Theoretical foundations and advanced applications with digital twins in various contexts

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ABSTRACT

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| Digital twin technology has become a key support for smart manufacturing and smart city construction by constructing virtual mapping models of physical entities to achieve data-driven real-time interaction and optimization. This paper systematically describes the core concept of digital twin and its basic principles, while supplementing it with the application of digital twin technology in various industries in China to enable readers to better understand digital twin technology.  In the analysis of the development history at home and abroad, this paper combs through the evolution path of digital twin from proof of concept to cross-domain application: foreign countries have experienced the early exploration of aerospace and military fields, the deep integration of industrial software, and eventually expanded to medical and transportation and other areas of people's livelihoods; domestically, through the policy-driven and technological integration, digital twins have been used in urban planning (e.g., Xiong ‘an New Area BIM area-wide modelling), industrial manufacturing (virtual optimization of workshop layout), and public safety (Beijing gas pipeline network). The article further analyzes the three key technologies of digital twin - high-precision modelling, multi-physical field simulation and Internet of Things (IOT) data fusion, and the study reveals that with the strategic deployment of the national ‘14th Five-Year Plan’ for the construction of digital twin cities, the technology will be used in the transformation of industry 4.0 and the construction of a smart society. The study reveals that with the strategic deployment of digital twin city construction in the national ‘14th Five-Year Plan’, the technology will unleash greater potential in the transformation of industry 4.0 and the construction of smart society, and promote the digital reconstruction and sustainable development of the whole industrial chain. |

*Keywords: Advanced Manufacturing; Digital Twins ; Status of Development;* *Key Technologie*

1 Digital twin and its basic principles

Digital Twin is a cutting-edge technology concept that aims to build digital models in virtual space that are highly similar to physical entities by fusing physical models, sensor data updates, and operational history information. [1]In short, Digital Twin technology can achieve two-way mapping between physical objects and digital models, and through the deep integration and feedback mechanism of data and information, create digital models that accurately reflect the characteristics of physical objects, thus providing powerful support for the design optimization and operation management of physical entities.[2, 3]

The realization process of digital twin can be summarized in three core stages. Firstly, various types of sensors, such as temperature sensors, pressure sensors and displacement sensors, are deployed on the physical entity to collect real-time state data of the physical entity. The data collected by these sensors are transmitted to the data processing centre via a network, where the network communication protocols may include Zigbee, Wi-Fi, etc. in the industrial IOT. At the data processing center, pre-processing operations such as cleaning and conversion are performed on the received data to ensure the accuracy and availability of the data.

Second, based on the pre-processed data, the digital twin model is constructed and dynamically updated by combining mathematical models, physical laws (e.g., Newton's laws of mechanics for modelling mechanical systems and heat conduction equations for modelling thermal systems) and computer algorithms. The model can accurately reflect the multi-dimensional characteristics of physical entities such as geometry, physical properties and behavioral patterns.

Finally, the digital twin model can be simulated and analyzed in a virtual environment. Taking the digital twin model of an automobile engine as an example[4], the performance of the engine under different working conditions can be simulated in the virtual environment. By adjusting the parameters of the virtual model (such as air intake, fuel injection, etc.), the impact on the engine output power, fuel consumption and other performance indicators can be analyzed, so as to achieve the optimization of the design and operation of the physical entity, and to provide a scientific basis and decision support for the actual engineering applications.[5]

2 The origin of the digital twin

The origins of digital twin technology can be traced back to NASA's Apollo programmed in the 1960s. To ensure the safety and success of space missions, NASA needed a technology that could accurately simulate space vehicles. At the time, the cost of physical testing and validation was enormous due to the complexity and high risk of space missions. So engineers began to build digital models of vehicles, using computers to simulate the behavior of the vehicle in a variety of space environments, including orbital calculations, flight attitude control, thermal management and many other aspects. These early digital models can be seen as the prototype of the digital twin.

The concept of digital twins began in 2002 when Michael Griffiths, an American doctor, proposed the use of computers to create a model identical to a real existing object. The concept was not developed until 2010, when NASA used the early technology of digital twins to significantly reduce the national investment in research in the space flight industry. A good example of early digital twin technology since then is the development and design of the Boeing 777.[6]



**Fig. 1.** Boeing 777 3D model

During the development of the Boeing 777, no paper design models were used, and all parts on the aircraft were modelled using digital twin technology to create and then test the models. According to reports, this technology enabled Boeing to reduce the workload by more than half compared to normal and the development cycle was reduced by 40 per cent compared to the previous total time taken. As computer technology, information technology, and modelling and simulation techniques continued to evolve, the concept of digital twins gradually expanded from aerospace to other industries. the late 20th and early 21st centuries saw a strong interest in digital twins in the manufacturing industry. Enterprises hope to improve product quality and optimize production processes by constructing digital twin models of products and production systems. For example, digital twins are used for virtual product design and production process monitoring in industries such as automotive manufacturing and mechanical engineering.

Meanwhile, the rise of the Internet of Things (IOT) technology has also provided digital twins with stronger data support. IOT enables a large number of physical devices to be connected to the Internet, allowing real-time collection and transmission of device status data, which is essential for building more accurate digital twin models. Advances in sensor technology have also led to more accurate and diverse data collection, which is like the ‘blood’ of the digital twin model, allowing the model to more realistically reflect the state of the physical entity. Some academics have analyzed that digital twin technology will become widespread in the world in the next few years, and even in the year or two after that, it will be widely used in more than half of the world's leading factories, with a certain degree of productivity increase that will follow. Both of these real-world examples are good examples of the value that digital twins can bring to scientific and technological research, and it is for this reason that digital twins are developing rapidly, fueled by real-world value.

3 Digital twin domestic and international development history

Digital twin technology is currently in the world is getting the attention of various scientific research institutions, but its development process can be said to be a long as more than ten years of dedication to the process of research.

**3.1 Foreign development history**

(1) conceptual germination stage (1960s - 2003): the prototype of the digital twin can be traced back to the 1960s NASA (NASA) Apollo programmed, when the NASA ground station to use simulators to train astronauts and command and control personnel, and the use of communications data to adjust the simulator environment parameters to simulate the damage to the spacecraft in the Apollo 13 rescue mission. In 2003, Professor Michael Graves of the University of Michigan proposed the concept of ‘virtual digital representation equivalent to physical products’, which can be seen as the enlightenment of the product digital twin.

(2) Conceptual clarification and preliminary application stage (2003-2014): In 2009, the U.S. Air Force Laboratory put forward the concept of ‘airframe digital twin’, applying the concept of digital twin to the aerospace manufacturing field. 2010, NASA formally used the ‘digital twin’ in the technology roadmap. In 2010, NASA formally used the name ‘digital twin’ in the technology roadmap and described the concept and function of spacecraft digital twin. 2011, Professor Michael Graves formally defined the concept of digital twin in his book. 2013, the U.S. Air Force Research Laboratory initiated a project to verify the feasibility of the digital twin concept.

(3) Rapid development stage (2014 - 2017): from 2014, industrial products and equipment become smarter, digital twin covers the entire product lifecycle, and the form and concept are constantly enriched. Siemens, Dassault, PTC, ESI, ANSYS and other well-known industrial software companies, all use the ‘Digital Twin’ terminology in their marketing campaigns, and one after another, they have done a lot of in-depth research and expansion of technical construction and conceptual connotations. [7]In 2017, Digital Twin technology was listed as one of the top ten strategic technological trends by Goldner Technology Consulting. one of the ten strategic technology trends, while Siemens, Boeing, General Motors and other companies have launched relevant projects to develop digital twin models.

(4) Widely used stage (after 2017): after 2017, digital twin technology goes to the deep water of industrial application, expanding comprehensively from aerospace and industrial manufacturing to various industrial fields such as transport and medical care. In the manufacturing industry, the loss of mechanical equipment can be predicted and maintenance plans can be formulated accordingly; in the medical field, the function of human organs can be simulated to promote accurate diagnosis of the condition of doctors and promote the development of personalized medicine; in the transportation industry, the flow of people and vehicles can be simulated for the development of the traffic system, which can provide a reference basis for the development of urban traffic planning.

3.2 Domestic Development History

(1) Technology introduction and single-point attempt stage (around 2010 - 2016): In 2010, NASA defined the example of future aircraft digital twin, influenced by the foreign market, digital twin technology gradually entered the domestic market, and domestic enterprises began to carry out a single-point attempt of the technology in the aerospace and military industry, manufacturing industry, construction, medical care and other fields. At that time, GIS and three-dimensional visualization enterprises were developing rapidly, and digital twin support technologies such as BIM, CAD/CAE, and Internet of Things were also gradually maturing, but they were in a state of mutual fragmentation, and the number of enterprises grew slowly.

(2) Exploration and application stage (2017 - 2018): in 2017, the China Academy of Information and Communication Research put forward the innovative concept of ‘promoting the construction of new smart cities with digital twin cities’, which caused a strong reaction in the industry, and the digital twin technology began to explore the application of digital twin technology in the fields of water conservancy, transport, energy and other fields. Although the market has not yet opened, the number of small and medium-sized enterprises such as visual rendering and twin modelling has begun to grow gradually.

(3) Rapid growth stage (2019 - 2024): As the value of digital twins emerges, ‘exploring digital twin cities’ is included in the 14th Five-Year Plan, and the Ministry of Housing and Construction, the Ministry of Natural Resources, the Ministry of Water Resources and other departments have issued relevant policies to promote the in-depth application of digital twin technology in the field of urban, water conservancy, energy, military, intelligent manufacturing and other fields. [8]The TOG (To Government) and TOB (To Business) markets are growing steadily, and various technologies such as AR/VR and AI are fully penetrating,[9, 10] smart terminals are achieving technological breakthroughs, and digital twin tooling and platforms are developing rapidly and the development threshold is being lowered. Huawei, Ali, Tencent and other head enterprises actively layout, the Internet Society of China Digital Twin Technology Application Working Committee and other alliances have been established to promote the integration of enterprise ecosystems, and the market standard is gradually unified. Since 2019, as shown in Fig. 2.,the number of winning projects related to digital twins in China's government sector has been growing rapidly year by year, reaching 296 in 2023 and 422 in 2024 as of 17 December, continuing the upward trend.[11]

**Fig. 2.** Number of digital twin-related winning events in China,2019-2024

(4) Mature and stable stage (2025-2030): It is expected to enter the mature stage of the industry around 2030, the demand side of the stage is absolutely dominant, TOG, TOB, TOC (To Consumer) presents a multi-flowering situation, and the application technology for complex scenarios is mature. The data and standards of different industries are integrated, the market is standardised and the market pattern is solid, but emerging companies can still rely on technological innovation to enter the market.[2] As shown in Fig. 3.,Fortune Business Insights expects the global data twin market size to grow at a CAGR of 39.8% from 2024-2032. With reference to this growth rate it is expected that by 2030, China's digital twin solutions market size will reach $26.1 billion.[11]

**Fig. 3.** China Digital Twin Solution Market Size Forecast,2025-2030

4 Key Technologies in Digital Twin Architecture

The realization of the digital twin architecture relies on the synergy of a number of key technologies that together form the core support of the digital twin. The following is a detailed description of the key technologies in the digital twin architecture.[12]

4.1 Modelling

Modelling is the core technology of the digital twin system, which provides the basic framework for the construction of the digital twin and its upper layer operations.[13] Modelling not only covers the 3D digitization of the geometric structure and appearance of physical entities, but also involves the full digital representation of multi-dimensional information such as the operating mechanism of physical entities, internal and external interfaces, software and control algorithms. Digital twin modelling has significant domain-specificity, i.e., the digital twin models of different physical entities differ significantly due to their domains and functional characteristics. Currently, digital twin modelling in different domains is mainly implemented with the help of various professional software. For example, CAD and MATLAB are mainly used for basic modelling, Revit focuses on Building Information Model (BIM) construction, while CATIA focuses on high-level Product Lifecycle Management (PLM).

4.2 Simulation

Simulation is a key method for verifying the correctness and validity of a digital twin model and goes hand in hand with modelling techniques. [14]Modelling is a digital abstraction of the characteristics and behaviour of a physical entity, whereas simulation simulates the operating state of a physical entity through software technology to verify that the model's understanding of the physical entity is accurate. Under the premise of accurate modelling and complete sensory data, simulation can more accurately reflect the state changes of physical entities within a certain time range. Simulation technology originated in the industrial field, with the advancement of industry 4.0 and intelligent manufacturing and other emerging industrial revolution, simulation software gradually and traditional manufacturing technology, emerging technologies, in-depth integration, and in the R & D design, manufacturing, testing and operation and maintenance play an important role.

4.3 Internet of Things

The Internet of Things (IOT) is a key technology for carrying data flow in the digital twin system, providing a basic connection for data interaction between digital twins and physical entities.[15] Through various types of information sensing technologies and devices, IOT is able to collect multi-dimensional data such as location, sound, light, electricity, heat and other data of monitored objects in real time, and transmit them to data processing centers through the network. IOT realizes the ubiquitous connection between things and objects, and between things and people, and completes the intelligent identification, sensing and control of monitoring objects. In the digital twin system, IOT senses the necessary operational data by deploying sensors in the key parts of physical entities and transmits the data to the digital twin with the help of short-range wireless communication technologies or long-distance communication technologies (e.g., the Internet, mobile communication networks, satellite communication networks, etc.) to realize the real-time data interaction.

In summary, modelling, simulation and IOT technologies are the three key technologies in the digital twin architecture. They collaborate with each other to support the construction, validation and operation of the digital twin, laying a solid foundation for the wide application of digital twin technology in various fields.

5 Recent Progress of Digital Twin in China

5.1Digital twin applications in industry

For industry, the workshop has a large number of large equipment, including electrical equipment, CNC machining centers, CNC lathes, cranes and transport vehicles, in accordance with traditional design methods, to make the highest efficiency of the production plant, the most reasonable and safe placement of equipment, the workshop design needs to be from the design → trial → evaluation → manufacturing repeated cycles, the need for repeated manufacturing and experimenting with physical prototypes, but due to the equipment back and forth is extremely inconvenient, from the trial stage will need to invest a lot of personnel and equipment, and then to the later manufacturing stage also need to invest in raw materials, in this way, not only trial and error time will be greatly extended, but also to the later manufacturing stage will also be required to put raw materials. Convenient, from the trial stage will need to invest in a large number of personnel and equipment, and then to the back of the manufacturing stage also need to invest in raw materials, in this way, not only the trial and error time will be greatly extended, but also makes the cost greatly increased, efficiency is reduced, and the risk of the work process will increase and most cases cannot be done to test all the cases, so the design of the workshop cannot be made to show the best results.

From the digital twin, the design -processing - assembly -evaluation stage of the production workshop can be carried out in a virtual environment, that is, we use computer software to design a virtual model, including the size of the equipment and the size of the space can be restored one to one, in the virtual model to repeat the design - processing - assembly - evaluation, in this way you can get the optimal situation in the virtual model, only the data obtained from this process can be transmitted to the physical model. [16]Data transmission to the physical model can be, so only need to invest in the actual manufacturing stage of raw materials, personnel, plant, equipment, etc., not only largely improve the efficiency of the time savings, greatly reducing the cost, the risk is also reduced, when the market fluctuations, but also to the market demand for rapid response. As shown in Fig.4, in the new energy vehicle manufacturing workshop, with the help of intelligent equipment, the introduction of robots, Internet of Things and other technologies to achieve intelligent upgrading of the production line, to improve the efficiency of the production capacity, compression of production expenses, and to promote the refinement of production.

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| **Fig. 4.** GAC New Energy Intelligent Eco-Factory |

5.2Application of Digital Twin Technology in Gas Industry

As we all know, gas in the city has a very high usage rate, most of the urban families are connected to the natural gas, however, natural gas is still an extremely dangerous gas, once the natural gas leakage occurs, the light is to make people respiratory damage, the heavy is to cause urban fires, and in the air in the confined space there is a great risk of explosion. For the traditional gas piping system, the gas pipeline can only be manually inspected, and manual inspection will appear a lot of uncertainty, which will lead to a lot of potential hazards can not be detected in time. In order to reduce the occurrence of similar special accidents, Beijing's gas station is the first in the country to use digital twin technology to ensure safe gas delivery. The digital twin technology helps the gas station in two main ways, one is to ensure the normal operation of the whole system, and the other is to be able to monitor the safety of the gas station in real time in order to prevent explosions from occurring. The system allows staff to see the amount of gas currently stored, as well as the current valve openings of each transport pipeline, and the flow rate and pressure of the gas in the pipeline. Also important is the detection of any leaks in the pipeline.[17]

The visual surveillance system has three dimensions, namely time, space and elements, from which the system comprehensively monitors the entire gas plant. In the previous simulation experiment of the pipeline network, it was found that in the pipeline network, there are many slits, these slits can not be entered by human beings, only some small animals can get in, and even some of them are so small that they can not be seen with the naked eye. The digital twin technology detects the possible fine cracks in the pipeline through visualization. In traditional systems for operating and maintaining gas pipelines, most often leaks are only detected by monitors when a valve actually loosens and a leak occurs. However, the digital twin system monitors and collects pipeline gas pressure and flow data, which can be used to estimate when a valve is loose. For example, installing piezoelectric pressure sensors and ultrasonic flow meters at pipeline joints and valves to monitor pressure anomalies (e.g., sudden drops >15%) or flow irregularities, which may indicate leaks or valve loosening; deploying methane (CH₄) infrared sensors along pipelines to detect trace gas concentrations (as low as 1–5 ppm) in real time. These sensors trigger alerts when thresholds exceed safe limits (e.g., >10% LEL\*).The above sensor data can be transmitted to PC via TCP or Bluetooth communication protocol. And then sends maintenance personnel to repair the pipeline in time to eliminate hidden problems and reduce the frequency of emergencies. This 3D visualization and monitoring system is revolutionary and significant in improving urban safety.[18]

Using digital twin technology, all equipment, all processes and all operations are recorded and tracked in a digital system. In the aftermath of a gas leak, these records can help investigate the root cause of the accident so that those responsible for the accident can be found, making the accountability system more transparent and scientific. The gas plant in Beijing is only partially using digital twin technology. For the whole industrial system, digital twin technology can really help the whole industry in digital transformation and the introduction of smart manufacturing.

5.3Digital Twin - Smart City

The combination of digital twin technology and cities is now a newly built city, as shown in Fig.5, that is Xiong ‘an New Area.[19] It is the only city that has been designed digitally from the start. All the buildings under construction and urban planning in Xiong ‘an New Area have been modelled in BIM. If a water and gas network is to be built in a certain area of Xiong ‘an New Area, it can be pre-designed in the BIM city model, and then the technology can calculate the feasibility of the scheme and the required capital investment.

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| **Fig. 5.** Staff are conducting operational demonstrations at the Xiong ‘an Urban Computing Centre |

Digital twin technology is no longer something that can only be seen in sci-fi films; it has been brought to life through the efforts of scientists. For example, digital twin technology can track vehicles in real time, and this technology is applied to medical aid to achieve the tracking of ambulances, ambulances can be encountered in the road information can be analyzed, so as to get the fastest route, in a timely manner to achieve the aid of the injured patients, saving time on the road. This is not only the application of digital twin technology in healthcare, but also its application in urban transport. In addition, digital twin technology can achieve real-time monitoring of the city's power grid, through the digital twin visualization platform to display the city's electricity consumption, including real-time voltage, power and so on. One of the most important things is to notify the maintenance personnel to repair the circuit faults in time when they are monitored. Cities that use digital twins to connect and integrate systems and services to improve resource efficiency, optimize management and services, and improve the quality of life of citizens are known as smart cities.

Analyzed from a scientific perspective, digital twin technology does not solve all problems. The application of digital twin technology needs to be adapted to different problems, scenarios and needs.

6 conclusion

Currently, the main application scenarios of China's digital twin solution market are focused on the design and operation management of cities, parks and buildings, water conservancy and water services, etc. Along with the continuous innovation of science and technology and the continuous growth of customer demand, the application of its field will be deepened on the basis of further expanding to a variety of scenarios, such as healthcare, education and other scenarios, while at the same time, the application of AI training and validation and user interaction and experience will also be further deepened to meet the diversified needs of customers. At the same time, the application of AI training and validation, as well as user interaction and experience, will also be further deepened to meet the diversified needs of customers. In addition, leading digital twin solution providers are expected to take the lead in focusing on the construction of the digital twin ecosystem, or will establish a unified industry standard through cooperation with various partners, play an important role in the construction of the digital twin ecosystem, and then build a complete digital twin ecosystem to promote the healthy development of the digital twin solution market. It is worth mentioning that digital twin solutions will be further integrated with generative artificial intelligence, which will not only accelerate the construction of digital twins, but also enable people to interact with the digital twin world in the form of natural language.

Disclaimer (Artificial intelligence)

Option 1:

Author(s) hereby declare that NO generative AI technologies such as Large Language Models (ChatGPT, COPILOT, etc.) and text-to-image generators have been used during the writing or editing of this manuscript.

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