MITRE's Response to the NSTC RFI on Digital Twins R&D

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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.