

A Binary Source of Truth: Connecting Digital Twins to Their Physical Counterpart

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ABSTRACT

This paper explores the critical link between digital twins and their physical counterparts, introducing the concept of a “Binary Source of Truth”. While such a phrase may seem like a contradiction, this illustrates how taking a “system of systems” approach to digital engineering provides a more complete picture of a project’s ground truth. Establishing a robust connection between the digital and physical representations of a system from a project’s earliest phases exposes new opportunities to leverage iterative design techniques, adapt to emerging behaviors, and evolve the system design as requirements become better understood. By viewing digital engineering through a systems engineering lens, this paper examines the opportunities and challenges associated with creating such a binary system, highlighting the importance of data integration, synchronization, and validation processes. Methodologies and technologies are explored to bridge the gap between digital twins and physical assets, including sensor data integration, IoT (Internet of Things) connectivity, and advanced modeling techniques. Furthermore, the paper discusses the implications of achieving a binary source of truth for industries such as training simulation and AEC. By enabling seamless data exchange and synchronization between digital twins and their physical counterparts, organizations can unlock new insights, improving the decision-making process and optimizing operational efficiency. Overall, this paper seeks to provide valuable insights into the integration of digital twins with the physical world as an expanded view of authoritative source of truth.

ABOUT THE AUTHORS

Kyle Simmons is a product manager for an innovative collaboration software platform called Cavnus. During his 20 years as an engineer designing mechanical and software systems for aerospace, training simulators, and immersive theme park attractions, Kyle has developed an expertise in leveraging game technology to promote continuous improvement in engineering pipelines.

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INTRODUCTION

The concept of an authoritative source of truth (ASOT) is critical to the process of engineering complex systems. Traditionally, a single source of truth ensures that all designers, decision-makers, and stakeholders base their work on a common dataset synchronized across both time and space. In every discipline of engineering, having a common representation of ground truth is a critical element to efficiently designing reliable systems that stand the test of time. For Architecture, Engineering, and Construction (AEC), a relational database describing a building's façade, structure, and electrical systems, for example, are combined to form a Building Information Model (BIM). In systems engineering, a Requirements Traceability Verification Matrix (RTVM) is maintained, refined, and verified to ensure the product is designed to Government and contractor-defined requirements. And for Quality Assurance (QA), test procedures are written to verify the stability and consistent outcome of software features. These standards must be consistently updated at a common storage point for distribution to the rest of the team, regardless of their geographic location. This centralization of data is pivotal in maintaining consistency and accuracy, enabling seamless collaboration across various disciplines. Maintaining an ASOT is a practice that centralizes an organization's data from multiple systems into a single location. The goal is to make all business data accessible to everyone in the company so that each member makes decisions based on consistent information, preventing silos and ensuring that all personnel are moving towards a common goal. A study by the National Institute of Standards and Technology (NIST) highlights the importance of an ASOT, showing that the construction industry alone could save an estimated \$15.8 billion annually by adopting integrated and interoperable data systems like BIM (NIST, 2004).

The Obsolescence of Engineering Models Post-Construction

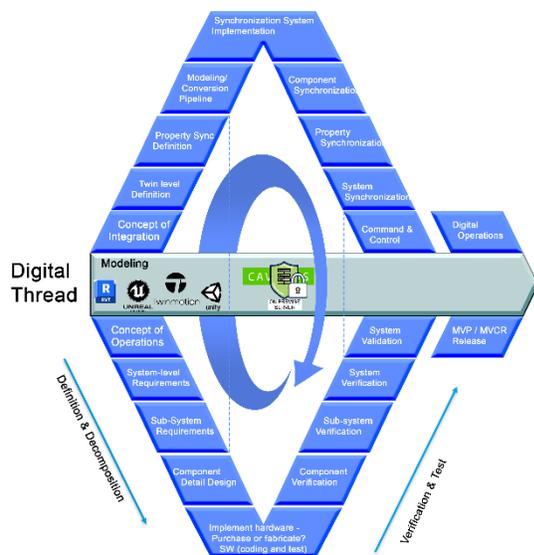
Traditional engineering projects relied on static databases, such as CAD models and associated drafting & requirements documents, to represent the overall design and performance of a system. Software and methodologies, such as BIM, have advanced to enable collaboration between multiple engineering disciplines, facilitating the creation of highly reliable assets. However, once the physical asset is constructed, the static model quickly becomes obsolete as it no longer reflects the current state of the asset. As many as 92% of construction professionals in 2011 recognized that discrepancies arose in the majority of construction projects between design models and the actual built environments due to factors such as wear, corrosion, and construction variations (Eastman et al, 2011). These factors override the strict dimensional tolerances of the original design documentation, and the newly constructed asset itself takes over as the sole representation of "Ground Truth". Over time, this divergence increases as emerging behavior discovered in the field may require adaptation to operational procedures. Mission evolution may cause some system features to become obsolete, while other system capabilities become new priorities that were never part of the original system requirements. While some engineering efforts are made to document these variances over time, using traditional techniques is a slow process, and more often than not these deltas are left uncaptured.

Digital Twins: The Evolution Beyond Static Models

Digital twins offer a solution to this problem by creating a live, continuously updated digital counterpart of a physical system. Through the integration of sensors and IoT devices, the digital twin can capture real-world data, providing an accurate and dynamic representation of the physical asset. Unlike static models which represent a

specific snapshot in time, digital twins are continuously updated with data from their physical counterparts. These updates can be made manually, automatically on demand, or consistently. Updating at regular intervals not only maintains the database's integrity as part of a system representing ground truth, but doing so at a rapid cadence, ideally in real-time, offers tremendous opportunities for system enhancement, longevity, and usefulness. A particular class of jet engine design from General Electric (GE) is equipped with hundreds of sensors which collect data on various parameters, allowing the digital twin to reflect the real-time condition and performance of the engines. This approach has resulted in a 10% increase in operational efficiency and a 25% reduction in maintenance costs (GE Reports, 2017). In this case, the synchronization of property data between a physical asset and its digital twin represents two components of a single source of truth. Each component in this system of systems can be accessed, measured, and tested in different ways, each providing different views of the total picture that the other could not provide alone. Synchronizing them together into a whole unit creates not just one source of truth, nor two distinct "versions" of truth, but rather a binary data source providing a more complete and data-rich representation of the "ground truth".

This paper uses the Model-Based Engineering (MBE) Diamond framework, introduced by Boeing in 2018, as a basis for unifying both the physical and digital systems of a product into a complete whole. For this binary system to be valid and relevant, a seamless flow of data and information must be maintained throughout the product lifecycle. This ensures that all phases of development, from initial requirements to final deployment and maintenance, are interconnected through a continuous stream of digital information. This "Digital Thread" enables real-time access to up-to-date data, fostering improved decision-making, traceability, and collaboration across various stages and disciplines. We emphasize the importance of this digital thread by illustrating a variation of the MBE Diamond below.



In this version, a third layer is introduced between the digital and physical layers highlighting the connection of both sides through each symmetric phase. This third layer is essential for standardizing communication protocols to ensure critical success factors such as data security and parity. The ideal middleware for this layer would expedite conversion of engineering models from the construction phase into digital twins by quickly synchronizing property data with sensor devices in the physical asset. In this way, the models would continue to provide value throughout the project lifecycle. This digital twin can then be used to enhance the decision-making process, improve operational efficiencies, and achieve a higher degree of accuracy in predicting future conditions.

The value of standardization for this digital thread layer cannot be overstated.

LEVERAGING A DIGITAL TWIN IN A DESIGN THINKING WORKFLOW

The integration of digital twins into a design thinking workflow revolutionizes decision-making by centralizing organizational data. This centralization ensures that all stakeholders have access to the same accurate and up-to-date information, facilitating consistency and precision in decision-making. According to a study by Deloitte, organizations utilizing digital twins report a 15-20% improvement in operational efficiency due to enhanced data visibility and accessibility.

Agile Systems Engineering: Convergence and Evolution

Agile Systems Engineering embodies the convergence of design processes and the evolving understanding of initial requirements. It emphasizes adaptability and responsiveness, which are crucial in today's rapidly changing

environments. The Agile methodology supports the continuous development, integration, and validation of system models, which grow in fidelity over time. This approach is reinforced by Model-Driven Engineering (MDE), which functions as both an independent value stream and a concurrent evolution with the product .

Key constructs of this methodology include:

1. **Knowledge Value Stream:** The flow of knowledge throughout the engineering process, ensuring that insights gained are continually integrated back into the system.
2. **Agile as an Empirical Process:** Utilizing iterative cycles to refine and adapt system designs based on real-world feedback.
3. **SysML and Analytical Models:** Systems Modeling Language (SysML) and other analytical tools that provide a framework for defining, visualizing, and analyzing complex systems.
4. **MIL, SIL, and HIL:** Model-in-the-Loop (MIL), Software-in-the-Loop (SIL), and Hardware-in-the-Loop (HIL) simulations that validate system components at various stages of development.
5. **Digital Engineering:** Integrating digital technologies to enhance the engineering process, ensuring that digital twins remain an accurate and functional representation of their physical counterparts .

Agile as a Means to Refine Understanding of System Requirements

The Agile methodology plays a crucial role in refining the understanding of system requirements through continuous analysis and updates to digital twins. This ongoing refinement is critical for long-term use and risk mitigation. The application of Agile principles, coupled with Building Information Modeling (BIM) technology, allows projects to evolve from early concept phases to completed construction efficiently. Maintaining a digital twin throughout the product lifecycle enables continuous predictive analysis, helping to extend the lifespan and optimize the performance of physical systems.

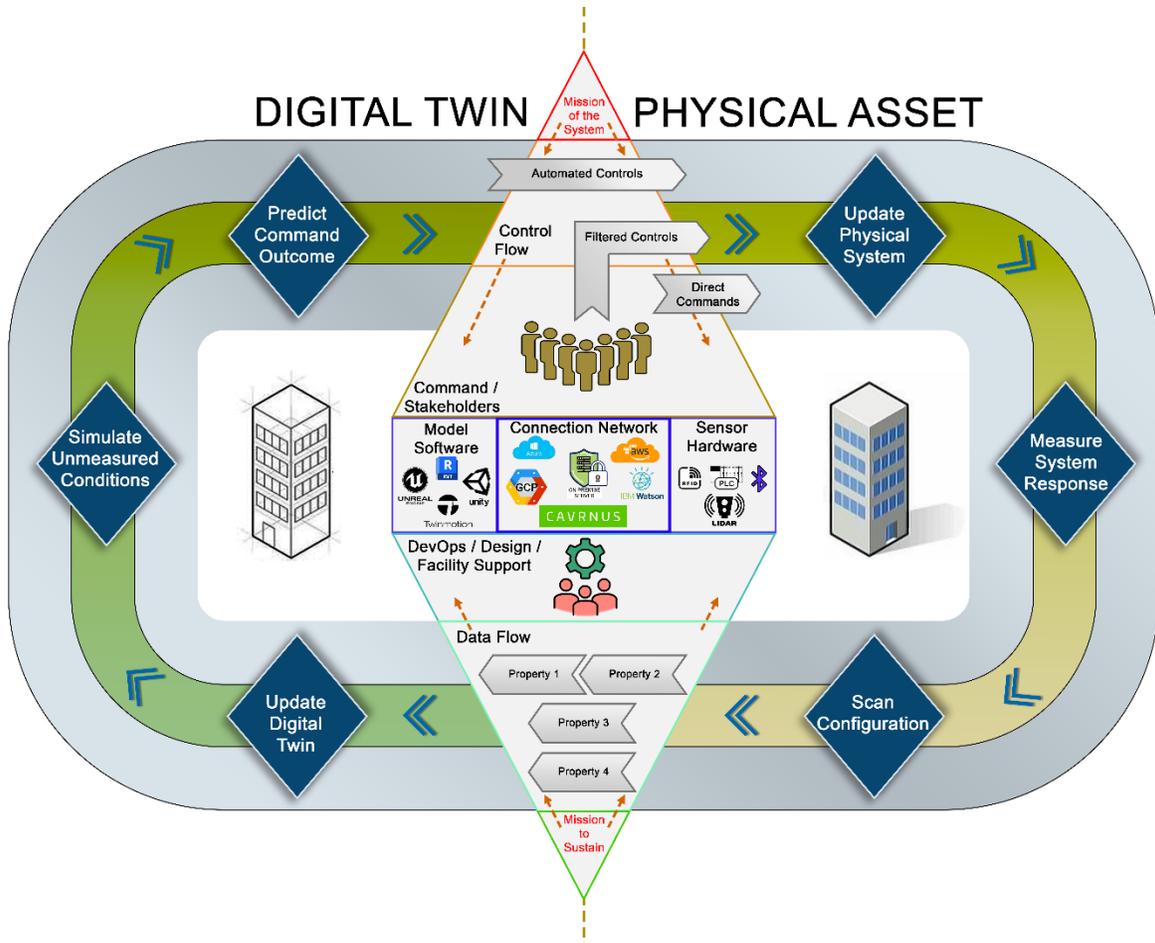
For instance, during the Mars Rover mission, engineering teams utilized both digital and physical models on Earth to predict the rover's response to commands. Given the significant time delay between instruction and response (measured in minutes), simulations were essential for verifying the validity of instructions before execution. This approach ensured the rover's operations were efficient and risk-free.

In real-time feedback loops on Earth, the decision-making process is compressed, with responses expected within seconds. With the advancement of real-time systems and machine learning, multiple decision paths can be tested and refined within the digital twin before implementation. This dynamic testing is contingent on the digital twin's configuration accurately reflecting the physical system, ensuring decisions are based on the current state rather than the idealized design. This binary source of truth, balancing the "what is" with the "what will be," enhances decision-making accuracy and system reliability.

Enhanced Decision-Making Capabilities Through Comprehensive System Analysis

The comprehensive analysis enabled by digital twins significantly enhances decision-making capabilities. By integrating real-time data and predictive analytics, digital twins provide a holistic view of system performance and potential future states. This capability is particularly valuable in military training and simulation, where accurate, real-time decision-making can have critical implications. As noted by a report from McKinsey, the implementation of digital twins in complex systems can lead to a 10-15% reduction in maintenance costs and a 20-25% increase in system reliability.

By leveraging digital twins within a design thinking framework, organizations can achieve a higher degree of operational efficiency, adaptability, and strategic insight, ultimately driving better outcomes in complex engineering projects.



THE FRAMEWORK OF A BINARY SOURCE OF TRUTH

Communication Layer Between Physical and Digital Models

A robust communication layer between the physical and digital models is critical for the functionality of a digital twin. This layer must be stable enough to handle demanding update cycles yet flexible enough to adapt to various projects and the evolution of a single project throughout its lifecycle. This adaptability ensures the digital twin remains a reliable and current representation of the physical asset, facilitating real-time decision-making and long-term planning (Grieves & Vickers, 2017).

Role of Sensors and IoT Devices

Sensors and IoT devices are essential components of digital twins. They collect real-time data on various parameters such as temperature, pressure, humidity, vibration, and usage, transmitting this data to the digital replica. This continuous data flow allows the digital twin to reflect the current state of the physical asset accurately, providing a basis for informed decision-making and predictive analysis (Lee, Bagheri, & Kao, 2015).

Types of Sensors

1. **Environmental Sensors:** Measure ambient conditions like temperature, humidity, and air quality.
2. **Motion Sensors:** Detect movement and orientation.
3. **Proximity Sensors:** Measure distance or detect the presence of objects.
4. **Condition Monitoring Sensors:** Monitor parameters like vibration, pressure, and temperature within machinery.

Sensor Networks

A robust sensor network is crucial for the effective operation of a digital twin. These networks ensure seamless data collection and reliable transmission to the digital twin for processing and analysis. The integration of these networks into the digital twin infrastructure supports real-time monitoring and optimization of physical assets (Tao et al., 2018).

Establishing Common Standards for Communication

To maximize the effectiveness of digital twins, a common standard for the communication layer is necessary. This standard would facilitate:

1. **Real-Time Bi-Directional Communication:** Ensuring that data flows continuously and accurately between the digital and physical models.
2. **Branching Capability:** Allowing multiple abstractions of the models, such as status updates to both the digital twin and physical mockups in engineering labs.
3. **Machine Learning Integration:** Enabling adaptive decision-making that aligns human decisions with system requirements.
4. **Secured Data Transmission:** Protecting data integrity and preventing command corruption or disinformation (Fuller, Fan, Day, & Barlow, 2020).

Middleware Enabling Digital Twin Integration

The rapid growth of Software as a Service (SaaS) companies specializing in real-time property updates is revolutionizing the digital twin landscape. These companies provide the essential technology infrastructure required for seamless communication between digital twins and their physical counterparts. By offering robust data interchange and software connectivity solutions, SaaS providers enable continuous synchronization of real-time data, ensuring that the digital twin remains an accurate reflection of the physical asset. This connectivity is critical for industries that rely on up-to-date information for operational efficiency and decision-making. SaaS platforms such as AWS IoT, Microsoft Azure Digital Twins, and IBM Watson IoT offer comprehensive services that facilitate the integration of IoT devices.

Taking the digital twins to the next level with immersive collaboration, companies such as Cavnus, Inc., Spatial, and even Autodesk's The Wild offer data management and advanced analytics in addition to VR integration, enabling teams to enhance decision-making by experiencing work together in a shared virtual space. These platforms not only enhance the functionality and reliability of digital twins but also provide scalable solutions that can be tailored to specific industry needs, driving innovation and operational excellence across various sectors (Gartner, 2023; IDC, 2022).

IoT Communication Protocols

Communication protocols are essential for the reliable transfer of data between sensors and the digital twin. These include:

Wireless Communication Protocols:

- Wi-Fi: Common due to high data rates and widespread availability.
- Bluetooth: Suitable for short-range communication with low power consumption.
- Zigbee: Ideal for low-power, low-data rate applications.
- LoRaWAN: Used for long-range, low-power applications, particularly in remote monitoring (Gubbi, Buyya, Marusic, & Palaniswami, 2013).

Wired Communication Protocols:

- Ethernet: Provides reliable, high-speed data transfer for connected devices.
- Modbus: A serial communication protocol often used in industrial applications.

Data Integration and Management

Effective data integration and management are critical for the functionality of digital twins. Technologies that support this include:

- **Cloud Computing:** Offers infrastructure for storing and processing vast amounts of data generated by sensors and IoT devices. It provides scalability, accessibility, and computational power needed for real-time data analysis (Hashem et al., 2015).
- **Edge Computing:** Complements cloud computing by processing data closer to the source. This reduces latency and bandwidth usage, enabling faster decision-making and real-time analytics (Shi, Cao, Zhang, Li, & Xu, 2016).

The Communication Layer – Where Decisions Are Made

At the communication layer, information flows from both the digital and physical twins, filtered and processed for effective decision-making. Differentiated levels of human commands—reflexive, filtered, and strategic—ensure that decisions made from this layer are executed appropriately:

- **Reflexive Level:** Immediate, low-level responses.
- **Filtered Level:** Intermediate decisions that require some analysis.
- **Thinking Level:** High-level strategic decisions that involve comprehensive analysis.

By providing a real-time, accurate representation of the physical asset, digital twins enable better-informed decisions. Stakeholders can analyze current conditions, predict future scenarios, and optimize operations based on reliable data (Negri, Fumagalli, & Macchi, 2017).

System Parameters – Call to Action

For a communication layer to be effective, it must be both performant and flexible. Key requirements include:

- **Branching Capabilities:** Allowing for multiple abstractions, such as simulation analysis without affecting the current status and physical mockups.
- **Machine Learning:** Enhancing adaptive decision-making.
- **System Reliability:** Ensuring data security and parity to maintain trust and functionality (Schleich, Anwer, Mathieu, & Wartzack, 2017).

DATA FILTRATION

Challenges of Comprehensive Data Collection

In the realm of digital twins, the challenge of comprehensive data collection is a balancing act between acquiring detailed information and avoiding information overload. While the availability of extensive data from sensors and IoT devices enhances the accuracy and utility of digital twins, it also risks overwhelming systems with excessive data, potentially impeding effective decision-making and exceeding data transfer capacities (Jouini, Rabai, & Aissa, 2014). Striking a balance between granularity and decision-making efficiency is crucial. Too much data can lead to analysis paralysis, where the sheer volume of information makes it difficult to extract actionable insights, whereas too little data can result in an incomplete or inaccurate representation of the physical asset.

Role of Digital Twin Systems as Data Interpretation Layers

Digital twin systems play a pivotal role as data interpretation layers, filtering and processing raw data to provide actionable insights. By implementing advanced data analytics and machine learning algorithms, digital twins can transform vast amounts of raw sensor data into meaningful information, which can then be used for predictive maintenance, performance optimization, and strategic planning (Grieves & Vickers, 2017). This capability ensures

that stakeholders receive only the most relevant information, enhancing decision-making efficiency and effectiveness.

Sensors and Data Tracking

The idea of equipping every possible aspect of the physical twin with sensors to inform the digital twin, while theoretically appealing, is practically problematic. Implementing such an exhaustive array of sensors would lead to significant data transfer issues and information overload. A focused approach is necessary, where critical parameters are identified, and sensors are deployed strategically to monitor these key aspects. This targeted data collection ensures that the digital twin receives sufficient information to accurately reflect the physical twin without being inundated with unnecessary details (Fuller, Fan, Day, & Barlow, 2020).

Avoiding Information Overload

Managing the potential for data overload requires robust data filtration mechanisms. Digital twins can serve as sophisticated filters, distinguishing between vital and non-essential data. This filtering process involves prioritizing data based on its relevance and impact on decision-making processes. For instance, real-time operational data might be prioritized for immediate analysis, while less critical data can be archived for future reference or batch processing. Effective data filtration not only prevents system overwhelm but also enhances the speed and accuracy of the digital twin's responses to changes in the physical asset (Negri, Fumagalli, & Macchi, 2017).

Real-World Applications and Solutions

In practice, digital twins that serve as data interpretation layers have been successfully implemented in various industries. For example, in aerospace, the use of digital twins for aircraft engines involves continuous monitoring of key performance indicators such as temperature, pressure, and vibration. These indicators are filtered and analyzed to predict maintenance needs and prevent failures, thereby improving operational efficiency and safety (Tao et al., 2018). Similarly, in the manufacturing sector, digital twins of production lines are used to monitor and optimize workflow, reducing downtime and enhancing productivity.

While comprehensive data collection is essential for the accurate functioning of digital twins, it must be balanced with effective data filtration to avoid information overload and ensure efficient decision-making. Digital twin systems, acting as data interpretation layers, filter and interpret raw data to provide actionable insights, thereby enhancing the overall utility and efficiency of the digital twin. This approach ensures that digital twins can continue to serve as reliable and dynamic representations of their physical counterparts, driving improvements in performance, maintenance, and strategic planning. Moreover, leveraging existing SaaS platforms such as Cavnus offers a cost-effective alternative to developing bespoke solutions for these challenges. These platforms provide robust, scalable, and flexible services that can be tailored to meet the specific needs of various projects, making it easier to implement and maintain an efficient digital twin framework.

USE CASES FOR DIGITAL TWINS AS A BINARY SOURCE OF TRUTH

Improved Operational Efficiency

Digital twins enhance operational efficiency by facilitating proactive maintenance and minimizing downtime. Continuous monitoring of asset conditions enables the identification and resolution of potential issues before they escalate into failures. For instance, Rolls-Royce uses digital twins to monitor the performance of their aircraft engines in real-time, allowing for predictive maintenance that significantly reduces unplanned maintenance and associated costs (Wright & Davidson, 2020).

Cost Savings

The integration of digital twins can lead to substantial cost savings across various domains. Efficient resource management, reduced maintenance expenses, and optimized operations collectively contribute to lowering overall costs. According to a report by Gartner, companies implementing digital twins in their operations have seen up to a 10% reduction in operational costs and a 20% improvement in asset utilization (Gartner, 2021).

Predictive Analytics and Simulation

Digital twins empower organizations with advanced predictive analytics capabilities. By simulating different scenarios, organizations can forecast the outcomes of various decisions and strategies, leading to better planning and risk management. For example, General Electric (GE) uses digital twins for their power plants to predict equipment failures and optimize maintenance schedules, which has resulted in a 25% reduction in maintenance costs and a 20% increase in reliability (Fuller, Fan, Day, & Barlow, 2020).

Data Representation and Visualization

Digital twins offer diverse forms of data representation, including visualization, which, while not the core value, serves as a crucial tool for interpreting and analyzing the system's state. Accurate, real-time visual representations enhance design processes and facilitate better understanding of complex systems. For instance, Boeing utilizes digital twins to create 3D models of their aircraft, which help in visualizing and optimizing the design process (Grieves & Vickers, 2017).

Non-Destructive Testing

Digital twins enable non-destructive testing (NDT), allowing for the examination and analysis of systems without causing physical harm. This capability is particularly valuable in scenarios where the physical twin is inaccessibly located or undergoing critical operations. Siemens, for example, uses digital twins for non-destructive testing of their turbine blades, ensuring reliability and safety without interrupting operations (Negri, Fumagalli, & Macchi, 2017).

System Inspection and Analysis

Digital twins facilitate remote system inspection and analysis when physical access is limited. This is especially relevant in aerospace and deep-space missions. For instance, NASA employs digital twins of the Mars Rover to perform remote diagnostics and system analysis, enabling the resolution of issues without direct access to the physical rover (Tao et al., 2018).

Mission Rehearsal and Simulation

Digital twins are invaluable for mission rehearsal and simulation, predicting the impact of new inputs on system performance. This capability is crucial in military training and simulation, where the ability to simulate various scenarios can significantly enhance mission readiness and effectiveness. The U.S. Department of Defense utilizes digital twins to simulate battlefield scenarios, allowing for thorough preparation and strategic planning (Lukaszewski, 2020).

Discovery of Emergent Behavior

Continuous monitoring through digital twins helps in identifying emergent behaviors that might not be evident through conventional analysis. This discovery is vital for maintaining system integrity and improving performance. For instance, digital twins in smart cities are used to monitor and analyze urban infrastructure, uncovering patterns and behaviors that inform better urban planning and management (Fuller et al., 2020).

CHALLENGES AND CONSIDERATIONS

Data Security and Privacy

The continuous exchange of data between physical assets and digital twins introduces significant challenges related to data security and privacy. Ensuring the protection of sensitive information from unauthorized access and breaches is crucial, especially in military and defense applications where data integrity and confidentiality are paramount. The implementation of robust cybersecurity measures, including encryption, secure communication protocols, and regular security audits, is essential to safeguard data. According to a report by McKinsey & Company (2021), organizations must prioritize data security to maintain trust and ensure compliance with regulatory standards.

Integration Complexity

Integrating sensors, IoT devices, and digital twins into existing systems can be a complex task, particularly when dealing with legacy infrastructure. Ensuring compatibility and seamless communication between diverse technologies requires meticulous planning and execution. This complexity often involves addressing issues related to different communication protocols, data formats, and interoperability standards. For instance, integrating a digital

twin into an older manufacturing system may require significant upgrades to hardware and software components to facilitate seamless data exchange (Tao et al., 2018).

Data Management

The vast amount of data generated by sensors and IoT devices presents a formidable challenge for data storage, processing, and analysis. Efficient data management strategies are essential to ensure that this data can be handled effectively. This includes implementing scalable storage solutions, such as cloud computing, and leveraging advanced data analytics to derive actionable insights from the collected data. The ability to manage and analyze big data is critical for the successful deployment of digital twins, as highlighted by Grieves and Vickers (2017), who emphasize the need for sophisticated data management systems to support the continuous operation of digital twins.

Cost of Implementation

The initial investment required for the implementation of sensors, IoT devices, and the necessary infrastructure for digital twins can be substantial. Organizations must carefully weigh these costs against the potential benefits to justify the expenditure. Factors to consider include the long-term savings from improved operational efficiency, reduced maintenance costs, and enhanced decision-making capabilities. A study by Deloitte (2020) found that while the upfront costs can be high, the return on investment (ROI) from deploying digital twins can be significant, particularly in industries such as manufacturing, aerospace, and defense.

Technological Evolution and Maintenance

The rapid pace of technological advancements presents both opportunities and challenges for digital twins. Continuous updates and maintenance are necessary to keep digital twin systems current and functional. This requires ongoing investment in technology upgrades and staff training to ensure that the system can adapt to new developments. According to a report by IDC (2021), organizations must plan for the lifecycle management of digital twin technologies, including regular updates to hardware, software, and cybersecurity protocols.

Standardization and Interoperability

The lack of standardized protocols and frameworks for digital twins can hinder their widespread adoption and integration. Developing common standards for data exchange, communication protocols, and interoperability is crucial for the seamless operation of digital twins across different platforms and industries. Efforts by organizations such as the Industrial Internet Consortium (IIC) and the Digital Twin Consortium aim to establish these standards, promoting greater interoperability and collaboration across the digital twin ecosystem (Industrial Internet Consortium, 2019).

Human and Organizational Factors

The successful implementation of digital twins also depends on the human and organizational factors involved. This includes ensuring that personnel are adequately trained to manage and utilize digital twin systems and fostering a culture of innovation and continuous improvement. Resistance to change and a lack of skilled professionals can pose significant barriers to the adoption of digital twins. Investing in education and training programs, as well as promoting a collaborative and forward-thinking organizational culture, is essential to overcoming these challenges (Schleich et al., 2017).

EXAMPLES OF DIGITAL TWINS IN AEC AND TRAINING SIMULATION

AEC Industry: Integration of Building Information Modeling (BIM) and IoT

In the Architecture, Engineering, and Construction (AEC) industry, the integration of Building Information Modeling (BIM) with IoT technologies exemplifies the use of digital twins as a binary source of truth. BIM serves as a centralized database that consolidates input from various disciplines, ensuring all stakeholders are working from the same set of information. This unified approach facilitates real-time updates and adjustments, enhancing collaboration and reducing errors. For example, a structural engineer can make adjustments based on real-time feedback from other disciplines, instantly updating the architectural model to reflect these changes. This iterative process embodies Agile Systems Engineering, where the project evolves through continuous feedback and refinement, ultimately converging to meet all design and engineering requirements (Eastman, Teicholz, Sacks, & Liston, 2011).

Moreover, the use of immersive technologies, such as virtual and augmented reality, further enhances collaboration by providing a visual and interactive representation of the BIM model. These technologies allow stakeholders to conduct virtual walkthroughs, identify potential issues early in the design phase, and make informed decisions, leading to potential cost savings and improved efficiency. A study by McKinsey & Company (2020) found that implementing BIM and IoT technologies can reduce project costs by up to 20% and improve project delivery times by 30%.

Military Training and Simulation: Creating Realistic and Adaptable Training Environments

In military training and simulation, digital twins play a crucial role in creating realistic and adaptable training environments. These digital replicas of physical systems allow for the simulation of various scenarios, providing trainees with a dynamic and interactive training experience. Digital twins enhance training programs through predictive analysis and real-time feedback, enabling the identification of potential issues and the adjustment of training protocols accordingly. For instance, the U.S. Army uses digital twins to simulate battlefield conditions, providing soldiers with immersive and realistic training experiences that improve readiness and adaptability (Defense Innovation Unit, 2019).

The integration of AI and immersive technologies, such as virtual reality (VR) and augmented reality (AR), further tailors training experiences to individual needs. These technologies allow for the customization of training scenarios based on the specific requirements of different missions, ensuring that personnel are prepared for a wide range of operational conditions. Additionally, the continuous feedback loop provided by digital twins ensures that training programs remain up-to-date with the latest tactics and technologies, reducing the gap between training environments and real-world operations (Hoffman, 2020).

Historical Context: Collaborative Design in AEC

Historically, structural engineers would recreate building floorplans from architectural models, often leading to discrepancies and inefficiencies. The advent of BIM has transformed this process by allowing all disciplines to work within a common database. This collaborative approach ensures that design decisions made by one discipline are immediately visible to others, facilitating instant communication and coordination. For example, a structural engineer's modifications that impact architectural features are instantly reflected in the BIM model, allowing the architect to make necessary adjustments in real-time. This method not only enhances collaboration but also aligns with the principles of Agile Systems Engineering, where design and systems engineering efforts evolve together towards a single source of truth (Volk, Stengel, & Schultmann, 2014).

Up-to-Date Training Simulations

In training simulations, maintaining up-to-date and relevant training content is crucial. For instance, a catapult launch trainer at NAS Lakehurst in New Jersey that uses outdated videos of Grumman F-14 fighters would be ineffective and fail to meet current mission requirements. By utilizing digital twins, training systems can be continuously updated to reflect the latest operational scenarios and equipment, ensuring that trainees are prepared for current field conditions. This adaptability is essential in maintaining the relevance and effectiveness of training programs (Williams, 2021).

FUTURE DIRECTIONS

Advances in AI and Machine Learning

The future of digital twins is closely tied to advancements in AI and machine learning. Integrating these technologies with digital twins can significantly enhance predictive capabilities and automate decision-making processes. AI algorithms can analyze vast amounts of data collected by digital twins, identifying patterns and anomalies that may not be apparent through traditional analysis. This allows for more accurate predictions of equipment failures, optimization of operational processes, and more informed strategic decisions. For example, Siemens uses AI-powered digital twins to optimize the performance of their gas turbines, achieving a 15% increase in efficiency and a 20% reduction in maintenance costs (Siemens, 2020).

Expansion to New Industries

Digital twins have demonstrated their value in industries such as manufacturing, aerospace, and healthcare, but their potential applications extend far beyond these sectors. Future developments could see the widespread adoption of

digital twins in agriculture, logistics, retail, and more. In agriculture, digital twins can monitor crop conditions in real-time, optimizing irrigation and fertilizer use to increase yields and reduce waste. In logistics, they can track shipments and predict delivery times with greater accuracy, enhancing supply chain efficiency. A study by MarketsandMarkets (2021) projects that the digital twin market will grow from \$3.8 billion in 2019 to \$35.8 billion by 2025, driven by expanding applications across diverse industries.

Enhanced Interoperability Standards

One of the key challenges to the broader adoption of digital twins is the lack of standardized protocols and frameworks. Developing enhanced interoperability standards is essential to facilitate the integration of digital twins across different systems and industries. Standardized communication protocols, data formats, and integration frameworks will make it easier to implement and manage digital twins, ensuring seamless data exchange and interoperability. Organizations such as the Digital Twin Consortium are working towards establishing these standards, which will help unlock the full potential of digital twin technology by enabling cross-industry collaboration and innovation (Digital Twin Consortium, 2020).

CONCLUSION

Digital twins represent a significant advancement in maintaining a project's single source of truth, bridging the gap between static engineering models and dynamic, real-time data. By integrating sensors and IoT communication devices, digital twins provide a continuously updated and accurate representation of physical assets. This technology enhances decision-making, improves operational efficiency, and offers significant cost savings. For example, General Electric's use of digital twins in monitoring jet engines has resulted in a 10% increase in operational efficiency and a 25% reduction in maintenance costs (GE Reports, 2017).

Despite the challenges, including data security, integration complexity, and data management, the benefits of digital twins make them a powerful tool for various industries. In the AEC sector, the integration of Building Information Modeling (BIM) with IoT technologies has demonstrated substantial cost reductions and efficiency improvements. A study by McKinsey & Company (2020) found that implementing these technologies can reduce project costs by up to 20% and improve project delivery times by 30%. Similarly, in military training and simulation, digital twins create realistic and adaptable training environments, significantly enhancing readiness and adaptability (Defense Innovation Unit, 2019).

Looking forward, the integration of AI and machine learning with digital twins will further enhance predictive capabilities and automate decision-making processes. AI algorithms can analyze vast amounts of data collected by digital twins, identifying patterns and anomalies that may not be apparent through traditional analysis. For instance, Siemens uses AI-powered digital twins to optimize the performance of their gas turbines, achieving a 15% increase in efficiency and a 20% reduction in maintenance costs (Siemens, 2020).

Moreover, the potential applications of digital twins are vast, extending to new industries such as agriculture, logistics, and retail. The digital twin market is projected to grow from \$3.8 billion in 2019 to \$35.8 billion by 2025, driven by expanding applications across diverse sectors (MarketsandMarkets, 2021). Enhanced interoperability standards are crucial for the broader adoption of digital twins, facilitating integration across different systems and industries. Organizations such as the Digital Twin Consortium are working towards establishing these standards, which will unlock the full potential of digital twin technology by enabling cross-industry collaboration and innovation (Digital Twin Consortium, 2020).

In conclusion, digital twins represent the future of a project's single source of truth, evolving beyond static models to incorporate dynamic, real-time data. The integration of AI, machine learning, and standardized protocols will further enhance their capabilities and applications, solidifying their role as an essential component of modern engineering and operations. To fully realize the benefits of digital twins, the industry must drive the development of a middle-layer protocol that standardizes communication between digital twins and their physical counterparts, ensuring data security, reliability, and seamless integration. This call to action is crucial for advancing the technology and achieving a more efficient, cost-effective, and interconnected future.

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