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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

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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

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[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.