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Research on Digital Twin Workshop System Construction and Virtual-Real Mapping Method

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Abstract. With the requirements of digital construction, real-time visual monitoring and efficient management of intelligent manufacturing workshop and production line, a universal digital twin workshop construction method was proposed. Based on the scientific and effective data interaction architecture, this paper studies the content, methods and key technologies of virtual real mapping. Through the construction of workshop virtual scenes, the fusion of multi-dimensional models, and the integration of functional modules and interactive modules, a high-fidelity digital twin workshop system is constructed. In addition, the construction method of the proposed digital twin workshop system was verified by an engineering case. The results showed that the real-time mapping delay of the workshop system was less than 400ms, which demonstrated the feasibility and effectiveness of the proposed method and provided support for the practical application of digital twin workshop.

Keywords: digital twin workshop (DTW); virtual-real mapping; system modeling.

1. Introduction

With the rapid development and application of intelligent manufacturing, many enterprises have completed the automation transformation of manufacturing workshops or production lines. However, most of them, especially small and medium-sized enterprises, still have a serious lack of digital construction capabilities, making it difficult to effectively monitor and manage the processing process in the manufacturing workshop [1]. As one of the important solutions for intelligent manufacturing, digital twin has become a research hotspot in recent years. Different from many traditional workshop simulation technologies, such as workshop logistics simulation, layout simulation, etc., digital twin workshop(DTW) takes real-time data as the core and uses information technology to build multidimensional and high-fidelity workshop dynamic model to realize real-time digital mirroring of physical workshop [2]. Research on DTW is of great significance to the transformation and upgrading of traditional industries and the improvement of country’s advanced manufacturing capacity.

In recent years, research on DTW have shown explosive growth, and research on its theoretical foundation has become increasingly complete [3-5]. In particular, the digital twin technology is an effective way to integrate the physical world and the information world. How to use real-time twin data to realize the two-way data mapping between the physical workshop and the virtual workshop is the focus of the research. Tao Fei et al. [6] discussed the basic theories and key technologies for realizing the cyber-physical fusion of DTW; Urbana Coronado et al. [7] introduced a new method of developing and realizing MES, which provided data integration for the digital twin system Basis; Bao Jinsong et al. [8] proposed a method for realizing virtual-physical fusion and information integration in a manufacturing environment; Ding Kai et al. [9] studied the virtual-real mapping and data modeling methods of intelligent manufacturing space, and carried out Experimental verification. On the basis of theoretical research, more and more researchers carried out practical verification in combination with the actual workshop or production line. Guo Dongsheng [10], Zhuang Cunbo [11], Liu Weiran [12] explored the application of digital dual systems in the aerospace structural parts manufacturing workshop, complex product assembly workshop, and satellite full life cycle process. Moreover, the services of DTW have also been expanded. Many scholars carried out research on logistics management [13], online prediction of workshop status [14], and other aspects based on digital twin.

According to the research status at home and abroad, relevant researches of DTW have gradually moved from theoretical to application. Its theoretical system, key technologies and application methods have a certain research basis, but there are still some problems: 1) the application examples of DTW are still very limited, and most of the existing research cases are "digital model" or "digital shadow" [15], which cannot realize the complete mapping of workshop. Therefore, the realization method of virtual reality fusion and mapping remains to be explored; 2) The modeling methods of DTW are different, and there is a lack of modular system modeling methods with stronger universality and better visualization. To solve the above problems, this paper proposes a DTW architecture and construction method, which realizes the two-way mapping and interaction of virtual and real workshop through the system data architecture construction. The universality of the modeling method of DTW system is improved through the modeling method of total factor and multi-level. This method can provide a feasible scheme for data management, real-time monitoring, remote control and fault alarm of physical workshop, and make it more widely used in intelligent manufacturing field.

2. DTW Data Interaction Architecture

The virtual-real mapping is the essence of the DTW. In order to realize the efficient two-way flow of real-time data between the physical workshop and the virtual workshop, the DTW system data interaction architecture is proposed, as shown in Figure 1, which consists of physical layer, data layer, driving layer and application layer.

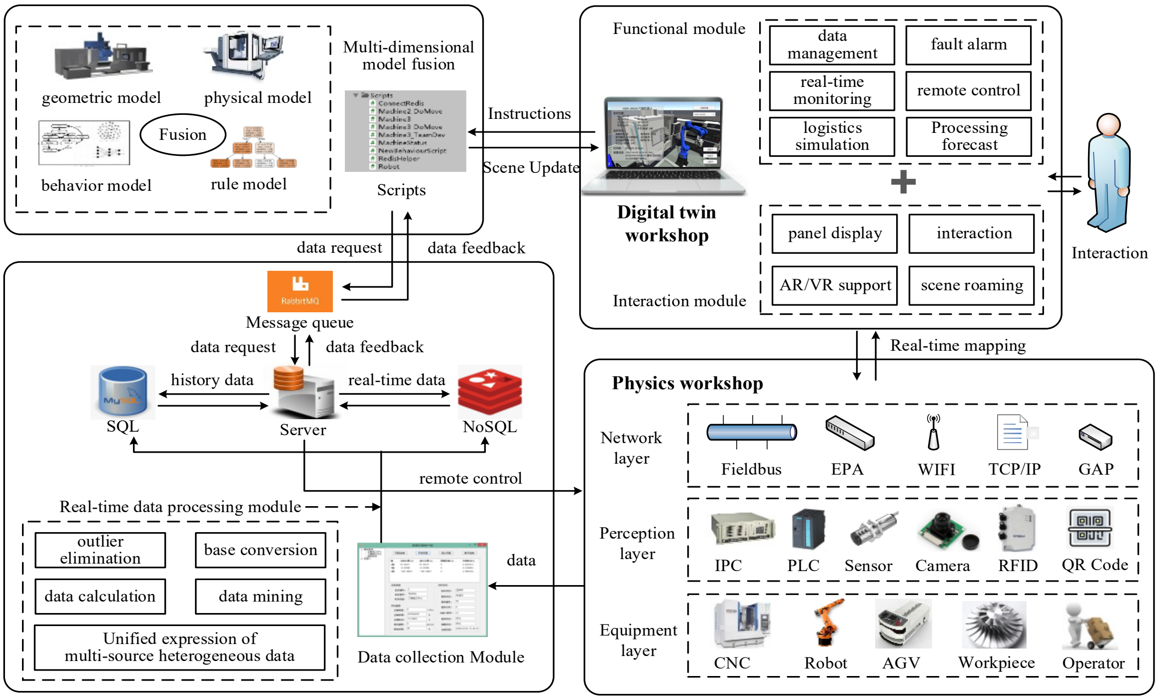


Fig. 1: Data interactive architecture of DTW

1) The physical layer: The physical layer is composed of all the entities of the physical workshop and can be further divided into the equipment layer, the perception layer and the network layer. It is the source of multi-source heterogeneous data in the system.

2) The data layer: The data layer is the key of data processing and consists of the data acquisition module, real-time data processing module, database, server and message queue. Among them, The data acquisition module is combined with the time data processing module to collect, preprocess, clean and store the multi-source heterogeneous data in the physical workshop. The server is the core of system data interaction, which can accept the request of upper real-time data, query and transmit data, and issue instructions. In addition, message queue is built between the client of the DTW and server to prevent errors in high concurrency scenarios. The data layer collects, processes and cleans data in real time, and stores and manages the data for use by the drive layer.

3) The driver layer: The driver layer uses program scripts to build the physical, behavior, and rule

models of the DTW and fuse them. The operation of the model is driven by real-time data and event response to simulate the internal operating rules of the physical workshop.

4) The application layer: Based on the virtual scene of the DTW, The application layer integrates various system function modules and three-dimensional(3D) visualization interactive modules to provide users with modular and scalable workshop service and interaction interface.

3. Virtual-Real Mapping Methodology

Based on the scientific and effective data interaction architecture, the following studies the methodology of virtual real mapping, and discusses the main content and key technologies of mapping.

3.1. The Content and Method of Virtual-real Mapping

According to the type of real-time data in the workshop and the characteristics of model response, the real-time mapping of the production process can be divided into equipment level, logistics level and product level.

1) Equipment level mapping

a) Pose mapping: The pose of the equipment in the physical workshop is freely developed, such as the axis of the machine tool, the joint of the mechanical arm, and the Automated Guided Vehicle (AGV). These numerical data reflect the real-time operation situation of equipment. In this case, the system can constantly request the real-time pose data of the equipment with a high frequency, and then carry out geometric transformation operations such as displacement and rotation of the model through the program scripts, so as to realize the synchronization of virtual and real operation.

b) Signal trigger mapping: In addition to numerical data, there are a large number of IO signals in the workshop, such as the opening and closing of machine tool doors, and the clamping and unclamping of robot grippers. These signals are boolean values that can change the state of the equipment or trigger specific actions. In this case, the response action of the equipment model can be predefined according to the actual situation. When the signal value changes, the response action of the model is triggered to realize trigger mapping.

c) State information mapping: During the production process, the equipment will generate many key status data and information, such as machine tool spindle load, cutting force, temperature, etc. These data do not participate in the real-time movement of the model, but can be used as an important indicator for equipment status monitoring and fault diagnosis. So, data of this kind need to be persistently stored and displayed in the form of user interface. In addition, data analysis module and fault warning module can also be added to the back end to monitor the status of the device.

2) logistics level mapping

The equipment in the smart workshop is not only an independent individual, but also a large amount of data interaction and signal transmission between each other. Data of this kind are critical to the synchronization of the logistics status. For this level of mapping, it is necessary to simulate workshop manufacturing resources, production process and workshop operation rules. Commonly used methods include queuing net method, Petri net method, Entity Flow Char, Complex Event processing, Finite State Machine and so on. For the construction of the theoretical model, it need to convert the interaction data between the devices into corresponding input and output events, and trigger the device state change through the event. Then, transform the theoretical model into a high-level programming language for simulation. Simulation strategy is established by methods of Event scheduling, Activity Scanning, Process Interaction, etc. Finally, simulation model is promoted by event table and simulation clock, and key logistics information such as equipment utilization rate can be obtained through statistical analysis of the data.

3) Product level mapping

The product mapping is based on the equipment and logistics mapping to realize the synchronization of the processing process of a single product and the overall production situation. For a single product, the data in the RFID tag can be used to determine the processing progress of the workpiece, and to update the position and the model of the product in the system. For the production situation of a batch of products, it is necessary to carry out statistical analysis on the logistics data of all products to obtain the overall production situation, and also to predict the future output.

3.2. Key Technology of Virtual-real Mapping

1) Real-time processing, integrated management and efficient transmission of multi-source heterogeneous data

The data sources in the physical workshop are complex, showing multi-source heterogeneous characteristics. To ensure the real-time and reliability of mapping, real-time preprocessing and integrated management of multi-source heterogeneous data are required. The frequency of real-time data collection in the workshop is very high, which leads to errors such as null value, repetition, jitter, and abnormality. The data can be processed and cleaned in real time by means of threshold detection, differential detection, null deletion, and data base conversion. In order to improve the efficiency of data transmission, the processed real-time data are managed in an object-oriented method. Encapsulate all the real-time data contained in each equipment in the workshop as classes. During the data collection process, the classes are instantiated and transmitted in JSON format for transmission, which can improve transmission efficiency. In addition, considering the clear expression of the data structure of the relational database and the efficient read and write performance of the massive data of the memory database, the two are used in combination. Redis is used for efficient transmission of real-time data, while MySQL is used for persistent storage and management of data. Figure 2 shows an example of robot data management. Through the above operations on real-time data, the efficiency and accuracy of the mapping are improved.

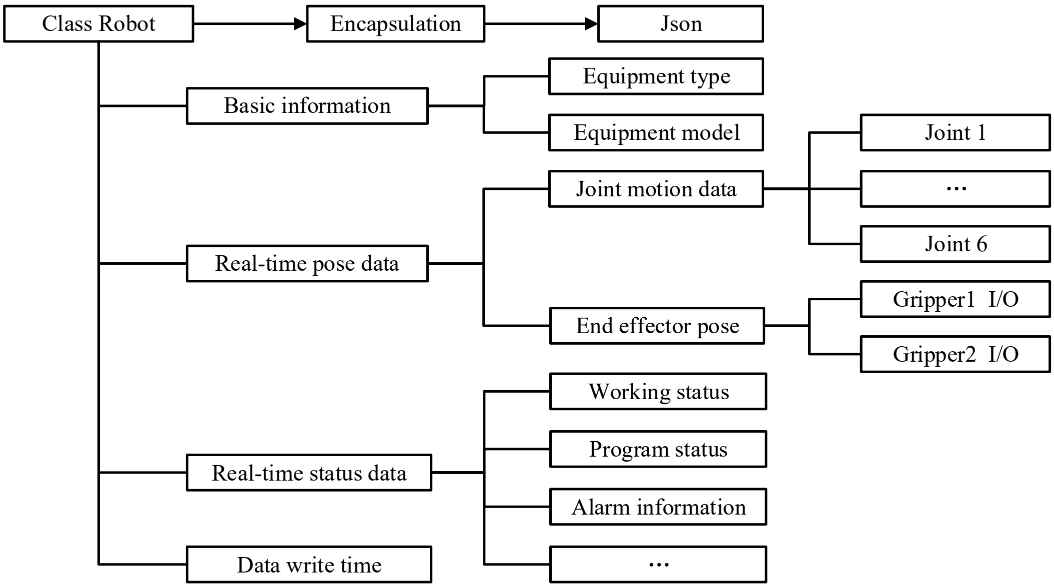


Fig. 2: Robot data management example

In addition, this article uses data polling and event subscription methods to obtain real-time data together. As shown in Figure 3, in the DTW system, a single device acts as a client and establishes an asynchronous long connection with the server for socket data communication. For motion-driven data, the client continuously sends real-time data requests to the server, and drives the model to synchronize the motion according to the returned data; for signal and instruction data, the event subscription method is adopted, and the server returns the current data when the status signal changes. The two methods are used in combination to ensure the real-time performance of the data while reducing the burden on the server to realize efficient data transmission.

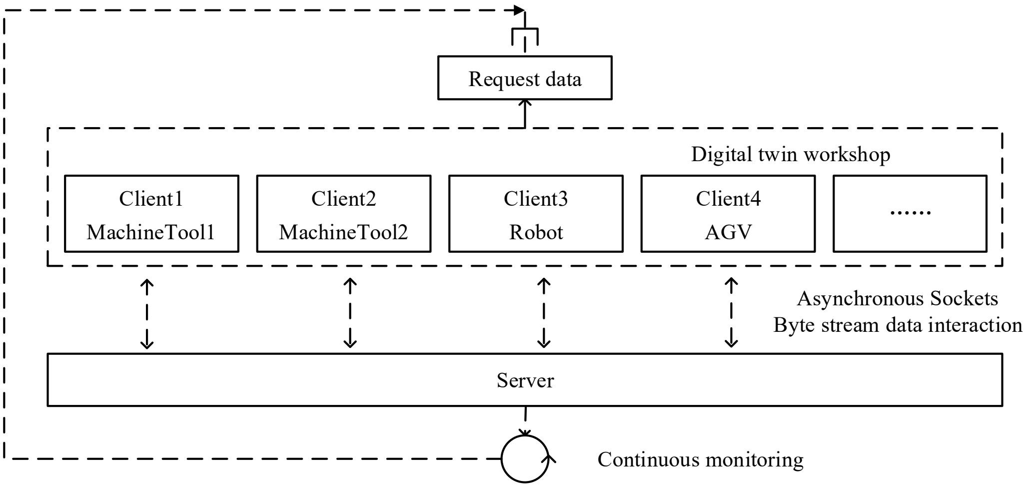
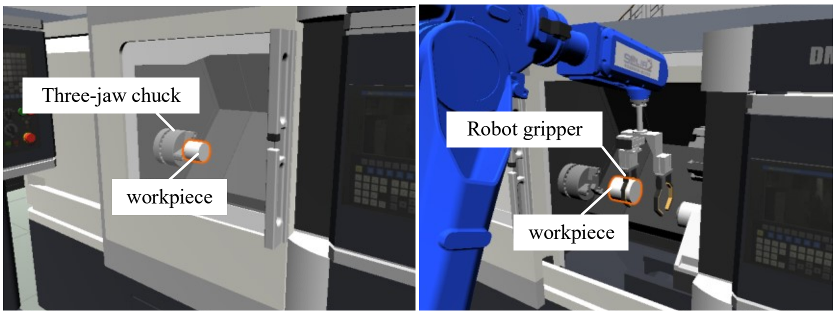


Fig. 3: Robot data management example

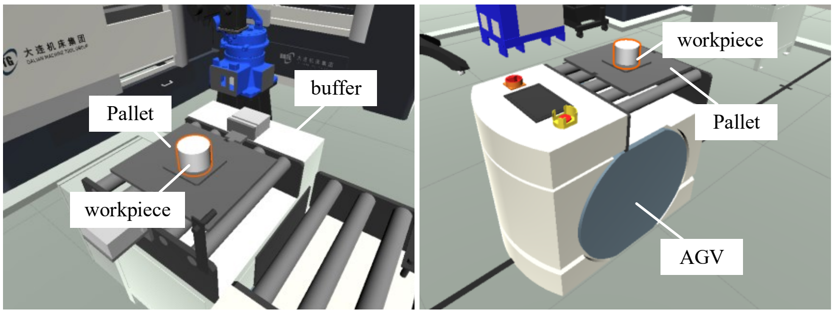
2) 3d model-driven approach based on real-time data

In order to realize the flexible driving of 3D models, it is necessary to modify and adjust the workshop geometry models. First of all, the moving parts are divided according to the actual movement of the equipment, and the 3D models are divided and assembled in a modular way. By adjusting the hierarchical relationship of the models, the father-son subordinate relationship of the master and slave moving parts is established. On the basis of the hierarchical model, the kinematic analysis of the equipment is carried out, and the local coordinate system and the origin of coordinates of the models are adjusted. Finally, the vector definitions of the 3D model are carried out through the program scripts, such as the positive direction of the robot moving joint, joint Angle, speed, acceleration, motion limit and so on. Through the above work, a set of workshop physical and behavior rule models are established to prepare for data driven.



(a) During lathe processing
Workpiece as a sub-object of the three- jaw chuck

(b) During Robot handling
Workpiece as a sub-object of the Robot gripper



(c) During the transfer of the workpiece
Workpiece as a sub-object of the pallet, and the pallet as a sub-object of the buffer or AGV

Fig. 4: Robot data management example

There are several ways of using real-time data to drive model motion: (1) For the equipment that can collect the movement data of all levels of mechanism completely, according to the actual master-slave movement relationship of the components, the corresponding real-time data are used to drive the model geometric transformation. (2) For the equipment that can only obtain the data of the end effector, the inverse kinematics analysis is carried out according to the structure of the device, and the pose of the intermediate mechanism is solved by the algorithm, and then the motion simulation of the model is realized by the pose data interpolation. (3) For the follow-up conditions of different equipment or institutions in the workshop, use scripts to change the parent-child relationship of the model to realize the synchronous movement of the model. Figure 4 shows the simulation of the movement of the workpiece in the workshop production process.

3) Initial status synchronization

Every time the system is started, an initialization operation is required to quickly map the virtual workshop to the current state of the physical workshop. According to the classification of the mapping described above, the system initialization can also be divided into three levels: equipment, logistics and product. The purpose of equipment initialization is to quickly synchronize the poses of all equipment models in the virtual workshop to the real situation. Specifically, a complete data request can be made immediately after each system startup, and the model can be quickly matched to the current state of the workshop through geometric transformation. Product initialization is mainly the synchronization of material information, workpiece location, and product data. It can be realized by analyzing historical processing data and RFID information stored in the database, and manual initialization can also be performed if necessary. For the logistics initialization between the above two, such as the synchronization of the processing status of the equipment and the process flow, it can be deduced through the status data of the equipment and the product data to initialize the settings.

4. Digital Twin Workshop System Constraction

4.1. Construction of Virtual Scene

At present, the methods for constructing virtual scene in DTW mainly include web3D technology, underlying graphics development tools, and multi-software collaborative development. Among them, the multi-software collaborative development method has gradually become the mainstream method of constructing DTW system due to its high system development efficiency and good portability. This artical uses Unity3d as the virtual scene construction platform, combined with a variety of professional software, to achieve the construction of high-fidelity virtual scenes. The virtual scene construction process is shown in Figure 5.

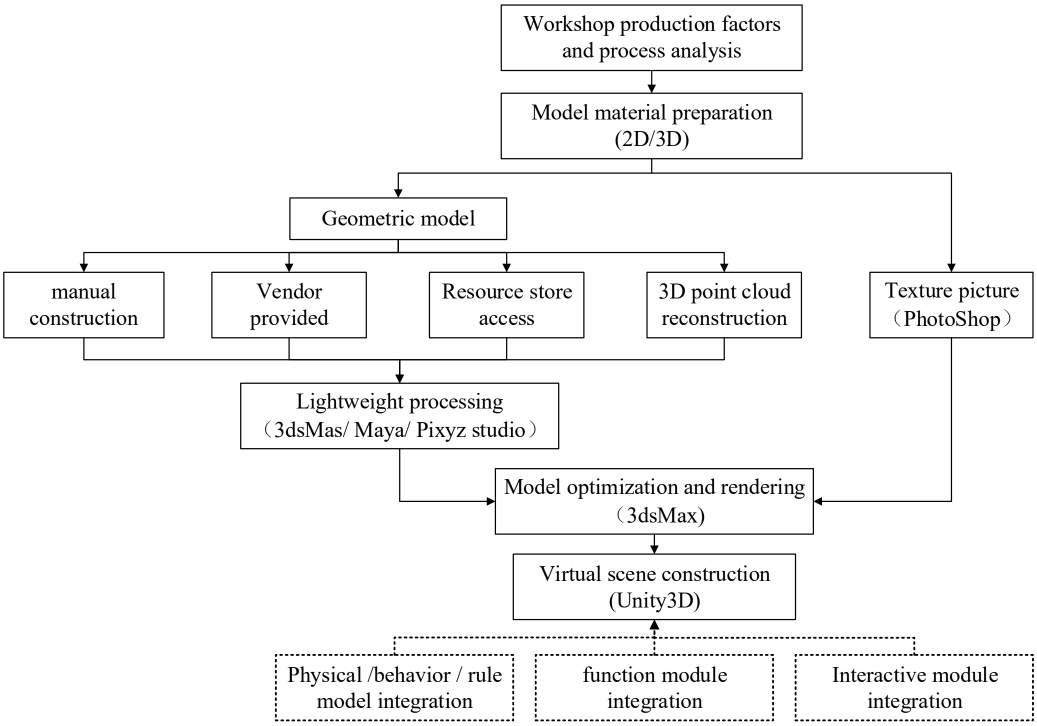
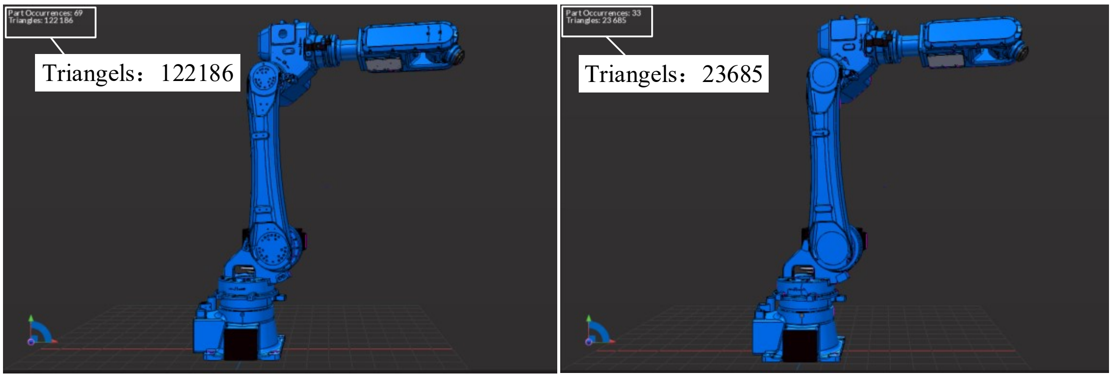


Fig. 5. Virtual scene construction process of DTW.

The geometric model can be constructed by laser scanning, manual construction, standard format model files provided by manufacturers, and resource store acquisition. Because there are many workshop models, and the original CAD data usually contain a large number of detailed features, invisible objects and parameter nodes, a large number of polygons will be generated after faceting. In order to reduce the operation load of digital twin system, the geometric models need to be lightweight. At present, the common method of geometric model lightweight in industrial field is to convert CAD model into polygon model for processing. Than, good lightweight processing results can be achieved by merging and reorganizing the model hierarchy, removing small objects and holes, removing invisible structures, decimating polygonal meshes, etc. Among the existing platforms and tools, 3dsmax, Maya and PIXYZ can be used as lightweight tools. Figure 6 shows the lightweight processing result of the robot model. The geometric model was converted to a polygon model. Before lightweight processing, the number of triangles in the model is 122186, and the model size is 8.64M; after processing, the number of triangles is 23685, and the model size is 1.27M. It can be seen from the results that, under the condition of ensuring the good visual effect of the model, the number of model triangles after processing is reduced by about 80%, and the size of the model is reduced by about 85%.



(a) Before (b) After

Fig. 6. Lightweight processing results of robot model.

In addition, 3dsmax, marmoset toolkit, substance painter and other tools can be used for model rendering to improve the visualization effect of the virtual scene. The optimized models are finally integrated in Unity to complete the construction of the virtual scene. Then, the physical model, behavior model and rule model are fused in Unity, and then the system function module and interaction module are added, finally realizing the construction of a complete digital twin system.

4.2. Multi-dimensional Model Fusion

In order to achieve a high degree of simulation of the twin system from appearance rendering to internal operation rules, and to restore the real physical workshop to the greatest extent, it is necessary to integrate the multi-dimensional model of the DTW. The abovementioned "multi-dimensional model" refers to a multi-level digital twin model which combines models of geometry, physics, behavior and rule.

1) The geometry model: Building the modular and expandable geometric model of the workshop often requires modification and secondary modeling on the original model. Modeling is based on the shape and size, geometric features, moving parts, and the assembly relationship and position relationship between the production elements of the physical workshop. For equipment involving motion, the moving parts are split and modeled to lay the foundation for the integration with the behavior model.

2) The physics model: The physical model construction needs to analyze the physical characteristics of the equipment, such as material properties and physical parameters. Physical model fusion is realized by adding model material, setting physical attributes and rigid body attributes, and adding triggers and colliders.

3) The Behavior model: To construct the behavior model, it is necessary to analyze the triggering conditions of each component of the sports equipment and the behavior coupling relationship between each other. Considering the sequence, concurrency and linkage characteristics of the equipment behavior, vector

definition and behavior response rule definition of the moving parts were carried out to drive the geometric model.

4) The rule model: The Rule model consists of workshop equipment association rules, interactive behavior trigger rules, production line operation evolution rules, etc. The rule model and the behavior model are integrated into the script program, and the behavior model is driven by the rule model.

4.3. System Application and Function Integration

Monitoring and remote control are the basic applications of the DTW. These two modules are introduced below.

1) Comprehensive workshop monitoring

Using the DTW system to comprehensively monitor the physical workshop, there are mainly two ways of 2D monitoring and 3D monitoring. The 2D monitoring can display the status information of the equipment and the logistics information of the workshop through the interface. For the key parameters, it can also be transformed into dynamic charts for intuitive display. In addition, the message prompt interface is also necessary for fault alarms and misoperation prompts. 3D monitoring is mainly realized through real-time mapping of equipment, logistics and products. For the equipment that is difficult to simulate accurately, its surveillance video can be connected to the system to realize comprehensive monitoring. In addition, with the development of AR/VR technology, real-time monitoring can also be combined with them.

2) Equipment remote control

Remote real-time control of equipment can effectively improve the efficiency of workshop management and realize deep virtual and real fusion and interaction. Remote control functions can be divided into two types: program control and instruction control. The former can control the transmission, loading, running and stopping of the equipment operating program, while the latter can control the operating instructions of the equipment. At present, the main remote control methods are as follows: (1) Based on external hardware such as external PLC, embedded chip and other ways to modify the PLC program; (2) Secondary development through the secondary development interface, commercial software, SDK and other ways provided by the manufacturer; (3) Commercial hardware solutions. Based on the aforementioned data interaction architecture, this article uses program scripts in Unity to develop the manual data input remote debugging function and G code uploading and loading functions of the machine tool, and simulates a real robot teach pendant to develop a comprehensive remote control function for the robot. Specifically, by designing user interaction interfaces, and adding colliders and trigger conditions to some 3d models in the scene (such as program loading buttons, emergency stop buttons, etc.), the above control functions are realized. In addition, in practical applications, functional modules should be developed according to specific equipment conditions and requirements, and the functional modules should be reasonably combined to avoid conflicts.

4.4. 3D visualization Interaction Module Integration

Compared with charts and video\surveillance, the advantage of the DTW system is to enhance the visual effect through the integration of visualization interactive modules, to achieve a 360-degree monitoring of the workshop, and to provide users with a strong sense of user immersion and interaction .

The Methods to improve the visualization effect of the system are as follows: (1) Add materials or textures to the the geometry model, render the workshop environment and lighting to achieve more realistic environmental effects; (2) Use particle special effects to simulate the effects of water, fire, fog, and air during processing; (3) Add 3D animation to simulate the action and behavior of equipment or personnel; (4) Build the system collision detection module by adding rigid body attributes and colliders to achieve a more realistic action trigger effect; (5) Design great user interaction interface and information display panel.

The methods to enhance the sense of interaction of the system are as follows: (1) Scene roaming. Using scripts to geometrically transform the virtual cameras in the scene, or switch between different virtual cameras, can achieve the effects of scene roaming and changing perspectives, so that users can comprehensively monitor the workshop. (2) Human-computer interaction design. The interaction between the user and the system can be realized by designing the interactive interface and adding external input event response. In addition to the two most basic input methods, mouse and keyboard, interactive methods such as touch, voice, and gestures are gradually being used. (3) AR/VR support. Under the architecture of the DTW, with the help of technologies such as AR, VR, and the Internet of Things, an immersive experience can be provided to achieve deeper human-machine interaction.

5. Case Study

The proposed DTW system construction method was verified on an intelligent production line of aero-engine impeller prototype processing in Xi'an Jiaotong University. The production line is composed of three machine tools, two sets of industrial robots, one AGV, two sets of material transfer tables, storage units, and auxiliary resources such as manpower, tools, fixtures, and measuring tools.

Based on the methods and technologies described above, the workshop multi-source heterogeneous data were collected and preprocessed. Redis and MySQL were used for collaborative data management, and a data server was constructed for data interaction and transmission, which realized the management and efficient transmission of twin data in the processing process. The workshop virtual scene was constructed by means of multi software collaborative development. C# and JavaScript were used to define the model's custom attributes and event scripts, to build the intelligent production line behavior and rule model, and real-time data-driven twin model was used. On this basis, interactive modules such as perspective switching, scene roaming and user interface, as well as functional modules such as remote control, collision detection, fault alarm and user management, were developed to realize the integration of DTW system, as shown in the figure7.

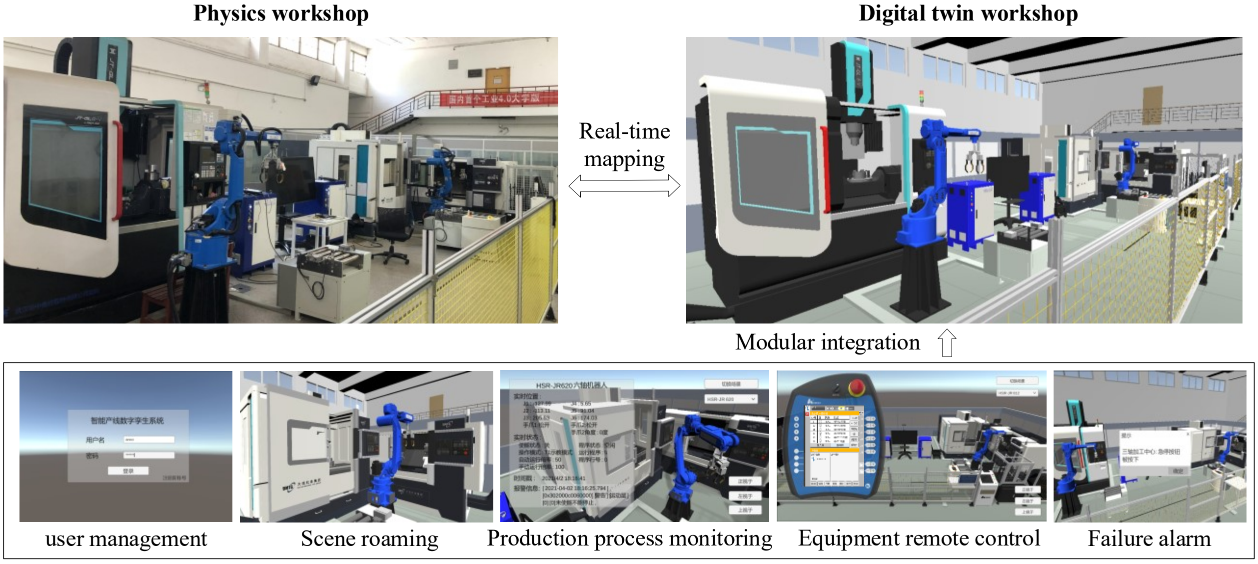


Fig. 7. Application of DTW system in an intelligent production line

The built digital twin workshop system was experimentally verified and the data transmission efficiency was tested. After many tests, it is concluded that the system delay time is always less than 400ms, which achieves the purpose of real-time mapping. To sum up, the constructed DTW system effectively solves the problems of chaotic workshop data management, insufficient workshop monitoring and equipment management capabilities.

6. Conclusion

With the rapid development of intelligent manufacturing, smart factories and digital workshops have become an inevitable development trend in the field of industrial manufacturing. Therefore, DTW have also become the focus of research. Aiming at the status quo that the existing research mostly stays in the "digital shadow", this paper proposes a general theoretical framework and implementation method of the DTW. By constructing an efficient and feasible data interaction architecture, and studying the mapping subjects, methods and key technologies, the comprehensive mapping between virtual workshop and physical workshop is realized. Through the construction of workshop virtual scenes, the integration of multi-dimensional models, and the integration of functional modules and interactive modules, a high-fidelity DTW system is constructed. This method has good adaptability and scalability for small and medium-sized workshops and production lines, which can provide support of data management, monitoring of the production process, remote control of equipment, and more workshop applications for more application of workshop. With the continuous development of 5g, artificial intelligence, big data analysis, physical simulation and other technologies, future work will focus on efficient data transmission and deeper simulation of equipment physical characteristics.

7. Acknowledgements

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