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UNDERSTANDING AND UTILIZING DIGITAL TWINS FOR NAS RESEARCH

David M Tuomey and Elisabeth Kim, The MITRE Corporation

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Introduction

The concept of the digital twin was first introduced in 2002. Since then, a variety of industries have used digital twins to monitor and control their systems, optimize their processes, make data-driven predictions or decisions in real time, or to inform the design of new products, services, and business models. Today, the concept holds great promise for aviation and air traffic management research.

Although no standard definition exists, the digital twin is essentially a virtual representation of a real-world physical system. It is enabled by simulation and a tight integration of data between the actual and digital systems. Because the digital twin serves as a living model of the physical system and is continuously updated to reflect the actual system's current state, it can be used for real-time prediction, optimization, monitoring, controlling, and improved decision making.

Recent advancements in technologies, such as the Internet of Things (IoT), data science, and artificial intelligence (AI) and machine learning (ML), have made the design and application of digital twins more appealing for industries such as manufacturing, healthcare, and urban planning. In a 2017 report, Gartner estimated that, by 2021, nearly half the major industrial companies would be leveraging digital twin technology to facilitate the assessment of system performance and technical risks [1]. Market research firm MarketsandMarkets estimates the digital twin market will be almost $16 billion by 2023, with annual growth rates approaching 40 percent [2].

Digital twins are already in use in a variety of sectors. For instance, Tesla creates a digital twin of every vehicle it sells. Sensors on the automobiles stream data to their simulated twins in the factory, where AI interprets the data and determines whether a car is working as intended or if it needs maintenance. For many maintenance issues, Tesla's software integrations are so thorough that problems can be fixed with software updates—for instance, adjusting the hydraulics to compensate for a rattling door [3].

Meteorological institutes throughout the world use the digital twin concept extensively. They integrate models of a region's terrain and buildings with high-fidelity physics simulators and data coming from multiple sources—including crowd-sourced data from smartphones—to provide both long- and short-term weather predictions.

At General Electric (GE), engineers create a digital twin for each of the jet engines the company builds. Each engine is equipped with about 100 sensors that measure its essential parts. If the data gathered by the sensors and the engine's digital twin do not match up, engineers know the engine needs servicing. The sensors also provide details on the different conditions each engine endures, such as strain from carrying heavy cargo or flying through sand-laden air. That overall understanding of how each engine lives out its life helps GE modify future engine designs.

The benefits of employing digital twins become especially pronounced when dealing with large, complex systems or systems of systems. The primary benefits are [4]:

- **Real-time remote monitoring and control:** The digital twin can be accessible anywhere and thus allows for real-time remote monitoring of performance of the physical system and control of the physical system using feedback mechanisms.
- **Greater efficiency and safety:** Digital twins enable greater autonomy with humans in the loop when required. This leads to greater efficiency

and safety by offloading the more dangerous, dull, or dirty jobs to robots with human control, freeing humans to perform tasks requiring creativity and innovation.

- **Predictive maintenance and scheduling:** Sensors monitoring the physical system generate big data in real time. The digital twins can analyze the data and detect faults in the system well in advance. This enables better scheduling of maintenance.
- **Scenario and risk assessment:** “What if” analyses can be performed on the digital twin without jeopardizing the physical system.
- **Improved decision support system:** Real-time access to quantitative data and advanced analytics will enable more informed and faster decision making.
- **Personalization of products and services:** A digital twin will allow the rapid and safe customization of processes and services to meet specific stakeholder requirements and to adjust to evolving market trends and competition.
- **Improved documentation and communication:** Digital twins provide real-time information and automated reporting that will keep stakeholders well informed. This improves intra- and inter-team collaborations: All the information is at their fingertips, and teams working on separate aspects of the system (or separate systems in a system of systems) will have access to authoritative data.

The classic example of a digital twin system of systems (SoS) is the smart city case, exemplified by arguably the smartest city on Earth—Singapore. Its digital twin provides uses for construction, transportation, and energy [4]. Virtual Singapore is a three-dimensional (3D) digital twin of the real Singapore. The detailed model is not only a static model (even including features such as curb height) but connects with sensors around the city to access real-time data on energy use, traffic flow, air quality, and more. Town planners, engineers, architects, business owners, and others use the digital twin to test solutions without having to take too many risks.

Many other cities are employing digital twins as well.

- Rennes Metropole in France focuses on urban mediation with citizens and urban development purposes, including sunshine simulation, noise modeling, and tree shadow impact on buildings.
- Helsinki, Finland uses digital twins to improve energy efficiency and for virtual tourism.
- Columbus, Ohio uses its digital twins to drive economic growth and foster sustainability by interconnecting and modeling infrastructure services, including transportation, housing, and healthcare.

Given its many applications and benefits, it’s time to consider applying the digital twin concept to National Airspace System (NAS) research.

Composition of Digital Twins

To envision how a digital twin might work in NAS research, it's helpful to understand the four components a digital twin needs to be fully integrated and interoperable:

1. A real-world **physical system**. This can be a product, component, system, or process.
2. A **virtual system model** representing the physical system's structure and characteristics.
3. A **virtual system environment** in which the virtual system model operates.
4. A **digital thread** containing historical and real-time virtual and physical system data and the means to connect the digital components to each other and the virtual to the physical.

The real-world **physical system** that is intended to be twinned can be a product, component, system, or process. The physical system can be hardware, software, or a combination of the two. The physical system needs to provide the necessary data elements via the digital thread, and its level of maturity and sophistication may greatly impact the quality and availability of this data. The digital twin may precede the physical system; in this case the necessary data will likely be supplied by the virtual system environment. The physical system is included as part of the digital twin since it is likely to require modifications to fully interface with or stay concurrent with the virtual components.

The **virtual system model** is designed to represent the physical system, describing the structure and its characteristics. Virtual system models can range from lightweight to full-up models. The lightweight models reflect a simplified structure and simplified characteristics to reduce computational load, especially in upfront engineering activities, whereas full-up models can include performance, health, and maintenance data from the physical system and are able to explore advanced behaviors and scenarios.

The **virtual system environment** is the environment in which the virtual system model operates; it contains the analytics and algorithms to predict, describe, and prescribe the behavior. The environment contains data storage, AI/ML, cybersecurity, environment simulation models, and intelligent agents, along with human-machine interfaces (HMI)

FIGURE 1. COMPONENTS OF A DIGITAL TWIN

containing advanced visualization and analytics. The environment simulation models are necessary to augment or replace the data supplied by the physical system to successfully drive the virtual system model. Users need the HMI to manage the sheer volume of data required to create and operate the digital twin and to gain meaningful insights. Intelligent agents, capable of taking actions in a complex environment, are necessary to optimally control the virtual system model and help users achieve their goals.

The purpose of the **digital thread** is to act as a hub for all information that is related to the digital twin. The digital thread connects digital things to each other and connects the digital to the physical. It contains the historical and real-time virtual and physical system data. Since the status, behaviors, and properties of the physical and virtual worlds dynamically change, all kinds of data are constantly being produced, used, and stored from the beginning until the disposal of a product. The digital thread is bidirectional, going to and from the virtual and the physical, creating a continuous learning and feedback loop between the two.

Application to NAS Research

The NAS will need to evolve to keep pace with new vehicle types, changing operational needs, and rapidly advancing technologies. Innovative platforms enabling accelerated deployment, equitable access, continuous learning and feedback, and system optimization will be needed to keep pace. The digital twin is one such platform.

The Federal Aviation Administration (FAA) operates the NAS to establish a safe and efficient airspace environment for civil, commercial, and military aviation. The NAS is made up of a system of air navigation facilities, air traffic control (ATC) facilities, airports, technology, and rules and regulations that are needed to operate the system [5]. In the context of the digital twin, the NAS is an SoS composed of existing and evolving physical systems that represent hardware, software, and human elements.

Approaches to Implementation

Given the size, complexity, and maturity levels of the systems in the NAS, two approaches and a hybrid of the two are proposed for creating a digital twin for NAS research.

In the **top-down approach**, a digital twin including all major systems of the NAS would be created from the onset. In this approach, many *virtual system models* would be created to twin their respective *physical systems*. Due to the sheer number of systems in the NAS, it is very likely that the models would be of low fidelity. However, they could be evolved over time as needed.

Virtual system models of NAS systems would need to be represented. These could include systems such as, but not limited to:

- Time-Based Flow Management (TBFM), the automation system that uses time instead of distance to manage air traffic flows efficiently

- Traffic Flow Management System (TFMS), a NAS-wide decision support tool for planning and implementing traffic flow management initiatives to mitigate demand/capacity imbalances
- Terminal Flight Data Manager (TFDM), a decision support tool that allows controllers, air traffic managers, airports, and aircraft operators to share awareness and better manage traffic on the airport surface
- En Route Automation Modernization (ERAM), the computer system the FAA uses at the air traffic control centers managing high-altitude, en-route flight
- ATC facilities
- Relevant stakeholder systems (e.g., airline Flight Operations Centers)

The *digital thread* would need to process the enormous amounts of data the NAS continuously produces. The digital thread would also need to pass data between the multiple virtual system models. To handle this level of data, emphasis would need to be on fully using and evolving big data technologies.

The *virtual system environment* would be shared between the many virtual system models. In this environment, the HMI, AI/ML, advanced analytics, and the environment simulation models would need to be interoperable and handle the different needs of the many virtual system models.

In the **bottom-up approach**, emphasis would be on creating an individual digital twin of one major NAS system and then integrating it with others as research and business needs arise. In this approach, the focus would be on creating a high-fidelity *virtual system model*. The goal would be to make the model as realistic as possible as it relates to behavior, performance, health, and maintenance of the physical system. In the past, realistic high-fidelity models have been criticized as being a bridge too far—too complex and too expensive. But digital twins overcome this criticism by having high-fidelity envisioned and built early in the life cycle. The physical system to be twinned would likely be one of the NAS automation systems described above (e.g., TBFM, TFMS, TFDM, or ERAM).

This virtual system model would be connected to the *digital thread* via real interfaces that can provide operational and historic data at or near real-time speeds. It would require that the *physical system* be fully instrumented to provide all the necessary data. In the case where the physical system has yet to be developed, the environment simulation models in the virtual system environment would need to provide the data.

The virtual system model would operate in a *virtual system environment* that again contains the HMI, AI/ML, advanced analytics, and the environment simulation models. But, in the bottom-up approach, these are highly optimized for the chosen virtual system model.

The **hybrid approach** combines the strengths of the two previous approaches. As in the bottom-up approach, a high-fidelity *virtual system model* would be developed to twin a physical system, with the goal of being as realistic as possible. But to ensure an evolution path that can include more virtual system models, the digital thread and the virtual system environment would use the top-down approach. As more digital twins are added, the virtual system will begin to behave and perform like an SoS and should be managed as such.

The *digital thread* would need to be able to process the enormous amounts of NAS data and handle all the data that are passed between the multiple virtual system models. Creating a common interface language that would be utilized by all the different

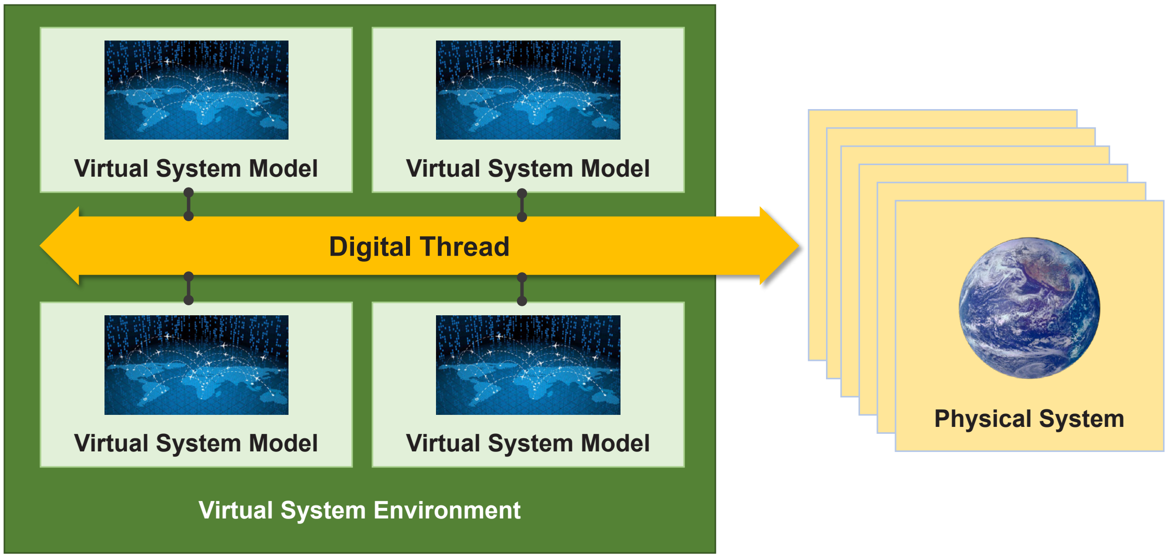

FIGURE 2. COMPONENTS OF A DIGITAL TWIN - HYBRID APPROACH

virtual system models will be a challenge to be addressed early in the development cycle.

The *virtual system environment* would be shared between the many virtual system models. In this environment, the HMI, AI/ML, advanced analytics, and the environment simulation models would need to be interoperable and support the multiple virtual system models. Here the early challenge would be creating environment simulation models that meet all the data needs and can be controlled through a well-designed HMI and a system of intelligent agents.

A Candidate for Implementation

A promising candidate for the hybrid approach would be TBFM, the automation system that uses time instead of distance to help the FAA manage traffic flow efficiently. A fully interoperable TBFM digital twin could be used for many purposes. These include:

- **Real-time remote access, monitoring, and control** – The TBFM digital twin can be accessed anywhere, keeping stakeholders (FAA, airlines, industry, and academic partners) well informed, thereby improving transparency. Cloud technologies will provide cost-effective scalability permitting the creation of many instances of the digital twin. This will provide the stakeholders the mechanisms to control their own instance and generate unique descriptive, predictive, and prescriptive analytics in real time that will assist in better-informed and faster decision making.
- **TBFM Operation Optimization** – The TBFM digital twin will allow a holistic approach to TBFM optimization, including human interactions of input parameters, traffic levels, flight routes, and TBFM adaptation. Capitalizing on the accessibility described above, this will allow optimization from many different perspectives, addressing economic, environmental, and quality concerns.

- **TBFM "What If" Scenarios** – The TBFM digital twin will enable "what if" scenarios, where potential decisions and results can be understood prior to acting on the real physical system. When used with scaling of multiple instances of the TBFM digital twin and in conjunction with fast-time simulation, it will be possible to play out different strategies and allow the stakeholder to learn and react in an efficient, timely manner.
- **Accelerate Deployment of New Capabilities** – The TBFM digital twin will enable significant risk reduction related to fielding changes to the real physical system. It will allow rapid development and testing of bug fixes on the existing system and of new applications and functionality before releasing and making changes operational. The rapid development will also reduce the risks associated with revolutionary changes to be made to TBFM and other NAS automation systems.

As with any digital twin, the TBFM digital twin would require a physical system, a virtual system model, a virtual system environment, and a digital thread. The Center for Advanced Aviation System Development (CAASD)—the federally funded research and development center (FFRDC) MITRE operates for the FAA—is well positioned to support construction of this digital twin.

The **physical system** would be the FAA's TBFM, an existing system consisting of hardware and software components and designed to be monitored and controlled by human actors. An instance of TBFM exists at each of the FAA's En Route facilities. The proposed digital twin would initially be representative of just one of those instances but would scale to add others as needed.

The **virtual system model** representing the TBFM physical system would be the latest version of the TBFM operational source code. Since this is the same code being used by the physical system, this source code replicates all the functionality and interfaces at the highest-fidelity level and requires interoperability with other NAS systems.

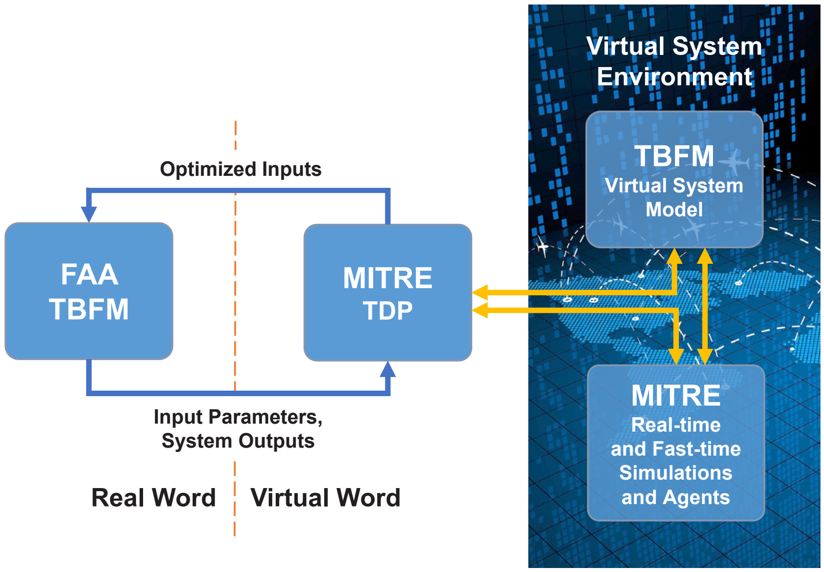

FIGURE 3.TWINS: TBFM/FMS EXAMPLE

CAASD's modeling and simulation capability contains a fast-time component called Akela and a real-time component, which provides real-time capability for human-in-the-loop experimentation and research, housed in MITRE's Integration Demonstration and Experimentation for Aeronautics (IDEA) Laboratory. Creating the **virtual system environment** would necessitate picking the most appropriate components from between Akela and the IDEA Laboratory and expanding and enhancing them to meet the specific needs of the TBFM virtual system model. CAASD has also developed numerous intelligent agents used to help achieve research goals within the modeling and simulation capability. More advanced agents, called "operators," have been created to control operational systems such as a flight management system; this pair of operators and operational systems closely represents a digital twin.

Digital twin research and development efforts can leverage CAASD's big data capability, the Transportation Data Platform (TDP). TDP can serve as the **digital thread** containing historical and real-time virtual and physical system data. Requirements for using TDP as a digital thread would include:

- The ability to provide bidirectional data connection between the TBFM virtual system model and the NAS
- The ability to support real-time and potentially fast-time connections between the TBFM virtual system model and its virtual system environment—specifically, those environmental system models that are needed to augment and replace physical world data, such as flight modeling and NAS system models
- The ability to store and make available all the digital twin data from the NAS, the TBFM virtual system model, and the virtual system environment

While CAASD has a diverse suite of modeling and simulation and data capabilities, these capabilities have limitations in the digital twin context:

- The modeling and simulation capabilities abstract the real interfaces for the purpose of efficiently meeting research needs. The interface needs of the TBFM virtual system model will necessitate the use of real interfaces and will impose further requirements on the data and the models that support those interfaces.
- The digital twin will need the real physical system data in real time. This will necessitate a streaming connection from the NAS and a way to stream historical data.
- Successfully controlling the TBFM digital twin will be a complex task. This will require building a suite of automated and intelligent agent controllers, along with an elegant HMI that can respond to the TBFM changing state.
- It is anticipated that research needs will require modifications to the TBFM virtual system model. This presents a series of needs around software development (agile development, continuous integration/continuous delivery, configuration management) and a community of developers with the skills and knowledge to successfully make the required changes to the complex TBFM operational code base.

To help further explore and enable digital twin research and development efforts, CAASD has developed an initial instantiation of a TBFM system digital twin as part of a proof-of-concept prototype that provides traffic management personnel with advanced insights about TBFM scheduling performance in the NAS [6]. This digital twin utilizes predicted traffic demand and predicted constraint information and is designed to enable traffic managers to explore mitigations and better understand predicted TBFM system performance outputs. This research and development effort was focused on providing an on-demand solution to address integrated traffic flow management predictive modeling needs.

The TBFM system digital twin leverages real-time data and represents the TBFM *physical system* using a *virtual system mode*l connected to the digital thread via System Wide Information Management (SWIM) data interfaces, which provide real interfaces necessary to acquire operational data (e.g., traffic demand, capacity, runway configurations, route adaptation files, adaptation parameter and settings) and make that data available at or near real-time speeds. The TBFM system digital twin operates in a *virtual system environment* that was developed using a modern technology stack and according to a microservice-based architecture in which a set of applications were designed and deployed independently. The resulting prototype technology stack leveraged a wide range of open-source software components that provided the underlying infrastructure to host the prototype software.

As described above, CAASD has demonstrated that the development of a TBFM system digital twin is feasible. Enabling other feasible and more sophisticated digital twin applications (beyond "what if" modeling and monitoring and tracking) may require modifications to the physical system—the real-world TBFM system. TBFM may need to be modified (i.e., outfitted with more sensors) to provide more in-depth operational data to meet the needs of the virtual system model. For added value, the real-world TBFM system will also need a way to ingest data from the virtual system model to move from a manual process where a human takes the virtual results and inputs them into the physical system, to a more automated approach leveraging a real-time connection to the physical system. These changes, if required, can be prototyped in the virtual system model and fully tested before being operationally deployed.

Conclusion

There are challenges to overcome, but the benefits of digital twins cannot be denied. Their use will continue to grow, and the concept will be applied in ever more innovative ways to optimize processes, make data-driven decisions in real time, and design new products, services, and business models. The FAA's FFRDC, CAASD, has successfully developed a scheduling digital twin of the TBFM system and showcased it as part of a proof-of-concept solution for helping to better manage traffic flows in the NAS. That digital twin application reflects just the beginning; if we continue efforts now, we can realize additional benefits for the nation's airspace system—and all those who use it.

Acronyms

3D	Three-Dimensional
AI	Artificial Intelligence
ATC	Air Traffic Control
CAASD	Center for Advanced Aviation System Development
ERAM	En Route Automation Modernization
FAA	Federal Aviation Administration
FFRDC	Federally Funded Research and Development Center
HMI	Human-Machine Interface
IDEA	Integration Demonstration and Experimentation for Aeronautics
IoT	Internet of Things
ML	Machine Learning
NAS	National Airspace System
SoS	System of Systems
TBFM	Time-Based Flow Management
TDP	Transportation Data Platform
TFDM	Terminal Flight Data Manager
TFMS	Traffic Flow Management System

References

[1] Gartner (2017), "Prepare for the Impact of Digital Twins," https://www.gartner.com/smarterwithgartner/prepare-for-the-impact-of-digital-twins

[2] MarketsandMarkets (n.d.), "Digital Twin Market worth $48.2 billion by 2026," https://www.marketsandmarkets.com/PressReleases/digital-twin.asp

[3] J. Coors-Blankenship, "Taking Digital Twins for a Test Drive with Tesla, Apple," Industry Week, https://www.industryweek.com/technology-and-iiot/article/21130033/how-digital-twins-are-raising-the-stakes-on-product-development, 2020

[4] A. Rasheed, O. San, T. Kvamsdal, "Digital Twin: Values, Challenges and Enablers," Cornell University, October 3, 2019, [1910.01719] Digital Twin: Values, Challenges and Enablers (arxiv.org)

[5] The Federal Aviation Administration (n.d.), Appendix A: National Airspace System Overview, https://www.faa.gov/air_traffic/nas/nynjphl_redesign/documentation/feis/media/Appendix_A-National_Airspace_System_Overview.pdf

[6] A. Frewin et al., "Towards Predictive, On-Demand Time Based Management Modeling," The MITRE Corporation, McLean, VA, 2021.

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