Unlocking the Potential for Digital Twins in the Federal Enterprise

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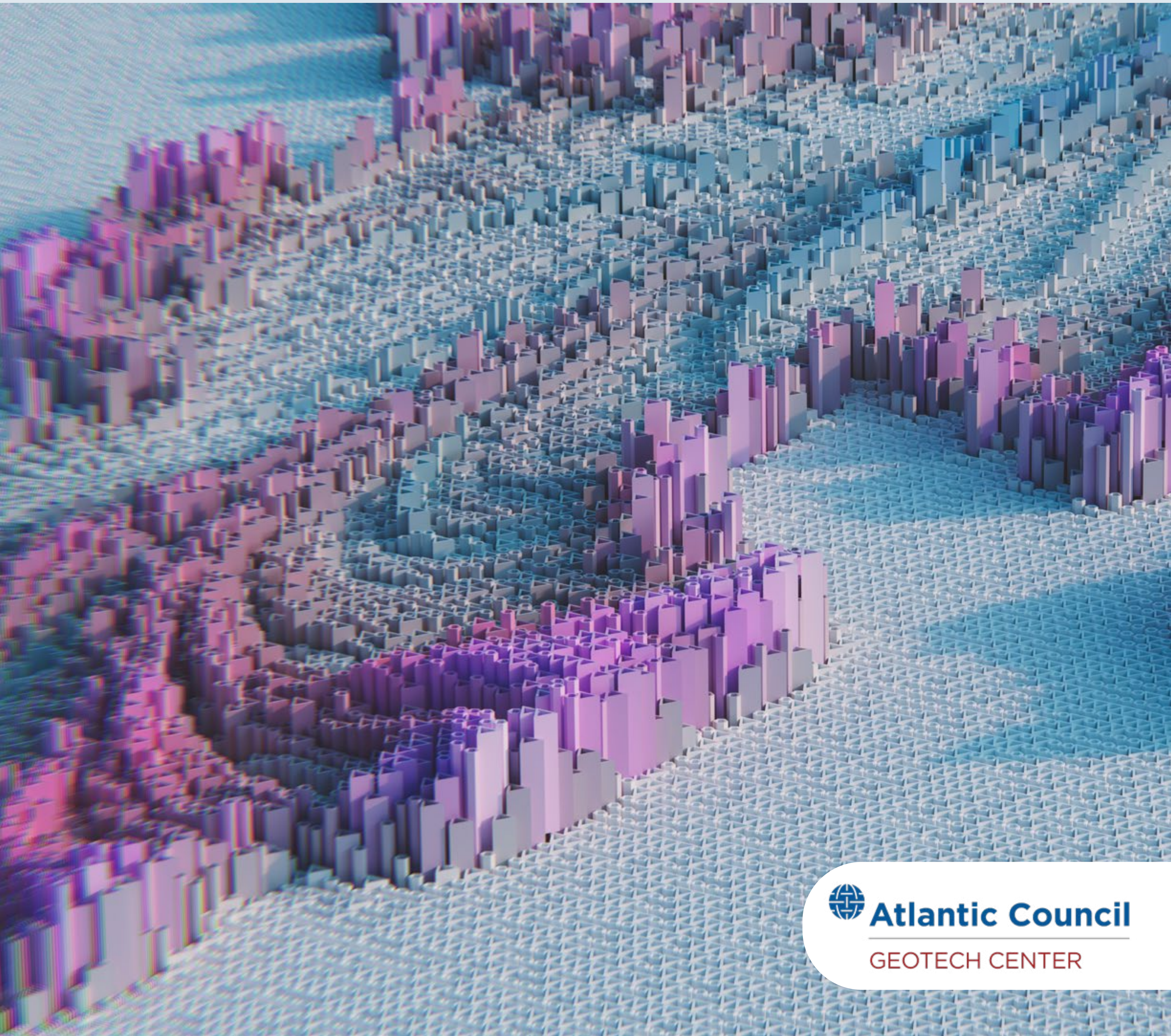

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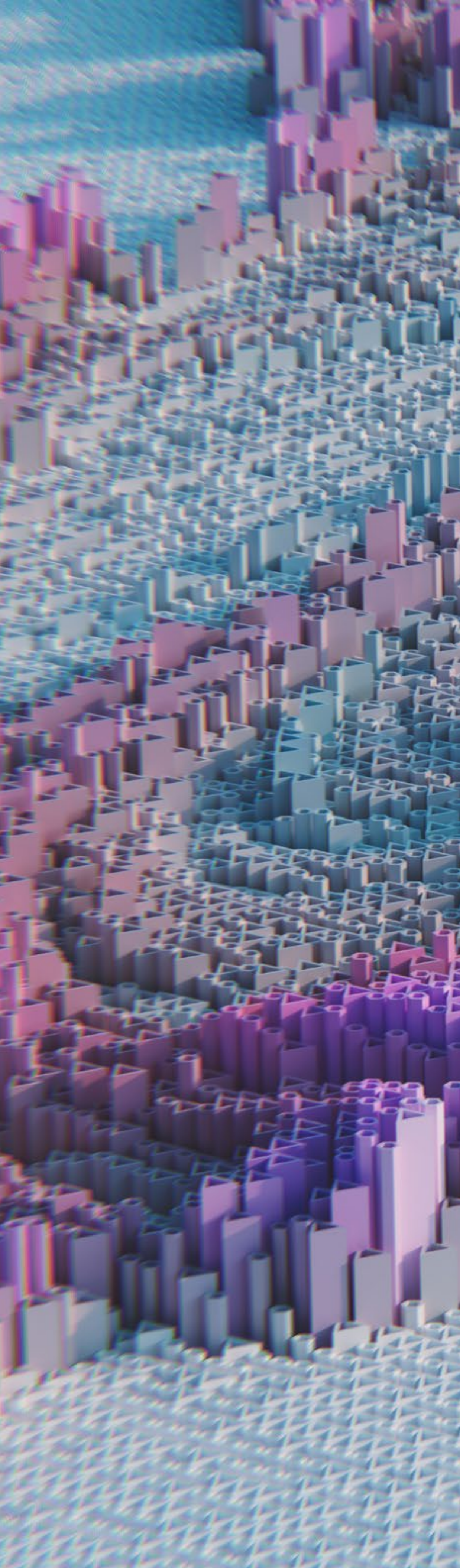

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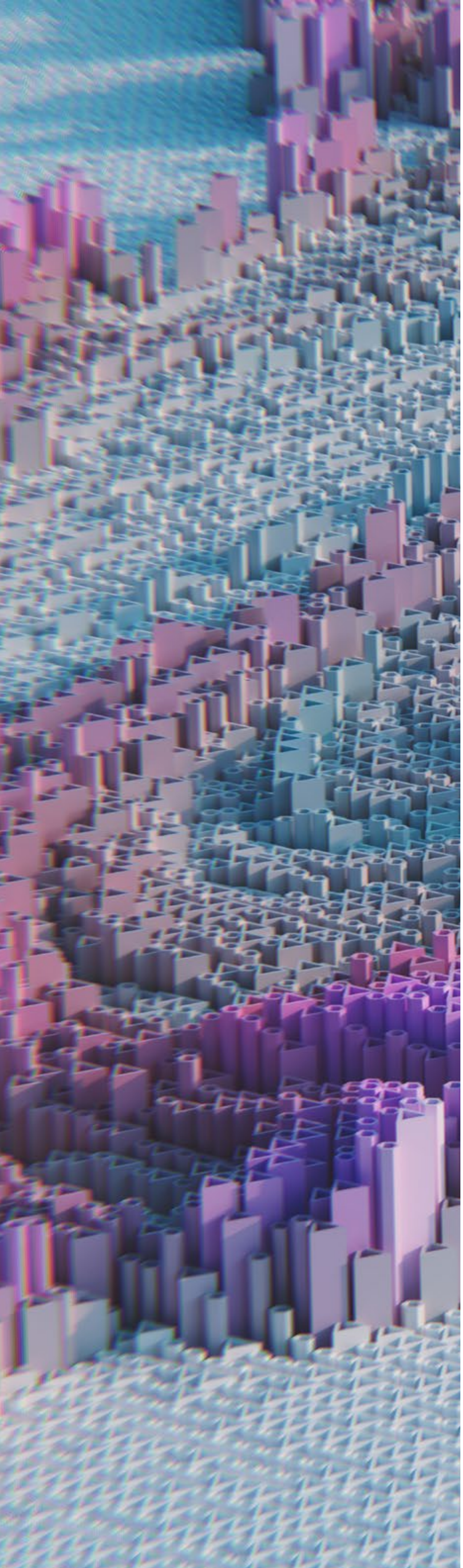

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BY SOLOMON WISE, GEOTECH CENTER, ATLANTIC COUNCIL

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Introduction

For decades, the automotive, aviation, and other advanced manufacturing industries have invested in digital modeling technologies to help reduce time to market, lower the cost of physical prototyping, and improve manufacturing productivity. With exponential advances in technologies such as artificial intelligence based on machine learning (AI/ML), advanced wireless communications (5G), virtual and augmented reality (VR/AR) or extended reality (XR), the Internet of Things (IoT), and others, the possibilities are rapidly increasing for digital models to extend beyond product and process development into other parts of the enterprise life cycle with direct connection to physical assets. The comprehensive integration of a digital model with a physical asset such as a manufacturing environment is one example of a *digital twin*.

Where might the government find use for such a digital twin? In short, everywhere. Just as enterprises see value in creating and deploying digital twins throughout all operations—from sourcing to sales to service—the same is true for government. Government activities are broad: from construction to public safety, through supply chains and logistics, to healthcare, and including national defense. Digital twins can potentially play a role in improving all these government functions.

This report explores digital twin use cases both in the private sector and in the federal government. The intent is to highlight some challenges, benefits, and risks associated with deploying digital twins to help inform government officials and policymakers. As other technologies such as XR and generative AI mature, they will further enrich the value of digital twins, leading to what we call *immersive digital twins*.

In this brief, a digital twin refers to a virtual representation of a real-world physical object, process, or system, where sensors located in the real-world relay data back to a virtual processing environment. Simulations are then run in the virtual processing environment, generating insights that can be shared back with the real-world object, process, or system.

Background and Key Definitions

The very first use cases for digital twins were likely within US government agencies. In April 1970, the National Aeronautics and Space Administration (NASA) launched its third mission to send a manned spacecraft to the moon, Apollo 13. Two days into the mission, oxygen tanks onboard the craft exploded, leaving the crew in grave danger hundreds of thousands of miles away from the earth. As the world held its breath, NASA's Mission Control Center worked together with the astronauts to return the crew safely to earth.

How did NASA's Mission Control Center manage to diagnose and solve problems on a physical asset orbiting the moon? This feat was accomplished using a digital twin.

Before Apollo 13's launch, NASA developed an array of powerful spacecraft simulators used to prepare astronauts for the mission. A simulator on its own, however, is not necessarily a digital twin, as it lacks the flow of information and insights between the real and virtual environments. During the Apollo 13 rescue mission, the astronauts used simple telecommunications devices to relay data to NASA mission controllers, who manually inputted this data into the simulators to reflect the actual conditions the spacecraft was facing—an early version of IoT—and helped quickly assess the impact of different solutions (Allen, 2021; Ferguson, 2020; Kienzler, 2019). Though we know the story has a happy conclusion, if it were not for the simulation technology, it would have been far more difficult to select an option with a high probability of a good outcome during such a high-stakes an time-critical situation.

The technological advances enabling much more rapid transmission of significant amounts of rich, real-time data have made today's digital twins far more powerful than NASA Mission Control's models of Apollo 13. The Apollo telemetry supported a maximum of 51 kilobits per second compared to the gigabits per second routinely achieved today; a millionfold increase (Painter and Hondros, 1965). IoT technologies now enable sensors located in or on the real-world object, process, or system to send data back to a virtual processing environment in real-time rather than via the manual input observed on Apollo 13, and emerging technologies such as XR and AI are poised to further expand the sophistication and fidelity of digital twins. These advances will enable new operating environments for digital twins that include immersive and collaborative ways for the user to interact with and manipulate digital twins in real time, and promote interoperability between different systems of digital twins, while also presenting new risks and challenges.

Levels of Digital Twins

It is useful to have a foundational taxonomy of digital twins and their applications to facilitate discussion. Diverse types of digital twins can be identified using a variety of taxonomies. These taxonomies will be useful for understanding the benefits and risks associated with several types of digital twins, as well as how future advances will impact digital twin applications. Here we describe one digital twin taxonomy that focuses on how a digital twin can *mature*.

To understand how digital twins can mature, one must consider several factors, including the complexity of the data, the system being modeled, and how the insights are being shared. First, applications of digital twins have multiple dimensions that may include developing and managing complex systems, and then interacting with these systems through rich 3D experiences to visualize and collaborate with the twin. Complex systems management applications provide digital twins of multifaceted processes, objects, or systems, where the twin is used to provide a realistic representation of the process, object, or system (asset) that integrates real-time (and often historical) data to model and provide insights into the real-world asset. An example of this type of application could be a digital twin of a facility that is used to model and predict operational flows and energy usage within the asset.

Three-dimensional experiences layer on modalities of interaction that could include being immersed within the twin and interacting with it through enabling technology such as XR. One example of such an application would be a digital twin of the physical layout of a geographic area particularly vulnerable to natural disasters. Training and planning by emergency response could be conducted in this virtual environment, eliminating the time and cost resources of being physically present at the location.

As both the modeling and data complexity increase and the interaction becomes more immersive, the potential value and expanded use cases for the twin multiply. Example applications usually involve a system or object that is “twinned” and is then able to be collaborated with and exercised by a user in an immersive environment (rather than just behind a computer). As immersive technology develops, the lines between complex systems management applications and these immersive experiences will be increasingly blurred.

MATURITY MODEL TAXONOMY

Applications of digital twins can also be viewed as being located along a *maturity* or *capability* continuum. In most cases, digital twins are built with Level One capabilities and then evolve over time as more data and the technology stack is enhanced to support higher levels. An example of one such continuum is shown on the following page.

There are many other ways to represent the maturity/capability of a given digital twin. Other maturity/capability continuums include differentiating between twins that represent a single element of a larger system (a *component twin*) and those that represent multiple components working together within a larger system (*system* or *process twin*) (Plank, 2019).

Private Sector Use Cases

Although this paper’s primary focus is on government applications of digital twins, it is nonetheless useful to review some current use cases of digital twins in the private sector given that many of the digital twin applications that are currently being or will be used in government are likely to be based on digital twin technologies or methodologies that have already been deployed.

Digital twins have proven to be a powerful tool for private-sector firms in many scenarios. The most common and most impactful applications of digital twins in the private sector are in product development and manufacturing/production line processes.

Across commercial product development and manufacturing/production line processes, digital twins can play a role at numerous stages. Digital twins can play a key role in the refine-

Characteristics of a Maturity Model for Digital Twins

Level One (Connectivity/Reporting)

A digital representation of an asset integrates real-time and historical data (and IoT sensors) to report on the performance of the physical asset at a specific point in time.

Example:
Digital twin of a building that provides sensor information on energy usage and occupancy state.

Level Two (Predictive)

Analytics parse data gathered by sensors to predict the performance of an asset and identify potential risks and problems ahead of time.

Example: Digital twin of a building that uses real-time and historical data to predict energy usage and crowd traffic flows.

Level Three (Prescriptive)

The digital twin is integrated into a system with comprehensive analytics capabilities that leverage AI/ML techniques in addition to all of the above in order to prescribe solutions to risks and problems that may arise.

Example: Digital twin of a building that uses real-time and historical data to predict energy usage and crowd traffic flows, and also provides recommendations for exit routes to avoid overcrowding and reduce energy usage.

Level Four (Autonomous)

The digital twin leverages AI to take autonomous action to prescribe solutions to risks and problems that may arise or already exist.

Example: Digital twin of building that makes real-time adjustments to HVAC settings to optimize energy consumption and control of traffic flows through availability of exits.

Source: Maturity model courtesy of Unity.

ment of designs in commercial products, allowing companies to use virtual prototypes with two-way data feeds to test products in a variety of different environments more quickly and cost-effectively. Additionally, many private-sector firms have also been utilizing digital twins on the factory floor itself.

By building a digital twin of an entire factory, companies can model the production process, identify variability and potential bottlenecks, and identify flaws in materials or processes. Digital twins offer the potential for continuous, autonomous monitoring of the production process, allowing teams to save time and labor costs while increasing monitoring precision. Digital twins can also be used to perform predictive maintenance in a production/factory setting. Sensors can be installed in factory components that feed data about their performance and longevity to a virtual processing system, and analytics leveraging AI/ML can both predict future maintenance issues before they arise, as well as prescribe a solution for how to keep the production line running efficiently during maintenance procedures.

Private-sector firms also have utilized digital twins for building use management. The digital twin of SoFi Stadium in Los Angeles is a prime example. SoFi Stadium's management group partnered with Willow Inc., using its WillowTwin software platform to create a digital twin of the stadium that would allow its users to predict energy usage and traffic flows within the building. Even more importantly to its owners, the digital twin enables all of the data being produced by the stadium to be gathered, analyzed, and controlled in one centralized system.

As immersive technologies advance, new capabilities emerge within a given digital twin application, and the line between complex system management and immersive experiences blurs. Extended reality is being applied to the digital twin of SoFi Stadium, allowing users to "jump" inside a virtual model of the stadium to take measurements of a space within the venue or visualize a given event setup (Clausen et al., 2021; Onechanh and Hedinsson, 2022). Immersive digital twins are also being utilized to help companies remotely develop, demonstrate, or advertise products that may be too big to transport in their physical form, such as complex, heavy machinery (Spangler, 2022). This approach blurs the line between the digital and physical, enabling inputs and collaboration that would be far more complex to obtain in the physical world alone.

Digital Twins in Government

Though government was an early adopter of digital twin technologies, it existed in limited domains. Now, digital twins are being considered and developed across government agencies to help advance a wide array of missions, notably for security-focused applications and as part of the US National Strategy for Advanced Manufacturing (National Science and Technology Council, 2022). There are numerous examples of how digital twins help government agencies improve their operations and program outcomes.

FOOD PRODUCTION AND SECURITY

The US Department of Agriculture (USDA) is currently developing digital twins across crop production processes, work that can help accelerate the development of sustainable agricultural operations at a time when food security is becoming a more salient risk factor to national policymakers. This digital twinning initiative covers two areas: (i) researchers are installing sensors on individual plants to monitor and predict the status of individual organisms, allowing for insights into plant genetics and physiology that will enable more efficient plant breeding; and at the same time, (ii) they are also creating a digital twin of the entire production process that can help inform decisions around planting, irrigation, and pesticide usage (Krapfl, 2022).

Next, this digital twin of the food production system could be coupled with a weather digital twin and perhaps then a supply chain digital twin. Now one can see the power of digital twins as they start to connect to one another in a larger ecosystem of data-driven insights that can impact future decision-making.

Digital twins can generate large amounts of data, providing a foundation for training predictive models and improving potential outcomes. This foundation can be expanded upon with immersive visualization capabilities that provide government agencies and policymakers the opportunity to take digital twins to a higher level of complexity and maturity, enabling interactions and bringing new insights through new modes of collaborative interaction.

SUPPLY CHAIN AND LOGISTICS

The pandemic brought to light the fragility of global supply chains and the resulting impact on the government's ability to deliver some services and maintain operations. For example, to support the required flow of critical materials needed for a host of essential products, the government would benefit from real-time insight into the complex supply systems, including details such as ports of entry and transportation networks. A digital twin that is well connected to the physical supply chain can augment and improve real-time insights while also allowing for strategic planning of multiple scenarios and foresight analyses.

With a model in place and supported by real-time data, it would be possible to strategically manage the full supply chain ecosystem, from ports of entry to warehousing and multimodal transportation. At a time when supply chain vulnerabilities have proven potentially disruptive, this capability can provide improved visibility that can aid in improving the resilience of vital national operations.

PUBLIC SAFETY AND SECURITY

Where digital twins were historically used to replicate industrial or mechanical systems, advancing technologies for rapidly mapping environments offer a means to more easily model and visualize entire three-dimensional spaces. This capability has significant implications for public safety and even national security.

With a robust 3D model, it is possible to offer an immersive, digital experience of a complex environment. Suppose one must secure a sports stadium in advance of a VIP visit. Using an immersive digital twin, security teams across various regions could don headsets and perform walk-throughs of the captured virtual spaces, strategizing the locations of exits, the placement of personnel, the potential bottlenecks, and other hazards.

The growing ability to map and digitize locations quickly and accurately could elevate the level of training for emergency personnel in a variety of situations. Suppose, for example, a team is training on an active-shooter scenario or a chemical or biological threat response. With a digital twin, it will be possible to add in new variables—things like weather data, crowd flow, or traffic patterns. One could potentially add data to the model on the structural integrity of the surrounding infrastructure to enhance training for a catastrophic event. Each of these enhancements could inform a higher level of preparedness. Moreover, participants could participate from anywhere in the world, bringing experts together remotely for broader collaboration and more effective training.

Detailed, 3D models would likewise inform on-the-ground operations. For example, a first responder could have a 3D reference to navigate the environment more effectively, directing resources and managing response with support from a detailed model while being provided with real-time data. This capability would provide a higher level of situational awareness, improving readiness and reducing risk.

Immersive Digital Twins

The evolution of digital twins—from pure data models to simple 2D object representations to complex 3D process models—will join with emerging technologies to create immersive digital twins. A range of technologies will support this vision of immersion, including not just AR/VR, but also edge computing, AI/ML, etc.—with digital twins at the center of it all. Artificial intelligence, and the recent surge in the potential for generative AI use cases, can enhance a digital twin and expand the immersive experience. The rise of commercially available digital twin tools is making such capabilities increasingly accessible and affordable. It is well within reach of government agencies to develop these immersive digital models and then to inform those models with synthetic data along with real-world IoT sensor information and other data streams. The tools for building immersive, 3D, and real-time digital twins become more advanced and accessible every day. This progress, in turn, will open the door for government to leverage its digital twins with improved visual content and collaboration tools. By further investing in these capabilities, the federal government can take advantage of the potential for immersive digital twins to transform the way defense, safety, and civilian agencies plan, train, anticipate, and operate.

Some Key Considerations

Digital twins will be game changers for agencies that adopt these tools quickly. Three key elements are needed to progress on this journey: developing the skilled workforce; building a solid technology foundation; and putting the right guardrails in place to ensure to mitigate issues around privacy, equity, and intellectual property.

The workforce changes required include data scientists, data engineers, and experts in managing sensor data streams and edge computing, as well as ethics experts. Digital twins will be captured in multiple ways, including photogrammetry, ingestion of 3D models, and images enhanced by 3D artists, developers, and designers who understand immersive platforms. Agencies will need individuals who are comfortable with the hardware and software that support learning and operating in these virtual environments. Agencies can start now to build an inventory of needed skills and to develop a recruitment plan to help ensure they have the right talent on hand to bring to life the promise of digital twins. Talent is scarce and private-sector recruiters will be competing to attract, hire, and retain this talent.

Building the right technology foundation also is essential, including establishing appropriate cloud and edge assets to allow not only the real-time capture of sensor information, but also to support environments for training predictive models and analysis trends. As we think about these more immersive digital twins, understanding the tools necessary to render and develop shared immersive experiences is also important. The implementation and application of digital twins rely on having a cloud-enabled infrastructure that can run rich simulations at scale (Attaran and Celik, 2023). This infrastructure allows for the cost-effective creation of digital twins that can accurately replicate and monitor the behavior of physical systems in real time. Cloud-enabled infrastructure allows mission owners of digital twins to store and process substantial amounts of data remotely and cut down the processing time of complex simulations (Attaran and Celik). As the development of this infrastructure advances—spearheaded by private-sector services such as Amazon Web Services SimSpace Weaver, NVIDIA Omniverse, and Siemens Xcelerator, among others—it will enable novel, more cost-effective, and faster applications for the federal government.

Federal agencies should consider investing resources to prototype, test, and understand the potential applications for these technologies on mission priorities. With the global digital twin market expected to be valued at $184.5 billion by 2030 (Pedersen, 2022), all agencies should start or expand their exploration of use cases now.

Implementation Concerns

While new and emerging applications of digital twins show promise for expanded use in both the private and public sectors, as with any modern technology these applications involve new risks to be mitigated and concerns to be managed. Additionally, as so-called metaverse-enabling technologies provide new immersive digital twin applications and advances in AI/ML enable more prescriptive and autonomous behavior from more mature digital twins, known risks and concerns will become more salient and new threats will emerge.

DATA QUALITY

One key concern for policymakers to consider is data verification. A digital twin is highly dependent on the underlying data it is provided and in cases of inaccurate data, a digital twin can predict unrealistic scenarios with the potential to negatively impact decisions and in extreme cases cause harm.

Consider a digital twin of a factory that is designed to capture the performance of machinery and parts through an IoT-enabled sensor data stream. If there is inaccurate or incomplete data from the machinery or part sensors it can impact decisions or actions being performed against the digital twin. This type of error on a connectivity/reporting twin, as outlined in the maturity levels above, would cause the user to see erroneous data about the performance of the part of the factory covered by the sensor. Such an error on a predictive twin could result in faulty data being used to make predictions about future performance, causing these predictions to be inaccurate as well. Such an error on a prescriptive or autonomous twin could cause a potentially dangerous situation, as the system could execute misguided actions based on incorrect data without human intervention. That is why it is critical to understand and validate data and build in human reviews and appropriate checks and balances before action is taken in response to a predictive twin.

PRIVACY

Privacy issues are also at the forefront of risks policymakers and practitioners face when considering the use of digital twins. Privacy concerns exist when working with data in both private and government applications. Digital twins are no different than any other visualization or forecasting system, with data privacy considerations incorporated into the design and operations across the maturity/capability continuum. When adding immersive experiences to digital twins, there are many features that can enhance the experience. For example, in training scenarios, one can track and record user actions, speech, and even eye movements and focus. This enhancement would provide details about how training participants interact with the digital twin; however, that advantage must be balanced with the risks associated with the underlying data collection. The data generated from eye tracking or recognition is a biometric product unique to each individual, and could potentially be used to identify a person, or even be used as a biometric password, creating concerns about how a user's confidential data is stored and used after it is captured (Ravi, 2017).

Consider the example of a digital twin of a sports stadium that predicts population flow and energy usage within the facility. The more granular the data that is collected and analyzed on users of the stadium, the better the insights that are generated by the digital twin. However, such detailed data collection requires careful consideration of the risks to the privacy of those individuals. As with any data collection tool, what data is collected, where it is stored, how it is used, and how/whether affected individuals consent to that use are critical considerations.

How can privacy concerns be mitigated? One potential option that has been considered is the creation of an industry review board (similar to the Entertainment Software Ratings Board in the video game industry) that would create standards for privacy for commercial digital twin applications that would be extended to government use, where appropriate and necessary. Other potential options include requiring digital twins' manufacturers to be transparent to consumers about the use of their data, as well as educating developers and engaging in awareness and advocacy campaigns around best practices to responsibly manage data privacy.

INTELLECTUAL PROPERTY AND TRUST

Digital twins are built on a great deal of information and domain knowledge, sometimes from a variety of sources. It is important that this intellectual property be properly protected both in use and in transit. Though encryption and other technology can protect the internal data and processes of a digital twin from unwarranted exposure, the connectivity likely to be required for most digital twin use cases—as for all connected systems—creates risks of malicious threats through hacking, misuse, and misappropriation. As the use and use cases expand, vigilant adoption of appropriate security measures will be critical to maintaining the trust and protecting the value of digital twins and the underlying technologies.

INCLUSION, EQUITY, AND ACCESSIBILITY

Emerging technologies are paving the way for exciting and immersive applications of digital twins, but it's important to address the accompanying inclusivity and access challenges. The digital divide among communities highlights the need to consider the accessibility of digital twins, as these advanced applications often require extensive technical expertise and expensive hardware. A primary concern is that digital twins may not be inclusively designed to take into account the needs and capabilities of a broad and diverse user community, further disadvantaging groups that already suffer from limited access or underutilization of digital technologies. For example, if a digital twin of a public transportation system is designed without considering the needs of those with limited mobility or other challenges to accessing public transportation, it could further perpetuate the societal barriers and increase marginalization. Additionally, the development and use of digital twins may assume a certain level of technical expertise or access to specialized equipment, which could further exclude people who lack those resources.

To foster a more inclusive and equitable future where the benefits of digital twins are accessible to all, it is essential to take proactive measures. Creating inclusive digital twins necessitates the active involvement of diverse stakeholders, including individuals from underrepresented communities, in the design and testing process. Furthermore, prioritizing accessibility features from the outset is integral to ensuring broad public benefit. By embracing these approaches, it is possible to address the concerns surrounding inclusivity and access, setting the foundation for a more equitable and accessible digital twin ecosystem.

Call for a Federal Digital Twin Strategy

Digital twins have already demonstrated their value and hold tremendous potential for further use in both the private and public sectors to bring greater insight into complex systems, further improve resiliency, and continue to transform the way defense, safety, and civilian agencies plan, train, anticipate, and operate. However, with the continuous advancements in technology, such as AI-driven interactivity and immersive experiences offered by emerging technologies, there arises a pressing need for policymakers and practitioners to confront the novel opportunities, challenges, and risks that accompany these developments. Issues such as data quality, privacy, intellectual property, security and trust, as well as inclusion and equity, must be actively addressed and carefully navigated in order to effectively harness the potential of these innovative digital twin experiences. Advanced digital twins will require investments in a cloud-enabled infrastructure that can run rich simulations at scale. With the convergence of emerging technologies such as IoT, AI/ML, and XR, more advanced digital twins with prescriptive and autonomous behavior become possible. Effective adoption of digital twin technology by the federal enterprise will require a coordinated understanding of the potential deployment challenges and needed risk mitigation strategies. Like other emerging technologies (e.g., AI, quantum information sciences, advanced manufacturing, biotechnology, etc.) when appropriately applied, digital twins can help achieve a wide array of missions and contribute to US leadership, national security, improved citizen services, and a more effective, productive, and resilient workforce. The time is now to develop a federal strategy aimed at investing in the technology and talent necessary to unlock the transformative capabilities and vast potential of digital twins.

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