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

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RFI RESPONSE: DIGITAL TWINS R&D PLAN

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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.