscaling via symbolic computing for thermal runaway analysis in Li-ion battery modules, JOCS, 2023

Some of the major challenges to address are:

- **Search**: Finding all potential interactions is currently prohibitively large. Using de Weck's formula[11], a Boeing 777 would have potentially 10^{10} interactions, which would require centuries to evaluate. On the other hand, AlphaGo beat a human even though the search space is 10^{170}. However, there are many ways to cull the search space because physics usually has a limited sphere of influence. The challenge is to autogenerate these "sphere of influences" from the DT descriptions.
- **Quantifying Interactions**: One direction of research is to develop the mathematics to describe emergent behavior as described above under Huygens. Another research direction is to leverage Qualitative Reasoning[12] (invented at PARC) which mimics how humans reason about physics without performing any detailed computations. The fall back is brute force simulation, which requires automatically generating new simulation tests without human interference. This requires additional technology development though inspiration may come from the gaming and animation industry with alternative methods to create simulators on demand (e.g., particle methods, cellular automata).
- **Ageing & uncertainty**: Nothing is manufactured perfectly; things age and wear out. This needs to be incorporated into DTs for either usage case (design & operations) to enable accurate predictions. SRI insight: DARPA META: Fault-Augmented Modelica Extension [13] which incorporated faults and wear in models

Facsimile of Intelligent Lifeforms (FOIL)

SRI is developing the Facsimile of Intelligent Lifeforms (FOIL) system to create and run cognitive simulacra of humans (digital twins) teaming with each other and AI agents in a task simulation environment. We will create twins for specific tasks and task-roles that can be adjusted to reflect variations in human factors such as trust and communicativity that are known to influence the effectiveness of human-AI teams (HATs). We will develop techniques to promote the fidelity of twins to humans by training from observed human task performance. More importantly, we will develop techniques that minimize the amount of human data required for training twins: the purpose of running simulations with twins is to reduce the need for human trials, which is defeated if numerous trials are needed to create twins in the first place.

We will validate our techniques for twin training with minimal data in a restricted setting and then show how it generalizes to other settings. The restricted setting will be a text-only version of the collaborative board game Pandemic. In Pandemic, between two and six players are assigned different roles, abilities, and resources, and must work together as a disease-fighting team to stop the spread of deadly viruses. It is known for its challenging game play and the need for players to work as a team to avoid quickly losing the game. Although the domain is relatively simple, it

[11] De Weck @ MIT: https://www.ssse.ch/sites/default/files/evt_files/SWISSED-2018-de-Weck.pdf
[12] Williams & De Kleer, "Qualitative reasoning about physical systems", AI, 1991.
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provides team-working complexity comparable to that required for real emergency response tasks. It is also a domain that already has digital environments and some AI players.

Coevolutionary Modelling of Emergent Teams (COMET)

SRI is interested in developing Coevolutionary Modelling of Emergent Teams (COMET) to build digital twins of a human-AI team (HAT). These digital twins abstract the operational environment while ensuring a rich interaction space between commander and an adaptive AI teammate. Figure 1 illustrates the capabilities of a COMET digital twin. A generative human simulation model is used to sample diverse behaviors. The HAT simulator directly models teams that emerge after adaptation (yellow rectangles) to the team-mate in a task (curved arrows). The underlying high-dimensional behavior embedding is trained to possess the property: the Euclidean distance between human and AI behaviors becomes smaller over the course of team adaptation. COMET enables realistic simulation of the HAT on novel tasks by simply sampling locally in this embedding space. COMET implements metrics to assess the real-world fidelity of the simulation and quantifies the nature of the HAT's interactions. The fidelity will be validated with multiple humans in-the-loop (HITL).

Thank you for the opportunity to respond to the National Science Foundation's (NSF) Notice Networking and Information Technology Research and Development Request for Information on Digital Twins Research and Development.

SRI POC: Christina Hildebidle, SRI

Federal Register Notice: 89 FR 51554, Federal Register :: Networking and Information Technology Research and Development Request for Information on Digital Twins Research and Development, June 18, 2024.

Request for Information on the National Digital Twins R&D Strategic Plan

Stephanie Armour

THE FUTURE OF EVERYTHING

A 'Digital Twin' of Your Heart Lets Doctors Test Treatments Before Surgery

Researchers create digital replicas of individual patients' organs using data from exams and wearable devices: 'You can run an infinite number of experiments'

By Stephanie Armour Follow

May 16, 2024 at 9:00 am ET

Patients diagnosed with heart disease, cancer and other ailments face myriad decisions: Which drug will be most effective? Will the side effects outweigh the benefits? Will surgery be enough?

Determining the best path forward may be far easier in years to come. Instead of trying a therapy and hoping it works, researchers are creating so-called digital twins to predict how a patient will respond before ever starting treatment.

"It's a paradigm change," says Emily Greenspan, a program director in the informatics and data science program at the National Cancer Institute. "You could be able to predict an individual's disease trajectory."

Natalia Trayanova, a professor at Johns Hopkins, is leading a clinical trial using 'digital twins' of patients' hearts.
PHOTO: JOHNS HOPKINS UNIVERSITY

In a Baltimore lab, Natalia Trayanova and her team at Johns Hopkins University are creating computational models of hearts. Each one mirrors the heart of a real patient with a potentially fatal arrhythmia, an irregular heartbeat that is often a result of scarring from heart attacks or other conditions.

The replicas, or "digital twins," appear as personalized 3-D hearts on computers, with areas of scarring shown in white. The team can use them to model how and where to make new tiny scars through a procedure called ablation to fix the arrhythmia.

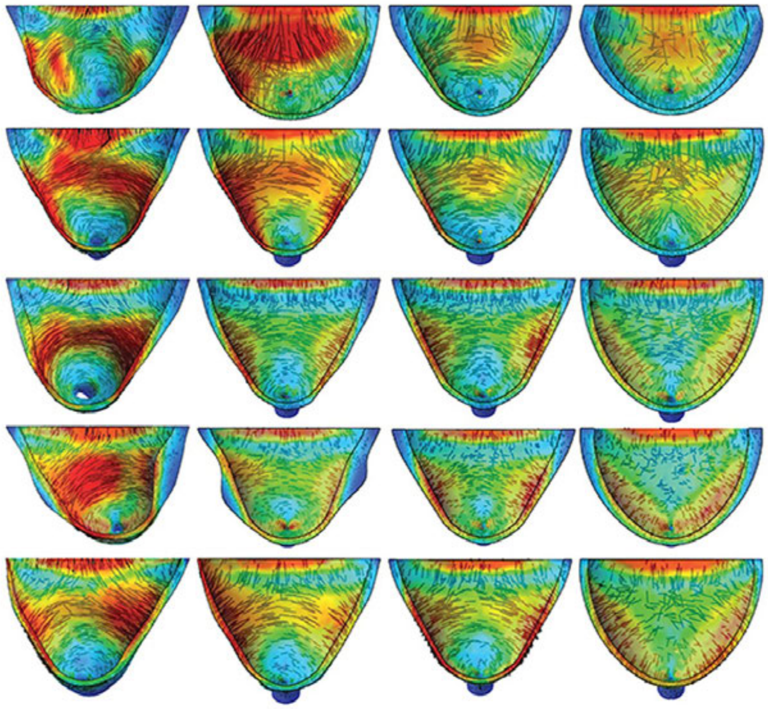
“You can watch it on the screen,” says Trayanova, a professor in the department of biomedical engineering at Johns Hopkins who is leading a clinical trial using these digital twins. “We want to know how to treat the patient in the most optimal way.”

Federal agencies, startups and academics are pouring billions of dollars into bringing digital twins to the forefront of healthcare in the next five to 10 years. The global digital-twins healthcare market was valued at $1.6 billion in 2023 and could reach $21.1 billion by 2028, according to a report by MarketsandMarkets. The growth in North America is attributed to government funding and investment, as well as companies already providing digital-twin technology to represent healthcare data, physical hospitals, human physiology and other areas.

Digital twins for all?

Clinicians envision a tomorrow where nearly everyone could have a digital twin created by artificial intelligence, using information from medical exams, wearable data devices and medical records. AI could search through data of others with comparable issues and run simulations while providing continuous monitoring of a patient's health.

Like a crash-test dummy, a digital twin could be used to test drugs and conduct trials without harming the actual patient. A digital twin of a heart could allow surgeons to visualize the procedure and the patient's specific vessels before an operation. The technology could be used to design highly accurate prosthetics or determine the most effective rehabilitation exercises. Digital twins of a patient's uterus and cervix could help predict pregnancy outcomes.



Digital-twin models of uterine walls in pregnant women show levels of stretch as the baby grows. The digital twins are used to help predict the course of the pregnancies. PHOTO: ERIN LOUWAGIE AND KRISTIN MYERS/COLUMBIA UNIVERSITY

While the concept has been used for decades in other industries such as mechanical engineering, digital twins are still relatively new in healthcare because modeling a human organ or body—at times to the cellular level—is so complex. Collecting personal data with wearable devices and sensors also requires addressing concerns about how to preserve privacy. Machine learning, or artificial intelligence, is still evolving and can at times produce biased results.

Researchers say it is also hard to move ahead because the concept involves so much agreement and buy-in from various stakeholders, including data scientists, doctors, engineers and others.

"There is a lot of trust that needs to happen," says Dr. David Spragg, an associate professor of medicine at Johns Hopkins Hospital in Baltimore specializing in cardiology and cardiac electrophysiology. He is also part of the team working on the clinical trial of digital twins for hearts.

Tackling tough questions

But the potential has generated enthusiasm from doctors and researchers who describe a not-too-distant future where digital twins could answer difficult medical questions. What side effects will a specific patient get from cholesterol-lowering drugs? How likely is a patient to get asthma or diabetes, and if so, how soon? How might a woman's specific pregnancy progress?

Researchers are already working on these ideas and, in some cases, putting them into novel use.

In the Johns Hopkins clinical trial on heart arrhythmia, the patients undergo a cardiac contrast-enhanced MRI. From the images, the biomedical engineering team reconstructs a three-dimensional model of the patient's heart, using artificial intelligence to put images together. The result is a 3-D heart that shows scarring and areas of damaged cells that can be rotated on the screen and looked at from different angles.

The digital heart is then populated with virtual cells that can each generate an electrical signal.

The team can then simulate a heartbeat in the heart digital twin, and poke and prod it by giving it small electrical signals here and there to see what happens with the heartbeat.

Using the digital twin, the team can predict the possible locations of disordered rhythms and identify the best locations for ablation before the procedure is carried out, says Trayanova, who is also a professor of medicine.

David Gakenheimer, an 80-year-old retired technology inventor who had arrhythmia, was a patient at Johns Hopkins and heard about the digital twin work. The hospital also has provided digital twins to patients who aren't in the clinical trial. So the team made one for Gakenheimer, who wanted to see how it would compare with the ablation procedure he underwent later from a doctor.

"I wanted to do a normal procedure and

compare it to her software," Gakenheimer says, referring to Trayanova. His successful treatment ended up matching the results from the digital twin: "The areas of her model accurately predicted them."

Previewing a pregnancy

Kristin Myers, a mechanical engineering professor at New York's Columbia University, is making digital copies of women's uteruses and cervixes, hoping this can help in determining how a pregnancy will go. To do this, Myers uses an ultrasound to create 3-D computational models as part of an effort to someday solve the problem of preterm births.

"The idea of digital twins in health is new," she says. "We can offer better diagnoses. You can run an infinite number of experiments."

At the National Cancer Institute, Greenspan envisions a novel way to treat oncology patients. Instead of trying a drug and hoping it works, doctors would create a digital twin of the patient to predict how the disease would respond to a certain drug.

The institute has been working on creating virtual twins for best treatments of lung cancer, for instance. In the next five years the technology will likely become part of clinical decision-making, Greenspan says.

“Predicting the best treatments and screening, these are blue-sky visions,” she said. “There is a lot of foundational research that’s needed.”

Write to Stephanie Armour at
[redacted]

Federal Register Notice: 89 FR 51554, Federal Register :: Networking and Information Technology Research and Development Request for Information on Digital Twins Research and Development, June 18, 2024.

Request for Information on the National Digital Twins R&D Strategic Plan

Synopsys

SYNOPSYS® | [redacted]

28 July 2024

Melissa Cornelius
Technical Coordinator, National Coordination Office (NCO)
Networking and Information Technology Research Development Program (NITRD)
[redacted]

RFI Response: Digital Twins R&D Plan

Dear Ms. Cornelius,

Synopsys, an American company, and core component of the chip design value chain, has extensive capabilities in process simulation and systems emulation. We are pleased to have the opportunity to respond to the Networking and Information Technology Research and Development Request for Information on Digital Twins Research and Development, and to inform the development of the Digital Twins R&D Strategic Plan. Our response to this RFI is contained in the following pages.

A Digital Twins R&D Strategic Plan is critical to align and encourage advancement of digital twin technology, acceleration of use, and early adoption of models. Thoughtful review of substantial existing investments in proprietary digital twin technologies as well as the challenges will increase innovation in digital twins and provide significant benefits to the U.S., such as virtual manufacturing floors to discover ways to improve products and expedite processes. Currently, the U.S. lacks a comprehensive lab environment for developing and validating digital twin technology (something that the CHIPS Manufacturing USA Digital Twin Institute seeks to develop).

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Thank you for the opportunity to share our perspective on digital twin technology development and enhancement. Please alert us to opportunities where our expertise can help move this initiative forward.

Best,
Dale

Dale Donchin

Dale Donchin
Principal Engineer
Synopsys
[redacted]

Introduction

Digital twins, as virtual stand-ins for their physical counterparts, enable essential requirements of simulation, verification, compliance, optimization, performance, functionality, exploration, and several other types of analysis without perturbation of the process or object they represent. This capability provides valuable knowledge of the physical entity without needing to manipulate it directly. For example, digital twins can predict how an aircraft will behave during a catastrophic failure without destroying the plane.

As stated in the 2024 National Academies Report, Foundational Research Gaps and Future Directions for Digital Twins, “Digital twins are emerging as enablers for significant, sustainable progress across industries.” The wide range of applications include medical (treatment efficacy), climate (correlation of weather, emissions, and other factors), business (ROI analysis), and microelectronics (manufacturing yield). As noted in the RFI, a variety of factors must be considered that are common to all digital twin instantiations.

The focus for Synopsys is on digital twins for semiconductor manufacturing through in-field products, covering the wide spectrum from atoms to systems. Synopsys has expertise in several of these areas, notably **Data, Ecosystem**, and **Standards**.

About Synopsys

Synopsys is an electronic design automation (EDA) company providing chip design and verification, silicon intellectual property, and software security and quality. Synopsys delivers the most trusted and comprehensive silicon-to-systems design solutions, from electronic design automation to silicon IP and systems, that accelerate technology innovation. We partner closely with semiconductor manufacturing and design customers across a wide range of vertical markets to maximize their R&D capability and productivity, powering innovation today that ignites the ingenuity of tomorrow. In a world where the pace and complexity of innovation is accelerating, the entire silicon ecosystem trusts Synopsys to pioneer new technologies and help them get to market faster without compromise. Our products support chip design, manufacturing, and product digital twin development and utilization. Digital twin capabilities are already present in many of the Synopsys tools, including Sentaurus TCAD, Fab.da, and Silicon.da (“da” is an acronym for “data analysis”).

Data

There are many methods for data representation and without proper thought and practice, incompatibilities arise as do implementation of proprietary formats. This is of utmost concern to digital twins since the intention from the outset is interoperability and use across a wide ecosystem and virtual models of many physical properties. Synopsys suggests consideration of the following data-related topics and provides recommended best practices.

Separation of data and access: Digital twin data contains the information necessary to model the digital twin's corresponding physical object and storage and access methods that present its interface to its compute environment, including API protocols and how information flows bi-directionally (ex. to/from sensors and simulation models). The access methods enable extensibility and portability of digital twins as the type of information, or the type of interface, changes. The separation of data and access also enables the model and its interoperability to evolve independently. Changes to the model, for example, to correct or enhance its performance, can replace the instantiation of a prior version of the digital twin. Meanwhile, changes to the interface, for example, to extend it to be used for future analysis tools, doesn't jeopardize how the model performs. This guidance has its roots in user interface architecture ("MVC"), where the Model of the data is distinct from how it's presented (View) and the interface (Controller) that supports the information transfer. The differentiation of these aspects enables the same information to be easily ported between, for example, different mobile phone models and orientations (vertically/horizontally held) and input styles (ex. keyboard, stylus).

Synopsys recommends that this best practice from the user interface domain carry forward to digital twin data. The model information and how it's connected to its consumer/provider must be defined separately. This suggestion protects confidentiality in that the interface can hide the implementation.

Methods for preserving confidentiality: Confidentiality is a concern with digital twins, as the processes they model may be proprietary, and can represent sensitive recipes, trade secrets, or contain anomalies not intended for public disclosure. There are several methods to mitigate this concern. One approach is to encrypt the digital twin data or employ homographic computation. However, in some instances, this might not provide sufficient protection if enough of the proprietary behavior is observable at the interface level. In this case, the interface itself may need to be encrypted or tied to a specific data "owner." This approach requires secure management of a decryption key, which raises issues of its own. An alternative option is to share only low fidelity digital twins that limit reverse engineering attempts.

Distributed data access: Data is also distributed, with different players in the value chain that have their own data. Access to data across the value chain makes the digital twins useful for end users. Training models on this distributed data without one entity having access to all the data, like federated learning, would be beneficial.

Benefits of varied model fidelity: Fidelity, the accuracy of the digital twin's representation of its physical manifestation, is a critical data aspect. While high fidelity is encouraged, as noted earlier, there are reasons to have models of varied fidelity. In fact, initial models may be low fidelity with their accuracy increasing as more experimentation and tuning occurs. The digital twin's fidelity must have a method for measurement, an understanding of the factors that may impact it (ex. aging), and a way to associate and document the accuracy of a digital twin.

Digital twins that mimic physical effects prone to change need a calibration procedure and recommendations for how often that process should be performed. For example, digital twins of climate behavior must adapt to and be calibrated at different temperatures, levels of humidity, air particulates, and similar real-world phenomenon. This is also true of AI-enabled digital twins that require training data. Using digital twins properly entails knowledge of their calibration requirements and how recently they were met.

Importance of unique identifiers: Since digital twins differ in their maturation stage, fidelity, modelling approach, enhancements and optimizations, and other attributes, a version identifier must be associated with each of them. This implies that a digital twin model has companion metadata that, at a minimum, specifies its version. Other metadata should include its author, its fidelity and calibration data mentioned earlier, and other aspects that describe it. The JSON format is a recommended format for the metadata file since it's human-readable, well-supported, easily parsed, and extensible.

Accounting for external factors: In the physical world, various entities interact with each other. Often, this interaction entails the behavior of one entity affecting the behavior of another. For example, when billiard balls collide, the direction and velocity of both changes. If this event were to be modelled using a billiard ball digital twin, mimicking the behavior of each requires bi-directional data transfer between them. Therefore, digital twins must be capable of not only modeling their physical counterpart but also reacting to external conditions. Implementation of digital twins requires inputs at their "outside" interface that affect the processing of the model "inside." For some ecosystems, the exchange of information between digital twins is continuous vs. one-time. Analysis of digital twin output must consider waiting for the digital twins to reach their steady-state values, which isn't a guaranteed outcome. This situation has consequences for both digital twins and the tools that perform their analysis.

Advantages of hierarchy simulation: Digital twins can stand in for very granular physical entities, such as one of the hundreds of manufacturing steps in the production of a semiconductor wafer or represent the entire wafer creation process. In the latter case, virtual simulation at a top-level may be implemented by utilizing lower-level digital twins. This is commonly called hierarchy. Digital twin creation should consider its use within another digital twin, or twins, forming a hierarchy of virtual representation. This consideration affects the "outside" of the digital twin, since the API must not only be bidirectional for input/output source/result transfer but also support data coming from/going to another digital twin. Hierarchy is a popular method of simulation. It's advantageous to isolate behavior to a low-level module that's referenced from higher-level routines. A change (bug fix or enhancement) in the low-level digital twin is reflected in all higher-level instances where it's referenced. Without hierarchy, that same change must be made in multiple places, introducing potentials for error in making the change and propagating it to all necessary instances.

Data management, provenance, and verification: Finally, digital twin models, the metadata referenced earlier, and the data they produce are valuable and require management, including backup and access controls. The storage system must enable provenance and integrity verification, providing authentication and anti-tamper assurance.

Ecosystem

A collaborative and open approach to digital twins is necessary to interoperate with the many current and future suppliers of the physical entities that jointly create physical processes and products. For example, a manufacturing plant contains equipment and consumes components from diverse companies and relies on a complex and global supply chain. Modelling that environment using digital twins requires flexible and common methods supporting companies individually and collectively as the final product depends on the contribution of each step and their interactions.

Synopsys offers several recommendations to create a harmonious digital twin ecosystem that spans multiple use cases.

Importance of interface interoperability: It's envisioned that several digital twins can be part of an end-to-end flow that model a broad ecosystem. This can be achieved through a series of hierarchical digital twins as mentioned earlier in this response (vertical ecosystem) or through an end-to-end connection (horizontal ecosystem). The prior section's discussion of digital twin data recommendations provides requirements for their use in an ecosystem.

Chief among digital twin requirements for use in an ecosystem is interoperability of its interface. An ecosystem typically involves different digital twin authors and must support stitching them, and any analysis tools, together. Thus, digital twin ecosystems are only possible when their interfaces are vendor agnostic and well-documented (see Standards section below). Note that this doesn't prevent the data representation from being proprietary.

Hardware emulation to mitigate compute requirements: Synopsys is especially interested in the digital twin ecosystem that's required as components scale from atoms to systems and beyond. EDA tools can simulate the many digital twin models that comprise an end-to-end flow from parts to products but trade-offs between computation and wall clock must be considered.

The performance of such a flow may suffer if a great amount of compute resources is required. Creation of an environment containing the stimulus for the digital twins, for example, varying their inputs and analyzing their outputs, is required. The use of digital twins doesn't stop with just having them – something must measure how they behave when subjected to the same conditions experienced by their physical counterpart. The ecosystem is thus beyond having the digital twin virtual representations. An environment is necessary that provides inputs, collects outputs, and performs analysis. As noted previously, that environment must consider the time requirements for digital twin processing, which is likely much slower than their physical counterparts. Training of AI-based models may also be required. These considerations amplify the compute processing needed.

Synopsys recommends the use of hardware emulation to mitigate high processing requirements. Hardware emulation uses hardware-based systems for concurrent software and hardware processing. As a result, they can be multiple orders of magnitude faster than software-based simulation. The hardware emulator (ZeBu™ is the Synopsys hardware emulator product) can also connect to many types of other hardware. This capability enables simulation of an entire ecosystem comprising both physical and digital twin elements.

Establishing a digital twin repository: The entity creating a digital twin ecosystem must source those models from a diverse community of digital twin authors. Availability and support are key factors. Synopsys recommends that a digital twin "store" is established to address these aspects of ecosystems. There are multiple methods to create this "store." A simple approach is the creation of a "Git" repository, which is commonly used to expedite shared content. Digital twins and support may also be provided by their authors as products and services. A collaborative consortium of digital twin providers is another possible mechanism. None of these methods are mutually exclusive. Whichever approach is undertaken, it's important that security concerns including authentication and integrity are considered. Similarly, digital twins should always be supplied from a trusted source.

Digital twin licensing: Digital twins have value, require access controls, and may be updated or revoked. Licensing is a means to respond to these digital twin properties. Licenses, which are granted, enforced, and tracked by license management applications, enable a digital twin supplier to specify the user, user's access type, usage permitted, and access duration, among other aspects. IP licensing is well-established in the semiconductor industry; however, it may not resolve all issues associated with digital twin usage. This is due to license controls placed outside of the IP.

Technical documentation: Comprehensive documentation is necessary to tie disparate digital twins together. This is analogous to integration guides that accompany semiconductor IP products, illustrating how they are configured, validated, and connected to other components in the ecosystem. Like the digital twins themselves, the documentation must be version controlled and provide a means to associate it with the corresponding IP version.

Identifying use case and audience: An important ecosystem consideration is defining the use case and audience. For example, the ecosystem may be intended for observation and analysis of the process that creates a product or the behavior of the product itself. Those interested in the results may be equipment vendors, operators, or application users. The degree of fidelity required may be minimal or of high accuracy. The audience could be university researchers, commercial firms, defense contractors, or end users of the product or function. The diversity of the audience impacts the cost, value, and benefit. Thus, there could be several ecosystems for the same or similar set of digital twins, each appropriate for who the audience is, their expectations, and intended benefit. Addressing reliability and security are primary requirements.

Standards

Synopsys enjoys a long tenure chairing and participating in many industrial standards committees and forums and is eager to share our experience for the benefit of digital twin standardization.

All ecosystems require industry standardization to be viable. Compilation, agreement, adoption, and compliance to common practice enable existing and new entrants to effectively communicate and interchange content. For digital twins, this includes data exchange protocols, tutorials and examples, community engagement and discussion, oversight, and public dissemination.

Standardizing communication through backplanes: As noted earlier in this document, the interface allowing digital twins to communicate with each other must be standardized. One implementation approach is to have each digital twin interact with a "backplane" instead of each other. An advantage of this method is that the digital twins only need to talk to one type of interface. The digital twin backplane can be the entity that supports different digital twin communication channels. A backplane also enables tracking and management of the digital twins collectively since it's the bridge over which all digital twin communication occurs. Backplanes are common interface technology. Synopsys suggests the same approach for digital twin communication.

Interface heterogeneity between digital twins and physical counterparts: Digital twins may communicate with its corresponding physical entity. The twin may receive data, perhaps needed to train an AI model, and/or transmit data, for example to affect a change in the ecosystem. Synopsys believes that standardizing interfaces to equipment will be difficult due to the vast diversity of equipment types, vendors, data and operational sensitivity, and other concerns. We recommend that the interface between the physical entity and its digital twin counterpart be free of standards and compliance restraints, with communication to/from the digital twin and the rest of its ecosystem achieved through the backplane approach mentioned above.

Benefits of initial voluntary standards: Standards can be of the "should" type or the "must" type. The former suggests adherence to a standard whereas the latter demands it. Digital twin development, while not at its infancy, has much room to grow. Accordingly, the "should" type is recommended at this stage of maturation.

Once "should" standards evolve to the "must" type, compliance tests need to be created by the standards body and certification given to those digital twin developments that can demonstrate adherence to the standard's dictates. Compliance test generation and validation of meeting requirements is a large undertaking. This is another reason why Synopsys suggests "should" terminology at standardization outset.

User group involvement: User groups aren't standards committees, but they serve a valuable role supporting them and helping others understand, debug, and comply with them. There are countless user group forums that exist in almost every domain, technology and otherwise. Synopsys recommends a similar notion to build a digital twin community.

Conclusion

Digital twins are becoming increasingly prevalent across multiple industries for virtual representation of physical behaviors. Synopsys welcomes this opportunity to share expertise and suggestions toward the successful deployment and use of this technology in all their applications, given our role in atoms to systems microelectronics.

A Digital Twins R&D Strategic Plan is critical to align and encourage advancement of digital twin technology, acceleration of use, and early adoption of models. Thoughtful review of substantial existing investments in proprietary digital twin technologies as well as the challenges will increase innovation in digital twins and provide significant benefits to the U.S.

Federal Register Notice: 89 FR 51554, Federal Register :: Networking and Information Technology Research and Development Request for Information on Digital Twins Research and Development, June 18, 2024.

Request for Information on the National Digital Twins R&D Strategic Plan

Texas Department of Transportation

Texas Department of Transportation

[redacted] txdot.gov

July 23, 2024

Ms. Suzanne H. Plimpton
Reports Clearance Officer
National Science Foundation
[redacted]

RE: Docket No. NSF-FRDOC-0001-3352

Dear Ms. Plimpton:

The Texas Department of Transportation appreciates the opportunity to respond to the National Science Foundation's (NSF) Request for Information (RFI) regarding "Networking and Information Technology Research and Development Request for Information on Digital Twins Research and Development."

TxDOT views digital twinning as a vital component in achieving our goal of being a forward-thinking leader delivering mobility, enabling economic opportunity, and enhancing quality of life for all Texans. Recently, TxDOT awarded the University of Houston's (UH) Cullen College of Engineering a three-year, $505,286 grant to advance research on digital twinning to "digitize" bridges using robots, data, and artificial intelligence (AI). UH's project, "Development of Digital Twins for Texas Bridges," seeks to use this technology to help solve complex issues related to highway bridge safety.

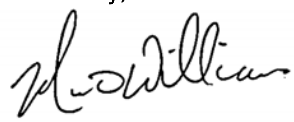
As the NSF seeks public comments on the creation of a "National Digital Twins R&D Strategic Plan," (the Plan) TxDOT has provided suggestions, and potential questions for consideration, below for how the Plan may provide guidance for "government investments in digital twins related research... to help guide further federal R&D coordination to advance technology and accelerate the use and early adoption of the digital twin models."

Topic	**Suggestions/Questions to Consider**
Asset Management	This includes managing assets that are used in different parts of a project lifecycle, including planning, design, maintenance, and operations. Examples of these assets include pavement design, signage, utilities, etc.
Work Zone Safety	How can a digital twin be used with a traffic control design to ensure safe traveling for the public?

	Can alerts be sent out to a GPS mapping application to reroute motorists to avoid work zones?
AI	What data should be generative and what can be reactive machines? For example, if a crash occurs on an interstate, what can be done on side streets for signal timing and other integrations to mitigate traffic while improving safety?
Data	What is the MVP (minimum viable product) for database structure (normalization) and the levels of AI it gives?
Data Security	What data will be open source and what data will be withheld? Additionally, what data can state Departments of Transportation share and allow connections to?
Return on Investment	This will help different agencies and stakeholders justify requests for additional funds to obtain digital twin infrastructure.
Tracking Real-time Bathymetric Conditions on Navigable Waterways	A considerable issue concerning the Gulf Intracoastal Waterway (GIWW) is shoaling of the channel where sediment flows into the GIWW and decreases channel depth, causing barges to be light-loaded and decreasing the efficient transportation of commodities. A digital twin could support near real-time monitoring, predictive modeling (including short-term forecasts and longer-term scenario modeling), and optimization of vessel operations.
Integration	Integrating roads, ports, and airports and identifying inefficiencies (such as bottlenecks) for current and future projects. For example, a larger harbor could mean more freight traffic and might require additional considerations such as rail or roadway expansion.

TxDOT welcomes the opportunity to provide suggestions and questions to consider in response to this RFI as the NSF drafts its Plan. If you have any questions, please call me at [redacted] or you or your staff may contact Melanie Alvord, Director, Federal Affairs, at [redacted] or Melanie.Alvord@txdot.gov.

Sincerely,



Marc D. Williams, P.E.
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Melanie Alvord, Director, Federal Affairs Section

Federal Register Notice: 89 FR 51554, Federal Register :: Networking and Information Technology Research and Development Request for Information on Digital Twins Research and Development, June 18, 2024.

Request for Information on the National Digital Twins R&D Strategic Plan

The MITRE Corporation

MITRE's Response to the NSTC RFI on Digital Twins R&D

July 27, 2024

For additional information about this response, please contact:

Duane Blackburn
Center for Data-Driven Policy
The MITRE Corporation
[redacted]

[redacted]

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About MITRE

MITRE is a not-for-profit company that works in the public interest to tackle difficult problems that challenge the safety, stability, security, and well-being of our nation. We operate multiple federally funded research and development centers, participate in public-private partnerships across national security and civilian agency missions, and maintain an independent technology research program in areas such as artificial intelligence (AI), intuitive data science, quantum information science, health informatics, policy and economic expertise, trustworthy autonomy, cyber threat sharing, and cyber resilience. MITRE's ~10,000 employees work in the public interest to solve problems for a safer world, with scientific integrity being fundamental to our existence. We are prohibited from lobbying, do not develop or sell products or services, have no owners or shareholders, and do not compete with industry, thereby allowing MITRE's efforts to be truly independent, objective, and data-driven. Our multidisciplinary teams (including engineers, scientists, data analysts, organizational change specialists, policy professionals, and more) are free to dig into problems from all angles, with no political, financial (profit), or commercial pressures to influence our decision making, technical findings, or policy recommendations.

In response to the increasing interest in Digital Twins (DTs) across academia, industry, and government sectors, MITRE has undertaken numerous independent research projects in recent years, many of which are sponsored by various government entities. These research initiatives have enabled MITRE to develop a comprehensive suite of tools and capabilities that collectively address the diverse aspects of DT technology. To support the wider adoption of DT capabilities globally, MITRE recently joined the Digital Twin Consortium and is exploring how to work collectively on the DT adoption challenges discussed below.

Introduction and Overarching Comments

MITRE has undertaken numerous independent research projects on DTs across academia, industry, and government sectors, many sponsored by government entities. These initiatives have enabled MITRE to develop a comprehensive suite of DT tools and capabilities. To support global DT adoption, MITRE recently joined the Digital Twin Consortium and is exploring collaborative solutions to DT adoption challenges

1. Establish a National Digital Twin R&D Ecosystem. DT applications are inherently systemic and cross-disciplinary, necessitating the coordinated input of experts from diverse fields. Establishing a unified ecosystem is crucial for fostering collaboration, sharing knowledge, driving innovation, and generating stakeholder value. This can be achieved by creating a centralized platform that facilitates seamless interaction among researchers, industry professionals, and government agencies. For example, the establishment of a national digital twin repository could serve as a foundational platform for storing and sharing digital twin models and data, thereby accelerating the development and implementation of DT solutions. Additionally, it will enable DTs to advance fundamental science by providing detailed and accurate simulations that can lead to new scientific discoveries and a deeper understanding of complex systems. By leveraging AI, DTs can significantly reduce the time to discovery, extend the nation's competitive edge in technological innovation, and address critical challenges in a diverse spectrum of sectors such as national security, energy, healthcare, transportation, and supply chain management. This approach aligns with broader efforts to

harness AI for scientific discovery and technological innovation, enhancing our understanding of complex systems and driving forward fundamental science.

2. Standardize DT Terminology and Implementation Approaches. The evolution of DT technology lacks consensus on key definitions and implementation methods. Establishing common terminology and lightweight frameworks is crucial for enhancing DT technology.[1] Standardized ontologies and reference architectures can facilitate interoperability and reusability across sectors, improving collaboration and innovation without cumbersome standardization processes. The convergence of AI and systems engineering leverages AI's predictive capabilities to advance scientific understanding and application, utilizing computable models in design stages and Digital Twins in testing and evaluation stages..

3. Manage Data, Security, and Trustworthiness. Effective DT implementation hinges on robust data management, stringent security, and trustworthiness. Implementing advanced data governance frameworks and cybersecurity protocols, such as end-to-end encryption and real-time anomaly detection, can significantly enhance the reliability and security of DT systems. Ensuring the models, data from real-world systems, and context information about the physical environment are accurate is essential for using the right models and modes of the DT. Best practices, cyber resilience, and rigorous verification methods should be incorporated. Utilizing the latest organizational and technical developments helps ensure that the data needed to develop and execute DT is available and can be transformed into the required formats. These efforts should be aligned with and inform the Federal Data Strategy.[2]

4. Foster Collaboration, Workforce Development, and Training. Advancing DT R&D requires a concerted effort across agencies and sectors to identify and address foundational research gaps and opportunities. This collaborative effort spans various areas such as biomedical sciences, environmental ecosystems, sustainability, climate change, smart and connected communities, scientific discovery, agriculture, and military and mission planning, as well as common mathematical, statistical, and computational foundations. Developing educational programs and training initiatives that incentivize cross-disciplinary STEM research across educational institutions is essential for cultivating a diverse and skilled workforce to drive innovation in DT technology. Emphasizing workforce development and training ensures that the necessary human capital is available to support and sustain the R&D efforts, thereby enhancing the overall impact and effectiveness of DT initiatives.

MITRE's Input on the RFI's Digital Twin Focus Areas

Artificial Intelligence (AI): AI and Digital Twins

AI significantly enhances the predictive-analytics capabilities of DTs, enabling them to model and simulate complex systems with greater accuracy. This integration can lead to new scientific discoveries and a deeper understanding of complex phenomena. However, integrating AI into DTs presents challenges, including managing training data sets and models, defining AI, and

[1] There is NSTC precedent: In the mid-2000s, the NSTC's Subcommittee on Biometrics published a "Glossary" document of biometric terms. As part of its formal approval, its parent NSTC Committees also instructed federal agencies to follow those definitions in their future activities. Non-governmental entities (mostly) aligned voluntarily as well.

[2] Federal Data Strategy: Leveraging Data as a Strategic Asset. 2024. Office of Management and Budget, https://strategy.data.gov/. Last accessed July 23, 2024.

addressing the computational costs of complex models. Developing tools for explainable AI/ machine learning (ML) methods is critical for modeling complex phenomena within DTs, increasing trust in AI/ML outputs by providing transparency and understanding of AI components within DTs. This will enhance the reliability and accountability of AI/ML outputs, further advancing fundamental science.

Management of Training Data Sets and AI Models. Effective management of training data sets is essential for accurate AI predictions within DTs. The pedigree and provenance of AI models are also critical pieces of information. Training data sets must be well managed, especially in dynamic environments like adversarial operations, Signal Intelligence, transportation, and economic activity. Implement measures to protect these data sets from unauthorized access or misuse, ensuring performance, accuracy, and accountability. AI Bills of Material and Data Set Bills of Material are new promising areas in AI management being pursued by the standards groups covering Software Bills of Material standards.

Definition of AI. A precise definition of AI is necessary to avoid confusion and ensure effective integration into DTs. AI encompasses neural networks, ML, and large language models. Establish a clear, comprehensive definition specific to DT R&D to facilitate better communication and implementation.

Tools for Explainable AI (XAI). Develop tools for XAI methods to enable modeling complex phenomena within DTs. XAI can enhance stakeholder confidence and understanding of the DT output, improve decision making and accountability, identify anomalies and bias in DT predictions, strengthen proactive risk management and mitigation, and raise educational and training value for stakeholders.

Business: Business Case Analysis

The application of Digital Twins in business contexts, particularly in mission-critical areas such as defense, presents unique challenges and opportunities.

Department of Defense (DoD) Mission Thread Analysis. Apply DoD Mission Thread Analysis to DTs to help determine how they can support various mission stages, identify potential challenges, and develop strategies to optimize performance. This involves examining a sequence of events or actions from mission initiation to completion.

DoD Mission Engineering. Utilizing DoD Mission Engineering provides a valuable framework for DT application. Work with artifacts from DoD Digital Engineering methods and tools to develop DTs tailored to specific mission needs and objectives, ensuring technical robustness and strategic alignment.

Business Case and Mission Impact Analysis. As part of Business Case Analysis and Mission Impact Analysis, develop DT cost and performance models to understand Return on Investment and Analysis of Alternatives, identify key performance indicators and key performance parameters, and so on. Develop DT optimization models to reduce cost and enhance performance.

Data: Encourage Adoption of Data Management Best Practices

Effective data management is crucial for the successful implementation of DTs, given the scale and complexity of the data involved. Implementing best practices such as data provenance tracking, data quality assessment, and metadata management can ensure the integrity and reliability of data used in DTs. The quality, integrity, provenance, and interoperability of data significantly impact its predictive-analytics capabilities, trustworthiness, and overall utility, aligning with the Federal Data Strategy. By ensuring reliable, accurate, and relevant data for DTs, we can enhance their ability to model and simulate complex systems that mirror their operational state and performance with a high degree of realism. Techniques such as data imputation and synthetic data generated from validated models should be applied to fill gaps in partial or incomplete data sets, further supporting the advancement of fundamental science.

Handling of Incomplete Data Sets. Apply techniques such as data imputation and synthetic data generated from validated models to fill gaps in partial or incomplete data sets. This approach is consistent with the Federal Data Strategy's emphasis on data quality.

Consideration of Data Types. Two types of data are essential: data used to train and test predictive algorithms, and data collected and operated on by the DT. Address privacy considerations, such as personally identifiable information and health data, to prevent the propagation of bad data, in line with data protection and privacy principles of the Federal Data Strategy. Establishing methods for ensuring the correctness of the data coming from the physical systems is paramount to being able to trust the DT system.

Importance of Data Governance. Develop guidelines, best practices, and standards for data documentation and amalgamation. Doing so supports the integration of data and validation of DT models, ensuring reliability and accuracy, which is a key aspect of the Federal Data Strategy's focus on data governance and interoperability.

Standardized Data Description. Develop lightweight APIs and frameworks for data description, rather than enforcing a common data model, to facilitate effective use of data from various sources. This approach enhances interoperability, interconnectivity, and discoverability, aligning with the Federal Data Strategy's goals.

Task-Agnostic Approach to Data Management. Develop a task-agnostic approach based on agreed metadata to allow for the description of heterogeneous and proprietary data formats. This ensures flexibility and adaptability in data management across different applications and tasks in the DT ecosystem, supporting the Federal Data Strategy's emphasis on data utility and accessibility.

Ecosystem: Establish a National Digital Twin R&D Ecosystem

Creating a robust and collaborative ecosystem is essential for advancing the research, development, and adoption of Digital Twin technology. This ecosystem will foster innovation, facilitate knowledge sharing, and drive the development of emerging applications.

Exploring Emerging Applications and Prerequisite Infrastructure. Focus on both emerging applications of DTs and the necessary knowledge, tools, technologies, and infrastructure to support them. This approach mirrors the strategic initiative undertaken at MITRE's Immersion Lab,[3] where we are actively exploring the potential of Digital Twins and working to develop the necessary supporting infrastructure. By focusing on both applications and infrastructure, we can ensure that the ecosystem is well equipped to support the development and implementation of Digital Twins across a wide range of sectors. Leveraging AI within DTs can significantly

[3] The MITRE Immersion Lab: Immersive Reality for Integrated Solutions. 2023. MITRE, https://www.mitre.org/news-insights/fact-sheet/mitre-immersion-lab-immersive-reality-integrated-solutions. Last accessed: July 23, 2024.

advance fundamental science by providing detailed simulations and predictive models that enhance our understanding of complex systems. This includes applications in biomedical sciences, environmental ecosystems, sustainability, climate change, smart and connected communities, and more. Such advancements will drive scientific discovery, foster innovation, and contribute to solving critical challenges across various domains. By integrating AI, DTs can also facilitate the development of new scientific methodologies and tools, further advancing our understanding of complex phenomena and driving forward fundamental research.

Utilizing Existing Tools and Artifacts. Utilize existing tools and artifacts to expedite DT development and build on established knowledge. For example, we can leverage tools and models developed by NASA to design and develop a foundational digital twin of a sustained human habitat on the lunar surface, in support of NASA's Artemis Program.

Developing Requirements for Data Transport. Conduct studies to determine the relevant data that should be sent from various sources to be fed into the DT, and vice versa. or the Artemis Program's digital twin, identify the relevant data that needs to be transmitted from the Moon to Earth and create novel methodologies for data transmissions in a bandwidth-constrained environment.. This would ensure that the Digital Twin is continuously updated with accurate and relevant data that is trustworthy, enhancing its predictive capabilities and overall utility.

International: International Collaborations on Digital Twins

Fostering global partnerships is essential for DT research, development, and adoption. By collaborating internationally, we can share knowledge, align standards, and address common challenges more effectively. One possible example is the Digital Twin Consortium, which has more than 180 members from around the globe and liaisons with more than 30 global technology associations and standards bodies in industries that are early adopters.

Addressing the Challenge of International Bad Actors. Encourage law enforcement agencies globally to collaborate to curb the misuse of DT-enabled applications by international bad actors. Sharing intelligence, coordinating responses, and developing strategies to mitigate risks are crucial steps.

Navigating Differing Data Regulations. The use and collection of data are subject to different regulations in various countries. Encourage stakeholders in the DT ecosystem to work toward a common understanding of these challenges. Engaging in dialogues, sharing best practices, and developing guidelines that respect the data regulations of all participating countries will ensure ethical and lawful use of data in DTs.

Long Term: Identify Long Term Research Investments

The long-term advancement of DT technology requires a forward-thinking approach that anticipates future needs and challenges.

Human-Centered Design of Digital Twin Applications. Focus on human-machine teaming to enable appropriate decision making by humans, machines, or a combination of both. This involves understanding the information needed for situational awareness and decision making, and presenting it through intuitive interfaces, including 2D graphical user interfaces or immersive 3D (Augmented/Virtual Reality) interfaces. By advancing AI capabilities within DTs, we can attract and build a talented workforce, fostering innovation and ensuring the United States maintains its competitive scientific edge. This will support the development of new scientific tools and methodologies, driving forward fundamental research and discovery. The integration of immersive technologies, such as Augmented Reality (AR) and Virtual Reality (VR), can further enhance the utility and usability of DTs, providing more intuitive and immersive ways to interact with DTs and leading to new scientific insights.

Integration of Immersive Technologies. Invest in the development and integration of immersive technologies, such as AR and VR, to enhance the utility and usability of DTs. These technologies can provide more intuitive and immersive ways to interact with DTs, leading to metaverse-enabled digital twin applications. This aligns with the vision of creating a "modelverse," where AI can dynamically search for and integrate various computable models and Digital Twins into a cohesive, interactive metaverse environment.

Novel Methods for Data Collection and Modeling. Develop novel methods and approaches for modeling, collecting, and systematically documenting training and real-life data on human performance, behavior, and decision-making processes. This will enhance the ability to integrate the human operator within mission contexts and enable in silico testing of mission problems involving human intervention and decision making.

Assurance About the Physical Systems Being Twinned. Mature and evolve the research and practices of supply chain assurance to enhance confidence that the real-world systems being modeled align with the models of the DT, because discrepancies would prove disruptive to using those DT models to manage the operational systems.

Regulatory: Regulatory Science Challenges Associated with the Use of Digital Twins

Addressing regulatory considerations is crucial for the development and implementation of DT technology. Developing regulatory frameworks that incorporate risk assessment, compliance monitoring, and ethical guidelines can ensure the responsible use of DTs.

Curbing Misuse by International Bad Actors. Encourage regulatory and law enforcement agencies to collaborate to prevent the misuse of DT-enabled applications by international bad actors. This includes developing strategies to mitigate risks such as targeted political advertising or disinformation campaigns.

Ethical Use of Data. Ensure the ethical use of data in DTs by implementing regulatory measures that address data privacy, consent, and the potential for data misuse. Guidelines on data collection and use, as well as mechanisms for individuals to control how their data is used, are essential to maintaining ethical standards.

Responsible: Promote Responsible Development & Use of Digital Twins

Ensuring the responsible development and use of DTs involves addressing various considerations related to data privacy, governance, and sovereignty.

Data Privacy. Prioritize data privacy by implementing measures to protect personal data from unauthorized access or misuse. Employ techniques such as encryption and anonymization to safeguard individual privacy rights.

Data Governance. Establish clear policies and procedures for data collection, storage, use, and sharing. Transparent data governance policies and compliance mechanisms are essential for responsible DT use.

Data Sovereignty. Respect data sovereignty by ensuring that DTs comply with the data protection laws of the countries from which they source data. Develop mechanisms to ensure compliance with various national laws, particularly for DTs using data from multiple countries.

Standards: Promote Development of Evaluation Tools, Methodologies and Consensus Standards for Digital Twin Development and Testing and Interoperability

Ensuring consistency, interoperability, and quality across DTs can be achieved through the development of lightweight APIs and frameworks, which avoid the delays and complexities associated with formal standardization processes.

Identification of Standards Gaps and Requirements. Conduct a thorough review to identify gaps and requirements in existing standards related to DTs. Assess current standards' applicability and identify areas that need new standards, such as model fit for purpose and ethical considerations.

Definition of Appropriate Ontology for Semantics and Reference Implementations. Develop a common ontology for semantics and reference implementations to ensure consistency and interoperability among DTs. Establish common definitions and structures to facilitate communication and collaboration across different systems.

Development of Maturity and Assessment Frameworks. Create maturity and assessment frameworks for DTs to evaluate their readiness for implementation. Utilize composable frameworks, open-source solutions, and system reference architectures to support this evaluation.

Learning from the Simulation Community. Leverage best practices and lessons learned from the simulation community, including hybrid modeling and simulation. Develop an integrating approach that aligns diverse individual solutions within the DT ecosystem.

Sustainability: Design and Develop Systems and Architectures for Digital Twin Sustainability

Ensuring the long-term viability of DTs involves creating adaptable systems and architectures that can evolve with technology and standards.

Deployment of Digital Engineering Ecosystems (DEEs). Focus on deploying DEEs that cater to the unique needs of DTs. Develop DEE Reference Architectures explicitly designed for DTs to provide a comprehensive framework for their design, development, and deployment. This approach would ensure that Digital Twins are built on a solid foundation that supports their long-term sustainability.

Development of Digital Twins Across Various Levels of Classification. Address the challenge of developing DTs across different classification levels, particularly for classified programs. Develop strategies and protocols to manage classification complexities, ensuring effective development and operation of DTs in various contexts.

Trustworthy: Realize Secure and Trustworthy Digital Twins

Ensuring the security, cyber resilience, and trustworthiness of DTs is critical for their reliable operation and must cover both the virtual models and the physical aspects of the systems.

Use of Synthetic Data in Absence of Real-Life Data. In scenarios where real-life data is unavailable, use synthetic, statistical data generated from probability distribution functions. This approach, while not perfect, provides a useful approximation for DT functionality, with transparency about its limitations.

Overlap with Trustworthy AI and Complex Simulations. Leverage lessons from the development of Trustworthy AI and complex simulations to enhance DT trustworthiness. Develop new validation methods to assess the reliability and accuracy of complex, interactive models. Ensure that trust measures guide the development process at all stages, not just at the final stage.

VVUQ: Develop Rigorous Methods for Verification, Validation, and Uncertainty Quantification for Digital Twins

Ensuring the accuracy and reliability of DTs requires robust VVUQ processes.

Integration of Verification, Validation, and Accreditation (VV&A) Best Practices. Integrate VV&A best practices from the DoD into VVUQ processes for DTs. This comprehensive framework should address the conceptualization of the physical twin, the development of the digital twin, and all aspects of automated data exchange and feedback.

Development of VVUQ Methods and Tools. Develop VVUQ methods and tools to assess the fit for purpose of DT models, especially for non-engineered, living/biological systems. Address the inherent uncertainty and variability in living systems by incorporating these factors into DT models. Develop methods to understand the extendibility of DT models across different parameter spaces, enabling model reuse in various contexts.

Workforce: Cultivate Workforce and Training to Advance Digital Twin Research and Development

Developing a skilled workforce is essential for the advancement of DT technology.

Implementing Virtual Training Environments. Utilize virtual and mixed reality concepts to create immersive training experiences. These technologies provide engaging and effective training, allowing workers to gain hands-on experience with DTs in a controlled environment.

Lessons from Engineering Management. Draw from lessons learned in Engineering Management, focusing on three key factors: technical maturity of solutions, organizational support for new technology, and an educated workforce. Ensure that organizations investing in DTs develop these areas to support successful implementation.

Other Areas of Input

Education and Training

To advance DT technology, it is essential to invest in education and training. A well-educated workforce equipped with the necessary knowledge and skills is crucial for driving innovation and effectively implementing DT solutions.

Developing Digital Twin Coursework. Create specific coursework at both the university and high-school levels to cover the technical workings, value, and evolution of DT technology. Include early-stage use cases and practical applications across various settings.

Establishing an Educational Accelerator Program. Initiate an Educational Accelerator program to foster a collaborative environment that accelerates DT research and development. Leverage the expertise and contributions of various stakeholders for joint project development.

Launching a Digital Twin Solution Architect Training Program. Develop a training program for Digital Twin Solution Architects to equip professionals with the skills and knowledge needed to design and implement effective DT solutions in various contexts.

Orchestrating Proof-of-Concept and Pilot Programs. Develop proof-of-concept and pilot programs to bridge the gap between theoretical knowledge and practical application. Provide hands-on experience and practical understanding of DT technology.

Producing Thought-Leadership Resources. Create thought-leadership resources, including technical papers, blogs, webinars, and videos, to disseminate knowledge, promote innovation, and showcase the latest trends in DT technology.

Highlighting Technology Showcase and Value Innovation Platform. Feature the Technology Showcase for DT use cases and the Value Innovation Platform, including real-world proof-of-concept testing environments, to inspire further innovation and demonstrate the real-world impact of DT technology.

Environment

Digital Twins have the potential to significantly reduce environmental impact of various processes by optimizing operations and promoting sustainability. Incorporating environmental considerations into DT development can lead to more efficient and eco-friendly solutions.

Promoting a Circular Economy. Utilize DTs to foster a circular or reusable economy. By simulating product life cycles, DTs can help extend product life and identify opportunities for reuse and recycling, aligning with sustainability goals.

Leveraging Data for Improved Services. Use the data-driven nature of DTs to enhance services. Analyzing usage patterns, performance, and user feedback can inform service improvements and drive innovation.

Enhancing Efficiency in Infrastructure Development. Apply DTs to reduce costs and increase efficiency in infrastructure design, construction, and operation. Simulating different design options, construction processes, and operational scenarios can help identify cost-effective and efficient approaches.

Communications Networks

DT technology can significantly enhance the optimization and resilience of communications networks. By simulating various scenarios, DTs can provide valuable insights into improving network performance and reliability.

Optimizing Network Design and Operations. Use DTs to simulate different network configurations and load scenarios. This can aid in capacity planning, network design optimization, and operational strategies, identifying the most effective approaches.

Conducting "What-If" Scenarios. Leverage DTs to conduct "what-if" scenarios, providing insights into network performance under various conditions. This proactive planning can inform decision making, improve network resilience, and enhance user experience.

Performing Network Survivability Analysis. Identify vulnerabilities and develop strategies to enhance network resilience. Utilize DTs to analyze network survivability in the face of potential threats such as cyber attacks, power outages, or natural disasters.

Understanding the Impact of New Technologies. Employ DTs to assess the effect of new technologies or services on existing networks without disturbing operational systems. This ensures that new technologies and services are integrated in a way that optimizes network performance.

Cyber Security

Given the heavy reliance on digital components, ensuring the cybersecurity of DTs is paramount. Each component, from the digital model to data exchange and feedback systems, presents potential access points for cyber attacks throughout the supply chains for their software, digital and physical components, and the maintenance and configuration during use.

Embedding Cybersecurity from Early Stages. Lessons from related domains, such as command and control and system of systems engineering, indicate that cybersecurity measures must be integrated into DT solutions from the early stages of development. Cybersecurity cannot be an afterthought; ensure it is a foundational element throughout the digital engineering of DT systems.

Focusing on High-Consequence Applications. The importance of cybersecurity is particularly pronounced in high-consequence applications of DTs, such as national security, healthcare, and transportation. Enhance the cybersecurity of DTs in these areas to maintain trust in these systems and protect sensitive information and infrastructure.

Application Areas Beyond Engineered Product Systems

While DT methods have traditionally been applied to engineered product systems, there is significant potential in new application areas such as human Digital Twins and societal Digital Twins. These areas require cross-disciplinary research and offer great promise.

Human Digital Twins. Develop digital models of the human body’s anatomy and physiology. Applications include monitoring of remotely operating humans (e.g., astronauts, soldiers, First Responders), response to emergency situations, smart prosthetics, surgical preparations, and long-term diagnosis. Cross-disciplinary collaboration is essential to align expertise and create effective solutions.

Societal Digital Twins. Utilize computational social sciences and related disciplines to create digital models of society. Applications include developing smart cities and artificial societies, and informing better societal decisions, such as policymaking. Examples include forecasting the effects of social distancing during pandemics or assessing the impact of healthcare policies on minority groups. Effective alignment of diverse expertise is crucial to avoid inefficiencies and build trust in the results.

Federal Register Notice: 89 FR 51554, Federal Register :: Networking and Information Technology Research and Development Request for Information on Digital Twins Research and Development, June 18, 2024.

Request for Information on the National Digital Twins R&D Strategic Plan

The Savic Laboratory at the University of California, San Francisco (UCSF)

Request for Information Response:

Networking and Information Technology Research and Development Request for Information on Digital Twins Research and Development

Submitted by members of the Dr. Rada Savic, PhD Laboratory, at the University of California, San Francisco

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The Savic Laboratory at the University of California, San Francisco (UCSF) offers the following submission for consideration in response to the Request for Information (RFI) by the Networking and Information Technology Research and Development (NITRD) National Coordination Office (NCO), National Science Foundation (NSF)

1. Introduction

From 2015 to 2017, an estimated median cost of $48 million was allocated for pivotal trials per approved drug.[1] Additionally, the average time for a drug candidate to receive regulatory approval is approximately 14 years.[1] Despite these efforts, roughly 90% of drug candidates fail to progress due to reasons such as inaccurate target selection, inaccurate patient recruitment, and unexpected adverse effects.[2] The traditional drug development process is lengthy and costly, encompassing several stages of clinical trials, from preclinical to human clinical trials. Although there have been numerous advancements in biomedical research and healthcare, with the increasing need for novel medications, modifications to the current bench-to-bedside methods of drug development should be considered from both a financial and practical standpoint.

Currently, randomized control trials (RCTs) remain the gold standard for evaluating efficacy and safety in humans. Despite providing rigorous scientific evidence to support approval from regulatory bodies, RCTs have drawbacks.[3] The logistical challenges and high costs associated with these trials can lead to extended durations, hindering the development and dissemination of new therapeutics. There is an urgent need to develop innovative techniques that can make RCTs more efficient, reducing the cost and time required to bring a new therapeutic to market while maintaining the validity of trial outcomes. Notably, digital twin (DT) techniques present a viable option to achieve these goals.

This request for information aims to elucidate the potential benefits of integrating DTs in clinical trials, and how this can advance the field of biomedical sciences and improve patient care. To this end, we summarized DT in clinical trial design, potential applications of DTs to clinical trials, standard methods to develop DTs, and considerations for integration of DT.

1.1 Topics addressed:

Applications of digital twins:

- ***Clinical Trial Design:*** *Significance of clinical trial design in drug development and precision medicine; role of modeling in improving clinical trial design and improving patient outcomes; significance of equitable representation of individual variability and patient characteristics*

Standard methods:

- ***Standards:*** *Promote Development of Evaluation Tools, Methodologies and Consensus Standards for Digital Twin Development and Testing and Interoperability: Ontology and data exchange protocols; encryption standards; address challenges related to evaluation of data-driven Digital Twin components; personalized applications derived from Digital Twins*

Considerations:

- ***Regulatory****: Regulatory Science Challenges associated with the use of DTs*
- ***Data****: Governance methods for data collection, sharing and usage; shared public datasets and repositories*
- ***Responsible****: Ethical use of digital twins; identifying ethical issues, mitigating and biases with respect to data ownership*

2. DTs in Clinical Trial Design

2.1 Inherent limitations in current clinical trials

To understand the characteristics of a drug or a drug candidate, investigators strive to minimize bias and confounding variables in clinical trials by utilizing randomization and implementing strict criteria for patient inclusion and exclusion. Although RCTs are the accepted method to evaluate the safety and efficacy of a drug, they have limitations that must be acknowledged.

One of the primary challenges is ensuring adequate sample size. Larger sample sizes or long-term trial durations for statistical power may not always be feasible or cost-effective. In the case of rare diseases or vulnerable populations, participant enrollment may not be sufficient. In addition, the narrow inclusion and exclusion criteria and controlled conditions often result in trial populations that do not equitably represent different patient populations,[4] especially for smaller trials. Furthermore, there may be issues with patient compliance or adherence to treatment protocols, which can impact the validity of the results.[5] As a result, it may be challenging to generalize the results of RCTs to certain patient populations.

2.2 Utilization of DTs in in-silico trials

Emerging DT technologies are starting to make a significant impact on drug development. By leveraging advanced simulations, modeling, artificial intelligence, and big data, these technologies are transforming the drug development process. Particularly, an *in-silico trial*, also known as a virtual clinical trial, in drug development has garnered significant support. For example, the Model-informed drug development approach runs models on virtual patients with appropriate simulated scenarios, aiming to evaluate the efficacy and safety profiles in a larger population without the need for actual recruitment. Likewise, testing the drug characteristics *in-silico* is beneficial for understanding the characteristics of a drug in vulnerable populations, particularly those who are underrepresented in current clinical trials.[6,7]

To ensure the development of trustworthy DTs, cooperative research is necessary to establish shared metrics, test methodologies, quality and security standards, development practices, and standardized tools for designing, developing, and utilizing DTs effectively. To this end, various configurations and mechanisms for public-private partnerships have been developed over the past few decades for different DT applications, such as the Digital Twin Consortium,[8] the Virtual Physiological Human,[9] and the Living Heart Project.[10] Expanding the reach of these mechanisms, improving their functioning and outputs for a more diverse set of participants and application spaces, and creating new forms of public-private partnerships are significant and valuable endeavors.

3. Potential Applications of DT Technologies

3.1 Vulnerable populations

Inclusion of specific populations, such as pediatric or pregnant individuals in RCTs is a prominent need that comes with several challenges. Pediatric RCTs often face difficulties including small sample sizes and challenges in obtaining informed consent, in addition to ethical concerns to test interventions in children. It is well known that “children are not small adults”, due to the differences in pharmacokinetics (PK) during their maturation.[11] As with pediatric populations, pregnant individuals have physiological changes which can affect the PK, potentially making treatment efficacy and safety different for pregnant individuals compared to non-pregnant individuals. The benefits and potential harm to both the mother and fetus must be rigorously evaluated to ensure ethical compliance. To ensure these steps, logistics to enroll pregnant individuals in clinical trials may be more rigorous. Obtaining informed consent from pregnant individuals is challenging due to their unique priorities and concerns. Regulatory bodies, such as the U.S. Food and Drug Administration (FDA), may have specific requirements for inclusion of such participants. For example, the FDA Guidance for Industry for PK studies state do not recommend inclusion of pregnant individuals, if the drug is not utilized in pregnancy or there is fetal-toxicity data.[12]

The integration of DTs may be a possible solution to model the complexity and time-dependent changes of the human body, those that occur in maturation of young children and in pregnancy. DTs can incorporate data on maternal and paternal risk factors, as well as environmental factors, to assess the overall risk to the mother and the newborn. Real-time data collection and analysis through DTs enable early detection of maternal and fetal health risks, allowing healthcare providers to intervene proactively and make informed decisions with their patients.[6,7] DTs may also provide insights on the long-term outcomes on pediatric patients. For example, researchers have been able to characterize infantile microbiome, create a DT, and subsequently utilize the DT to predict the probability of neurological deficits depending on the microbiome composition.[13,14] Similarly, the effect of pharmacological agents either exposed to the infant *in utero* or during breastfeeding may be studied with DT. Finally, DTs may provide benefit to pediatric populations in areas endemic to poverty-related diseases. Pediatric dosing often follows weight-based dosing for medications. Malnourished children, who are underweight for their age, are thus risk of being underdosed.[15] As RCTs may particularly be of a challenge in these populations, the utilization of DTs to simulate different dosing strategies may provide an economical solution for global and equitable medication utilization.

3.2 Precision medicine

In the realm of healthcare and therapy development, the concept of DTs has recently emerged, particularly in oncology. A DT of a cancer patient and their tumor could significantly inform clinical decisions such as treatment options and clinical assessments. The DT approach can be utilized for precision medicine, in which patient-specific therapies are designed based on the DTs’ ability to predict treatment outcomes for real patients. One example is the development of patient-specific DTs using individual quantitative MRI data from patients with triple-negative breast cancer.[16] A mechanism-based predictive model was applied to predict the DTs' response to neoadjuvant systemic therapy.

To evaluate the predictive capability of the generated DTs, patient-specific images from the first three visits were used to create the DTs and predict the treatment outcome. After obtaining the real treatment outcome, it was subsequently compared with the predicted outcome provided by the DT. Results showed that the DT approach significantly improved prediction performance compared to the machine learning model (AUROC increased from 0.78 to 0.89).[16]

The DT can also be utilized to explore the biological factors underlying a patient's response and associated biomarkers. In a previous study, virtual patients were generated in large numbers for each actual patient with non-Hodgkin's lymphoma, taking into account the patient's specific dose level and treatment schedule.[17] For each simulated virtual patient, the individual tumor profile was estimated using a quantitative systems pharmacology (QSP) model. The difference between the simulated tumor measurement of the virtual patient and the actual post-treatment tumor measurement of a real patient was then calculated. The top 25 virtual patients with the smallest error were selected as the DTs of each actual patient. With the use of these DTs, the QSP model was able to predict the efficacy of mosunetuzumab. Additionally, biomarkers that influenced the responsiveness of the DTs to mosunetuzumab were identified. Based on these identified biomarkers, patients that are more likely to get a response can be selected for further clinical trials. Therefore, the success rate of clinical trials will increase.[17]

4. The Development Process of DTs

The development of DTs can be divided into three primary stages, as follows:

(1) Creation of a data-driven or mechanism-based model, which is subsequently validated through predictive performance metrics.

(2) Collection of baseline data from the real patient and construction of the DT based on actual measurements.

(3) Utilization of the DT to simulate various "what if" scenarios and comparison of predicted outcomes with the actual outcomes from the real patient to assess the DT's performance. Once a validated DT has been created, it can be employed with real-time, real-world data from the actual patient to continuously monitor, diagnose, and forecast the patient's condition.[18]

Implementing DTs in healthcare presents several challenges, including data integration, privacy and accuracy, ethical considerations, and regulatory compliance. Standardized data formats and interoperability standards are necessary for seamless exchange and use of health data, which is stored in various formats across different systems. Ensuring data privacy and security is crucial as DTs rely on extensive patient data, including sensitive health information.

Strict adherence to regulations such as Health Insurance Portability and Accountability ACT (HIPAA) and General Data Protection Regulation (GDPR), along with robust measures for data encryption and secure storage, is required. The accuracy and quality of input health data is essential for creating reliable DTs, but it is often limited by fragmentation, noise, and biases. Longitudinal data, necessary for capturing changes in health over time, is frequently scarce and may have gaps, making accurate DT maintenance challenging. Ethical considerations, such as informed consent, data ownership, patient autonomy, and preventing healthcare disparities, must be addressed with specific guidelines for responsible data sharing and unbiased models.[19]

5. Considerations for DT Technologies

5.1 Data management and governance

Data generation for drug development and healthcare purposes is rapidly increasing due to advancements in technology for drug discovery and bioanalytical methods, as well as the collection of complex data such as genomic data and clinical information from hospitals.[20] However, managing this vast amount of data presents challenges for those in the field. Personalized medicine in drug development and healthcare is based on genetic, biochemical, physiological, and behavioral aspects of individuals.[21] As the use and application of personalized medicine increases, unmanaged data can result in low data quality and increased time and costs. Therefore, efficient data management is a crucial consideration for developers and organizations.[22]

The implementation of data governance is beneficial in respect to managing the data and minimizing the risks associated with the utilization of big data.[22] Data governance for DT comprises a comprehensive structure of policies, guidelines, and procedures designed to effectively manage and control massive data.[22,23] Data governance can encompass data protection, data classification, compliance, security, and privacy,[24] and it is applicable to DT in the healthcare sector.[25] The healthcare industry's data is diverse in form and lacks standardization, emphasizing the need for uniform data management.[22] Given that DT in healthcare primarily focuses on individual health-based information, data management must be closely monitored using tools or audits. Data governance for healthcare should concentrate on data management, security, privacy, and data depletion.[22] As data governance for DT in healthcare is not widely proposed, general guidelines for data governance should be followed.[23]

5.2 Guidelines for standardized analysis

DTs have vast potential in the realm of healthcare, extending beyond the boundaries of biomarker and drug discovery, design optimization, drug development, and personalized medicine.[19,26] Despite their advantages, the use of DTs remains fraught with challenges, mainly due to the absence of standardized documentation for each application, varied expectations for model assessments, and differing levels of understanding regarding the principles and concepts. Comprehending the technological intricacies of artificial intelligence (AI) and DTs, as well as their interdependent and complementary relationship, is indispensable for the advancement of DTs in healthcare.

In essence, DT technology leverages machine learning algorithms to process data and identify patterns. However, the complexity of DTs surpasses the capabilities of computational modeling and AI/ML algorithms alone, thereby complicating standardized analyses for DT studies.[19] Consequently, these obstacles hinder the evaluation of data quality, the robustness of analyses, the impact of modeling, and the credibility of applications. As a result, valuable opportunities for maximizing the benefits of DTs in various applications and improving decision-making have been missed. To overcome these challenges, it is crucial to establish detailed and standardized data formats and interoperability standards tailored to the specific purposes of DTs.[27] By doing so, consistency and reliability can be enhanced across regulatory assessments and applications, thereby unlocking the full potential of DTs in healthcare. Although a guideline specifically related to deep learning techniques (i.e., DTs) has not yet been released, the Good Machine Learning Practice (GMLP) guideline for Medical Device Development, which was issued in 2021 by the FDA, Health Canada, and the United Kingdom's Medicines and Healthcare products Regulatory Agency (HMRA), can be consulted for various applications of DTs.[28] This guideline was specifically designed for medical device development authorities. However, its message can also be applied to various applications of DTs, as computational modeling and AI/ML algorithms are widely used in the field of DTs. The ten principles emphasized in the GMLP guidelines are as follows:

- Multi-disciplinary expertise is leveraged throughout the total product life cycle
- Good software engineering and security practices are implemented
- Clinical study participants and datasets are representative of the intended patient populations
- Training datasets are independent of test sets
- Selected reference datasets are based upon best available methods
- Model design is tailored to the available data and reflects the intended use of the device
- Focus is placed on the performance of the Human-AI Team
- Testing demonstrates device performance during clinically relevant conditions
- Users are provided clear, essential information
- Deployed models are monitored for performance and re-training risks are managed

Therefore, it is imperative that guidelines be established to illustrate how physical entities can be described, as well as their corresponding virtual replicas, and the relationship between the two. Additionally, it is crucial to provide clarity on how to maintain the transparency of hypotheses and data utilized in developing DTs,[29] validate methods for verifying DT analysis results,[30] and establish ethical guidelines for trustworthy DTs.[21] Furthermore, an organization that can continuously provide feedback on DT applications is necessary. This organization can ensure that studies employing DT models are accurate, reliable, and adhere to ethical standards. The formation of interdisciplinary review committees may be a viable approach to achieve this. Similar to pre-Investigational New Drug meetings, which can assist sponsors in addressing questions regarding their new drug candidate applications, meetings with interdisciplinary review committees can help sponsors prepare to submit applications for personalized medicines, for instance.

5.3 Ethical issues related to DTs

DTs are used in healthcare for diagnosis, prognosis, and personalized treatment based on health-related data. The data used to build DT ranges from general or specific genetic information to individual baseline lifestyle, health information, and disease status. Additionally, a large amount of data may be required to develop DT in healthcare, which is gathered from public sources.[31] However, the process of gathering and using this data raises ethical issues. The data collection is the first step in developing DT, and efforts to gather as much data as possible to create an appropriate model may result in the hypercollection of data, thereby compromising individual privacy.

After data collection, data management is carried out by developers according to their respective strategies, which can lead to barriers in accessing data.[32] If the provider fails to adjust the proper management of the model associated with DT, data accessibility can be disrupted. Outdated or disrupted data can make it difficult for individuals using healthcare services using DT to access health-related information, ultimately affecting the quality of healthcare services. Data brokerage is also a significant ethical issue in data management.[33] Before using data for DT development, data ownership should be characterized, and consensus on data ownership and informed consent from the provider should be established.

The process of data analysis using DT may inadvertently result in biased algorithms or biased training datasets, leading to unexpected discrimination.[31] To address this issue, developers must ensure that the algorithms use appropriate proxy or training datasets that are consistently labeled and accurately represented in the data features. The ultimate goal of implementing healthcare using DT is to provide prognosis of diseases and preventive healthcare. However, there are concerns about the use of DT in healthcare, particularly the risk of overdiagnosis.[31,32] In practice, early diagnosis and treatment can lead to overdiagnosis and overtreatment, resulting in increased individual and social costs. Therefore, organizations can encourage developers of healthcare using DT to collaborate with clinicians and researchers to ensure comprehensive interpretations.

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Federal Register Notice: 89 FR 51554, Federal Register :: Networking and Information Technology Research and Development Request for Information on Digital Twins Research and Development, June 18, 2024.

Request for Information on the National Digital Twins R&D Strategic Plan

Thomas Yankeelov

Via FDMS

Thomas Yankeelov, 7/17/2024

[redacted]

I would respectfully stress that we need to make sure the strategic plan is not only focused on the methods of artificial intelligence, big data, and data science. While these are certainly important areas, in recent years they are dominating funding decisions at the expense of under-funding mechanism-based modeling which, of course, is the backbone of science and engineering. Thank you for hearing my suggestion. Sincerely, Thomas Yankeelov, Ph.D. W.A. "Tex" Moncrief Chair of Computational Oncology Director, Center for Computational Oncology, Oden Institute for Computational Engineering and Sciences Director, Cancer Imaging Research, Livestrong Cancer Institutes Co-leader, Quantitative Oncology Research Program, Livestrong Cancer Institutes Adjunct Professor of Imaging Physics, MD Anderson Cancer Center Professor of Biomedical Engineering, Diagnostic Medicine, Oncology The University of Texas at Austin

Federal Register Notice: 89 FR 51554, Federal Register :: Networking and Information Technology Research and Development Request for Information on Digital Twins Research and Development, June 18, 2024.

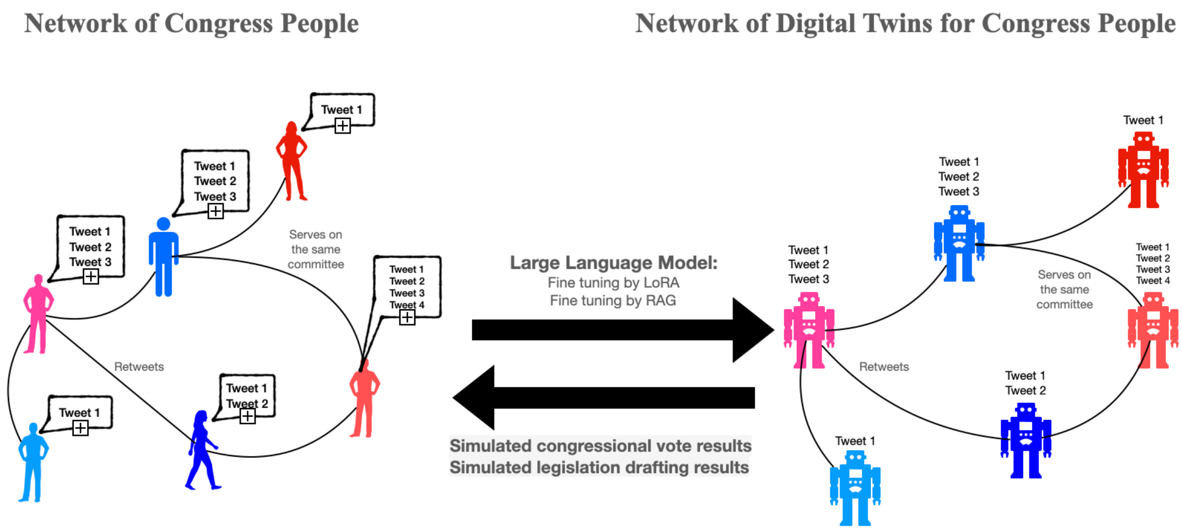
Request for Information on the National Digital Twins R&D Strategic Plan

Tianyi Chen and Hayden Helm

As with the promise of applications of digital twins for biomedical research, aerospace engineering, and earth systems, the recent cohort of generative models -- e.g., Large Language Models (LLMs) and diffusion models – have enabled progress towards a Digital Twin for Society. Insofar as an individual LLM is a proxy of an individual within a community, collections of LLMs can approximate entire communities. By properly modeling individuals within a community and defining appropriate interaction and update mechanics for subsets of the LLMs, we will soon be able to simulate political and social interventions at scale.

As a first step, we use tweets from congress people to train LLM to create digital twins for them. As illustrated below.

On the left side are the real congress people, forming a social network with edges between them. The edges can be undirected, such as indicating whether they serve on the same committee (0/1), or directed and weighted, such as representing how often A retweets B’s tweets, with the edge weight reflecting the number of retweets. On the right side are the digital twins of congress people, where large language models are fine-tuned using each congress person’s tweets. The digital twins serve as good approximations, demonstrated by their ability to predict real bill votes accurately. Additionally, these digital twins can simulate future bill votes, helping to identify weak points within a party, thereby having a real impact.



By Tianyi Chen and Hayden Helm

Federal Register Notice: 89 FR 51554, Federal Register :: Networking and Information Technology Research and Development Request for Information on Digital Twins Research and Development, June 18, 2024.

Request for Information on the National Digital Twins R&D Strategic Plan

Trimble

July 28, 2024

Melissa Cornelius
Technical Project Coordinator
National Coordination Office for NITRD
National Science Foundation
[redacted]

Subject: Federal Register Docket No. 2024-13379, Networking and Information Technology Research and Development Request for Information (RFI) on Digital Twins Research and Development

Dear Ms. Cornelius:

Trimble welcomes the opportunity to provide comments to the National Coordination Office for Networking and Information Technology Research and Development (NITRD) on the creation of a National Digital Twins Research and Development (R&D) Strategic Plan.

Trimble is transforming the way the world works by delivering solutions that enable our customers to thrive. Core technologies in positioning, modeling, connectivity and data analytics connect the digital and physical worlds to improve productivity, quality, safety, transparency and sustainability. From purpose-built products to enterprise lifecycle solutions, Trimble is transforming industries such as agriculture, construction, geospatial and transportation.

Trimble offers the following comments as the NITRD looks to shape this important research and development effort related to digital twins across all domains.

Artificial Intelligence (AI)

AI and digital twins: Possible focus areas: integration of digital twins with artificial intelligence (AI); leverage generative AI for digital twin modeling & simulation with the consideration of the potential impact on a digital twins' physical counterpart.

In the construction and transportation industries, AI's role in digital twins is already transforming how state infrastructure owners are approaching how they manage assets over their lifetime. AI is playing a key role in capturing and processing existing conditions and asset data for use by planning, design, survey, construction and contractor teams. Its role in asset management is even larger considering how much AI processing is lowering the costs for state owners to capture information on their infrastructure assets including the condition of those assets. State Departments of Transportation (DOTs) like Minnesota Department of Transportation (MnDOT), Texas Department of Transportation (TxDOT) and the California

Department of Transportation (Caltrans) are leveraging more mobile mapping (LiDAR and image data capture) statewide to improve asset data used across multiple departments. Mobile mapping integrates laser scanning with high-resolution imagery enabling the collection of large amounts of accurate, georeferenced spatial data which can be transformed into a digital twin of the physical world. By providing an accurate digital twin for design engineers, mobile mapping avoids delays and rework. It also enables construction crews to verify specification conformity and increases worker safety by removing the need to have workers near an active roadway project site for data capture.

Today owners in the European Union (EU) are focused on the use of generative AI, parametric modeling and simulations as part of their planning and design process, where they can rapidly optimize planning and design options, including costs. National Highways England is an example owner moving forward with this approach today. U.S. state owners are also interested in moving in this direction to optimize design and project costs.

In addition to the growing owner interest in AI use for digital twin modeling and simulations at the U.S. state owner level, it is also being widely adopted by the design engineering consultant community who serves the owners. The opportunity for return on investment (ROI) and value creation using AI with owners could for example allow them to rapidly iterate on both design options for a bridge and the 30 year maintenance and asset management options and costs that design option will have long term. With the majority of a state construction owner's costs tied to asset management and maintenance post project, this type of approach has tremendous promise at optimizing infrastructure operations long term.

Trimble also sees a growing interest with U.S. state owners in leveraging field data, including monitoring sensors in the field to better manage sustainability and climate change impacts to their infrastructure assets. Annual maintenance plans can be developed, optimized and monitored to make informed decisions for future work related to climate change impacts. AI processing of this type of data would allow owners to move from being reactive to environment challenges to taking a proactive approach, with modeling based on real world conditions.

Business Case Analysis

Possible focus areas: foundational research cost; evaluate value/return on investment; cost and time to implement.

Value and return on investment (ROI), cost and time to implement are key items to consider as part of the business case analysis. All U.S. state owners today want to better understand their technology and data investment ROI at a state level along with where they should be considering their next investments.

Increasing safety is also a key part of the business case analysis that U.S. state owners are looking at today. A key example is their interest in using mobile mapping and AI processing to capture roadway data with vehicle systems instead of asking people to capture data along the active roadway.

Total cost of ownership (how costs can be reduced) and enterprise value are key elements of the business analysis that U.S. state owners need to better understand when it comes to how they should invest in technology and data. Today investments are often siloed within a single department, leaving the enterprise-wide opportunity for its data and technology untapped.

Encourage Adoption of Data Management Best Practices

Possible focus areas: governance methods for data collection, curation, sharing and usage; shared public datasets and repositories; real-time data integration.

Perhaps the most foundational element when it comes to maximizing an owner's investment in technology and data is having data governance that drives both workflow and data flow at the enterprise level. This was so critical to infrastructure owners in the EU that the Norway Road Authority created a new organization to focus solely on data governance and data standards for the owner’s enterprise operations.

Open API’s and data interoperability are also foundational elements of maximizing ROI from technology and data investments. The use and re-use of data and AI across an enterprise can exponentially reduce costs and accelerate ROI. There are even opportunities today for owners to leverage AI to help them better understand and standardize their data at the enterprise level. The concept of “data lakes” that hold data from multiple sources, vendors and technologies is also an important part of the future landscape so construction owners can acquire larger sets of data across the above continuum and make even better decisions and outcomes.

Adoption is also tied directly to education as there is a need from every state owner in the U.S. to shift to educating our next generation of transportation professionals on the use of data across the enterprise for asset lifecycle management. Certain states, such as California, have even developed first of their kind programs focused on teaching students how data is used across a state construction owner organization to improve management of tax payer assets.

Establish a National Digital Twin R&D Ecosystems

Possible focus areas: collaborations across agencies to identify and address foundational research gaps and opportunities that spans areas such as biomedical sciences, environmental ecosystem, sustainability & climate change, smart and connected communities, scientific discovery, agriculture, military & mission planning, as well as common mathematical, statistical, and computational foundations.

There is a great opportunity for owner data collaboration at the national, state, local and utility level, even impacting other agencies that rely on transportation information such as emergency services. State owners like Colorado are passing data sharing and standards laws for agencies already, with their first policies helping the Colorado State Department of Transportation (CDOT), local government owners and utilities owners share data in a standard way for all projects statewide. Now imagine applying AI analysis to that shared data to help each level of owner improve on their asset operations.

Trimble's view of establishing a national digital twin R&D ecosystem is that it would increase the ROI potential of both owner data and AI processing, allowing any part of an owner's enterprise to engage with industry to explore the use of digital twins technologies and AI analysis.

Additionally, Trimble works very closely with the U.S. military and U.S. Army Corps of Engineers (USACE) as they have very similar needs when it comes to digital twins as the state DOT owners. They have some R&D projects in progress that would benefit state infrastructure owners in the future and state owners like Caltrans are educating USACE as well on their innovations. Trimble would like to see more of this type of innovation sharing available for all owners.

For the military, digital twins can address the complexity of multi-domain operational environments and associated operational constraints which can be identified earlier in systems design and impact decision-making for a more informed understanding of tradeoffs. Although the U.S. military needs to internally decide on requirements, industry can contribute software engineering expertise for the standardization of digital twins. As with construction, virtual representations of a system allow interoperability of data for design, development and maintenance or sustainment of a system's life cycle.

At Trimble, half of our work is also focused on building owners and project teams. State owners of infrastructure also own many buildings so Trimble works across a diversified group of technology owners, healthcare owners, bio-medical owners, manufacturing and oil and gas owners. They too are innovating today with digital twins and AI processing. There are benefits that all customers are missing because of a lack of a national standard approach to sharing innovation and information related to digital twins and asset lifecycle management.

International Collaboration on Digital Twins

Possible focus areas: global scale digital twins across foreign markets; global issues and digital twin development consensus standards; opportunities for international collaboration (e.g., European Union's Horizon 2020 program funding digital twin projects).

BuildingSMART International and IFC (Industry Foundation Classes) are key pieces of Trimble's international efforts surrounding digital twins. As a standardized, digital description of the built asset industry, IFC provides an open, international standard promoting vendor-neutral capabilities across different software platforms, hardware devices and interfaces allowing for collaboration and information sharing. Much of our experience today with digital twins and use of digital twins for asset lifecycle management comes from regions like the Nordics or Singapore who leverage open data standards.

Asset owners including all Trimble customers are concerned with the costs of technology as innovation accelerates. One way to offset the rising costs of technologies is to look at global standards for digital twins with open data standards. Today vendors like Trimble, Bentley, Autodesk and Environmental Systems Research Institute, Inc. (ESRI) can manage up to 20 different data formats depending on the projects and regions.

When looking at other industries that have adopted global standards, it is easy to see via the data results the explosion in innovation (as startups are able to take advantage of open standards and global scale) as well as a reduction in costs due to lower operating costs and more competition. Trimble would ask why the construction and transportation industries have not considered what has already worked in other industries.

Long Term Research Investments

Possible focus areas: novel approaches for interactive data-driven modeling and simulation, both crosscutting and fit for purpose; research enabling the bidirectional flow between the virtual and the physical assets; creating test environments for digital twins ensuring sufficient resources and sustainable high-performance computing.

Trimble believes that a focus on the long term impacts of data-driven asset management and maintenance owners who are leveraging asset modeling, maintenance planning and capital planning along with AI analysis would help owners lower the total cost of ownership of all assets. Of particular interest to state owners is asset data updates and inventories and determining long term what is the best approach to best providing a full transportation system inventory of assets and updates on those assets that are not years old.

Regulatory

Regulatory science challenges associated with the use of digital twins.

There will be many regulatory challenges coming as industry members learn to better use data and technology like AI to create workflows and models that could incorporate more variables than ever considered in the past. Examples include whether there is a need to change how road design and materials are analyzed based on more real time weigh in motion data (dynamic vehicle weighing) from long haul trucking. Another example is how airport owners need a cost and time efficient way to capture runway conditions at night (their only downtime), which is a perfect fit for mobile mapping and AI analysis; however, regulations have not been updated to allow for this approach. The use of drones is also putting pressure on regulatory restrictions.

Trimble's view is that regulatory updates need to be made with an understanding of Moore's Law, that technology is advancing rapidly and regulatory changes are not keeping pace.

Promote Responsible Development & Use of Digital Twins

Possible focus areas: ethical use of digital twins; identifying ethical issues, mitigating and biases with respect to data ownership, intellectual property and privacy.

Responsible use of digital twins is tied to transparency. For example, owners in the EU are being transparent about their work as they work on digital twins, including the data they want to use and why they want to use it. They share this with the public and with their project partners, gaining the trust of both the industry and the public, especially as the benefits of using digital twins are tied to improvements in infrastructure for the public. This is another reason why open and interoperable data standards are critically important for digital twins.

Promote Development of Evaluation Tools, Methodologies and Consensus Standards for Digital Twin Development and Testing and Interoperability

Possible focus areas: community of practice, ontology and data exchange protocols; encryption standards; taxonomy; address challenges related to evaluation of data-driven digital twin components; continuous and multi-modal data sources; personalized applications derived from digital twins; transferability, generalizability and robustness of digital twins.

The development of evaluation tools and methodologies and building consensus standards is a large gap area today for state owners. While all state owners would like to move to digital twins, they will need a playbook or guide to help them understand this effort at an enterprise level.

There is also a large value opportunity for owners who are willing to share their data, with data being the new currency. Owners have an opportunity to increase the value of their data through the development of apps, sharing with industries, and in cases like local owners or utilities owners exchanging data currency to help each other's operations.

There is also a lack of a standard for the transportation and construction supply chain. When viewing other industries of similar size, they have all established standards and technologies for an electronic supply chain. One of the key items within a digital twin are the materials coming in through the supply chain, not just for project delivery, but over the lifetime the asset is being maintained. Without standards for supply chain, the efficiency gains from digital twins will be limited. Connecting the owner's entire supply chain (both field and office) with all data related to the built asset gives the owner a complete dynamic digital twin to the physical asset.

Design and Develop Systems and Architectures for Digital Twin Sustainability

Possible focus areas: sustainment as the operating systems and computational models on which they are based evolve and the data which they ingest are updated; intentional organizational effort and purpose-built modeling ecosystems energy-awareness; early consideration of computational requirements and effective workflows; develop approaches for the design, development, and deployment of digital twins; the ability to create interoperable digital twins with evolving technology and standards.

Based on the reality of Moore's Law, Trimble sees a key need for this approach as new AI models and input variables to AI models will constantly evolve. Owners of infrastructure will need to adopt new technologies, new data sources and even new data standards, such as the expanding visualization data standard Universal Scene Description (USD) from NVIDIA as one example. USD is an open-sourced 3D framework that allows for the interoperability of tools to create and exchange content.

To realize the scale and efficiency of digital twins as stated above, there is a need for a global approach to standards that all technology providers and consumers can support. A global, standardized and structured approach would again drive innovation and lower costs to sustain digital twins. Imagine having a global standard established for how all cars on all roads would use sensors and cameras to help owners capture ongoing conditions of those assets. AI processing on top of that data would provide a wealth of information in real time that owners are missing today and expand to many other industries that want access to that type of data.

For digital twins, the need for supply chain information is growing. Trimble works with organizations such as ETIM International (https://www.etim-international.com/) to help owners, design engineers and contractors with supply chain standards that support both project and asset work. ETIM is the international classification standard for technical products which adds structure to the flow of information between B2B professionals within the value chain. Trimble also plays a key role in providing trade services (https://www.tradeservice.com/) product and supply chain data to our contractor customer base that enhances the value of a digital twin.

Realize Secure and Trustworthy Digital Twins

Possible focus areas: develop solutions to assure the security, cyber resilience, and trustworthiness of digital twins (taking into account all components of DTs such as their code base, data and data processing, operational environments, networking and connectivity with the physical counterpart); develop capabilities to utilize DTs to improve the security and cyber resilience of the physical counterpart, such as through threat analysis, attack modeling, risk analysis, security testing and similar analyses conducted on the digital twins.

The lack of cyber standards between state owners within the U.S. will create a dramatic increase in technology costs as technology providers work to try to align to 50 different standards. These state standards may or may not align to federal standards for cyber security, or local owner cyber security standards. A more scalable standard is needed not just for digital twins, but for transportation and infrastructure data in general. Trimble has presented on this topic already to state DOT owners.

Develop Rigorous Methods for Verification, Validation and Uncertainty Quantification (VVUQ) for Digital Twins

Possible focus areas: foundational and cross-cutting methods as well as domain specific; integration of VVUQ into all elements of the full digital twin ecosystem.

EU owners have built in VVUQ to their project, maintenance and asset management based workflows and data flows, which in turn generate and/or update their digital twins. While the industry will need VVUQ to help them manage digital twins over time, Trimble has seen that the impact of implementing VVUQ at the project level greatly improves the verification, validation and certainty for digital twins without post-project processing or analysis.

Cultivate Workforce and Training to Advance Digital Twin R&D

Possible focus areas: diverse talent recruitment; incentivize cross-disciplinary STEM research programs across educational institutions.

As mentioned previously, Trimble believes education plays a critical role in the adoption of digital twins. While Caltrans provides an example to highlight in this area, there is a definitive need for a more data-focused approach to workforce development and training. This approach has the potential to attract a younger workforce interested in data science, AI and app development, increasing the importance of state owners working closely with their local universities.

In conclusion, Trimble applauds this effort to provide guidance for government investments and further federal R&D coordination in digital twins related research through a National Digital Twins R&D Strategic Plan. Digital twins allow the owner the ability to have a complete dynamic virtual representation of the physical asset through the linkage of departments within an organization with the entire supply chain and all relevant data of the built asset. Trimble believes that leveraging digital technology across all parts of asset lifecycle management and sharing information among stakeholders results in infrastructure assets that are built faster, greener, more sustainable and operate more safely while providing equitable outcomes to all.

Trimble looks forward to working with NITRD to advance the technology and accelerate the use of and early adoption of digital twin models to shape a whole-of-government approach on R&D related to digital twins.

Thank you for your consideration.

Sincerely,

Stephen Kittle
Director - Proposals, Contracts & Grants Programs

Federal Register Notice: 89 FR 51554, Federal Register :: Networking and Information Technology Research and Development Request for Information on Digital Twins Research and Development, June 18, 2024.

Request for Information on the National Digital Twins R&D Strategic Plan

UC Davis

UCDAVIS

July 26, 2024

Subject: Networking and Information Technology Research and Development Request for Information on Digital Twins Research and Development

To Whom It May Concern:

UC Davis is pleased to provide a response to this RFI from the Networking and Information Technology Research and Development National Coordination Office regarding the creation of a National Digital Twins R&D Strategic Plan. Enclosed are responses from Drs. Samuel T. King, Pantelis Loupos, and Joseph Teran. Further communications regarding the content of this RFI response may be directed to [redacted] and [redacted] respectively.

On the Trustworthiness topic of interest, one specific application of relevance to digital twins approaches is the development of automated insulin delivery systems. Information generated from software modeling human metabolism is used to mediate the injection of insulin, which has great implications for human health and safety if the process is not secured. In use cases such as this one, trustworthiness must be a key consideration in the future construction of healthcare systems.

Regarding the Ecosystem topic of interest, there is an interest in characterizing emergent behavior in network formation and dynamics. Digital twins approaches may be used to simulate and observe emergent behaviors in different types of networks, such as social, transportation, or neural networks. Furthermore, these approaches may lend themselves to enabling the analysis of how changes in individual behaviors or connections influence overall network dynamics, helping predict and manage subsequent large-scale network transformations.

Additionally, in relation to the Artificial Intelligence topic area, the emerging field of digital humans warrants future investigation and consideration.

The UC Davis Office of Research appreciates the opportunity to provide input pertinent to NITRD's directives and looks forward to future collaboration.

[redacted]

Federal Register Notice: 89 FR 51554, Federal Register :: Networking and Information Technology Research and Development Request for Information on Digital Twins Research and Development, June 18, 2024.

Request for Information on the National Digital Twins R&D Strategic Plan

Prof. Tarek Zohdi (on behalf of University of California Berkeley)
Associate Dean for Research, College of Engineering, UC Berkeley

July 17, 2024

NITRD National Coordination Office
[redacted]

Dear NITRD,

RE: RFI Response: Digital Twins R&D Plan

The memo below is a response to the RFI for **Networking and Information Technology Research and Development Request for Information on Digital Twins Research and Development** on behalf of UC Berkeley. UC Berkeley has had a long history in the pioneering of modeling and computational methods, such as Finite Element Methods, Optimization, High-Performance Computing, Artificial Intelligence, etc. which are the backbone of industrial-scale digital twin technologies, across a vast spectrum of engineering design and analysis as well as across several other fields. We wish to comment that our campus view is largely consistent with the report of the US National Academies of Sciences, Engineering, and Medicine have recently (2024) on digital twins, *Foundational Research Gaps and Future Directions for Digital Twins,* which makes recommendations to advance mathematical, statistical, and computational foundations for digital twins. The report identifies use case examples in the domains of biomedical sciences, climate change, smart cities, and scientific discovery. In that report, their working definition of a digital twin is a set of virtual information constructs that mimics the structure, context, and behavior of a natural, engineered, or social system (or system-of-systems), is dynamically updated with data from its physical twin, has a predictive capability, and informs decisions that realize value. The report also emphasizes a key characteristic of a digital twin, namely the bidirectional interaction between the virtual and the physical worlds. Furthermore, they list a number of related topics that have synergy with digital twins, namely:

- Artificial Intelligence (AI);
- business case analysis;
- data management best practices;
- establishment of a national and international digital twin ecosystem;
- identification of long term research investments;
- development of regulatory systems;
- ethical development and deployment of digital twins;
- development of evaluation tools and methodologies;
- design and development of systems and architectures for digital twin sustainability;
- trustworthiness of digital twins;
- development of rigorous methods for verification, validation, and uncertainty quantification for digital twins; and

- workforce development and training to advance digital twin research and development.

As the report indicates, there is quite a lot of potential growth in this field, which represents a logical next stage of scientific computing. The topics above are actively being investigated by several of the faculty on our campus. Some further topics which we believe should be considered are:
- Climate change, infrastructure vulnerabilities, urban resilience;
- Social-ecological systems;
- Ecosystem development for sustainable responsible digital twins; and
- Providing precise clean data to digital twin structures.

We emphasize that modern rapidly computable scientific models facilitate the concept of a digital twin of physical reality, i.e., a digital replica of an engineering design, device or process, that can be safely manipulated and optimized in a virtual setting and then deployed afterwards in the physical world, with the goal being to reduce costs of experiments and to accelerate the development of new technologies. Equally as critical is that the digital twin run in tandem with the physical counterpart. Advanced semiconductor manufacturing provides one very critical example, requiring spatio-temporal multiscale-multiphysics analysis, chiplet design and assembly, novel materials, cross cutting enabling technology, supply chain integration methodology and education and workforce development. In this case, the objective is to enable the seamless integration of digital twin models into U.S. semiconductor manufacturing, advanced packaging, assembly and chiplet paradigms, enabling rapid adoption of digital twin innovations and enhancing domestic competitiveness for decades. This is one of many examples that UC Berkeley faculty actively work in, related to digital twins. In general, we wish to:

- Advance digital twin-enabled curricula and best practices for training workforces nationwide;
- Create a digital twin marketplace for industry, including entrepreneurs, to access digital models and to de-risk digital twin development and implementation;
- Develop a shared marketplace that enables data aggregation across companies, while protecting proprietary data, to make powerful digital twins available at low cost; and
- Develop an education and workforce development program, which may include partnerships with a network of educational institutions.

The overall goal is to construct a robust Digital Twin library of experimentally validated tools for engineers and scientists to easily use across a wide spectrum of applications of interest to society and industry. We wholeheartedly support the development of a national initiative on **Digital Twins Research and Development.**

Regards,
Prof. Tarek Zohdi (on behalf of UC Berkeley)
Associate Dean for Research, College of Engineering, UC Berkeley

Federal Register Notice: 89 FR 51554, Federal Register :: Networking and Information Technology Research and Development Request for Information on Digital Twins Research and Development, June 18, 2024.

Request for Information on the National Digital Twins R&D Strategic Plan

Knights Digital Twin Initiative, University of Central Florida,

Institute for Simulation and Training / School of Modeling Simulation and Training

The UCF's Knights Digital Twin Initiative Research and Development

Submitted by:

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Executive Summary:

Through its Knights Digital Twin Initiative, the University of Central Florida (UCF) responds to the U.S. government's Request for Information on Digital Twins (DT), addressing critical aspects of Artificial Intelligence (AI) integration, verification and validation, and workforce development. Drawing on expertise from specialized labs, UCF highlights key challenges and future directions in digital twin technology. In AI integration, the focus is on mitigating hallucinations in generative models for critical applications. For Verification, Validation, and Uncertainty Quantification (VVUQ), UCF emphasizes standardized frameworks and improved real-time modeling and simulation modeling techniques. when it comes to workforce development, it emerges as a crucial area, with recommendations for interdisciplinary training and standardized accreditation. An additional area that is not adequately represented in current DT research is the question for the most effective way to present and interact with DT systems. Key priorities for future focus include enhancing AI accuracy in digital twins, creating standardized VVUQ frameworks, establishing comprehensive training programs, and addressing the cybersecurity workforce shortage. UCF proposes strategies such as developing national computational resources, implementing advanced modeling techniques, and fostering academia-industry partnerships. By addressing these challenges and implementing the proposed strategies, the U.S. can strengthen its position in digital twin technology, driving innovation and maintaining global competitiveness across various sectors. This response provides a roadmap for advancing digital twin capabilities in the abovementioned topics,

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emphasizing the importance of collaboration between academia, industry, and government in this critical technological domain.

Introduction:

This document aims to provide comments and insights in response to the Request for Information (RFI) issued by the U.S. government, Networking and Information Technology Research and Development (NITRD) National Coordination Office (NCO), and National Science Foundation (NSF). The University of Central Florida (UCF) has actively engaged in digital transformation through its pioneering Knights Digital Twin (KDT) Initiative[3]. The KDT Initiative, led by the School of Modeling Simulation and Training (SMST) embodies UCF's commitment to innovative digital transformation, and several specialized labs have been instrumental in this effort. Moreover, it positions UCF at the forefront of advancing the U.S.'s global competitive advantage by fostering collaboration across academia, industry, military, and government. The ultimate goal of this initiative is to develop an integrated ecosystem comprising digital/physical twins, data, models, simulations, and comprehensive lifecycle analyses within a multi-domain environment.

In this document, we address three critical aspects outlined in the RFI: "*AI and Digital Twins,*" "*Verification, Validation, and Uncertainty Quantification for Digital Twins: Possible focus areas,*" *and "Workforce Development".* It is worth mentioning that all mentioned gaps provided in the following section are purely based on the real-life experiences and insights of KDT-UCF experts in the adoption and implementation of digital twins in various aspects and based on extensive research experiences.

Through this response, UCF aims to provide valuable insights and recommendations that will support the U.S. government's efforts in harnessing the potential of digital twin technology. By addressing these key areas, we strive to contribute to the development of robust, innovative, and effective digital twin solutions that can drive progress across various sectors. We look forward to continued collaboration and the opportunity to contribute to the advancement of digital twin technology, reinforcing the U.S.'s position as a global leader in digital innovation.

[3] https://www.ist.ucf.edu/labs/knights-digital-twin-initiative/

AI and Digital Twins:

State-of-the-Art

The state-of-the-art artificial intelligence (AI) with digital twins is the ability to combine real-time data collection, data modeling for analytics, and explainable AI to assist in human decision-making. These intelligent digital twins are leveraging advancements in GPU hardware, large language models (LLMs) including Generative AI, and optimized machine learning algorithms to accelerate automated identification of trends and insights within vast quantities of data and explain to the user why the AI is making certain recommendations in easy to understand written and spoken word. There are several examples to illustrate the impact of these advancements. First, semiconductor manufacturing technicians can identify when expensive equipment will fail and when preventative maintenance should occur and receive an automated explanation of why something is occurring. Secondly, intelligent digital twins can dynamically represent individual military personnel's comprehension level of new training and present custom remediation to the trainee to solidify their concept understanding. A third example is that through AI and digital twins, ground vehicles and aircraft can be modeled to provide insight to manufacturers into how drivers and pilots are truly using the hardware for next-generation system design and rolling software updates, similar to Tesla's over-the-air software updates that improve the efficiency and safety of their vehicles.

Furthermore, often times our government and military sponsors / partners have limited access, restrictions, or limited bandwidth to research cutting-edge technologies such as AI. KDT-UCF employs an evergreen method of meta-analysis with a focus on post-quantum technologies and it has been a leader in integrating protocols and standards based on blockchain, NIST, and MIL-STD guidelines and regulations. Industry and government organizations' guidance on digital engineering and performance continues to steer the multimodal integration of explainable and assured AI for multiple data inputs and outputs to Digital Twins. This integration extends beyond web and mobile interfaces to include AR/VR/XR and, where appropriate, holographic 3D displays and other novel modes of Digital Twin integration. For example, KDT-UCF receives a Department of Energy (DOE) Minority Serving Institution Partnership Program (MSIPP) grant. This grant will help train a workforce prepared to address DOE missions involving nuclear security through the use of AI, Digital Twins, AR/VR, and other novel technologies such as

holographic tables and haptic feedback gloves. A holographic table (10” in depth with no glasses) will soon be housed at the Institute for Simulation & Training (IST). Interested partners in Digital Twin research, tabletop exercises, and more will use it. I will utilize this table and an AI application layer to control assets in scenarios / Digital Twin simulations.
In addition, we often helps our sponsors/partners accomplish AI-based DT technologies as an honest broker of technology while understanding the requirements of government and military contexts and needs when vetting solutions such as LLMs, visualization hardware, etc.

Unsolved Gaps / Limitations:

The most significant limitation of generative AI in digital twin deployment is their susceptibility to presenting wrong information as fact. These *hallucinations* are acceptable in general usage, such as with OpenAI’s ChatGPT, but not in serious scenarios, such as in healthcare, personnel training, and business operations. Methods are needed to enhance the accuracy of generated results and build trusted AI models.

We are actively exploring methods to mitigate hallucinations and elevate the accuracy of LLMs in the use of automated reporting for intelligent digital twins. We are also developing methods to assess the quality of LLMs, designing new methods to improve model memory through fine-tuning techniques, and generating methods that combine the strengths of multiple LLM models interacting with each other to find consensus before generating final responses.

Recommended Government Support for Solutions:

- Research funding opportunities should be created to develop standards for digital twin integration with generative AI models.
- National computational resources should be provided to researchers to develop, test, and enhance their digital twin projects. Particularly, generative AI is computationally expensive. National digital twin computational resources will lower the barrier to scientific entry and support innovation typically stifled by limited computational support.
- Central data repositories should be created so researchers can focus on developing digital twins and spend less time on data acquisition. Data drives digital twins and artificial intelligence. A nationally supported repository will seed model creation and innovation.

Develop Rigorous Methods for Verification, Validation, and Uncertainty Quantification for Digital Twins:

State-of-the-Art

Verification, Validation, and Uncertainty Quantification (VVUQ) is a critical process in ensuring the accuracy, reliability, and applicability of complex models and simulations, particularly in the context of digital twins. This process involves systematically assessing the correctness of model implementation, evaluating how well the model represents real-world phenomena, and quantifying uncertainties in model predictions.

As a part of our efforts, we focus on developing digital twin solutions for urban mobility monitoring, leveraging existing infrastructure, advanced computational models, and state-of-the-art system integration to enhance traffic safety, mobility, and sustainability. These works have led to the adoption of these systems by Traffic Management Centers for visualizing mobility patterns and implementing proactive traffic management strategies.

We conducted research on various issues at the urban scale, such as human mobility, climate change adaptation, and critical infrastructure (e.g., smart airports). We are also involved in developing advanced methods for multi-dimensional data collection (2D, 3D, real-time) and harmonization, geospatial systems interoperability, Geospatial AI (GeoAI), and real-time urban modeling and simulation. Enabling intelligent decision-making in digital twins, we develop hybrid models that quantify uncertainties using fuzzy-based, ensembled, and multi-criteria decision-making methods.

Meanwhile, the we are exploring the integration of advanced VVUQ techniques, such as Bayesian inference and Markov Chain Monte Carlo (MCMC) simulations, into digital twin ecosystems across various domains, with a particular emphasis on high-stakes sectors like healthcare, where they are validating digital twin models of human organs to predict surgical outcomes with high accuracy.

Unsolved Gaps / Limitations:

A recent work of our team has revealed significant gaps and challenges in VVUQ for digital twins, particularly in urban contexts. We identify the need for comprehensive integration of sub-domains in urban mobility digital twins, difficulties in transitioning research to practice, and the lack of systematic assessment frameworks. We also report challenges in accurately modeling diverse urban environments, managing heterogeneous data, and integrating subsystems with varying uncertainty levels. They also identified issues in validating models against limited real-world data, particularly for rare events (e.g., urban storm waters), and quantifying uncertainty in complex urban settings with human-infrastructure-technology interactions. In addition, we highlight the challenges in developing robust methodologies to handle inherent uncertainty, especially with limited or noisy data and integrating VVUQ into digital twin ecosystems. We also report issues of interoperability, standardization, and the complexity of multi-scale and multi-physics modeling.

Recommendations

- Develop standardized VVUQ frameworks, protocols, and evaluation methods specific to urban digital twins, including improved infrastructure for real-time data collection, management, and integration of heterogeneous sources.
- Implement advanced modeling techniques, including machine learning, multi-scale, and multi-physics approaches, to enhance computational efficiency, scalability, and adaptability to changing urban dynamics.
- Improve uncertainty quantification methodologies, particularly for complex systems and human behavior models, and develop innovative visualization techniques to communicate uncertainty to decision-makers effectively.
- Establish partnerships with city authorities and urban planners for real-world validation, creating benchmark datasets and rigorous cross-validation protocols using diverse urban scenarios.
- Invest in high-performance computing infrastructure and interdisciplinary research teams to address the multifaceted nature of urban systems and facilitate large-scale simulations.
- Bridge the gap between research and practice by developing methods for continuous model updating, learning from real-time urban data, and transitioning mobility research into practical, applicable systems.

Cultivate Workforce and Training to Advance Digital Twin Research and Development: Possible focus areas:

Current State of the Art

Workforce development in the age of Digital Twins has not only integrated with advanced technology and processes but also aligned with a culture of an intergenerational workforce. Next-century skills and a focus on critical thinking, caring, and quality are important life skills focused on society's needs amid a fast-approaching transhumanist capability set. Specifically, Modeling and simulation workforce development has become pivotal in nurturing the skills necessary to advance digital twin technologies. In recent years, there has been a remarkable upsurge in the demand and interest surrounding applications that necessitate the development of digital twins.

The SMST focused on training and education to address the gap in digital twin expertise and future workforce demand. Our team received a three-year grant from the Department of Education for graduate certification on the digital twin to equip the next generation of professionals from diverse backgrounds and industries with the knowledge and skills necessary to harness the potential of the Digital Twin technology.

Through the development and delivery of this certificate, we empower graduates, including minoritized students, with the expertise they need to design, implement, manage, and innovate using Digital Twin solutions. The program is designed to accomplish the following objectives: (1) Develop a graduate certificate program in Digital Twin (CDT); (2) Develop and implement a multi-mode version of CDT to allow students to complete the program online, in person or hybrid mode; (3) Immerse students in industry and research motivated by real-life applications for effective workforce development in modeling and simulation; and (4) Serve Hispanic and other underrepresented student populations with intention.

Our target population comprises professionals from diverse industries such as manufacturing, education, energy, healthcare, transportation, defense, and smart cities, among others. This includes simulation analysts, engineers, data scientists, social scientists, urban planners, project managers, and executives who seek enhanced DT skills and knowledge.

In addition, we received a training grant from IEEE Systems, Man, and Cybernetics Society to focus on the fundamental skills and knowledge necessary to prepare, integrate, and utilize Digital Twin technologies to create real-time visualizations and presentations. The program will upskill the current professionals in various domains to prepare multi-dimensional data and integrate it into a DT for the application of models and simulations in potential use cases (e.g., fall detection, indoor navigation/wayfinding, routing, and identifying traversable routes) within the DT environment. The program will also cover GeoAI, Geospatial ML (GeoML), and Geospatial IoT (GeoIoT) as available technologies, standards, and possibilities of AI, ML, and IoT in geospatial contexts. Thus, this course will provide a foundational understanding of the range of possibilities of Digital Twins to support data-driven decision-making.

Unsolved Gaps / Limitations:

With our nation facing a shortage of cybersecurity professionals, we highlight the need for workforce development pipeline that increases recruitment and skills training in AI, Blockchain, and Cybersecurity (post-quantum), and quantum computing in DT training programs. There is a desire from groups such as the Department of Energy to train this workforce early and from within.

Another notable gap is the insufficient integration of interdisciplinary training in graduate programs. Traditional curricula often do not encompass the cross-disciplinary skills necessary for Digital Twin technology, such as combining AI, VVUQ, and domain-specific modeling and simulation. Furthermore, there is a lack of standardized accreditation and certification programs for professionals specializing in Digital Twins. This impedes the recognition of skill sets and expertise, limiting career advancement opportunities. Current pedagogical approaches may fall short in providing hands-on experiences and practical applications, which are crucial for mastering the complexities of digital twin ecosystems.

We are receiving a Department of Energy Minority Serving Institution Partnership Program (MSIPP) grant. This grant will help train a workforce prepared to address DOE missions involving nuclear security and cybersecurity through the use of AI, Digital Twins, AR/VR, and other novel technologies such as holographic tables and haptic feedback gloves. Through this MSIPP grant, we will hire students to work on real-world projects for DOE, participate in DOE internships, and have a path to DOE careers.

Recommendations

- Interdisciplinary Curriculum Development: Encourage and support the creation of interdisciplinary curricula that integrate AI, VVUQ, and domain-specific modeling and simulation within graduate programs for digital twins.
- Standardized Certification Programs: Develop and implement standardized certification and accreditation bodies for digital twin professionals to ensure recognized expertise and skill validation.
- Collaboration between Academia, Industry, and government: Foster partnerships to align graduate programs with current and future industry needs, hands-on training, and enhancing employability and innovation.

New Topic: User Interfaces and Visualization for Digital Twins

This topic was not listed in the RFI and it was also not included in the National Academies report, which we think is a significant omission.

Current State of the Art

Currently the research in DTs is understandably focused on the simulation and sensor integration aspects of DTs. If they have any user interface at all and are not just simulations, the user interfaces for these DTs are general fairly simple and come in the form of, mostly web-based, dashboards to observe and control the DT operation. We expect this to be insufficient in the future for more complex and interconnected DTs, especially if more complex aspects like uncertainty and what-if configurations and simulations need to be included and communicated.

Unsolved Gaps / Limitations:

Effective means of visualizing and interacting with large DTs of complex systems is not a very well understood field. Current dashboards are limiting in their expressiveness and information density, and we expect that new, different methods will be needed to fully utilize all the information a DT can provide.

Recommendations

We think it would be beneficial for the field as a whole to start thinking about scalability and visualization issues that will arise with the more wide-spread use of DTs and the expected increase in complexity of the developed DTs. It is early enough that the groundwork can be done in time for large-scale deployment of DTs. More work in better understanding of the UI/visualization requirements of DTs will enable better matching of display and interaction methods that allow optimal utilization of the DT results. Exploration of immersive visualization as well as in-field augmented and other more direct and immersive interactions will enable us as a nation to reap the benefits of our Digital Twin leadership.

Conclusion

In response to the U.S. government's Request for Information on Digital Twins, the Knights Digital Twins Initiative at the University of Central Florida has identified significant gaps and future directions in three key areas: AI integration, verification and validation, and workforce development. The primary challenge in AI and digital twins is mitigating hallucinations in generative AI models, especially for critical applications. The gaps for verification, validation, and uncertainty quantification (VVUQ) include standardized frameworks, improved uncertainty quantification methodologies, and better integration of VVUQ into complex digital twin ecosystems. Workforce development faces challenges like insufficient interdisciplinary training and a lack of standardized accreditation for digital twin professionals.

To address these issues, UCF recommends focusing on four key areas in the future: developing robust methods to enhance AI accuracy and trustworthiness in digital twins; creating standardized VVUQ frameworks specific to real-time modeling and simulation; establishing comprehensive interdisciplinary training programs for digital twin professionals; and addressing the cybersecurity workforce shortage in the context of digital twin technologies. In addition, we highlighted the significant value of immersive visualization and interaction to optimize the utilization of DTs. These priorities, along with implementing advanced modeling techniques, creating national computational resources and data repositories, and fostering industry-academia-government partnerships, aim to advance U.S. capabilities in digital twin technology across various sectors. By addressing these gaps and implementing the proposed strategies, the U.S. can strengthen its position in digital twin technology and drive innovation in this critical field.

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Request for Information on the National Digital Twins R&D Strategic Plan

University of Utah

VICE PRESIDENT FOR RESEARCH
THE UNIVERSITY OF UTAH

The **University of Utah** Response to the Networking and Information Technology Research and Development Request for Information on Digital Twins Research and Development

Submitted by the Vice President for Research Office
University of Utah
Dr. Erin Rothwell, Vice President for Research

July 28, 2024

This report represents the response of the University of Utah Vice President for Research Office (OVPR) to the *Networking and Information Technology Research and Development Request for Information on DTs Research and Development*. The University of Utah – the flagship higher education institution in Utah, Utah's R1 university, and AAU member – has a long history of innovation and collaboration. As a university, we are committed to the generation of knowledge that can be used to transform for the better, in a responsible and equitable way, our state, the intermountain region, and the nation.

As denoted in the solicitation, the United States National Academies in 2024 published a report entitled *Foundational Research Gaps and Future Directions for Digital Twins* (2024) in which they made eight recommendations spanning mathematical foundations to workforce development. In alignment with the report, the University of Utah (UofU) holds that cross-agency investments in Digital Twins (DT) – from mathematical foundations to cyber and physical infrastructure to workforce training and applications – is needed to maintain the United States' economic competitiveness. In this report, we will first summarize our perspective on DT technologies. We will then provide a discussion of the unique places in Utah and the Intermountain West where DT development and deployment, under UofU leadership, can make a difference. We will then address thematic research areas that we hold are vital to the next generation of DT applications. Finally, we will conclude by highlighting the unique strengths at the UofU which can be marshaled to meet the next generation of DT challenges.

The University of Utah's Perspective on DTs

To set the stage for reasoning about DT, we must first look to its physical (biological) counterpart. In the world of biology, since at least the Elizabethan era, two competing factors have dominated the debate concerning 'fate': nature (genetics) versus nurture (environment). As our ability to accomplish (scientifically) controlled human experiments increased, we were successful in isolating many environmental factors involved in human outcomes. With the NIH-funded *Human Genome Project* of the 1990s, we were able to further isolate many genetic factors involved in fate. The debate, however, continued – in part due to questions arising from identical twins. Early nature-versus-nurture studies hoped that studying identical twins (those that have the same genetic starting material) would elucidate the factors over which nature (genetics) is dominant and those things that would be "left to nurture." These types of studies have generated a new area of research: *epigenetics*[1]. Robert Sapolsky, in his 2017 book *Behave: The Biology of Humans at Our Best and Worst*, highlights that access to genetically identical twins growing up in different environments opened up a new era of science, allowing scientists to begin to tease out when environmental stressors to which twins are *individually* exposed dictate the genes that are 'turned on' (expressed), leading to different outcomes. In short, 'twins' revolutionized the way we think of nature versus nurture.

Building off this line of thinking, the concept of DT technologies provides us the potential for both scientific and engineering advancements in understanding 'manufactured' (broadly defined) components from the micro (system-level building blocks) to the macro (e.g., aircraft). The Academies report, referencing a 2020 AIAA committee document, defines a DT as follows:

> *A Digital Twin is a set of virtual information constructs that mimics the structure, context, and behavior of a natural, engineered, or social system (or system-of-systems), is dynamically updated with data from its physical twin, has a predictive capability, and informs decisions that realize value. The bidirectional interaction between the virtual and the physical is central to the Digital Twin.*

Given this definition, DT technologies allow, through data assimilation and modeling, a reductionist (mechanistic) understanding of what the physical twin is experiencing. It allows for *digital empathy* – the idea that "what's really going on" within the physical twin can be inferred through inspection and interrogation of its DT. Like biological twins before their parents: although one twin (e.g., the physical twin) may remain silent, its (digital) twin tells it all. The straightforward application of this idea is *monitoring*. The second application, as indicated in the definition, is *prediction* using the DT that then informs the actions of its physical counterpart. These engineering applications also give way to a more scientific approach. Consider the example of two aircraft built in the same

[1] Jordana T. Bell and Tim D. Spector, "A twin approach to unraveling epigenetics," *Trends in Genetics* 27, issue 3 (March 2011), 116.

facility from the same ‘homogeneous’ building blocks. These two aircraft are ‘identical twins’. However, after leaving the factory, these two aircraft may encounter very different operating environments, and hence the measurable characteristics of its components (i.e., fatigue) may differ drastically. This set of twins (physical twins with their corresponding DTs) now facilitates scientific enquiry into the differences operating environments might play on engineered systems.

We hold that expansion of DT technologies beyond their current nascent stage will require a hierarchical yet interconnected structure of expanding protected environments. At the bottom of the hierarchy are sandboxes in which DTs can be tested in very protected and very controlled environments. The physical twin, DT, and two-way compiling exist in some form, but in a mix-and-match fashion that allows extensive and controlled testing. As one increases the risk level, allowing more uncontrolled but still well-characterized influences, living laboratories are needed. As we move beyond these laboratory environments, we move into full testbeds in which the true control and interaction can be tested. Such an approach is needed to allow testing at all levels.

Unique Places Where DT Can Make A Difference

From the National Academies report, it is clear that DT technologies will make a difference in the transportation sector (e.g., aircraft) and the manufacturing sector (e.g. factory optimization). The UofU certainly has an interest in these traditional areas, but also is seeking to make a difference in areas of socio-economic impact. For instance, the State of Utah is very interested in air quality sensing – hoping to put in place proactive measures to reduce air particulates. Without DTs that are not only designed with sound engineering principles in mind but also other factors, such as social and economic impact of particular actions, DT technologies could inadvertently penalize the already disadvantaged. Air quality, environmental resilience (e.g., impact of fluctuating levels in the Great Salt Lake), denote the future applications of DTs for societal good.

Research Thematic Areas

The UofU has DT efforts spanning our university from engineering to science to medicine. We highlight our strengths associated with the thematic areas below.

***Artificial Intelligence (AI)**: AI and DTs*. AI plays a crucial role in DTs of any system because of the need to make real-time predictions and ingest/process new information on the fly, something that is difficult to achieve using physics-based modeling (which is computationally intensive). Something that must be acknowledged is the acquisition of training data, which seems too often to be an overlooked but crucial component to developing reliable AI. We must ask from where the data will come. They could come from experimental/physical observation, but they must also come from our best physics-based models. As a consequence, physics-based modeling for training data generation will be paramount. AI, in the absence of foundational physics-based models, will be rendered ineffective.

***Data**: Encourage Adoption of Data Management Best Practices*. The UofU brings unique strengths towards the development of data management and curation techniques for "dual use" (or multi-use) data. Large amounts of data are collected for specific use cases and are a massive untapped opportunity for general use. This is relevant in a number of the other areas listed, especially AI (above). Taking a (large) dataset and data collection and making it usable for a new purpose is extremely challenging. A plethora of challenges exist, spanning curation, metadata, access modes, provenance, and governance, often making it impossible to use a dataset collected from a particular experiment (e.g., study of the characteristics of a new material) and incorporate it as part of a new training set for machine learning (ML) model development. Developing DTs is a large data-intensive activity and being able to reuse existing data originally generated for different purposes will be essential to making rapid and sustainable progress.

***Ecosystem**: Establish a National DT R&D Ecosystem*. The UofU brings unique strengths towards addressing foundational research gaps surrounding scientific discovery, and common mathematical, statistical, and computational foundations. This should be done in multiple ways, to include: (1) DTs at scale that fully utilizes advances in high-performance computing (HCP) and (2) Integration of DTs with human interaction, specifically the use of visualization and human-computer interaction (HCI) methodologies. It is imperative to invest in integrative cyberinfrastructure to support DTs. Such infrastructure should address the DT needs expressed herein with a mind towards interconnectivity with other national assets such as those already hosted and/or empowered by the UofU: National Data Platform (NDP), National Science Data Fabric (NSDF), POWDER (Platform for Open Wireless Data-driven Experimental Research), and SAGE (Software Define Sensor Network).

***Testbeds**: Establish DT Testbeds prior to launch*. The major requirement for the advancement of DT technology is the establishment of research and development focused 'DT testbeds.' A clear, attainable, and useful first instantiation is for autonomous advanced air vehicles, for which DT represents an innovative approach to improve trust in the deployment of urban air vehicles. Such a testbed would leverage a multifaceted integration of all the aforementioned technologies to create a comprehensive ecosystem for the development, testing, and enhancement of autonomous drones (acting as a scaled-down surrogate for full-scale autonomous urban air vehicles). The primary motivation is to build a robust framework that ensures the reliability, safety, and performance of urban air vehicles, addressing concerns that have hindered widespread adoption. Within such a testbed, both physical and digital twins will cooperate, and the consideration of identical twins is also implemented through a practical number of drones interacting within a transportation system.

At the heart of this testbed is the use of 3D polymer matrix composite printing to manufacture autonomous drones. This technology allows for rapid prototyping and customization of structural designs, enabling the creation of highly specialized and optimized air vehicles. By using advanced materials, the drones can achieve better strength-to-weight ratios, enhancing their performance and durability in urban environments. However, the application of advanced materials and structures concepts poses a major challenge toward certifying next generation air vehicles. The ability to quickly iterate on designs based on feedback from the testbed is crucial for refining and improving drone capabilities and generating sufficient data to support certification efficiently.

Complementing 3D printing would be the implementation of 3D scanning technology. This technology ensures some level of quality control but also initiates the as-manufactured DT model. Upon flight, acquired in-flight sensor data is fed back into the DT, updating the DT model predictions with observed state data. This requires the use of embedded sensors that provide real-time feedback from the physical drones to their digital counterparts. These sensors monitor various parameters such as strain, temperature, and vibration, offering insights into the operational status and any emerging issues. These data also provide direct insights that differentiate identical twins during their life. Advanced life management and sustainment methods are then integrated into the testbed to monitor and prognose the materials and structures throughout the vehicle lifecycle. The continuous flow of acquired sensor data ensures that the DT remains a true reflection of the physical drone's condition. The collaboration between the physical and digital models is critical for the foundational DT concept.

A closed-course autonomous flight environment equipped with customizable wind tunnels is then used to simulate expected (or possible) urban environments. These will create variable wind patterns and turbulence, challenging the drones in ways that mimic real-world urban settings. This controlled environment allows for rigorous testing of autonomous flight algorithms and the assessment of drone performance under different scenarios. The data gathered from these tests is crucial for validating the DT predictions.

Autonomous algorithm testing is another critical component of the testbed. By running various flight algorithms in both virtual and physical environments, developers can identify and resolve issues, optimize performance, and enhance the safety and reliability of autonomous operations. The DT serves as a platform for pre-flight testing, reducing the risk associated with deploying new algorithms in the real world. This iterative testing process helps in refining the autonomous capabilities of the drones.

Validation of DT predictions involves comparing the simulated performance and material behavior with actual flight data. This process ensures that the physics-based and data-driven models used in the DT accurately represent real-world behavior. Any discrepancies identified can be used to improve the models, leading to more reliable predictions. This continuous validation and refinement cycle enhances the trustworthiness of the DT as a tool for predicting drone performance and identifying potential issues.

The integration of DT-informed AI further enhances the capabilities of the testbed. AI algorithms analyze the data collected from both the DT and physical drones to identify patterns, optimize flight strategies, and predict maintenance needs. This intelligent analysis helps improve flight performance, reduce operational risks, and extend the life of the drones. The AI's ability to learn from every flight test and simulation enables it to provide increasingly accurate recommendations over time.

The testbed lastly includes a feedback loop to the 3D printer for the next generation of drones. Insights gained from the DT, AI analysis, and swarm feedback are used to inform design improvements. This cycle of continuous improvement ensures that each new iteration of drones is more advanced and capable than the previous one. By combining all these elements, the DT testbed creates a powerful framework for advancing the technology and trust in autonomous urban air vehicles. Finally, while this discussion and vision are presented within the context of materials, structures and flight algorithms, the discussion is analogous to propulsion systems, batteries, and any other aspects of the vehicle system.

Trustworthy: Realize Secure and Trustworthy DTs. The UofU brings unique strengths towards DTs combined with anomaly-detection algorithms, allowing one to detect 'bad' (unfavorable) behavior in autonomous vehicles to ensure safety. The same techniques can be used to refine DTs when physical data is available using techniques such as information theory and probabilistic approaches. Likewise, DT fused with data and AI/ML anomaly-detection schemes can be used for threat analysis (in networks, military applications, etc).

VVUQ: Develop Rigorous Methods for Verification, Validation, and Uncertainty Quantification for DTs. The UofU brings unique strengths toward the development of DTs for scientific discovery in areas such as climate science, chemistry, and material sciences/manufacturing. Specifically, we are seeking to address questions such as (1) How can we enhance the robustness of DTs (i.e., resilient to variations in input) and (2) How can we provide trustworthiness of DTs (i.e., verification, validation, and uncertainty quantification)?

Unique University of Utah DT Strengths

Part of the UofU's interest in DT technologies stems from its long-term interaction with the DoD and NASA, with particular ties to Hill Air Force Base (located in Utah). The DT concept was initially motivated as a promising approach to modernize the current airframe lifecycle management (ALM) paradigm. Establishing DT as the next ALM paradigm will require developments to enable close-coupling of as-built aircraft models and as-experienced loads and environments within fatigue crack growth and risk assessment codes. The benefit of this holistic integration of aircraft models and usage data will be the reduction of uncertainty in fleet management and tail-number specific inspection and maintenance schedules. From the perspective of cost and mission readiness, DT would mitigate current requirements that lead to unnecessary inspections, maintenance, and early retirement of aircraft components.

Close-coupling of the as-built models and usage data within risk assessment codes will require a broad and concerted effort among high-fidelity modeling, non-destructive evaluation, in-service usage monitoring, uncertainty quantification, machine learning, and artificial intelligence. The UofU and NASA researchers have already demonstrated that uncertainty can be reduced by four orders of magnitude in lab-scale testing of representative metallic components using high-fidelity modeling, AI/ML methods and Bayesian updates in a proof-of-concept DT framework. Additionally, Air Force Research Laboratory (AFRL) is nearing completion of the Spiral 1 demonstration of DT technology using two F-15C wings, which has helped define the following requisite next developments: close-coupling of structural-scale models and usage data; integration of usage data with physics-based models for in-time decision making; quantification of the effect of subscale model updates on accuracy of the global DT model; and integration of DT data in an augmented reality system for improving maintenance procedures and training future maintainers.

In alignment with the AFRL S&T 2030 strategy and with broad support from various DoD agencies, the Utah team has implemented modeling capabilities to support a broad range of structural prognosis and sustainment activities. Examples include a high-fidelity numerical framework to simulate 3D fatigue-crack propagation in aerospace-grade materials using voxel-based adaptive remeshing. Recently, data acquired using the high-fidelity modeling framework were used to train a deep-learning (i.e. ML) algorithm to rapidly predict crack evolution in an experimentally measured polycrystalline material, and uncertainty associated with the ML-model predictions was quantified. To advance the state-of-practice for design engineers, the UofU team is developing modeling methodologies and guidelines for the determination of when simplified material and cracking models may be safely used and where higher-fidelity models must be employed. In such cases, one aim of utilizing AI/ML is to ensure that higher-fidelity models can be employed in a manner that is straightforward, readily accessible, interpretable, and relevant for decision-making.

Researchers from the UofU and AFRL are currently evaluating and advancing an AFRL-developed progressive-damage simulation tool, BSAM, to extend its use to existing challenges associated with sustainment of composite aircraft structures within the USAF. To date, the UofU/AFRL team has successfully used BSAM to predict damage and failure in a variety of test articles with progressively complex geometries, repair types, and loading scenarios. In addition, the team has proposed and developed a new, parallelized version of BSAM, called SPAWC, which will enable the use of supercomputing, simulations of damage and failure of large-scale and highly detailed composite structures.

To summarize, the UofU holds to the National Academies report that emphasizes the two-way coupling in DTs. We believe that to enable research opportunities at all levels, it is necessary to structure funding programs to enable both sides of the one-way coupling (physical side and digital side) as well as testbeds to allow two-way compiling. One must enable data generation and storage, encouraging the development of simulation and machine learning DT technologies, and one must create proxy simulators and emulators to aid those doing the physical testing in DTs. There must also then be environments for examining the implications of two-way coupling so that the DT concept can be fully realized. Such a structured approach, which allows participation on the many components of DT as well as the end-to-end DT solution, is the only way we can move forward on the plethora of DT challenges that remain to make DT a working reality. UofU is eager to engage to meet this challenge.

Federal Register Notice: 89 FR 51554, Federal Register :: Networking and Information Technology Research and Development Request for Information on Digital Twins Research and Development, June 18, 2024.

Request for Information on the National Digital Twins R&D Strategic Plan

UNLEARN

UNLEARN

Comment on "Networking and Information Technology Research and Development Request for Information on Digital Twins Research and Development" [Document No. 2024-13379]

Date:

July 24, 2024

By Electronic Delivery To:

Attn: Melissa Cornelius

[redacted]

[redacted]

To Whom It May Concern:

Unlearn.AI, Inc. (Unlearn) is submitting these comments in response to the June 18, 2024 Networking and Information Technology Research and Development (NITRD) Request for Information on Digital Twins Research and Development (R&D).

Unlearn is innovating advanced machine learning methods to leverage generative artificial intelligence (AI) in forecasting patient health outcomes, starting with the domain of randomized clinical trials. We produce a distribution of longitudinal forecasts for individual trial participants (i.e., their "digital twins"), enabling smaller and more efficient clinical trials to bring effective medicines to patients sooner.

We appreciate that the NITRD National Coordination Office (NCO), National Science Foundation is seeking information to assist in creating a National Digital Twins R&D Strategic Plan. In order to better understand how this document can serve as a national guide for government investments in digital twin research, it is important to align on a standard definition for "digital twin" and develop a shared vocabulary among stakeholders. This will promote a mutual understanding that facilitates collaboration rather than impeding innovation.

We believe that the definition of "digital twin" provided in The National Academies report is broad enough to encompass a variety of applications while also highlighting the term's key characteristics: digital twins 1) have predictive capabilities and 2) are bidirectionally interactive with their physical counterpart.[1] In the field of clinical trials and/or healthcare, a patient's digital twin can be defined as a virtual representation of that individual, typically built from physical theory, multimodal patient data, population data, and/or real-time updates on patient and environmental variables.[2] As stakeholders begin to rapidly develop their own field-specific terminology, it is clear that there also needs to be alignment on the methods used to evaluate digital twin models.

The digital twin's intended context of use is critical to determining the risk level associated with using the model. For this reason, it is imperative that these models are evaluated in a sector-specific manner, by experts in the field, rather than being subjected to sweeping federal regulations. Allocating federal funds to support the review of these technologies by the field's appropriate regulatory agency would accelerate the adoption of digital twin models to address national priorities and expedite agency missions.

Artificial Intelligence (AI): While there are many types of models that can successfully create digital twins of inanimate objects or processes, AI systems are especially suited for modeling the complexity of the human body. Deep learning models are able to take in vast amounts of data, learn from the relationships among variables, and become more precise in their predictions over time. Because of this, AI-generated digital twins of patients have immense potential for solving problems in healthcare that typically require months or even years of trial and error. We define an AI-generated digital twin of a patient as a virtual representation of that patient, created by modern AI methods applied to large clinical datasets, from which predicted trajectories that are statistically indistinguishable from the patient's real data can be generated.[3]

Data: The AICPA Trust Services Criteria[4] and the 2013 COSO Framework[5] have established data privacy and security trust criteria guidelines that can be utilized by stakeholders to encourage proper data management. These frameworks require companies to show that they have acceptable internal and external data protections, which include using secure servers, encryption techniques, access controls, and authentication mechanisms to safeguard stored data against unauthorized access, breaches, and cyber threats. This also includes using cloud computing and secure communication protocols, such as Secure Sockets Layer (SSL) or Transport Layer Security (TSL), for data transmission. In addition, employee training is required to ensure the efficacy of the appropriate structural controls.

Regulatory: The National Academies report recommends that federal agencies should "identify targeted areas relevant to their individual or collective missions where collaboration with industry would advance research and translation" (p. 120).[1] While we agree with this sentiment, the report lists the National Institutes of Health (NIH) as the federal agency for *in silico* drug discovery and clinical trials rather than the Food and Drug Administration (FDA). We endorse the FDA as the agency responsible for the review and regulation of AI technologies used in drug development, including digital twin models. The FDA released a discussion paper and request for comment in 2023 titled, *Using Artificial Intelligence and Machine Learning in the Development of Drug and Biological Products* that provides an overview of how digital twins can be used to make clinical research more efficient.[6] This discussion paper provides an introductory example of how regulatory frameworks should provide sector-specific guidance on the acceptable use of digital twin models according to the risk level associated with the context of use.

Standards and Trustworthiness: The following are practices currently used by Unlearn in model development and implementation to maintain standards and enhance trustworthiness:

- Description of the generative AI model, including summaries of the underlying architecture, data sourced, and training and validation procedures
- Analysis of model performance in a population similar to that of the planned trial
- Documented SOPs and controls
- Pre-specification of version-controlled model in Statistical Analysis Plan (SAP)

- Controlled and monitored secure cloud computing environment with automated version control, metadata, and audit trail
- Methods for probing model explainability include input sensitivity (measure of how much a given performance metric changes when a given feature is masked from input data) and SHAP (SHapley Additive exPlanations, which show how each feature contributes to individual predictions, regardless of how well that prediction matches to the data).[7]

Stakeholders can also consider the value of certifications and audit mechanisms, such as Service Organization Control Type 2 (SOC2) and frameworks from the National Institute of Standards and Technology (NIST), in both promoting trust and in improving internal processes.

VVUQ: When evaluating the validity of models, the paramount criterion should be performance in the specific context of use. This should be tested multiple times in a variety of scenarios that comprehensively address the breadth of situations that the model is likely to encounter with pre-established criteria for success. There are multiple types of validation approaches that can be used to understand different aspects of model performance, but specific choices should be justified. Cross-validation techniques are used to quantify model performance using available data, while external validation is conducted by testing the model on independent datasets or benchmarking against established methods. Model calibration and confidence estimation are used to assess reliability and uncertainty. Regardless of initial validation procedures, continuous monitoring of deployed models ensures the continued accuracy, reliability, and applicability of digital twins.

Rather than imposing broad federal regulations that align with the suggestions provided above, we believe that digital twin models should be evaluated by the appropriate regulatory body, according to the risk level associated with their context-of-use. Allocating federal funds to sector-specific experts, such as the FDA, for evaluating these models would accelerate the adoption of digital twin models and ensure their safe use.

Thank you for taking the time to review our response to the National Digital Twins R&D Strategic Plan Request for Information.

Best regards,

Jess Ross

Senior Government Affairs Lead, Unlearn

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Request for Information on the National Digital Twins R&D Strategic Plan

Dr. Alhassan S. Yasin

RFI RESPONSE: DIGITAL TWINS R&D PLAN

July 26, 2024

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Table of Contents

1.0 RFI Objective

Digital twins, innovative virtual replicas of physical systems or processes, hold immense potential for enhancing various domains. This Request for Information (RFI) seeks input to shape a comprehensive government initiative focused on research and development related to digital twins. The goal is to harness their capabilities across diverse fields, including biomedical sciences, climate change, smart cities, and scientific discovery.

The RFI invites respondents to propose research and development topic areas that the strategic plan should prioritize. Additionally, it seeks details to consider when elaborating on these topics within the strategic plan. The RFI welcomes other relevant suggestions from stakeholders and partners. Topics could include but not limited to AI, Business, Data, Ecosystem, International, Long Term, Regulatory, Responsibility, Standards, Sustainability, Trustworthiness, VVUQ, and Workforce.

1.1 Key Drivers for Digital Twins

Digital twins have become a powerful tool for organizations across various domains. Here are some key drivers for adopting digital twins:

1. **High-Stakes Areas with Real Revenue**: Digital twins are most valuable in areas where high costs and real revenue are at stake. For instance, optimizing supply chains, public transit systems, and assembly lines can significantly impact efficiency and profitability.
2. **Business Model Innovation**: Around two-thirds of organizations consider introducing new business models and customer-centricity as top-line drivers for digital twin adoption. These models can transform how businesses operate and interact with customers.
3. **Reducing Time to Market**: More than half of respondents recognize the importance of reducing time to market. Digital twins enable faster development, testing, and optimization of products and processes.
4. **Safety, Sustainability, and Brand Reputation**: Investments in digital twins are driven by safety, sustainability, and brand reputation. Organizations recognize that digital twins can enhance safety protocols, reduce environmental impact, and improve their overall image.

Digital twins are not a one-size-fits-all solution; their value depends on specific circumstances and the problem being addressed. Digital twins play a pivotal role in exploration, enabling efficient operations, risk reduction, and informed decision-making. They bridge the gap between physical systems and virtual models, enhancing our understanding of this dynamic environment.

2.0 Considerations to Address

When introducing digital twins, it's essential to consider several technical aspects.
Information Modeling:

- A digital twin comprises data, computational models, and service interfaces. The core information relates to different lifecycle phases of the underlying entity (such as an asset, process, or system).
- Data digital twin includes real-world object data required by models to represent and understand the object's states and behaviors throughout its lifecycle.
- Contains computational or analytic models used to describe, predict, and prescribe actions related to the real-world object.
- Service interfaces allow access to data and capabilities within the digital twin.

Technical Characteristics:

- Physics-based models, analytical models, time series data, and visual models contribute to a comprehensive digital twin.
- Consider data from design, production, operation, and even end-of-life phases.
- Augmented reality models aid human understanding of operational states and behaviors.

Digital twins play a crucial role in various domains, and understanding these considerations ensures effective implementation.

2.1 Applications of Digital Twins and Necessary Features

Roles and Impacts

What roles do digital twins DT play in exploration? Categorize as critical, priority, supportive, desirable, low impact. What is the impact of these different roles? What does success look like for an organization when it comes to Digital Twins? What are the desired features of DTs? Both technical and non-technical aspects while maintaining a standard and interoperability lens. Why are these features important?

Digital twins (DTs) are poised to play a multifaceted role in exploration, serving as a bridge between physical systems and their virtual counterparts. The categorization of their roles, are as follows:
Critical:

- **Evaluation of Power Systems and Communications**: They enable engineers to evaluate various scenarios, including the deployment and operation of systems, and to optimize the design for energy efficiency and reliability. For communications, DTs can simulate signal propagation and interference, ensuring robust communication links.
- **Mobility Systems Simulation**: DTs allow for the testing of these systems against challenging terrain, including the real simulation of interactions. This ensures that mobility systems are well-equipped to handle the environment before actual deployment, reducing the risk of mission failure.
- **Human-System Interaction Analysis**: DTs critically assess the impact of human actions on systems. By tracking the bidirectional data flow, they provide insights into how human, systems, and environmental interactions affect system performance and mission outcomes. This analysis is vital for understanding human factors in system design and operation.
- **Investment and Constraint Visualization**: DTs are critical in visualizing the investments made by companies and the constraints they face. This includes showcasing the financial and technological contributions to the mission and the limitations that must be navigated, such as resource availability and environmental challenges.
- **Impact**:
    - By simulating these systems in a virtual environment, DTs help identify potential issues and optimize designs before actual deployment. This reduces the risk of mission failure and enhances the safety and efficiency of operations. The ability to test and refine these systems in a simulated environment saves time and resources, leading to more robust and reliable solutions.
    - DTs enable mission control to monitor the status of all systems and operations continuously, allowing for immediate adjustments in response to anomalies or changing conditions. This capability enhances the flexibility and responsiveness of missions, ensuring that any issues can be addressed promptly to minimize disruptions and maximize mission success.

Priority:

- **Accelerated ConOps**: DTs facilitate the acceleration of ConOps by providing a virtual platform to plan and test various operational scenarios. This includes establishing base plans, contingency operations, and a common operational picture. DTs enable live updates and real-time adjustments to operational plans, allowing teams to refine the trade-offs between different systems. DTs support the development of base plans and contingency operations, facilitating a faster and more efficient decision-making process

- **Time Sequence and Operation Monitoring**: DTs can prioritize the tracking of time sequences in operations, offering a time-lapse view of mission progress. They enable mission planners to check the status of all elements at any given time, ensuring that every phase of the mission adheres to the planned schedule and identifying potential delays or issues. Also, they can enable the scheduling and evaluation of various missions occurring in parallel which can be crucial to cooperative collaboration.
- **Training and Familiarity**: The digital generation's familiarity with virtual environments positions DTs as a priority tool for training and mission preparation. Team members, already adept in digital navigation, can leverage DTs to simulate operations, potentially enhancing the reliability and effectiveness of the DTs themselves. Provides opportunity to engage generations adept in digital worlds to support various operations and challenging problems in a safe and reliable way.
- **Impact**:
    - This is critical for developing and testing technologies that will operate. Accurate simulations lead to better understanding and preparation for the unique challenges posed by the environment, ultimately improving the performance and reliability of technologies.
    - By simulating various scenarios and time sequences of operations, DTs help identify the most efficient strategies and prioritize critical systems. This leads to better-prepared missions with well-defined plans and contingency measures, reducing the likelihood of unforeseen issues and enhancing overall mission success.

Supportive:

- **Resource Management and Asset Categorization**: DTs support the management of resources that will be used or manufactured. They provide a virtual environment to document available resources, plan their utilization, and categorize assets critical for mission success. This aids in the efficient orchestration of all elements involved in exploration.
- **Team Performance and ConOps Planning**: DTs offer a supportive role in evaluating team performance and planning ConOps. They help identify gaps in operations and plan out tasks to ensure a coherent schedule of actionable items. DTs also allow teams to demonstrate and evaluate their capabilities, ensuring that they do not overpromise and underdeliver.
- **Accelerated Evaluation and Planning**: They enable teams to simulate operations faster than real-time, which is essential for testing procedures and preparing for unexpected events.
- **Financial and Product Investment Analysis**: DTs assist organizations in understanding the payout of their investments in terms of money and products. They provide a platform for analyzing both short-term and long-term financial factors and compensation, aiding in strategic planning and resource allocation.
- **Impact**:
    - This ensures that all resources are used effectively and that missions can be executed smoothly. The ability to simulate and visualize different routes and scenarios helps optimize mission plans and improve the efficiency of operations.
    - DTs provide a realistic and immersive training environment, allowing teams to prepare for the challenges of missions. This leads to better-prepared teams with higher performance levels and greater confidence, ultimately enhancing the success of missions.
    - Enabling faster-than-real-time evaluation of systems and operations allows for quick adjustments and optimization. This capability helps maximize the return on investment and ensures that all resources are used effectively, leading to more efficient and successful missions.

Desirable:

- **Automated Linguistic Mapping**: DTs can automate the process of navigating the surface by mapping out different capabilities and providing step-by-step procedures. This enhances the efficiency of operations and helps in identifying the best routes for mobility systems.
- **Resource Documentation and Management**: DTs aid in documenting available resources and manufacturing capabilities at the site, which is beneficial for long-term mission sustainability. This documentation helps in planning and managing resources effectively, ensuring that all necessary materials and equipment are available when needed.
- **Dynamic Mission Planning**: DTs are desirable for dynamic mission planning, providing up-to-date and real data for predictive measures. They help in pre- and post-anomaly assessments and enable dynamic adjustments to mission plans based on real-time data.
- **Enhanced Decision-Making**: They provide a comprehensive view of operations, resources, and personnel, allowing for informed decisions that align with mission goals and constraints. With the ability to simulate and evaluate various scenarios
- **Dynamic Adaptation and Improvement**: Ideal for their ability to dynamically adapt to new data and improve mission plans. They facilitate the incorporation of real-time information into the mission strategy, ensuring that operations remain flexible and responsive to changing conditions.
- **Impact**:
    - Documenting available resources and manufacturing capabilities is beneficial for long-term mission sustainability. DTs help in planning and managing resources effectively, ensuring that all necessary materials and equipment are available when needed. This leads to more efficient and sustainable operations, reducing the risk of resource shortages and improving mission outcomes.
    - Supporting environment checks, buy vs. build decisions, and dynamic mission planning enhances overall mission flexibility and responsiveness. DTs help identify the best strategies for dealing with various challenges and ensure that missions can adapt to changing conditions. This leads to more resilient and adaptable operations, improving the likelihood of mission success.

Low Impact:

- **Post-Mission Analysis and Learning**: DTs can have an immediate impact; they are valuable for post-mission analysis and learning. They can assess how human interactions with systems affected the mission and provide insights for future improvements. They enable the analysis of the entire mission lifecycle, providing insights that can inform future missions and improve system designs.
- **Environment Checks and Decision Making**: DTs can assist in environment checks and decision-making processes, such as 'buy vs build' decisions, their impact has a direct role in the non-scientific decision making.
- **Cultural and Educational Impact**: DTs can significantly influence cultural and educational aspects. They serve as a tool for engaging the public and the next generation of explorers, demonstrating the technological advancements and opportunities.
- **Impact**:
    - These functions enhance operational efficiency and support mission planning, but they are not essential for mission success. However, they do contribute to smoother and more efficient operations, reducing the cognitive load on mission personnel and improving overall mission efficiency.

In summary, digital twins serve as a pivotal tool in exploration, offering a spectrum of functionalities that range from critical to low impact. Their ability to replicate and predict the behavior of complex systems in an environment makes them an indispensable asset in the planning, testing, and operational phases of missions. The integration of DTs into exploration endeavors enhances the fidelity of simulations, accelerates operational readiness, and contributes to the overall success and safety of the missions. They provide a comprehensive platform for analyzing human-system interactions, visualizing investments, monitoring operations, training personnel, and planning financial strategies. The detailed categorization provided here reflects the extensive capabilities of DTs in supporting and advancing exploration efforts.

Quantifying Success

What does success look like for organizations when it comes to DT?

Success for the organizations in the context of digital twins (DTs) is multifaceted, encompassing several key dimensions:

Clear Goals and Objectives: Success begins with defining clear goals, objectives, and requirements for DT implementation. This involves addressing systems engineering problems with a structured approach, ensuring that every aspect of the DT aligns with the mission's overall objectives. By setting these parameters, we can measure progress and outcomes effectively.

Informed Investment Decisions: For stakeholders and venture capitalists (VCs), success means having a comprehensive understanding of the investments involved. DTs provide detailed insights into the potential returns and risks, enabling better-informed decisions. This transparency fosters open conversations and more strategic decision-making, ensuring that investments are leveraged optimally.

Widespread Adoption and Community Engagement: The true measure of success is the widespread adoption of DTs across the entire community. This includes not only the use of DTs but also the roles and responsibilities associated with their adoption. A democratic approach to tool usage and capability sharing ensures that the benefits of DTs are accessible to all, fostering a collaborative environment.

Robust Risk Management: Success also involves effective risk management, allowing anyone to contribute to the conversation. DTs are grounded in scientific work and risk models, providing a solid foundation for identifying and mitigating potential risks. This collaborative approach enhances the robustness and reliability of DTs.

Metadata and Operationalization: Leveraging metadata for large language models (LLMs) to facilitate data management and operationalize outcomes is another critical aspect of success. This involves ensuring that data is accurately captured, processed, and utilized to inform decision-making and optimize operations.

Error Detection and Visualization: Success includes the ability to detect errors and visualize outcomes effectively. DTs should provide clear, accurate visual representations of data and scenarios, enabling stakeholders to understand and address issues promptly. The bidirectional nature of DTs ensures continuous feedback and improvement.

Fidelity and Grounded Systems: Finally, success is achieved by ensuring the fidelity of the DT system at every level. This means that the DT accurately represents the physical system it models, providing reliable and actionable insights. A grounded approach ensures that the DT remains relevant and effective in real-world applications.

In summary, success for the organization in the realm of digital twins is defined by clear objectives, informed investments, widespread adoption, robust risk management, effective data operationalization, accurate error detection, and high system fidelity. These elements collectively ensure that DTs deliver maximum value and drive innovation in exploration and beyond.

2.2 Technical Gaps in Implementation of DT and Collaboration

Gaps, Infrastructure, and Collaborative Efforts

What are the technical gaps? What collaborative efforts are needed and how might that be best facilitated? How can we properly facilitate collaboration and leverage each-other's expertise and resources (data, compute, scientific, software, hardware)? What infrastructure, if any, is needed?

Addressing the technical gaps in the implementation of digital twins (DTs) and collaboration involves several key challenges and considerations:

Current State Representation: Ensuring that the DT reflects the current state of the environment, including historical records and configuration management systems is crucial. This requires a robust system of record that can capture and maintain a baseline for comparison and updates.

Descriptive, Predictive, Prescriptive, and Cognitive analytics:

- **Descriptive Analytics**: This level involves an accurate description of the current and historical states of the environment. It requires a comprehensive system of record that can capture and maintain a baseline, allowing for the DT to be continuously updated to reflect the actual state of the surface and its environment.
- **Predictive Analytics**: Predictive models are essential for forecasting future states and conditions of the environment. This includes predicting the impact of various factors such as meteorite impacts, temperature fluctuations, and human activities on the surface.
- **Prescriptive Analytics**: At this level, the DT should not only predict what might happen but also suggest actions to achieve desired outcomes. This could involve recommendations for mission planning, resource allocation, or contingency measures in response to predicted changes in the environment.
- **Cognitive Analytics**: Cognitive capabilities in a DT involve self-learning systems that use data mining, pattern recognition, and natural language processing to simulate the human thought process. A cognitive DT would be able to improve its predictive accuracy over time and provide insights into complex phenomena.

Diagnosis Levels and Trade-offs: The DT must be capable of diagnosing issues at various levels of complexity, from simple component failures to complex systematic problems. Trade-offs between model complexity, computational resources, and real-time performance need to be carefully managed.

Perception: The DT should have advanced perception capabilities to accurately interpret sensor data and environmental inputs. This is crucial for creating a reliable representation of the environment.

Domain-Specific Applications: DTs must be tailored to specific applications, which necessitates domain awareness and the ability to conduct forensic analysis. This specialization can lead to challenges in memory management and the handling of large volumes of data.

Infrastructure and Deployment: The infrastructure needed to support DTs includes distributed systems, containerization (e.g., Docker), and version control systems (e.g., Git). Deployment challenges include bandwidth limitations, API integration, and ensuring that the DT can be easily updated and validated.

Collaboration Facilitation: Effective collaboration can be facilitated through shared centralized repositories and platforms that allow for the exchange of data, models, standardized APIs for integration, computational resources, scientific expertise, software, hardware, and agreed-upon protocols for collaboration. This will be essential for integrating diverse systems and enabling seamless interaction.

Model Parameterization and Resource Allocation: Automating data modeling and description is necessary to manage the parameterization of models and allocate resources efficiently. This involves defining default behaviors and allowing the system to deploy in different configurations.

Validation and Verification: The validation of models is a critical step to ensure their accuracy and reliability. This includes validating environmental factors such as shadows, lighting, and surface reflectivity. A collective agreement on standards, such as what constitutes the environment, is needed to ensure consistency across different DTs.

Reference Model and Standard: We have models and standards like Global Atmospheric Reference Model (GRAM) and Flexible Image Transport System (FITS) to facilitate data and model standards. Some contextual standers need to be laid out. A similar standard could be developed for data to ensure that all information about the environment is stored and transmitted in a consistent and interoperable format as reference.

Digital Bidirectional Models: These models allow for two-way interactions between the physical and digital worlds. In the context of exploration, this means that changes in the physical environment can update the DT, and simulations in the DT can inform physical operations.

Ecosystem of Models: Developing an ecosystem of commonly accepted and validated models, along with their APIs, is important for creating a comprehensive and accurate representation of the environment. This ecosystem should facilitate the reconstruction of failures and the tracking of version control history.

To address these gaps, a multi-faceted approach is needed that combines technical solutions with collaborative efforts. These aspects can enhance the fidelity, accuracy, and utility of DTs, thereby supporting more effective collaboration and decision-making in exploration and development. This includes developing shared standards and protocols, investing in infrastructure that supports high-fidelity modeling and simulation, and creating platforms that enable the integration of various models and resources. The goal is to create a DT that not only represents the environment but also aids in its understanding and the planning of future missions. This requires a concerted effort from various stakeholders, including scientists, engineers, and mission planners, to develop and adhere to shared standards and practices.

2.3 Next Steps for DT and Goals

Goals and Low Hanging Fruit

What is a reachable goal and low hanging fruit?

Reachable Goals

Objective: Create a comprehensive digital twin (DT) ecosystem framework and a proof of concept that integrates aspects of mission planning, execution, and analysis of tools, systems, subsystems, and environments.

Details:

- **Integration framework of Systems**: Develop the protocols for integration of communication, mobility, power, and resource management systems within the DT framework. This includes real-time data synchronization and bi-directional data flow to ensure accurate and up-to-date simulations.
- **Standardization and Interoperability**: Establish industry-wide standards for DT implementation, ensuring interoperability between different organizations and systems. This involves creating a clearinghouse of standards and best practices and promoting their adoption across the community.

- **Advanced Simulation Capabilities**: Mapping out the fidelity required of DT simulations to accurately represent the environment and operations. This includes simulating human interactions, environmental conditions, and system performance under various scenarios.
- **Collaborative Platform**: Develop a collaborative platform that allows multiple stakeholders to contribute to and benefit from the DT ecosystem. This platform should facilitate real-time communication, data sharing, and collaborative decision-making.

Impact: Achieving this goal would revolutionize exploration by providing a robust and reliable framework for mission planning and execution. It would enhance the efficiency, safety, and success rate of missions, and foster greater collaboration and innovation within the community.

Low Hanging Fruit

Objective: Establish standards for protocol integration, facilitate organization and partner communication, and begin implementing basic DT functionalities for initial missions.

Details:

- **Protocol Standardization**: Develop and standardize the properties and procedures to ensure consistent and reliable testing of surface operations and integration of various DTs. This involves collaborating with research institutions and industry partners to define and adopt these standards. Facilitate representation and constant working groups with AIAA, IEEE.
- **Initial DT Implementation**: Start with basic DT functionalities that focus on specific aspects of missions, such as communication and mobility simulations. This includes setting up initial DT models, conducting simulations, and refining the models based on feedback and data.
- **Documentation and Best Practices**: Create detailed documentation and best practices for the initial implementation of DTs. This includes guidelines for data collection, simulation accuracy, and integration with physical systems.
- **Stakeholder Engagement**: Engage with key stakeholders, including government agencies, industry partners, and research institutions, to promote the adoption of these standards and best practices.

Impact: Achieving this goal would provide a solid foundation for more advanced DT implementations. It would ensure that initial missions are well-prepared and that the technologies and methodologies used are reliable and effective. This approach would also build momentum and confidence in the use of DTs, paving the way for more ambitious projects in the future.

By focusing on these goals, we can ensure that our efforts in digital twin development are both ambitious and achievable, driving significant advancements in exploration.

3.0 Takeaways and Next Steps

3.1 Potential Initial Phases and Plans

To operationalize digital twins (DTs) for exploration, a graduated series of activities can be structured to systematically address the identified roles and ensure successful implementation. Here could be some initial plans:

Phase 1: Initial Setup and Standardization

- **Define Initial Activities**:
  - **Objective**: Establish the first set of activities to be conducted on the surface.

- **Actions**: Identify and prioritize initial tasks such as site selection, habitat setup, and initial scientific experiments.
- **Set Standards for DT Implementation**:
  - **Objective**: Develop and establish standards for creating and using DTs.
  - **Actions**: Define protocols for data collection, simulation accuracy, and integration with physical systems. Establish a core set of environmental parameters and digital constructs (DC).

Phase 2: Requirements Breakdown and Core Competencies

- **Break Down Requirements by Group**:
  - **Objective**: Identify and categorize the requirements of different groups and organizations involved.
  - **Actions**: Map out the core competencies of each group, such as communication, power, energy, and resource management. Determine common dependencies and unique needs.
- **Map Mission Planning and Best Practices**:
  - **Objective**: Create a comprehensive map of how DTs are used in mission planning.
  - **Actions**: Identify best practices and gaps in current methodologies. Document how different organizations facilitate mission planning and execution.

Phase 3: Infrastructure and Communication

- **Build Core Infrastructure**:
  - **Objective**: Develop the necessary infrastructure to support DT operations.
  - **Actions**: Establish communication networks, power systems, and resource management frameworks. Ensure interoperability between different systems and platforms.
- **Facilitate Communication Among Groups**:
  - **Objective**: Enhance collaboration and information sharing.
  - **Actions**: Set up platforms for real-time communication and data exchange. Promote transparency and collaboration across all involved entities.

Phase 4: Standards and Needs

- **Develop and Implement Standards**:
  - **Objective**: Standardize processes and protocols for DT usage.
  - **Actions**: Create a clearinghouse of standards and best practices. List organizations and their roles, ensuring alignment with overall mission objectives.
- **Assess and Document Information Needs**:
  - **Objective**: Identify and address information gaps.
  - **Actions**: Determine what data is generated by DTs and what additional information is needed. Develop strategies to provide missing data and enhance DT capabilities.

Phase 5: Strategic Planning and Recommendations

- **Write White Papers and Recommendations**:
  - **Objective**: Provide strategic guidance and recommendations to leadership.
  - **Actions**: Document findings, best practices, and strategic recommendations. Present these to leadership for decision-making and policy formulation.
- **Plan and Facilitate Initial Missions**:
  - **Objective**: Ensure readiness for the first missions.
  - **Actions**: Develop detailed mission plans, including government support and market considerations. Build necessary tools and structures to support mission objectives.

Phase 6: Funding and Incentives

- **Facilitate Funding and Investment**:
  - **Objective**: Secure funding and investment for DT initiatives.
  - **Actions**: Identify use cases and potential sources of funding. Develop strategies to demonstrate return on investment for startups and organizations.
- **Incentivize Participation and Innovation**:
  - **Objective**: Encourage participation and innovation in DT development.
  - **Actions**: Create incentives for organizations to engage in DT projects. Address potential risks and provide clear expectations to mitigate uncertainties.
- **Markit Place for Organizations**:
  - **Objective**: Facilitate marketplace for organizations and products.
  - **Actions:** Commerce agencies map out the growth for the community and validation/trust comes from government evaluation.

Phase 7: Dual-Use Applications and Strategies

- **Explore Dual-Use Applications**:
  - **Objective**: Identify applications for both civilian and government use.
  - **Actions**: Develop models and use cases for defense and civilian industries. Leverage synergies to enhance overall system capabilities.
- **Develop Digital Twin Strategy**:
  - **Objective**: Integrate DT efforts with initiatives.
  - **Actions**: Map out activities and collaborations across different domains. Develop a "twin of twins" strategy to ensure coherence and alignment.

We can systematically operationalize digital twins to meet the identified roles and ensure successful exploration. This approach can ensure aspects of DT implementation are addressed, from initial setup and standardization to strategic planning and dual-use applications.