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Research on Remote Operation and Maintenance Based on Digital Twin Technology

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Abstract: With the wide application of a new generation of information technology, remote technical services are receiving an increasing amount of attention in the manufacturing field. In view of the fact that most mechanical and electrical equipment manufacturing enterprises still need to send a substantial number of employees to the site to provide operation and maintenance services for customers, and the operation and maintenance costs of enterprises remain high, a remote operation and maintenance method of mechanical and electrical equipment based on digital twin technology is proposed. A digital twin remote operation and maintenance services model is constructed, and digital twin remote operation and maintenance technology is divided into four basic levels: virtual simulation, software/hardware-in-the-loop virtual commissioning, virtual and real synchronization, and cloud–end interconnection. With this, we conduct in-depth research on the key technologies involved in these four levels. The digital twin remote operation and maintenance service platform has been built; this platform can provide maintenance, repair, overhaul, and operation services for enterprise equipment. The feasibility of both the digital twin remote operation and maintenance services model and the digital twin remote operation and maintenance service platform was verified through cases, which provided an efficient and feasible solution for enterprises to improve service efficiency and reduce labor costs.

Keywords: remote operation and maintenance; digital twin; virtual commissioning; MRO



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1. Introduction

In recent years, enterprises or organizations engaged in MRO (maintenance, repair, overhaul and operation, MRO for short) services need to dispatch on-site staff or assign temporary staff when facing customer operation and maintenance requests. This often results in unacceptably high costs and inefficiencies. Enterprises have gradually begun to focus on the value generated by services, with MRO playing an increasingly important role in the whole life cycle of products as a service mode within the manufacturing field. Remote operation and maintenance technology has existed for a long time, but the existing remote operation and maintenance technology has a single service dimension and obtains little product information, so it is impossible to form a reliability prediction for the product. MRO services contribute to making digital twin technology, based on the entire life cycle, more comprehensive. By combining digital twin technology, the remote operation and maintenance process can obtain multi-dimensional information, making MRO services more efficient and cost-effective. This is not only to judge the operation status of the product but also to form a prediction of the product and optimize the production plan and inventory of the product in the enterprise.

It has been nearly a century since the terms maintenance, repair, and overhaul first appeared in official documents. The application field of MRO services has expanded from aircraft maintenance, which is primarily used in the aviation industry, to the realm of complex equipment [1]. Specialized MRO companies have emerged in the market that provide MRO services to airlines to prevent possible AOG (aircraft on the ground, AOG for short) situations. Nowadays, OEMs (original equipment manufacturer, OEM for short) have started to provide MRO services to reap more benefits [2]. A considerable number of enterprises and units also refer to MRO as maintenance and repair operation, and MRO at this time represents the management of non-productive materials. The meaning of MRO has expanded. Wang J. M. et al. think, from the perspective of the whole life cycle of products, MRO has developed into a modern MRO, namely maintenance, repair, operations, and overhaul [3]; Liu M. Y. et al. pointed out that MRO does not provide a fixed product, but a service that is just right for the enterprise [4].

Remote operation and maintenance are technologies that emerge within the MRO service model. They can enhance the efficiency and convenience of MRO, and enable operation and maintenance service providers to reduce costs and increase efficiency through the use of remote operation and maintenance. There are many research fields of remote operation and maintenance. In the field of power systems, Peng Z. Q. et al. proposed a remote operation and maintenance technology for a substation monitoring system based on GSP, and applied this technology in the power grid system of Jiangsu, China [5]. Zhang C. J. et al. proposed a cloud service method for remote operation and maintenance of offshore wind turbines based on big data, which reduces the need for operation and maintenance engineers to be stationed in wind power plants, thereby reducing operation and maintenance costs and improving the operation efficiency of wind turbines [6]. In the field of manufacturing and automation, Mourtzis D. et al. designed an IoT-based remote operation and maintenance platform that can provide remote monitoring and predictive maintenance for industrial equipment, which has been validated through the case of refrigerator and cold storage systems [7]. Fang K. studied a remote visual support system for equipment, which enables engineers to achieve remote fault diagnosis and prediction of equipment [8]. Li Q. et al. reviewed the key technologies for equipment and production lines to achieve monitoring and maintenance in the industrial Internet, and mentioned that digital twins can help equipment achieve remote monitoring to obtain a comprehensive understanding of equipment operation information in order to make the right decision [9].

The concept of a digital twin was first proposed by Professor Grieves, who constructed a three-dimensional model of a digital twin, including a physical entity, a virtual entity, and the connection between the two [10]. After that, Tao F et al. proposed a general digital twin five-dimensional model on the basis of the three-dimensional model, which includes a physical entity, a virtual entity, a connection, data, and services [11]. The development of digital twin theory has promoted research in related fields, such as manufacturing; Liu H. et al. studied the application of digital twins in the field of workshops robotics [12]; Leng J. et al. investigated the application of digital twins in the field of production lines. In the field of smart cities [13], Sharifi A. et al. studied the impact and application of digital twin on drainage system infrastructure in cities [14], and Liu Y. et al. studied the application of urban logistics in digital twins and carried out case verification in Paris. In the field of medicine [15], Corral-Acero J. et al. have applied digital twins to the treatment and diagnosis of the human heart [16], and Sun T. et al. believe that digital twins represent a new direction in medical development, which can achieve an accurate diagnosis and personalized treatment in medicine [17]. With the deepening of digital twin research, any existence with virtual–real mapping characteristics can be called a digital twin.

Liu M. et al. established a digital twin model of the aircraft overhaul workshop to form a dynamic capacity assessment of the aircraft overhaul workshop and improve the MRO service capability of the workshop [18]. Eversberg L. et al. applied a digital twin to a cognitive assistance system with augmented reality capabilities and demonstrated the potential of the system by performing a turbine blade repair process with a manual grinding workstation [19]. Xia J. and Zou G. proposed an operation and maintenance method for offshore wind farms based on digital twin technology and proposed a corresponding digital twin model [20]. Chit T. W. et al. proposed a scalable, hybrid cloud-based data management framework for ship equipment, which can be deployed on ships to implement the SaaP business model and provide better remote operation and maintenance services for ships [21]. Hong W. et al. applied digital twin to the remote operation and maintenance of ships and established satellite or 4G and 5G communication technologies to establish the communication between the digital operation and maintenance model of the ship and the ship so as to form a health management system of the operation status of the ship's key equipment, reduce operating costs, and provide a reference for the research of unmanned ships [22]. Yu G. et al. propose a tunnel operation and maintenance decision analysis framework based on digital twins, which can be used to realize the automatic and efficient analysis of tunnel equipment [23]. Hosamo H propose a digital twin predictive maintenance framework for air handling units based on automatic fault detection and diagnosis, which can be used to detect the faults of air handling units and predict the operating status of the equipment [24]. Yu B. et al. proposed a service-oriented digital twin modeling method for weaving workshops, which proved that the method can effectively reduce the average error of the predicted warp-out time [25].

To sum up, there are abundant studies on digital twins and remote operation and maintenance, but there are few studies focusing on the application of digital twin technology to remote operation and maintenance. These works are concentrated in the fields of power energy and transportation equipment, while there are few studies pertaining to automated electromechanical equipment in the manufacturing industry. Existing relevant research primarily focuses on fixed equipment and cannot be readily extended to a wider range of mechanical and electrical equipment. Additionally, few researchers have explained how digital twins facilitate remote operations from the perspective of service providers offering services to customers.

The novelty and contribution of this paper can be summarized as follows:

By combining digital twin technology with remote operation and maintenance services, a digital twin remote operation and maintenance service model is formed. The technology required to realize this digital twin remote operation and maintenance service model is divided into four levels. A digital twin remote operation and maintenance service platform is built utilizing these four levels of technology, and this platform is used to verify the digital twin remote operation and maintenance service model. From the service provider's perspective, this model describes the digital twin-driven remote operation and maintenance service method for electromechanical equipment. This method can enhance the role of OEMs in operation and maintenance services and change the form of goods. Goods are not only a single device but also include the supporting digital twin model of the equipment. The stages of the product's life cycle may overlap or even change.

2. Construction of Digital Twin Remote Operation and Maintenance Service Model

The products of the traditional manufacturing industry refer to the physical products produced by enterprises, and in the intelligent manufacturing stage, the products of enterprises encompass both tangible physical products and intangible services. With the

advent of digital twin technology, the company's products now also include twin models of physical products. Leveraging the characteristics of digital twins to reflect and control the real world with virtual entities, the monitoring, and diagnosis of physical products can be transferred to the twin models. Through the operation and maintenance of these twin models, a corresponding operation and maintenance service for the physical products is established. The cloud server enables virtual–real interconnection between the physical product and its twin model, allowing MRO enterprises to provide remote operation and maintenance services for their customers' physical products via the twin model from a remote location.

After analysis and totaling, this paper builds the DTRS (digital twin remote operation and maintenance service, DTRS for short) model (M_{DTRS}), as shown in Formula (1):

$$M_{DTRS} = (PE,VE,MROS,CDB,DS) \quad (1)$$

In the formula, PE represents a physical entity, VE represents a virtual entity, MROS represents an MRO service, CDB represents a cloud database, and DS represents the data stream between various communications. According to Equation (1), the structure of the MRO DTRS model is shown in Figure 1.

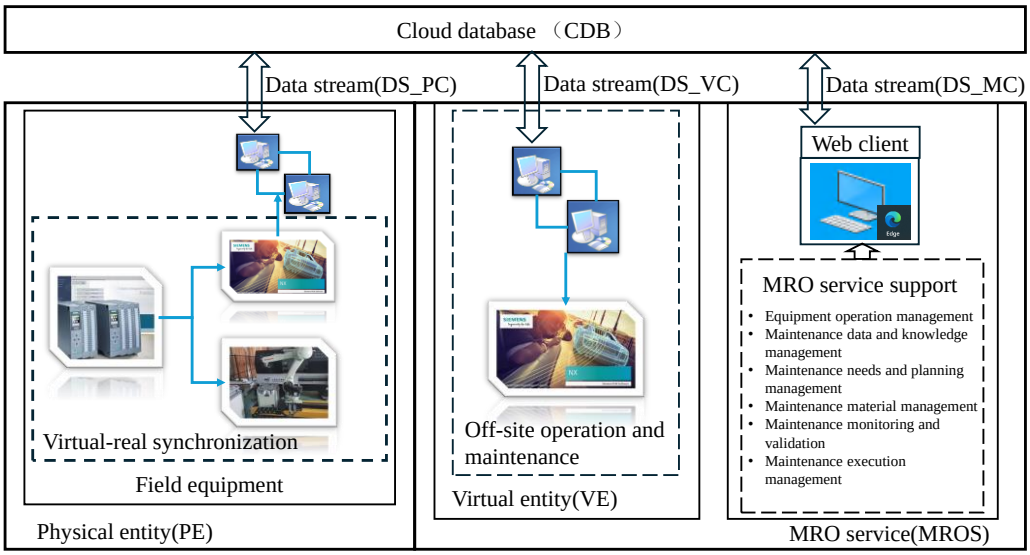


Figure 1. Conceptual model of the digital twin remote operation and maintenance service.

PE is the object served by digital twin remote operation and maintenance, and it is also the basis for the construction of M_{DTRS}. The PE constructed in this paper refers to the equipment on the enterprise site, not a single physical device in the traditional sense; the field equipment should establish a local virtual and real synchronization virtual commissioning level. On this basis, the data generated by PE is uploaded to CDB through DS via the data acquisition service software, thereby forming a complete set of PE within M_{DTRS}.

VE refers to an off-site operation and maintenance organization composed of software with a physics engine that can perform motion simulations and utilize data acquisition service software, as well as software with a physics engine capable of motion simulation, such as NX, SolidWorks, and Unity 3D.

MROS refers to the entire MRO service, including remote operation and maintenance services, specifically encompassing both web client service programs and VE. It provides remote operation and maintenance services for customers through VE and web clients, and web clients are used to achieve MRO core business support.

CDB refers to a cloud database, which can contain all the data of the entire composition of M_{DTRS}.

DS refers to all data streams in the entire MROS process, which can be composed of various communication protocols, such as the OPC protocol and TCP protocol, among others.

In the process of operation and maintenance services, the local on-site devices constitute the PE, and the operation and maintenance service provider builds a VE in a remote location. The PE sends DS_PC to the CDB, and the VE obtains the equipment operation data from the CDB, which is referred to as DS_VC. The entire VE, along with the web client, constitutes what is known as MROS. The operation and maintenance service provider conducts remote operation and maintenance of the local on-site equipment through MROS, thereby realizing the application of digital twins in the MRO field.

The virtual commissioning technology provides the foundation for the digital twin technology. The VE model in the digital twin is the high-fidelity model utilized in the virtual commissioning process. Digital twin technology extends virtual commissioning technology by leveraging the model's understanding, prediction, and optimization of reality. The software/hardware-in-the-loop virtual commissioning technology serves as the primary means to establish communication between the digital twin's PE and VE. During the commissioning process, virtual and real synchronization between the PE and the VE is achieved, thereby constructing a single-dimensional, lowest-level digital twin. The cloud–end interconnection between virtual and real entities serves as the basis for data analysis and service generation in digital twin technology. Therefore, the continuous improvement of virtual commissioning technology has contributed to the ongoing development of digital twin technology.

In this paper, after the M_{DTRS} is constructed, the technology for realizing the DTRS is subdivided into four levels in terms of functions, as shown in Figure 2. These levels are virtual simulation, software/hardware-in-the-loop virtual commissioning, virtual–real synchronization, and cloud–end interconnection. In these four levels, starting from virtual simulation and gradually increasing functions and modules, the level is gradually improved and finally constitutes all the main technologies of DTRS in the cloud–end interconnection stage. In the application process of DTRS, there exist both inclusive and horizontal relations between the upper and lower levels of these four technology levels.

The first level of virtual simulation (L1) is to create a twin model of the physical object in a virtual environment with a realistic physics engine and use the virtual model motion to simulate the physical motion. The second level of software/hardware-in-the-loop virtual commissioning (L2) is based on virtual simulation, adding input and output signals to realize software/hardware-in-the-loop virtual commissioning. The third level of virtual–real synchronization (L3) uses the controller to synchronously control the model and the physical object and synchronizes the virtual model's movements with the physical object in real space. The fourth level of cloud–end interconnection (L4) maps the data generated during the synchronous operation of physical and virtual entities in the cloud. The data is encrypted and uploaded to the cloud, and the cloud server uses mature and reliable service provider solutions. A large amount of data is the premise of forming a service, and there is cloud data storage, which can enable optimal control of the PE by analyzing the data. At the same time, the data in the cloud can be provided to the remote equipment operation and maintenance service team in the remote location. OEMs are often considered to be ideal operation and maintenance service providers because they have all the data on the equipment and do not require additional training, thereby enabling tracing of the equipment's operational history, analysis for decision-making, and the realization of operation and maintenance services. Based on this, the DTRS provides equipment monitoring and equipment status analysis services, such as monitoring equipment PE

through its equipment VE and analyzing running data to assess equipment running status. Figure 3 shows the relationship between the four levels of DTRS and digital twin technology.

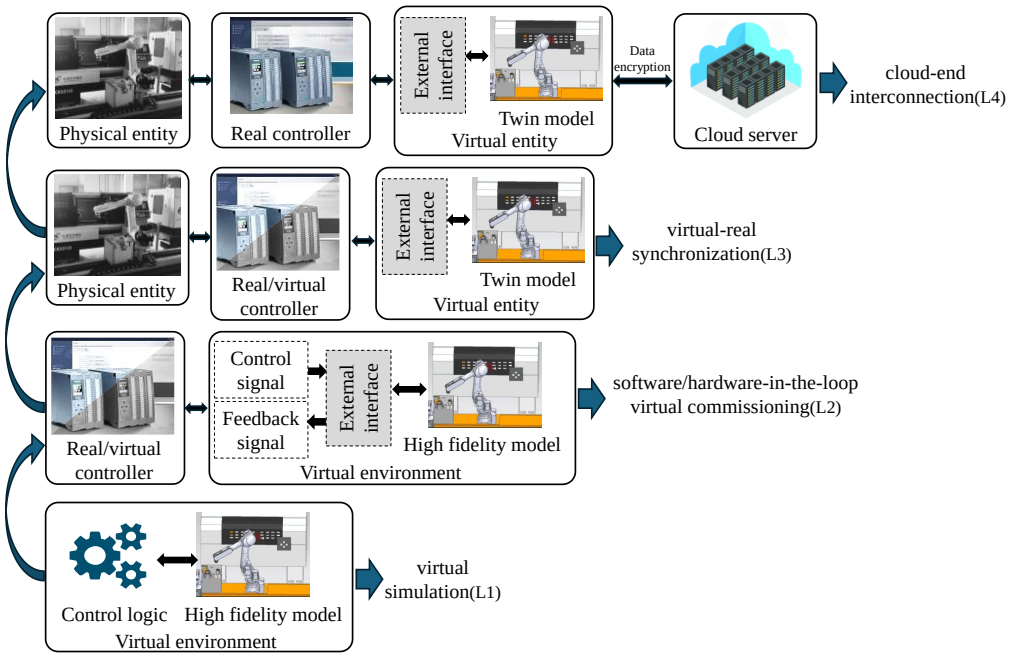


Figure 2. Four levels of digital twin remote operation and maintenance service technology.

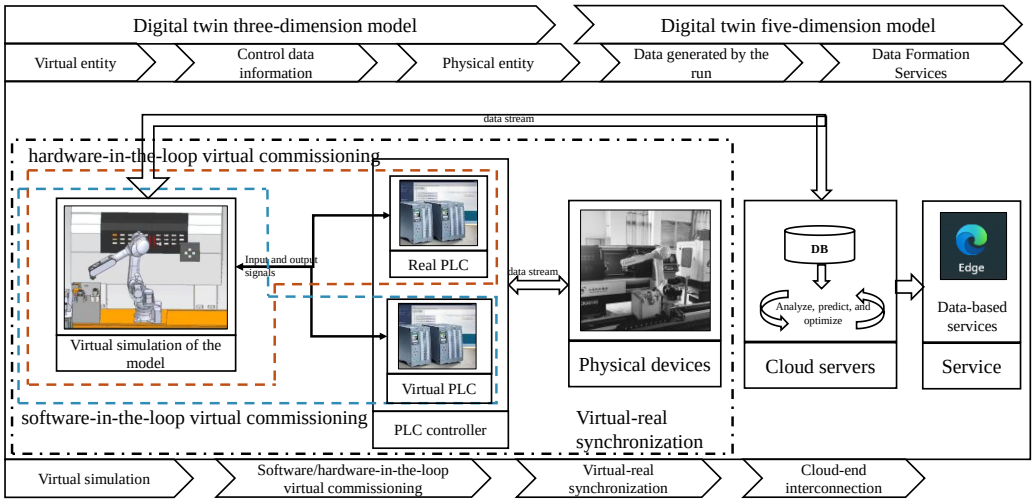


Figure 3. The relationship between the four levels of digital twin remote operation and maintenance service technology and digital twins.

3. Key Technologies of Digital Twin Remote Operation and Maintenance Services

The key technologies of DTRS are embodied in four levels of virtual commissioning: virtual simulation, software/hardware-in-the-loop virtual commissioning, virtual–real synchronization, and cloud–end interconnection. In terms of the difficulty of technical implementation, virtual simulation, and software/hardware-in-the-loop virtual commissioning are relatively more straightforward. Therefore, this paper will make a more detailed demonstration of virtual–real synchronization and cloud–end interconnection levels.

There are many software programs that provide virtual environments. In this paper, NX MCD is used as the virtual environment application of VE. Siemens developed Mechatronics Concept Designer (MCD) based on the NX CAD platform UG 8.0 Module. Its

mechatronic co-design digital solution provides multi-disciplinary, multi-departmental information interconnection integrated technology; the internal physical engine can simulate the complex motion of mechatronic systems, and support virtual commissioning.

3.1. Virtual Simulation and Software/Hardware-in-the-Loop Virtual Tuning Technology

Virtual simulation, as the first level, is the basis for providing DTRS. Any software equipped with a physics engine can achieve virtual simulation in the mechanical industry. The key to virtual simulation technology lies in using simulation software with a physics engine to create a virtual prototype that reflects the actual equipment operating state of the real equipment, as shown in Figure 4. During the commissioning stage of the whole life cycle of the product, the three-dimensional model of the equipment is added to the simulation software, and the electromechanical properties and internal control logic of the model are added to the virtual environment of the simulation software. In the virtual environment of the simulation software, electromechanical properties and internal control logic are added to the model. The electromechanical properties mirror the real equipment's running properties, while the control logic drives the model to move according to the preset motion mode. After completing the virtual simulation setup, the software is run and commissioned. The virtual prototype in the simulation software can reflect the operating status of the real equipment. In this process, errors can be identified in advance, allowing for product optimization prior to manufacturing. This can lead to cost reduction, efficiency improvement, risk mitigation, and enhanced innovation capabilities. Subsequently, the corresponding production plan, processing techniques, and other production and manufacturing documents are formulated. The model, having been verified through virtual simulation, is then used to guide production and manufacturing.

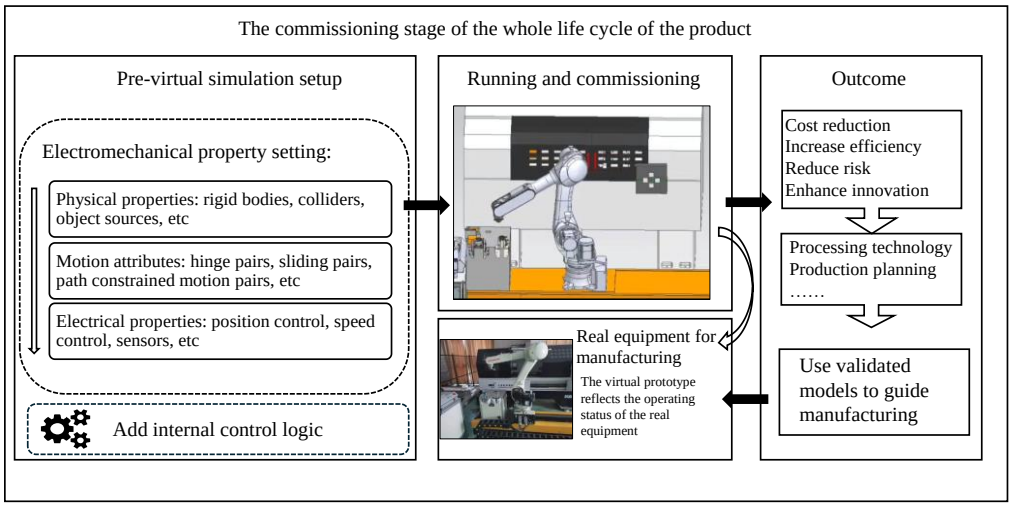


Figure 4. Virtual simulation schematics.

In the traditional product life cycle, the order of design, manufacturing, commissioning, operation, and maintenance is fixed. The manufacturing industry begins to produce parallel designs after entering the stage of digital integration, and the order of the product life cycle overlaps. In the intelligent manufacturing stage, the digital twin technology has made great progress, and the overlapping part of the order in the product life cycle has increased or even completely changed. Figure 5 shows the relationship between the whole life cycle of a product and the period and stages in which the manufacturing industry is located.

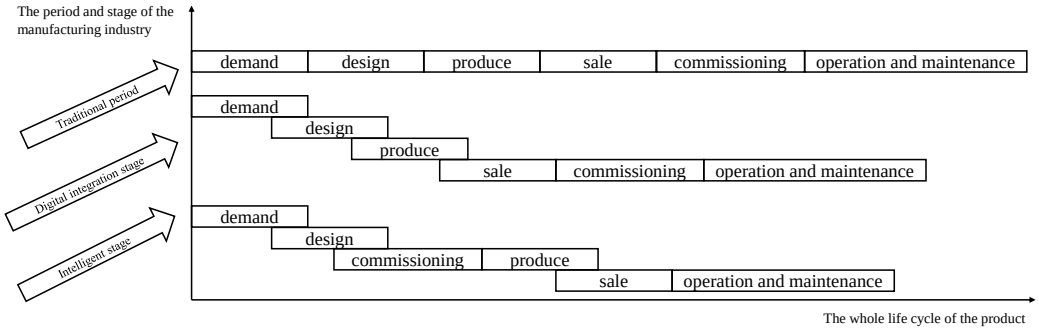


Figure 5. The relationship between the whole life cycle of the product and the period and stage of the manufacturing industry.

The virtual simulation discussed in this paper is the first level of the DTRS. It can be in the commissioning stage of the intelligent manufacturing stage, as shown in Figure 5. When the 3D design of the product is formed, the simulation software can be used for virtual simulation, such as crash testing of the equipment's operation. The necessary commissioning of the equipment can be carried out during the simulation process, and the results of the simulation can be used to optimize the design. In this way, the digital products verified by simulation and commissioning can reduce the defects in the product design. Furthermore, the products can be directly handed over to customers after completing the manufacturing process, thereby shortening the production cycle of the product and improving the flexibility of the manufacturing industry.

When the model design is completed, on the basis of the virtual simulation realized in the simulation software, the input and output signals are added, as shown in the schematic diagram of the software/hardware-in-the-loop virtual commissioning technology shown in Figure 6. The real controller in the real space can be connected with the signal in the simulation software through the OPC communication software. Similarly, the virtual controller in the virtual space can be connected to the signal in the simulation software via the OPC communication software. In this way, the control of the simulation model by the external controller is realized. The hardware-in-the-loop virtual commissioning is constituted when the real controller is used, and the software-in-the-loop virtual commissioning is constituted when the virtual controller is used. The use of software/hardware-in-the-loop technology can verify the effectiveness of communication and control logic and provide a foundation for subsequent virtual–real synchronization technology and cloud–end interconnection technology.

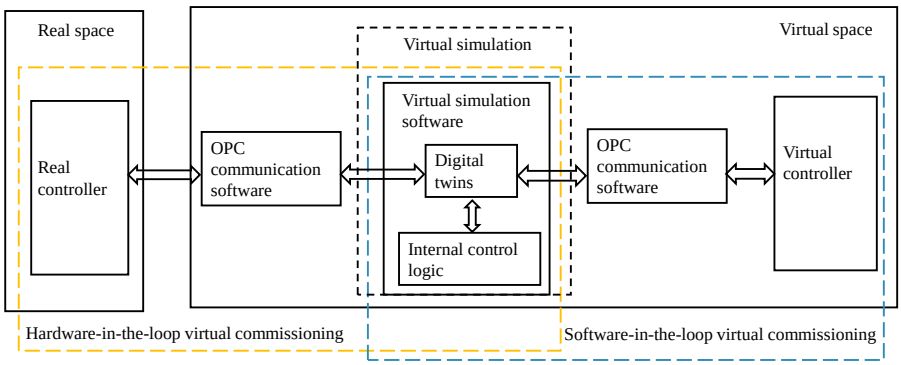


Figure 6. Schematic diagram of software/hardware-in-the-loop virtual commissioning technology.

3.2. Virtual–Real Synchronization Technology

Virtual and real synchronization represents the third level of virtual commissioning, and achieving this level necessitates the support of two foundational technologies: virtual

simulation and software/hardware-in-the-loop virtual commissioning. These technologies establish the foundational layer of the digital twin system within the single dimension of physical motion and also serve as the cornerstone for constructing PE within the M_{DTRS}.

The synchronization principle of virtual–real synchronization is illustrated in the schematic diagram shown in Figure 7. The upper computer is connected to the controller, and the controller realizes two-way communication with the field device and communication software, respectively. Additionally, the equipment model in the simulation software is connected with the other end of the communication software, enabling real-time communication between the controller and the equipment model.

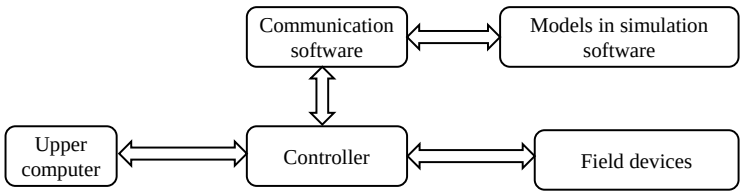


Figure 7. Schematic diagram of virtual–real synchronization.

This paper uses the control case of cylinder assembly to show the process of realizing virtual and real synchronization. The synchronization process is simulated utilizing TIA Portal, PLCSIM Advanced 3.0, and NX MCD. The synchronization principle is illustrated in Figure 8. PLCSIM Advanced 3.0 simulates the real PLC, while the model in MCD simulates the field equipment. This paper takes the cylinder assembly model located in the upper right corner of Figure 8 as an example for experimental verification. In the lower right corner of Figure 8, a PLC control program is presented. The function of the program is to control the position of the cylinder rod to move to 45 mm (the cylinder rod movement speed has been set to 10 mm/s in the MCD); after the cylinder rod starts to move, the timer starts to time for 5 s, and after 5 s, the cylinder rod shrinks to the initial 0 mm position.

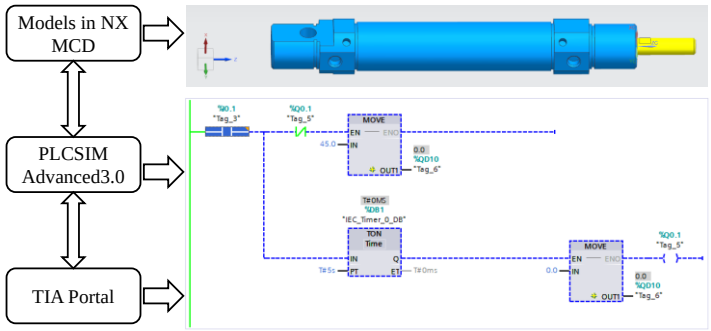


Figure 8. Simulate the schematic diagram of virtual and real synchronization.

The signal connection in the MCD and the signal in the PLC control program are shown in the Table 1 signal mapping table.

Through experiments, the location curve of the cylinder rod's motion position, as shown in Figure 9, is obtained. The curve indicates that the highest location value reached is 45 mm, after which the curve returns to the position of 0 mm. At the top of the figure, there is a straight line where the location value remains unchanged. This is because it takes only 4.5 s to reach 45 mm, but the timer is set for 5 s, resulting in the straight-line segment at the top. The process aligns with expectations, and the implementation principle of virtual and real synchronization is also verified.

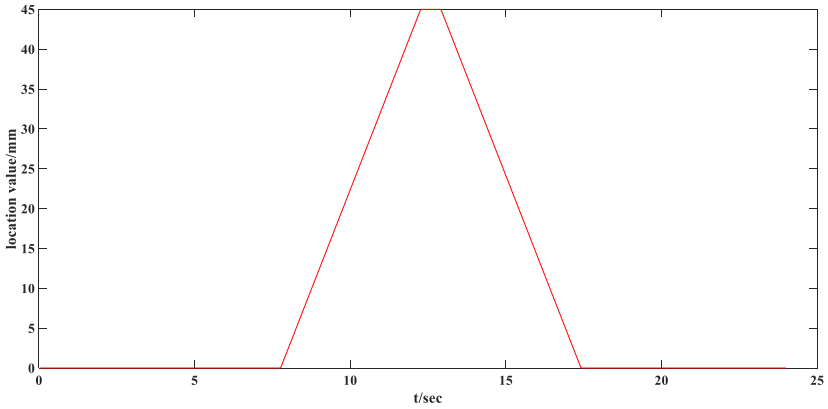


Figure 9. Location curve of cylinder rod movement position.

Table 1. Signal mapping table.

Illustrate	Signal in MCD	Control Signals in the PLC
A signal that controls the amount of motion position of the kinematic pair of the cylinder assembly	position control	QD10
The kinematic pair sensor shows the amount of motion position of the current kinematic pair	location	——

3.3. Cloud–End Interconnection Technology

Cloud–end interconnection constitutes the fourth level of virtual commissioning, serving as the foundation for generating MROS and furnishing technical support for remote operation and maintenance. The fundamental principle of cloud interconnection is illustrated in Figure 10. Utilizing data acquisition software, the system ensures that model motion data from the simulation software is stored in real time on the cloud server database. The web terminal retrieves this real-time model motion data from the cloud server, enabling it to display the model's motion. Additionally, the web client can exercise control over the motion of the MCD model by modifying the data resident on the cloud server.

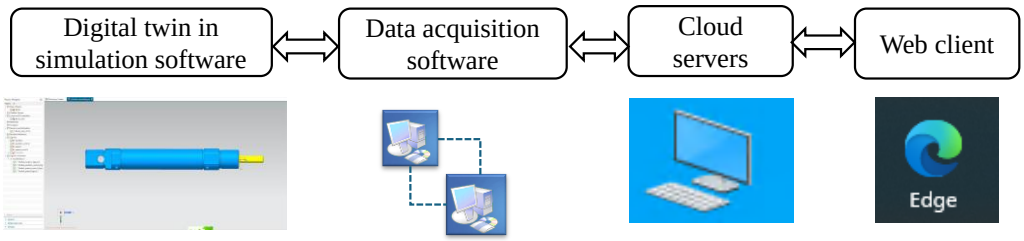


Figure 10. Schematic diagram of cloud–end interconnection.

This paper also uses the cylinder assembly model shown in Figure 8 for experimental verification; the data acquisition software is a service application written in C#. After the setting starts to run, the cylinder rod moves from 0 mm to 50 mm position. In the initial diagram of Figure 11a cylinder control, there are two observation quantities in the runtime inspector in NX MCD: position control is the signal that controls the sliding pair position of the model, and location is the sensor signal of the sliding pair position of the model. In Figure 11a, both the location and position control indicate that the current position of the cylinder rod is 50 mm, and a position data of 10 is sent via the web terminal to instruct the cylinder rod to shrink to 10 mm. In Figure 11b, the cylinder control result diagram, after

sending the position data 10, the motion position parameter of the current cylinder rod is displayed in the real-time position section, specifically in the second column of the web client, and the real-time position of the model of location feedback is consistent with the data change in the web page. The location curve graph of the Figure 11c control cylinder shows that after sending the control information 10 through the web page, the location value changes from 50 mm to 10 mm, and the motion control and monitoring of the model are smoothly realized through the web page. In the process of multiple simulations and commissioning, it can also be seen that there is a little communication delay on the website, which is related to the communication time difference and the frequency of updating the data of the web client. This delay, which is currently negligible, can be optimized in the future.

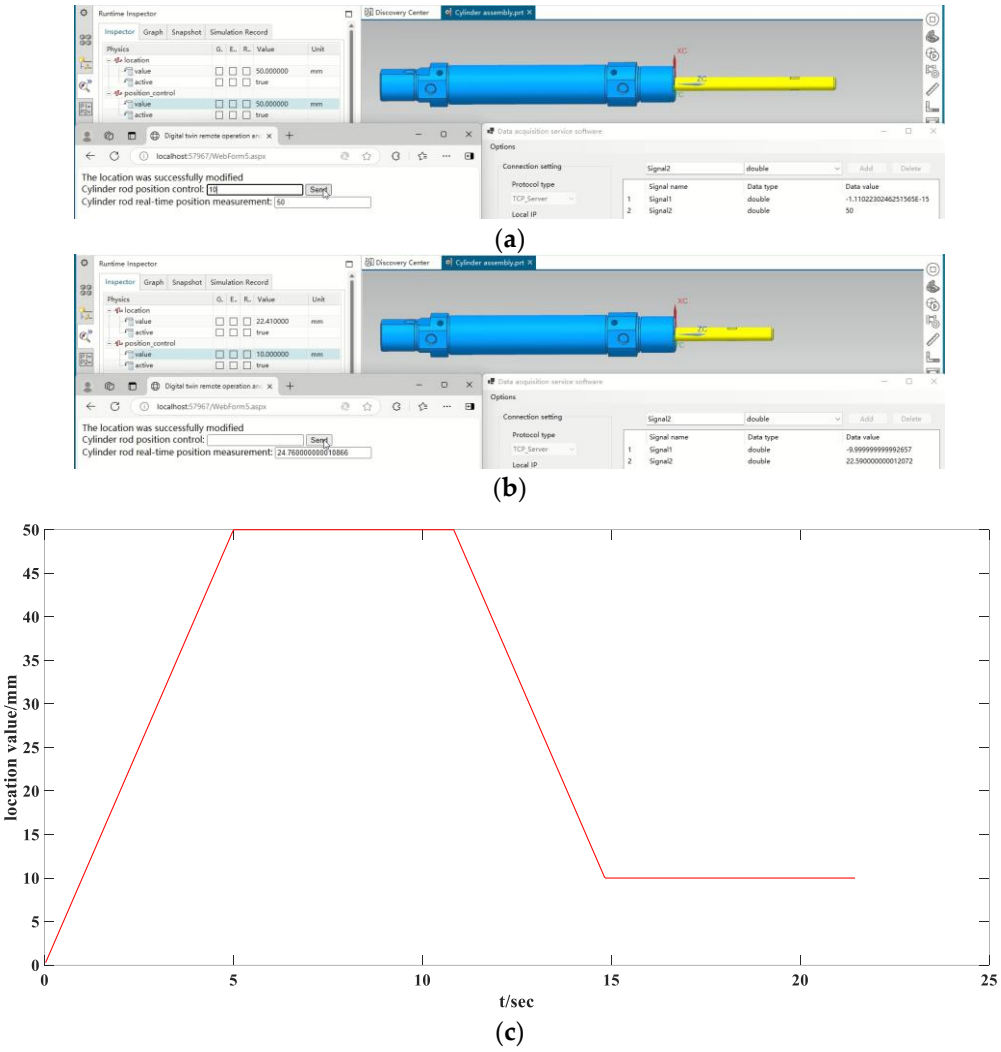


Figure 11. Process and results of cloud–end interconnection experiment. (**a**) Initial diagram of cylinder control; (**b**) result diagram of cylinder control; (**c**) cylinder location graph after control.

After the cloud–end interconnection technology is realized, services can be generated from data analysis, which is MROS in the M_{DTRS}.

4. Construction of Digital Twin Remote Operation and Maintenance Service Platform and Case Verification

As shown in Figure 12, the DTRS platform is mainly implemented via the third and fourth layers of virtual commissioning. The CDB obtains the operational data of the on-site

"physical entity", and the "virtual entity" in the remote place uses the data in the CDB to achieve a comprehensive virtual and real mapping. The operation and maintenance team then offers the DTRS through the diagnosis of the operation status of the "virtual entity".

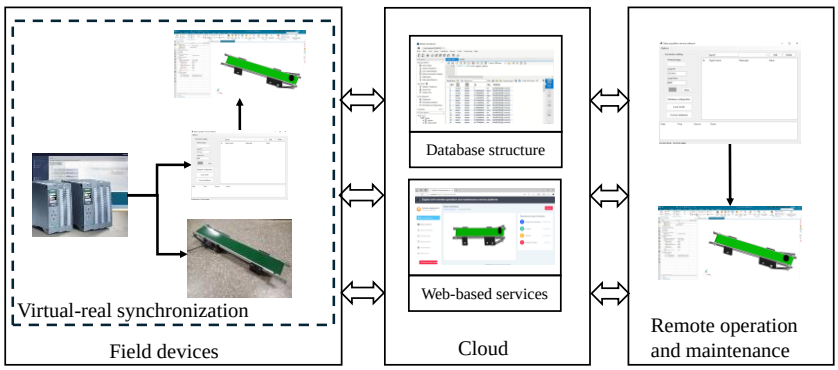


Figure 12. Digital twin remote operation and maintenance service platform.

The verification process of remote operation and maintenance case designed in this paper is as follows: First, the PE is constructed, achieving virtual-to-real synchronization between the physical device and the virtual model in MCD within the local field environment. Secondly, the VE is constructed, utilizing MCD to establish a virtual commissioning environment for equipment. Then, the CDB is added, the database structure is set in the cloud environment, and the web server is added. Finally, the connections between each component (DS) are established, enabling the data in the local MCD to be uploaded to the cloud through data acquisition software, and enabling the cloud to have real-time data of the equipment's operation. In the remote location, data acquisition software is run to facilitate real-time loading of cloud data into the MCD, enabling remote mapping of the on-site equipment. Remote engineers can not only access historical data to replicate device status remotely but also connect to real-time updated device data for remote monitoring, thereby realizing MROS and accomplishing the purpose of verifying the remote operation and maintenance case using the DTRS platform.

This article uses the conveyor belt equipment in Figure 13 as a case verification device, using Siemens S1500 PLC to control the conveyor belt for material transportation. Two networked computers were used in the experiment: one computer simulated the local on-site environment, and the other simulated the operation and maintenance process in a remote location. NX MCD was running simultaneously on both the 'on-site computer' and the 'off-site computer', with real-time mapping performed from the conveyor belt model on the 'off-site computer' to the one on the 'on-site computer'. The conveyor belt model on the 'on-site computer' is synchronized with the real conveyor belt model. Therefore, observing and comparing the operation status and operation data of the conveyor belt model between the two locations can realize and verify the operation and maintenance process of the local equipment by the remote operation and maintenance team.

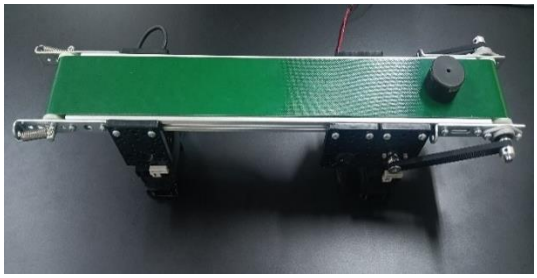


Figure 13. Conveyor equipment.

Step 1: Build a PE. Using the Siemens PLC control box depicted in Figure 14 as the field controller, the control lines for the conveyor belt are connected to the Q0.0, Q0.1, and Q0.2 interfaces on the PLC, with Q0.0 controlling the forward rotation, Q0.1 controlling the reverse rotation of the conveyor belt, and Q0.2 controlling the main power switch of the conveyor circuit. After configuring the project properties in the TIA Portal and writing the conveyor control program, download the program to the PLC.



Figure 14. PLC control box.

Step 2: Build a local virtual–real synchronization level. Open the conveyor simulation model locally with NX MCD and set the necessary physical and collision properties for the conveyor model, including rigid body and collider properties for the conveyor belt and material, as well as motion control for the conveyor belt. Add the conveyor's motion control signal using a signal adapter to create forward, reverse, forward_f, and reverse_f signals. Add a TCP connection to the MCD external signal configuration. The data acquisition software serves as the TCP server to establish virtual and real synchronization between the simulation model and the conveyor belt equipment. The process is shown in Figure 15.

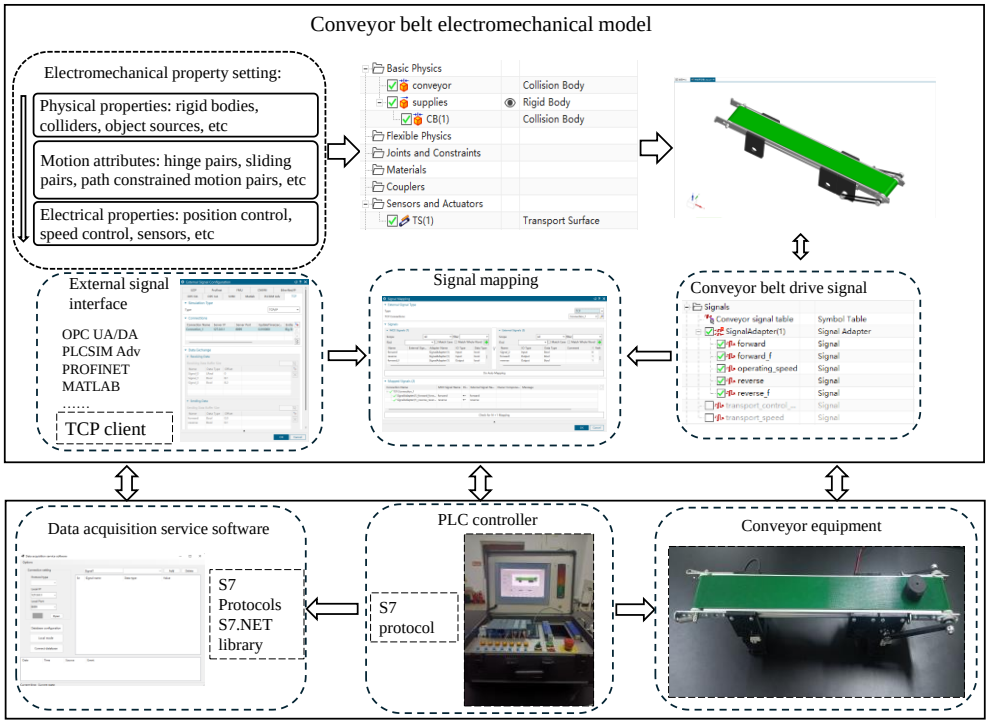


Figure 15. The process of establishing virtual–real synchronization.

Step 3: Build a VE. The VE only needs to use the MCD to open the conveyor model on a computer that represents an off-site location. Following a similar process to the previous step, configure the electromechanical properties of the conveyor model, but only create

forward and reverse signals in the signal adapter. Add a TCP connection to the data acquisition software located off-site.

Step 4: Establish the corresponding database and signal data table structure in a MySQL database hosted on the cloud server, and set the corresponding connection configuration so that the data acquisition software can access and modify the form information in MySQL.

Step 5: Conduct a digital twin remote operation and maintenance experiment. The process is shown in Figure 16. The first row is the conveyor belt equipment. On the second row, the PLC controller is on the left, the laptop in the middle is the "on-site computer", and the IPC on the right is the "off-site computer". The "on-site computer" realizes the virtual and real synchronization with the conveyor belt equipment, while the "off-site computer" VE and the local PE form virtual and real synchronization. The figure illustrates the synchronization of these environments between local and remote locations at this moment, and the running status of local devices is mapped in the remote VE.

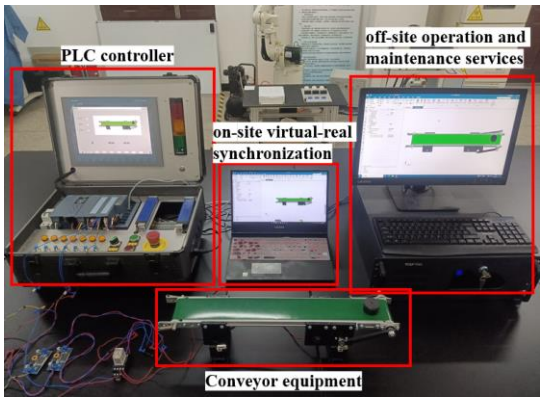


Figure 16. Experimental process.

Step 6: Simulate the process of remote operation and maintenance services. The process of the experiment includes two parts: local and remote synchronization experiments, and remote operation and maintenance judgment after local equipment failure.

The local and remote synchronization experiments mainly verify the ability of the remote twin model to perform motion mapping of the local equipment. Additionally, the remote twin model can serve as the monitoring device for the local equipment by accurately reflecting the operating state of the local equipment. During the experiment, the on-site conveyor equipment was controlled to start from its initial position of 0 mm and undergo a reciprocating motion between 0 mm and 350 mm. The remote twin model synchronously mapped the running state of the local conveyor belt. Figure 17 is a comparison chart of the position value of the on-site conveyor equipment and the position value of the twin model during the experiment.

In the figure, the red dotted line represents the position value of the remote twin model, and the blue solid line represents the position value of the on-site equipment. The red dashed line does not reach the 0 mm position around 25 s, indicating that there is a motion distortion of the twin model here. Before 25 s, the red dotted line follows the blue solid line, with a growing time lag developing as time increases. Around 25 s, when the on-site equipment changes from reverse operation to forward operation, the latest forward operation signal is then updated to the twin model's control system. This results in the red dashed line appearing ahead of the blue solid line in the figure. Until the twin model reaches 350 mm and comes to a halt, the red dotted line again follows the blue solid line after a new reverse operation signal from the on-site equipment. As can be seen from the figure, the remote twin model can map the running state of the on-site equipment.

However, the position value of the off-site model does not perfectly match the position value of the on-site equipment due to a certain time delay in the process of the on-site equipment uploading data to the cloud server and the off-site twin model reading the data from the cloud server. It is believed that this delay can be technically reduced to the millisecond level or even lower, thus considering the local and remote synchronization experiment to be successful.

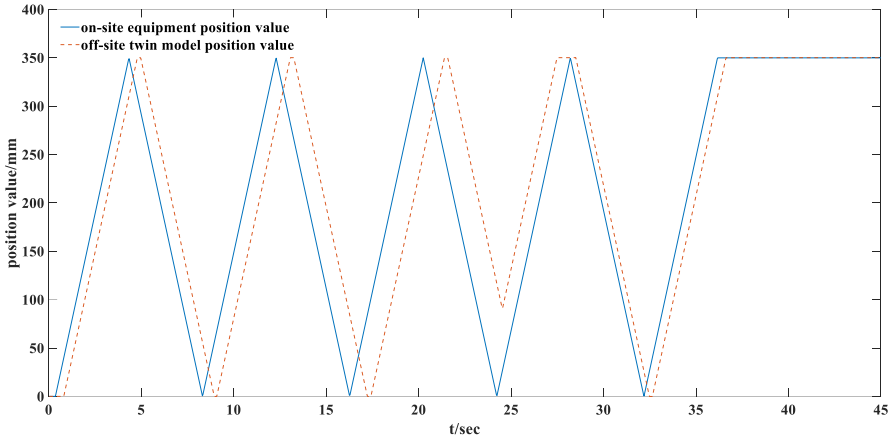


Figure 17. Comparison chart of local equipment and twin model running data.

Remote operation and maintenance judgment is to simulate the operation and maintenance process after a local device fault occurs. When the local physical device fails and stops running, the remote virtual entity will also stop running. At the same time, the remote operation and maintenance team can locate the fault point by viewing the data and then notify the local customer responsible for the equipment to repair the fault point, enabling the equipment to resume operation after maintenance. This process is significantly more efficient than the customer having to locate the fault point and repair it themselves.

The experimental results show that the conveyor belt model in the 'off-site computer' can map the movement of the 'on-site computer' conveyor belt model. By operating and maintaining the off-site conveyor belt model, one can manage the local conveyor belt equipment accordingly. During operations and maintenance, it is found that there is a communication delay between the 'off-site computer' and the 'on-site computer', which is not only related to the frequency of data sending and receiving but is also influenced by the time required for data communication in the cloud. This delay can be reduced through various optimizations, and the impact of these delays on the outcomes of remote operation and maintenance experiments is negligible.

5. Conclusions

This paper studies the remote operation and maintenance of electromechanical equipment driven by digital twin technology. It mainly includes the following three parts:

Firstly, the digital twin remote operation and maintenance services model is constructed, which realizes the remote operation and maintenance service of on-site real equipment by the remote twin model with the help of the characteristics of virtual entities that can map physical entities and virtual entities that can control physical entities.

Secondly, this paper divides the technical composition of the model into four levels: virtual simulation, software/hardware-in-the-loop virtual commissioning, virtual–real synchronization and cloud–end interconnection, and conducts theoretical analysis and experimental tests on these four levels. A digital twin remote operation and maintenance service platform is built in the laboratory environment using four-layer technology, which can help MRO enterprises reduce costs and increase efficiency.

Finally, this paper verifies the effectiveness of the digital twin remote operation and maintenance services model and platform through a specific remote operation and maintenance case study.

The digital twin remote operation and maintenance service model proposed in this paper is relatively basic and needs to be further studied in detail and depth. MRO exists in this article as a remote operation and maintenance service, and current research shows that the digital twin remote operation and maintenance service can realize the status monitoring of real equipment and obtain the real-time operation data of the equipment—determining how best to use this data for fault prediction and diagnosis services will be studied in the future. The current research method is still confined to the scope of a single piece of equipment, and further research is needed on how to enhance service capabilities and achieve large-scale deployment of multiple equipment. The model used in the remote operation and maintenance case is relatively simple; the model operation is stuck, and the communication is intermittently delayed. In view of the problems existing in the case, the optimization design will be carried out in the future, and the remote operation and maintenance test will be carried out with complex electromechanical equipment so as to conduct a higher-level study on the application of digital twins in the field of operation and maintenance services.

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