Original Article

THE DIGITAL TWIN REVOLUTION: DRIVING VERSATILITY AND INNOVATION ACROSS INDUSTRIES

Ming Yue Zhang and Jun Feng Wang

Xi'an Research Inst. of Hi-Tech, Xi’an, China

Abstract: Digital twin technology has garnered increasing recognition and prominence. Notably, leading nations have embraced digital twins as a pivotal innovation, tailoring their adoption strategies to suit various domains. In the United States, digital twins have assumed a central role, with a particular focus on military applications and large-scale equipment. The United Kingdom, in its pursuit of digital excellence, has established a dedicated digital construction center, coupled with ambitious plans to establish a national digital twin infrastructure. Similarly, China, in its comprehensive "14th Five-Year Plan" unveiled in 2020, incorporated digital twins as a cornerstone, positioning them as a vital component of the nation's digital transformation.

Digital twin technology, regarded as a paramount tool for enhancing production efficiency, offers a multitude of advantages, especially in the realms of product design, experimental data collection, analysis of experimental outcomes, and predictive capabilities. It is within this landscape that the imperative of researching key digital twin technologies comes to the fore, as it stands to bolster the widespread application and progression of China's digitalization endeavors. This research not only holds the potential to significantly elevate the industrial and technological landscape within China but also to serve as a testament to the nation's commitment to embracing digital transformation and innovation.

Keywords: Digital Twin Technology, Digitalization, Key Technologies, Product Design, Experimental Data Analysis

Original Article

1. Introduction

With the continuous advancement of intelligence and digitalization in various fields, digital twin technology has received more and more attention. The United States takes digital twins as the main carrier, focusing on military and large-scale equipment and other fields; The UK has set up a digital construction center with plans to build a national twin; In 2020, China also wrote digital twins into the "14th FiveYear Plan", which became an important part of the construction of digital China. As an important technical means to improve production efficiency, digital twin has great advantages in product design, experimental data collection, experimental result analysis and prediction, etc., and the research on key technologies of digital twin to promote its application and development will effectively promote China's digital process.

2. The evolution of digital twins

At the beginning of the twentieth century in the aerospace field, due to high manufacturing costs, complex design, inconvenient flight test data collection and other problems, in the process of product design and development, the concept of "simulation" appeared. Early simulations focused on physical mapping of entities to describe the internal characteristics or environmental conditions of the system. With the rapid development of computer technology, simulation technology has gradually developed into all-digital simulation based on mathematical models. However, there may be a large modeling error or inability to model the physical object in the all-digital simulation, so it is tried to connect the physical object in a certain part of the simulation loop and test it under the conditions that meet the overall system performance, resulting in semi-physical simulation. In the early eighties, "Virtual reality" technology was proposed, which refers to simulating the environment through computers, so that participants can have different sensory experiences and understand the objective world from the virtual environment. Due to the interactivity and realism of virtual reality technology, simulation technology has been greatly developed.

With the continuous maturity of a new generation of information technology and its deep integration with simulation technology, digital twins have emerged. In 2002, Professor Michael Grieves of the University of Michigan introduced two systems, real and virtual, when demonstrating product lifecycle management [1], which laid the foundation for the emergence of digital twins. Subsequently, Professor Grieves proposed the concept of "digital representation of physical products in physical space". In 2010, the term "Digital Twin" was officially proposed in NASA's technical report and defined as "the simulation process of a system or aircraft that integrates multiple physical quantities, multiple scales, and multiple probabilities" [2]. In 2012, NASA and AFRL defined a digital twin for an aircraft as an integrated multiphysics, multiscale, probabilistic simulation model for an aircraft or system that utilizes the best available physical models. Updated sensor data and historical data, etc., to reflect the state of the flight entity corresponding to the model [3]. As an important tool to improve efficiency, digital twin can effectively promote the integration and development of digital economy and real economy.

3. The basic components of a digital twin

According to the different definitions of digital twin, the composition of common digital twin systems is proposed as shown in Figure 1, which is mainly divided into physical layer, transport layer and virtual layer.

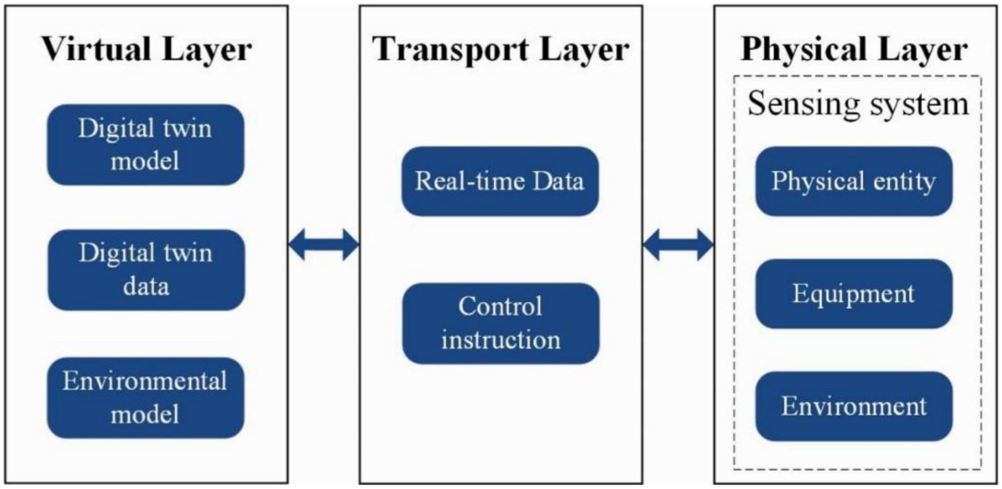

Figure 1: Basic components of the digital twin system

3.1. Physical layer

The physical layer consists primarily of modeled objects and sensing systems in physical space. Modeling objects mainly include entities, various equipment, and operating environments; The sensing system mainly relies on various sensors to perceive and measure the operating state of the modeled object, and at the same time monitor the operating environment and collect data in real time.

The physical layer involves sensing and monitoring technology [4]. In a complete digital twin system, the acquisition of the operating environment and the state data of the digital twin components itself is an important part of the accurate mapping and real-time interaction between all elements, all states and the whole process between physical objects and their digital twin systems. In order to establish a comprehensive IoT perception system and achieve accurate monitoring of the operation situation of physical objects, perception technology needs to rely on more accurate physical measurement technology, and also need to consider the synergy between the perceived data On the surface or inside the system structure, a distributed sensor network is used to determine the spatial location and unique identification of the target to ensure that the equipment is trusted and controllable.

3.2. Transport layer

The transport layer is the bridge that connects the physical layer and the virtual layer. The transport layer transmits the physical operation data obtained by the sensing system to the virtual layer, realizing real-time mapping from the physical layer to the virtual layer [6]; At the same time, the control instructions issued by the virtual layer are transmitted to the physical layer, thereby intervening in the operation of the entity, so that a two-way data flow is formed between the physical layer and the virtual layer.

The creation and control of digital twins are based on data collected in real time, so the system needs to have faster information transmission speed and shorter latency. It can achieve high bandwidth, low latency, support distributed information collection, and have high security and high reliability. With the help of the Internet of Things, blockchain, 5G, quantum communication and other means, the information of the physical layer is transmitted quickly and accurately, and the security and reliability of information need to be guaranteed.

3.3. Virtual layer

Original Article

The virtual layer is the core part of the digital twin system, which is the mapping of the physical layer in the digital space, containing a model as close as possible to the physical object and synchronized with the physical layer. The implementation of digital twin should be driven by data and supported by the model, and the twin model is a true description of the physical layer entity, mapping the physical layer from different dimensions and different aspects, so that the entity state is reflected in the virtual space. The twin data comes from real-time monitoring data and historical data at the physical layer, and is processed to drive the twin model.

The establishment of virtual layer model mainly applies to complex system modeling technology. Digital twin model includes visual model and mathematical model, by studying the structural composition and assembly relationship of physical entities, 3D MAX, SolidWorks and other threedimensional modeling tools can be used to establish the corresponding models of each part, and synthesize after verification to obtain a visual model reflecting the overall appearance, structure, size and other information of the physical object [7]. Since the mathematical model has the characteristics of involving many disciplines, diverse forms, many types, and large quantities, it can be modeled according to the product composition relationship of different subsystems [8]. The connection and motion law of each subsystem of the physical object were analyzed, the corresponding mathematical model was abstracted by means of mechanism modeling or parameter estimation, and simulation tools such as MATLAB/Simulink and Modelica were used to carry out simulation research under different conditions and parameters [9]. In addition, the digital twin system can be more closely related to the actual system by modeling the environment and analyzing the operation status of the digital twin under different conditions [10].

The data received by the virtual layer usually has the characteristics of multiple types, large volume, and high application value. By establishing a corresponding database to store data, and using big data analysis technology, real-time screening and processing of data, fully activating and releasing data value, and exploring the interrelationship between different data to achieve the purpose of diagnosis, prediction and decision-making [11].

4. Current state of digital twin research

At present, digital twins mainly include theory, data, technology, etc., as shown in Figure 2.

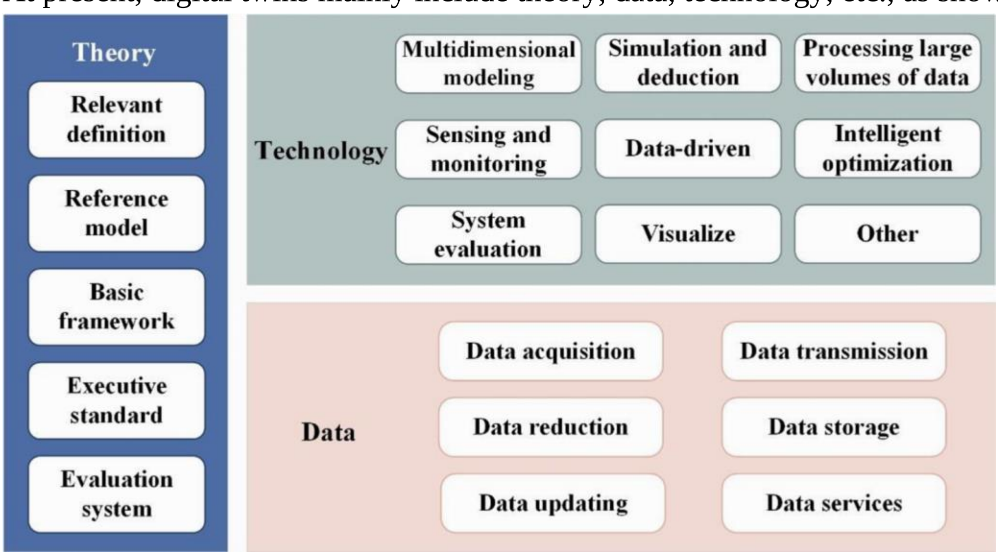

Figure 2: Digital twin research direction

Original Article

In terms of theoretical research, Zhuang Cunbo [12] reviewed the background and concept of digital twin, and introduced the specific connotation of product digital twin. Tao Fei [13] aimed at the establishment of digital twin models, put forward the construction criterion of "four modernizations, four can be used in eight ways" of digital twin models, and carried out research and practice on the construction theory of digital twin workshop models. Jia Shiqi [14] summarized the current development of digital twin technology, summarized its practical results and future application directions, and looked forward to the needs and prospects of digital twin standardization according to the current standardization process. Zhou Junhua [15] analyzed the development process of digital twin technology, pointed out the necessity of applying digital twin technology to weapon system research and practice, and elaborated its concept and composition. Zhang Dawei [16] introduced the application of digital twin technology in equipment life cycle cost management, and pointed out the existing problems and solutions, so as to provide reference for improving the cost efficiency of equipment.

In terms of technical analysis, Liu Yang [6] analyzed the connotation, development context and significance of industrial digital twin, focused on the development direction of industrial digital twin, and put forward several suggestions on its development. Jiang Haifan [17] put forward the concept of digital twin evolution model, and gave the application methods, key technologies and working platforms of the three evolution stages of digital twin. Wang Huixia [18] analyzed the main differences between digital twin technology and simulation technology, refined the key technologies involved in digital twin, and designed the basic framework and application mode of digital twin of launch vehicle control system. Lu Qing [19] discussed the application of digital twin technology in aircraft architecture model design, multi-model architecture integration, model parameter identification and verification, and provided important guidance and technical support for the development of aircraft models and integration tests. Wang Wei [20] analyzed the development and value of digital twin, elaborated the basic characteristics and architecture of digital twin, introduced the key technologies of digital twin on this basis, and finally looked forward to its development prospect. Wu Yan [21] based on digital twin technology, sorted out the concept of digital twin, and discussed digital twin technology in manufacturing.

In terms of data processing, Zhang Suming [3] introduced a rocket test and launch process health management system based on digital twin technology, and carried out design optimization and performance analysis, realizing data analysis, diagnosis collaboration, and fault handling decision support. Fan Rui [22] discussed the application of digital twin technology in data monitoring of intelligent production systems, and discussed how to achieve an efficient combination of production site and production management. In order to solve the problems encountered in the modeling and data acquisition of digital twin workshop, Zhou Shuaichang [23] proposed to use the half-side folding algorithm to make the complex three-dimensional model lightweight, and the improved fuzzy C-means algorithm to improve the accuracy of the data.

5. Typical applications of digital twin technology

5.1. Application of digital twins in industrial manufacturing

Siemens has been closely following the development trend of Industry 4.0 and intelligent manufacturing in Germany, and has been committed to the development and application of digital twin technology in recent years, and has integrated digital twin technology into its digital strategy in the past two years. Siemens uses digital twin technology to digitally design, optimize and validate production processes, modify plant layouts, select production equipment, optimize production processes, and more. The automation system is verified through virtual commissioning technology, enabling it to be commissioned quickly and efficiently on site. Control the physical world in the virtual world, so that the entire workshop can achieve complete integration, so as to achieve efficient and reliable production; Complete production planning, production execution and quality inspection through the manufacturing operation management system; With Mindsphere, all machines and equipment can be monitored in real time to analyze and evaluate actual production. Through analysis and forecasting, we can drive continuous improvement of actual production and products, thereby shortening the product design optimization cycle.

In the application of machine tools, with the help of digital twin technology, enterprises can complete simulation and verification from cutting to maintenance and fault diagnosis in the digital world in advance during the development stage. It can not only save the debugging cost of mature models and extend the life cycle, but also improve the research and development efficiency of new models and reduce trial and error costs. For machine tool end users, digital twin software can be used to test cut and proofing parts without physical prototyping and environmental construction, which can significantly reduce the risk and cost of the machining process. In addition, users can also use the digital twin to train personnel and effectively avoid the risk of machine collisions caused by insufficient personnel experience by simulating the operating environment.

5.2. Application of digital twins in smart cities

Urban digital twin is a technical means of simulating modeling and interactive control of the whole life cycle process of urban physical entities through the digital virtual mapping of the city, with the help of historical data, real-time data, spatial data and algorithm models, etc., which can express and present all elements of physical objects, relationships, activities, etc. in the urban physical space and social space in the digital space, so as to realize the comprehensive perception and precise control of the city and promote the intelligent and digital development of the city [24]。

During the construction of Xiong'an New Area, it proposed to "adhere to the synchronous planning and synchronous construction of digital city and real city", based on the theory of urban complex adaptation system, to build a digital twin of the city, so that the physical city and the digital city can be connected in real time and dynamic feedback, constantly track and identify the changes of the city, so that the "hidden order" of the city can be made visible, so as to better follow the law of urban development [25]. All elements of Xiong'an New Area will be built synchronously in the digital city according to the construction sequence, and updated with the development of the city, and jointly iterated, which is an ecosystem that can evolve. The biggest innovation of digital twin cities lies in the fact that physical cities and digital cities can coexist and grow together, and the virtual and real can be integrated.

The digital twin technology is introduced into the urban flood disaster assessment and early warning system, and realizes the visual integration of the city by establishing an intelligent perception system covering all elements of urban flood disaster, integrating real-time data such as land, water system, and transportation. Use data to realize the dynamic evolution of urban digital twin, drive urban flood disaster scenario simulation analysis and decision-making system, predict the development trend of flood disaster through intelligent algorithms, and automatically issue early warning signals when necessary. The optimized system solves the problems of insufficient perception and dynamic response ability of the original system and poor real-time decision-making, and integrates the functions of urban real-time rain monitoring, flood disaster assessment, disaster prevention simulation and early warning [26].

Digital twin library refers to the use of physical model data and multi-scale simulation technology to comprehensively model the physical entities of the library in the virtual space in order to complete the iterative optimization of all elements, holographic intelligent monitoring, and global intelligent construction. Through the whole process of data mining, operation monitoring and integrated analysis of the physical entities of the library, a new model library that can realize intelligent interaction between virtual and real is built. Its essence is to build the digital expression of the physical entity of the library, realize the extension of the full life cycle service of the library, carry out virtual and real interaction, tracking and analysis and two-way real-time mapping in the virtual information space, and maintain the synchronous update of data transformation, and accurately optimize the physical services, facilities and resources of the library [27].

5.3. Application of digital twins in aerospace

In the design and development, manufacturing and assembly, operation and maintenance of aircraft, the introduction of digital twin technology can effectively shorten the development cycle and significantly reduce costs. By establishing a digital twin of the aircraft, the product testing and verification is completed virtually in the digital space, and defects are found in the design stage and the design is improved in time to avoid waste caused by repeated modifications [28]; In the actual production and manufacturing, the processing status of each part can be tracked in real time, and the existing manufacturing process can be continuously optimized through reasonable allocation of resources to reduce downtime; In the maintenance stage, sensors are used to monitor the status of the aircraft in real time, reflect the real flight conditions, and can realize the dynamic update of the model by combining intelligent algorithms, improve the prediction ability, and can also be used to diagnose the cause of abnormal situations and evaluate after the occurrence of failures [29].

The digital twin satellite is a collection of digital models with the same origin, data sharing, coevolution, real-time interaction, synchronization between heaven and earth, and extended survival of the physical satellite [30]. The digital twin satellite can reflect the formation process, real-time status and behavior of the physical satellite, and predict, evaluate and optimize the physical satellite in the digital space. It is the twin asset and efficiency multiplier of the whole life cycle and the whole value chain of the satellite product. On the basis of realizing the digital twin function of general aircraft, the digital twin satellite can also optimize the shape parameters and deployment process of the satellite solar wing using the entity data; And the use of digital twins for ground thermal test can further save the resources on the satellite [31].

The application of digital twins to rocket testing and launch processes can effectively improve the reliability of rocket launches. In the ground test stage, the ground digital twin system monitors and interprets the data of each instrument during the test, and at the same time identifies the abnormal data to assist the profession Personnel make decisions; During the ignition take-off phase, the engine thrust status diagnosis is carried out, and the takeoff process will be performed only after the digital twin on the arrow and the ground judge that the rocket starts normally; In the rocket flight phase, the digital twin system regularly receives the data transmitted by the telemetry system, carries out real-time simulation prediction, accelerates the determination of alternative solutions when a fault is detected, and issues control instructions to the rocket to minimize the occurrence of failure [32].

6. Summary

With the continuous deepening of the research on digital twins by scholars from all aspects, the technology has made rapid development in recent years. However, in the application process of digital twins, there are still problems such as the lack of unified standards, the lack of interdisciplinary integrated design platform, and the need to further improve the application of core technologies. Therefore, most of the current work is concentrated in the theoretical research and experimental verification stage. Nevertheless, because of the great advantages of digital twins such as virtual-reality mapping, real-time synchronization, symbiosis and evolution, it is of great significance to study its key technologies, break through the difficulties encountered one by one, and promote its application in manufacturing, aerospace, urban management, smart medical and other fields to promote China's digital process.

References

Dong Leiting, Zhou Xuan, Zhao Fubin, et al. Key Modeling and Simulation Technology of Digital Twin of Aircraft Structure [J]. Journal of Aeronautics, 2021, 42(3): 113-141.

Wang Falin, Guo Yaowen, Gong Jianhua, et al. Dynamic Construction Method of Cable Assembly Process Model for Complex Electromechanical Products Based on Digital Twin [J]. Computer Integrated Manufacturing Systems,2022: 1-22.

Zhang Suming, Yue Mengyun. Research on Health Management Technology of Rocket Test and Launch Process Based on Digital Twin [J/OL]. Computer Measurement and Control, 2021, 29(5): 8-14. [4] Meng Songhe, Ye Yumei, Yang Qiang, et al. Digital twin and its application in aerospace[J]. Journal of Aeronautics, 2020, 41(9): 6-17.

Liu Yang, Zhao Xu. Research on industrial digital twin technology system and key technologies [J]. Information and Communication Technology and Policy, 2021, 47(1): 8-13.

Du Yingying, Luo Ying, Peng Yibing, et al. 3D visual monitoring of industrial robots based on digital twin [J]. Computer Integrated Manufacturing Systems,2022: 1-15.

Li Hao, Tao Fei, Wang Haoqi, et al. Integrated Development Framework and Key Technologies for Design and Manufacturing of Complex Products Based on Digital Twin [J/OL]. Computer Integrated Manufacturing Systems, 2019, 25(6): 1320-1336.

Li Kai, Qian Hao, Gong Mengyao, et al. Digital Ship Based on Digital Twin Technology and Its Application Exploration [J/OL]. Ships, 2018, 29(6): 101-108.

Original Article

Ji Guang, Hao Jianguo, Zhang Zhongjie, et al. Twin simulation study of flight process of quadrotor UAV [J]. Computer Engineering and Applications, 2022, 58(12): 66-73.

Laukotka F, Hanna M, Krause D. Digital twins of product families in aviation based on an MBSEassisted approach[J/OL]. Procedia CIRP, 2021, 100: 684-689.

Yin Haijun, Xiao Tangwei, Li Xin. Technical framework for digital twin workshop control of production line [J/OL]. Modern Manufacturing Technology and Equipment, 2021, 57(10): 1-6. [12] Zhuang Cunbo, Liu Jianhua, Xiong Hui, et al. Connotation, architecture and development trend of product digital twin [J/OL]. Computer Integrated Manufacturing Systems, 2017, 23(4): 753-768. [13] Tao Fei, Zhang He, Qi Qinglin, et al. Theory and Application of Digital Twin Model Construction [J/OL]. Computer Integrated Manufacturing Systems, 2021, 27(1): 1-15.

Jia Shiqi, Han Li, Qin Chao, et al. Research on Digital Twin Application and Standardization Requirements [J]. Information Technology and Standardization, 2021(11): 18-22+30.

Zhou Junhua, Xue Junjie, Li Heyu, et al. Some thoughts on digital twin of weapon system [J/OL]. Journal of System Simulation, 2020, 32(4): 539-552.

Zhang Dawei. Application of Digital Twin Technology in Equipment Life Cycle Cost Management [J]. Command Control & Simulation, 2022, 44(3): 122-127.

Jiang Haifan, Ding Guofu, Xiao Tong, et al. Digital twin evolution model and its applications in Intelligent Manufacturing[J]. Journal of Southwest Jiaotong University, 2022, 57(6): 1386-1394.

Wang Huixia. Research on digital twin technology and its application in space control[C/OL]. Chinese Society of Simulation, 2021: 387-393.

Lu Qing, Wu Shuang, Zhao Zhe, et al. Application of digital twin technology in aircraft design verification [J/OL]. Civil Aircraft Design and Research, 2019(3): 1-8.

Wang Wei, Liu Yongsheng, Liao Jun, et al. Key Technologies and Architecture of Digital Twin [J]. Post and Telecommunications Design Technology, 2021(8): 10-14.

Wu Yan, Wang Xiaojun, He Yong, et al. Review of key technologies and applications of digital twin in manufacturing industry[J/OL]. Modern Manufacturing Engineering, 2021(9): 137-145. Fan Rui, Liu Qingchuan, Gao Jian. Data Monitoring Technology of Intelligent Production Line System Based on Digital Twin [J/OL]. IC Application, 2021, 38(11): 120-121.

Original Article

Zhou Shuaichang, Liu Lilan, Gao Zenggui. Model and Data Acquisition Optimization of Digital Twin Workshop [J]. Industrial Control Computer, 2021, 34(12): 14-16.

National Beacon Committee Smart City Standards Working Group. White Paper on Urban Digital Twin Standardization (2022 Edition)[R/OL]. [2022-09-20].

Zhou Yu, Liu Chuncheng. The logic and innovation of building a digital twin city in Xiong'an New Area [J]. Urban Development Research, 2018, 25(10): 60-67.

Li Qiang. Analysis of urban flood disaster assessment and early warning system based on digital twin technology [J]. Journal of Beijing University of Technology, 2022, 48(5): 476-485.

Li Jingmin, Tang Yi, LI Keyu. Research on the Application of Digital Twin Technology in Library Construction [J]. Information Exploration, 2022(3): 77-82.

Cui Yihui, Yang Bintao, Fang Yi, et al. Application of digital twin technology in aero-engine intelligent production line [J/OL]. Aero Engines, 2019, 45(5): 93-96.

Zhang Lei. Research on Predictive Maintenance Model of Equipment Based on Digital Twin [J]. Special Equipment for Electronics Industry, 2021, 50(3): 12-15.

Cui Yufu, Liu Zianjia, Wang Jing. Development and prospect of digital twin satellite technology [J]. Space International, 2021(10): 27-31.

Cui Yufu, Liu Zianjia, Wang Jing. Digital twin satellite technology and engineering practice [J]. Spacecraft Engineering, 2021, 30(6): 62-69.

Zhang Suming, Yue Mengyun. Research on Health Management Technology of Rocket Test and

Launch Process Based on Digital Twin [J/OL]. Computer Measurement and Control, 2021, 29(5): 8-4.