

# A Review of Industrial Digital Twin Technology Research: Progress, Challenges and Future Directions

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## ABSTRACT

With the rapid development of industrial Internet, Internet of Things (IoT), and big data technologies, digital twin technology has emerged as a pivotal tool in enhancing industrial productivity, optimizing resource allocation, and driving the evolution of smart manufacturing systems. This paper provides a comprehensive review of the current state of research on industrial digital twins, exploring their applications across various sectors such as production processes, equipment management, and quality control. The review highlights the technological advances that have enabled the widespread adoption of digital twins, including virtual modeling, real-time data transmission and processing, and data fusion. It also discusses the key challenges faced by industries in implementing digital twins, such as data accuracy and integration, the complexity of virtual model construction, and the need for standardization and cross-platform integration. Additionally, the paper addresses the ongoing development trends in the field, including the increasing integration of digital twins with artificial intelligence, machine learning, and cloud computing. Finally, the paper provides an outlook on the future directions of digital twin research, identifying areas for further innovation and application, and offers recommendations for overcoming current limitations to support wider industrial adoption. By summarizing the progress and challenges, this review aims to provide theoretical insights and practical guidance for advancing industrial digital twin technology.

## KEYWORDS

Industrial Digital Twin; Smart Manufacturing; Virtual Modeling; Data Fusion; Real-time Monitoring.

## 1. INTRODUCTION

In recent years, the rapid development of information technologies has ushered in a new era of industrial transformation. The concept of "digital transformation" is no longer a distant future but a current reality, reshaping how industries operate across the globe. Among the most promising innovations driving this transformation is digital twin technology. A digital twin is a virtual model that mirrors a physical object, system, or process, with real-time data synchronization allowing it to reflect the current status and behavior of its real-world counterpart. By providing a precise digital replica, digital twin technology enables advanced monitoring, predictive analysis, and real-time decision-making. As industries seek ways to improve efficiency, reduce costs, and optimize resource use, digital twins are rapidly becoming a cornerstone of smart manufacturing and the broader Industrial Internet of Things (IIoT).

Digital twin technology has its roots in the aerospace industry, where NASA first applied it to monitor spacecraft and optimize performance during missions [1]. Today, the technology has evolved far beyond its original applications and is now deployed in sectors ranging from manufacturing and automotive to healthcare and energy. The key to its growing success lies in the ability of digital twins

to bridge the gap between physical systems and their virtual counterparts, creating a dynamic, real-time model of how physical assets behave and interact within larger systems. This has profound implications not only for improving operational performance but also for enabling more efficient and sustainable practices across various industries.

The core idea behind digital twins is the creation of a virtual representation that remains synchronized with its physical twin, capturing real-time data through sensors and other data-gathering devices. This synchronization allows for continuous monitoring, fault detection, predictive maintenance, and performance optimization, offering companies unprecedented visibility into their operations. By integrating data from multiple sources—such as machinery, sensors, and enterprise systems—digital twins facilitate data-driven decision-making, helping industries achieve higher productivity, lower costs, and better resource allocation.

One of the primary industries benefiting from digital twin technology is manufacturing. In traditional manufacturing environments, production processes often rely on complex systems and multiple machines that work in isolation. Information about the operational state of these systems is often siloed, resulting in inefficient communication, delayed decisions, and costly downtimes. Digital twins address these issues by enabling real-time data collection and integration across the entire production process. This interconnectedness allows for predictive insights into machinery performance, better coordination across departments, and faster identification of inefficiencies or potential failures.

Furthermore, smart cities and infrastructure management are also becoming key areas of focus for digital twin applications. Urban environments, which are complex systems of roads, utilities, and buildings, can be modeled using digital twins to monitor traffic patterns, air quality, energy consumption, and more. By offering a virtual replica of a city, digital twins enable urban planners to make data-informed decisions, optimize traffic flows, improve energy efficiency, and reduce environmental impact.

However, despite its vast potential, the implementation of digital twin technology is not without challenges. One major issue is the data—creating and maintaining an accurate digital twin requires high-quality, real-time data from diverse sources. The volume and variety of data involved often pose significant challenges for companies looking to implement digital twins effectively [2]. Data must be continually updated, and its integration must be seamless across different systems and platforms to ensure that the virtual model remains synchronized with the real-world counterpart.

Moreover, modeling itself is another challenge. While digital twin models can range from simple virtual representations of machines to complex simulations of entire systems, building high-fidelity models for industrial applications often requires advanced simulation techniques, computational power, and expertise. As industries scale up their use of digital twins, the demand for more sophisticated, high-precision models will continue to grow, further complicating the modeling process.

Additionally, interoperability and standardization across different industries and platforms remain a major hurdle. Each industry has unique requirements for data collection, processing, and analysis, making it difficult to establish universal standards for digital twins. As such, there is a pressing need for the development of common frameworks and protocols that can ensure compatibility and data sharing between systems. Achieving cross-industry and cross-platform integration is key to unlocking the full potential of digital twin technology.

Despite these challenges, the adoption of digital twin technology is accelerating, particularly in smart manufacturing and predictive maintenance. Manufacturers have started integrating digital twins with advanced analytics and AI-driven algorithms to automate decision-making and improve operational efficiency. For instance, by using predictive maintenance models, companies can forecast when machines are likely to fail, minimizing downtime and extending the lifespan of equipment. Furthermore, digital twins allow companies to test various scenarios in a virtual environment,

providing valuable insights before making physical changes to production processes or machinery. This ability to simulate real-world behavior before actual implementation helps to optimize production schedules and reduce costs.

The potential of digital twins is immense. The technology's ability to provide a comprehensive, real-time view of physical systems is transforming how industries manage resources, optimize performance, and reduce costs. As digital twins continue to evolve, they will play an increasingly central role in industry 4.0, driving greater automation, efficiency, and innovation.

Looking ahead, the integration of digital twin technology with artificial intelligence, machine learning, 5G networks, and edge computing will unlock new opportunities. AI and machine learning algorithms can enhance the predictive capabilities of digital twins by allowing them to learn from historical data and improve their accuracy over time. Real-time data processing through 5G and edge computing will enable faster decision-making and the implementation of digital twins in more time-sensitive applications, such as autonomous vehicles or supply chain management.

In conclusion, digital twin technology is a powerful enabler of digital transformation across industries. Its ability to model, monitor, and optimize physical systems in real time provides businesses with unprecedented insights that can improve efficiency, reduce costs, and support more sustainable practices. As the technology continues to mature and integrate with other advanced technologies, digital twins will increasingly become an essential tool in driving the future of manufacturing, urban planning, and beyond. The next phase of development will focus on overcoming existing challenges such as data integration, modeling complexity, and standardization, while expanding the use of digital twins to new sectors and applications.

## **2. CURRENT STATE ANALYSIS**

### **2.1. Foreign Research Status**

Since the concept of digital twins was first introduced by Michael Grieves in 2003 at the University of Michigan [3], this technology has made significant progress and is now used in a variety of industries including aerospace, automotive, and industrial manufacturing [4]. Over time, digital twin technology has evolved from a tool primarily focused on product lifecycle management (PLM) to one that encompasses the entire production process, integrating virtual models with physical systems to enhance operational efficiency and decision-making.

#### **2.1.1. Aerospace and Military Applications**

Digital twin technology was initially deployed in high-stakes industries like aerospace and defense. In 2010, NASA was one of the first organizations to adopt digital twin technology, incorporating it into the health monitoring and management of spacecraft [5]. The agency developed models that replicated the spacecraft's physical condition, which allowed for remote diagnostics and decision-making in real-time, reducing downtime and enhancing safety.

Following NASA's early work, other organizations like the U.S. Air Force Research Laboratory (AFRL) advanced the concept further. They established the digital twin standards for future aircraft, which integrated real-time data and simulation models to predict aircraft performance, remaining service life, and mission readiness. Lockheed Martin, a key player in aerospace manufacturing, also successfully integrated digital twin technology into the production of the F-35 fighter jet, improving manufacturing efficiency and enhancing the quality of the final product. These early applications proved the feasibility of digital twins and paved the way for their expansion into other fields.

#### **2.1.2. Industrial Internet and Manufacturing**

The application of digital twins has extended significantly into the realm of industrial manufacturing, particularly with the advent of the Industrial Internet of Things (IIoT). General Electric (GE), a

pioneer in industrial Internet platforms, utilizes digital twin technology within its Predix platform to monitor and maintain equipment such as aircraft engines. Predix allows real-time condition monitoring, fault detection, and predictive maintenance, optimizing performance and minimizing the risk of costly downtime [6].

In Germany, Siemens has played a crucial role in integrating digital twin technology into smart manufacturing systems [7]. The company developed a comprehensive digital twin framework that includes virtual factories, digital workshops, and production lines. By using these digital models, Siemens has been able to improve factory operations, optimize production efficiency, and reduce waste. This virtual manufacturing ecosystem is an example of how digital twins are facilitating the digital transformation of traditional manufacturing industries, promoting lean manufacturing principles, and reducing operational inefficiencies.

Similarly, Tesla has implemented digital twin technology in the production of electric vehicles, creating a virtual model of each vehicle to monitor performance, improve design, and update vehicle software in real time using sensor data. This integration of digital twins with real-time sensor networks allows Tesla to continuously improve the quality and performance of its products throughout the entire production lifecycle.

Through these diverse applications, digital twin technology has become a cornerstone of advanced manufacturing practices, driving improvements in quality control, product design, equipment performance, and predictive maintenance.

## **2.2. Domestic Research Status**

In recent years, China has made significant strides in digital twin technology, particularly in smart manufacturing. With the introduction of strategic initiatives like “Made in China 2025” and the “14th Five-Year Plan,” the country has committed to advancing industrial digitalization, integrating advanced technologies like digital twins into the fabric of its manufacturing industry [8]. This has led to substantial progress in both research and practical applications.

### **2.2.1. Policy Support and Strategic Deployment**

The Chinese government has placed considerable emphasis on the development of digital twin technology, particularly in areas like smart manufacturing, industrial automation, and green manufacturing [9]. According to the “14th Five-Year Plan for the Deep Integration of Informatization and Industrialization” and the “14th Five-Year Plan for Smart Manufacturing Development,” the government has laid out clear goals to promote digital twin systems that cover the entire industrial lifecycle. This includes the development and revision of standards for digital twins and other related technologies. These strategic plans offer strong policy backing and financial support for the growth of digital twin research and its industrial implementation.

China's policy initiatives also aim to foster the development of an intelligent manufacturing ecosystem where digital twin technology plays a crucial role in enhancing automation, optimizing resource usage, and improving production efficiency. Several government-backed programs encourage the adoption of digital twins across industries, such as automotive, textiles, and heavy industries, to boost China's competitive edge in global manufacturing.

### **2.2.2. Industrial Applications**

The application of digital twins in China has been growing rapidly, particularly in the manufacturing and industrial sectors [10]. Notable success stories include Tencent’s collaboration with Ruitai Magang to create a “transparent factory,” where digital twin technology was implemented to optimize production lines, reduce fault rates, and achieve energy-saving goals. By integrating real-time monitoring and predictive maintenance, Ruitai Magang was able to enhance operational efficiency and ensure smoother production cycles.

Wenzhou Fengyong Intelligent Technology Co. has also leveraged digital twin technology in creating smart factories for discrete manufacturing industries. The integration of digital twins with automation technologies has allowed companies to implement flexible production systems, improving their ability to adapt to variable demand and minimize production errors. These examples highlight the successful adaptation of digital twin technology in enhancing the flexibility, efficiency, and sustainability of Chinese manufacturing operations.

Furthermore, many Chinese research institutions, including the Chinese Academy of Sciences, are actively advancing digital twin research, with a focus on areas like real-time data processing, cloud computing, and system integration. Additionally, leading tech companies like Huawei and Alibaba are developing digital twin solutions for a variety of applications, including smart cities, industrial automation, and logistics management.

## **2.3. Gaps and Challenges**

While China has made significant progress in adopting digital twin technology, several challenges remain, particularly when compared to advanced implementations in the U.S. and Europe. These challenges include technological bottlenecks, data handling capabilities, and standardization issue.

### **2.3.1. Technological Bottlenecks and Standardization**

Despite the progress made, China still lags behind in some aspects of digital twin technology, particularly in the areas of high-precision virtual modeling and real-time data synchronization. Many domestic industries struggle to achieve the level of accuracy and performance seen in international counterparts. The complexity of integrating digital twin systems across different platforms and industries also presents significant challenges. Additionally, the lack of standardized protocols and frameworks for digital twins complicates interoperability between systems, limiting the full potential of digital twin applications across industries..

### **2.3.2. Data Collection and Processing Capabilities**

Digital twins rely heavily on real-time data, yet many Chinese enterprises face difficulties in collecting and processing large volumes of data from diverse sources. In large-scale production and custom manufacturing environments, gathering and analyzing vast amounts of heterogeneous data in real time remains a critical issue. The inability to efficiently manage this data not only impacts the quality of digital twin models but also limits their ability to provide timely and actionable insights.

As data collection systems become more advanced and the Internet of Things (IoT) becomes more widespread, addressing these data-related challenges will be crucial in ensuring that digital twins can operate at their full potential.

### **2.3.3. Collaboration and Innovation in Applications**

Although digital twin applications have been explored in China, there is still considerable room for improvement in terms of cross-domain collaboration [11]. In particular, the integration of digital twin systems across diverse industries such as automotive, aerospace, and energy has not yet reached the level of seamless interaction seen in countries like the United States and Germany. Many Chinese companies are still in the early stages of digital twin adoption, and they face difficulties in applying the technology to more complex manufacturing environments where real-time monitoring and optimization are critical

Furthermore, the innovation around the applications of digital twins is somewhat limited. While digital twins are used primarily for equipment monitoring and production optimization, their full potential for lifecycle management, product design, and integrated production management has not been fully realized in China..

#### 2.3.4. Talent and Research Investment

The rapid development of digital twin technology requires significant investment in talent and research. While China has a robust engineering talent pool, there is still a shortage of interdisciplinary professionals who can bridge the gap between different fields such as data analytics, artificial intelligence (AI), and system integration. The domestic research landscape also lacks sufficient funding for cutting-edge, high-risk research, which hampers the ability to develop next-generation digital twin solutions.

At present, most digital twin research in China is driven by engineers and traditional industrial experts, rather than interdisciplinary researchers who can explore new applications and innovations in digital twin technology. More investment in research and talent development will be essential to enable China to catch up with global leaders in this field.

### 3. TREND PREDICTION

As information technology continues to evolve and industrial demands become more sophisticated, the application fields of digital twin technology will keep expanding. This expansion will span across smart manufacturing, green manufacturing, the industrial Internet, and beyond. The future development of digital twin technology will present the following key trends:

1) **Multi-Physics Modeling and Realization:** One of the major trends in digital twin technology will be the increasing reliance on multi-physics modeling and realization. While digital twins today primarily focus on creating virtual models of physical systems, future models will need to incorporate multiple physical properties and more complex simulations to better reflect the real-world behaviors of systems [12]. Multi-physics modeling refers to the integration of various physical domains such as thermodynamics, fluid dynamics, mechanics, and electromagnetics into a single, cohesive model. For instance, in manufacturing systems, a digital twin might need to simultaneously account for temperature changes, mechanical stresses, electrical properties, and even chemical processes that occur within the equipment. This shift will allow digital twins to become far more realistic, providing a more accurate representation of a product's performance throughout its lifecycle. As industries such as aerospace, automotive, and energy evolve, the accuracy and detail required from digital twins will increase. Achieving this will require more advanced simulation technologies and the ability to integrate real-time data across multiple physical domains. As computational power continues to grow and data integration techniques advance, digital twins will move from being simple representations to comprehensive systems capable of simulating complex, real-world phenomena.

2) **Deepening Full Lifecycle Management:** Another important trend is the deepening of full lifecycle management. Currently, digital twin technology focuses on different stages of product life: design, production, and post-production. However, as industries seek more comprehensive and long-term solutions, digital twins will increasingly be applied to cover the entire lifecycle of a product or system—from design and manufacturing to usage, maintenance, and even recycling. In the near future, digital twins will be increasingly integrated with predictive maintenance systems [13], enabling continuous monitoring of assets throughout their entire operational lifespan. This development will allow businesses to proactively manage equipment and systems, reducing downtime, extending the lifespan of assets, and ensuring optimal performance throughout. For example, in manufacturing, a digital twin could provide insights into when a machine is likely to fail based on accumulated wear, usage patterns, and environmental factors. This predictive capability will lead to a more cost-effective and sustainable approach to operations. Moreover, the shift toward more sustainable and circular production systems will also be supported by digital twins. By tracking products from their creation, through their use and eventual disposal or recycling, digital twins can help manufacturers optimize the use of raw materials and reduce waste, thus supporting a circular economy. This will play a significant role in sectors like automotive manufacturing, where products like electric vehicle batteries are being designed with reuse and recycling in mind.

3) **Fusion and Integration with Emerging Technologies:** The integration of digital twins with other emerging technologies like artificial intelligence (AI), big data, machine learning (ML), edge computing, and blockchain will be a significant trend in the next phase of digital twin development [14]. Currently, many digital twin systems rely heavily on real-time data streams from sensors and IoT devices, but the future will

see these models becoming smarter through the incorporation of advanced analytics, AI, and machine learning. With AI and machine learning, digital twins will evolve from static models to dynamic systems that can continuously learn, adapt, and improve their predictions and optimizations based on historical data and changing conditions. For example, machine learning algorithms could be used to predict failures, suggest design improvements, or optimize manufacturing processes. The ability of digital twins to learn and adapt autonomously will be a game-changer in industries that rely on precision and efficiency. Edge computing, which brings data processing closer to the source of data generation, will also play a crucial role in the future of digital twins. By processing data on-site or in real-time at the edge of the network, digital twins can reduce latency and improve the responsiveness of real-time applications, such as autonomous vehicles or real-time supply chain monitoring. In environments like factories or energy grids, where real-time decision-making is critical, edge computing will enable faster and more efficient operation of digital twin systems. Additionally, integrating blockchain technology with digital twins could enhance the traceability and security of data within the digital twin ecosystem. Blockchain can provide an immutable record of all interactions between the virtual model and the physical system, ensuring the integrity of data and making digital twins particularly useful in industries with high regulatory requirements, such as pharmaceuticals or aerospace.

4) **Increased Use of Virtual and Augmented Reality (VR/AR):** Virtual Reality (VR) and Augmented Reality (AR) are technologies that have already begun to intersect with digital twin systems. In the future, the integration of VR/AR with digital twins will enhance the way users interact with virtual models of physical systems. This trend is particularly relevant in industries such as manufacturing, healthcare, and construction, where VR/AR can help workers visualize and interact with digital models in an immersive way. For example, in manufacturing, workers could use AR goggles to view a digital twin of a machine or assembly line in real-time, allowing them to perform maintenance, troubleshoot issues, or monitor performance without the need to consult a physical manual or remote expert. Similarly, VR could be used to simulate complex assembly processes or to conduct training sessions in a virtual environment, allowing for more effective and cost-efficient learning. As VR/AR technology becomes more accessible and sophisticated, the role of immersive experiences in digital twin applications will increase. This will make it easier for operators, engineers, and even consumers to engage with the digital model of physical systems, improving decision-making and enhancing overall productivity.

5) **Wider Adoption Across Industries:** Finally, as digital twins continue to mature, their adoption will expand to even more industries. While digital twin technology has already made significant inroads in sectors such as manufacturing, aerospace, and automotive, it will increasingly be adopted in sectors like healthcare, energy, logistics, and urban planning. For instance, in healthcare, digital twins of patients (often referred to as "patient twins") are being developed to simulate various medical conditions, helping to personalize treatment plans and predict patient outcomes. Similarly, in urban planning, cities are beginning to build digital twins to model infrastructure, traffic flow, and resource distribution, enabling more efficient and sustainable urban management.

As the technology becomes more standardized and accessible, smaller and medium-sized enterprises (SMEs) will also start to adopt digital twin technology, driving further innovation and democratizing access to these powerful tools.

## **4. CONCLUSION AND OUTLOOK**

Industrial digital twin technology, as an innovative cutting-edge technology, is gradually infiltrating production and management across various industries. By closely combining physical entities with their virtual models, digital twins not only provide real-time equipment monitoring and fault warnings but also help optimize production processes, improve resource utilization, reduce production costs, and enhance product quality. The core advantage of digital twin technology is its ability to achieve intelligent, automated, and refined management of production processes through precise models and data fusion, thus driving smart manufacturing.

Currently, significant progress has been made in digital twin technology both domestically and internationally, especially in aerospace, automotive manufacturing, and energy management. However, compared to foreign countries, challenges still exist in standardization, system integration,

and data processing capabilities in China. Although digital twin technology has made progress in application, there are still technical bottlenecks, talent shortages, and limitations in technological innovation.

To better promote the application of digital twin technology, China should focus on several aspects for further breakthroughs:

- 1) **Strengthening Technological Innovation and Research:** Digital twin technology still faces many technological challenges, especially in high-precision modeling, real-time data processing, and system integration. In the future, China should increase investment in digital twin research, promote algorithm optimization and technological innovation, and improve the precision and efficiency of digital twin systems.
- 2) **Promoting Standardization and Cross-Industry Application:** Since digital twin applications span multiple industries and fields, achieving cross-industry and cross-platform integration depends on the standardization of digital twin technology. In the future, China should strengthen industry collaboration and push for the standardization of digital twin technology to ensure interconnectivity and data sharing across industries.
- 3) **Cultivating Cross-Disciplinary Innovation Talent:** The development and application of digital twin technology require professionals in engineering, data analysis, artificial intelligence, and other fields. Therefore, fostering interdisciplinary and innovative talents is crucial. In the future, China should intensify talent development in digital twin-related fields, promoting collaboration between universities and industries to cultivate professionals who can integrate different technologies.
- 4) **Promoting Industry Chain Collaboration and Integrated Applications:** The widespread application of digital twins requires collaboration across equipment manufacturing, data acquisition, sensor technologies, and cloud computing platforms. China should strengthen collaboration throughout the industry chain, facilitate technology sharing and collaborative innovation among enterprises, and promote the deep integration of digital twins in smart manufacturing, smart logistics, and smart cities.

In summary, digital twins, as a key technology for driving industrial intelligence and digital transformation, have vast application potential and development prospects [15]. With the continuous advancement of technology, digital twins will play an increasingly important role across various industries globally. In the future, digital twins will contribute significantly to enhancing production efficiency, reducing resource waste, and driving green manufacturing, becoming a key technology for upgrading industries and achieving high-quality development.

By promoting technological innovation, strengthening standardization, cultivating talent, and facilitating industry chain collaboration, digital twin technology will make significant strides in the industrial digital transformation process, helping the global manufacturing industry achieve intelligence, sustainability, and green development.

## **CONFLICTS OF INTEREST**

The authors declare that they have no conflict of interest.

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