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RESEARCH ARTICLE

Establishment of Web-Based Digital Twin System for Truss Gantry Crane

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ABSTRACT The concept of digital twin intends to establish a real-time mapping between physical and virtual spaces, which individuals can use for real-time monitoring and remote control of product operation. This paper presents a web-based truss gantry crane digital twin system. It elucidates the gradual design process of a web-based digital twin system for analyzing the structural performance of heavy equipment. The construction of a six-layer architectural framework for the digital twin system involves an analysis of its components and motion relationships. Sensors perform data collection to provide data support for real-time mapping of digital space to physical space. The setup of an Express server and the integration of routing files accomplish the data collection, transmission, and processing of the communication system, thereby avoiding a decrease in operational efficiency due to data read and write operations and making full use of the server's capabilities. Use Chrome V8 engine to build 3D visualization space based on HTML and Three.js. Users only need to install a browser to log in to the system at any time and any place to carry out the corresponding operations. Upgrade and maintenance of the system is realized through the operation of the corresponding server, which greatly reduces the maintenance cost.

INDEX TERMS Truss gantry crane, digital twin, express server, Three.js.

I. INTRODUCTION

In recent years, Digital Twin (DT) technology [1], [2], as an important part of cyber-physical systems (CPS). Digital twins are widely used in manufacturing and other industries due to their advantages of dynamic consistency [3], virtual-real interactive feedback [4], [5], and broad application prospects [6]. However, in the digital twin system for industrial Internet, there are still many problems in real-time information interaction [7], virtual-reality synchronisation [8], [9] and mutual control [10], etc. Exploring and researching these key technologies is of great significance for the digitalization and intelligence of industrial equipment [11], [12]. With the continuous development of science and technology, truss gantry cranes are widely used in manufacturing due to the advantages of strong carrying capacity, easy operation, and taking up less ground space, and have become an indispensable tool for improving work efficiency, ensuring production quality, and reducing production costs [13].

Most of the truss cranes have problems such as long working cycle, high intensity, and large load fluctuation during operation, and untimely operation monitoring may cause dangerous consequences [14]. With the release of a series of policies related to safety, operating environment and digital transformation. In order to ensure staff safety, realize the smooth operation of truss gantry cranes, and further improve the degree of automation to realize remote control, it is necessary to carry out real-time monitoring of its operational status and make dynamic safety assessment, and reduce the risk of failure of truss cranes.

Traditional monitoring methods mainly include: Visual inspection: check whether there is obvious wear, cracks, deformation or other damages by visually observing the crane

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components; Sound detection: judge the working condition of the crane by listening to the sound produced during its working process. Abnormal noise may mean that a component is malfunctioning or worn out, requiring further inspection; Safety device detection: check the crane's safety devices, such as limiters, heavy load protection devices, etc., to ensure that they are working properly and that the crane operates within a safe range, etc. Although these traditional monitoring methods can monitor the operating status of the crane and possible problems to a certain extent, they usually require offline inspection or regular manual operation, and cannot achieve real-time, automated monitoring [15]. The introduction of digital twins into industrial equipment inspection can be an effective solution to the above problems. Digital twin can simulate the actual equipment operation state and monitor the problems occurring during equipment operation, make timely responses and adjustments, so as to improve the reliability of equipment operation; It can obtain a large amount of information from the model, such as equipment parameters, sensor data, etc., and compare it with the expected operation, so that it can be quickly diagnosed or even automatically corrected when equipment problems occur, thus improving the efficiency of equipment maintenance; It can be Provided real-time equipment, health assessment and prediction based on equipment models and big data analysis. By monitoring information such as equipment sensor data, equipment condition, and operating parameters, it is possible to predict potential failures and take appropriate maintenance measures to avoid downtime and production delays before equipment failure occurs [16].

Many scholars have conducted in-depth research on operation and maintenance management [17], process monitoring [18], [19], and condition prediction [20], [21] based on the basic concept of digital twin [22] and using related technologies [23], [24]. Ritto et al. constructed their digital twin system for the detection of structural damage using machine learning analysis and analyzed the effect of several parameters, such as velocity, on the accuracy of the digital twin, which is informative for the detection of structural damage [25]. Ali et al. proposed a digital twin framework to support human-computer collaboration for design, construction and control [26]. Fei Tao et al. proposed an emerging DT technique for complex devices to achieve physical-virtual fusion. A generalized numerical model of complex devices is constructed and a new approach based on DT-driven prediction and health management is proposed. The interaction mechanism of DT is effectively utilized with data fusion [27]. Siemens has placed digitalization at the heart of its new corporate strategy, along with electrification and automation, with the launch of its new analytics platform [28]. Using IoT, AI and other technologies, the digital twin can monitor and optimise the production process in real time, reduce energy consumption and waste disposal costs, and reduce the impact of the business on the environment. Moreover, the digital twin system can monitor the status of equipment and production lines in real time, and through data analysis and simulation, it can predict potential malfunctions and equipment failures, and carry out repairs and maintenance in advance, which can reduce unexpected malfunctions and down times, and improve the availability and productivity of equipment [29].The above study shows that the use of digital twins has good results compared to traditional operation, management and fault prediction [30]. However, digital twins are dynamic rather than static [31], so the real-time and compatibility of data transmission is yet to be challenged [32]. Involving the historical operation data of the equipment, the cache of real-time sensor acquisition data, the cache of real-time analysis and calculation results of the equipment structure and performance information data, as well as the corresponding model resource files, it is very difficult to deal with [33]. Secondly, in terms of software, digital twins require various types of software to work together to achieve rapid output of data as well as analysis and processing, which involves a huge amount of computation.

To address the above problems, this paper proposes a Web-based digital twin system for truss gantry cranes. The main contributions of this paper are as follows.

- In response to the demand for real-time monitoring of the performance of truss gantry cranes, each component of the digital twin performance monitoring system is planned, which contains three parts: physical entity model, sensor and communication system, and digital space. Web-based Browser/Server (B/S) architecture is chosen for the construction of the digital twin system. A six-layer architecture of the twin system is built from three components. The physical entity part of the digital twin system for truss gantry cranes was built and sensors were arranged at reasonable locations based on finite element analysis. It provides data and hardware support for the realization of the virtual-reality interaction of the digital twin system for truss gantry cranes.
- The development environment was configured and the basic framework was constructed for the communication module of the digital twin system for truss gantry cranes. Completed data acquisition and transmission based on Modbus and WebSocket, and developed remote synchronous control communication network for truss gantry cranes to meet the communication needs of digital twin virtual and real mutual control.
- Using a browser engine in the 3D visualization scene, the Three.js 3D graphics library based on HTML5 as well as WebGL achieves real-time mapping of twin models to solid models in digital space. Demonstrates the extreme position and Overload warning of lattice gantry cranes, real-time view of the sight screen, and remote control.

The article is structured as follows: chapter 2 describes the general framework of the crane digital twin system and the building of the physical entity part. Chapter 3 builds the communication system part of the gantry crane digital twin system. Chapter 4 verifies the feasibility of the digital twin

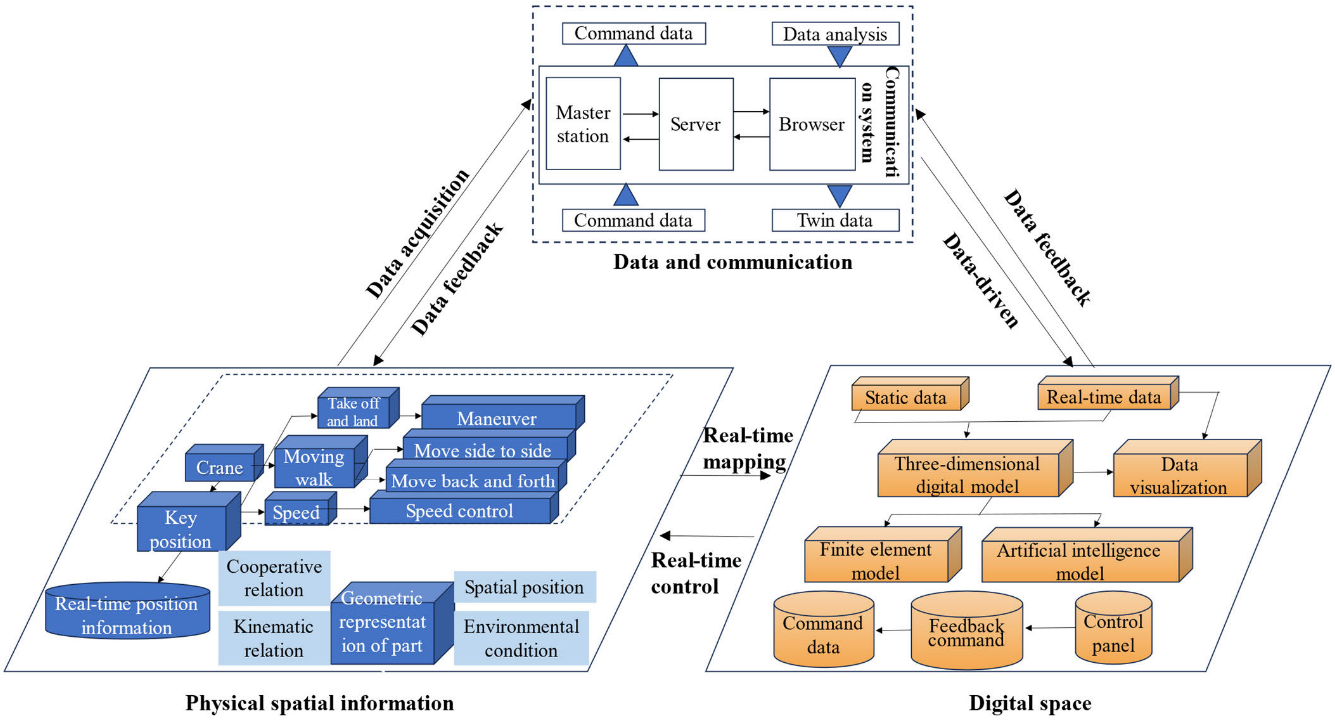


FIGURE 1. Digital twin system architecture design.

system for truss gantry cranes. Chapter 5 summarizes the whole paper.

II. OVERALL FRAMEWORK DESIGN AND PHYSICAL SPACE CONSTRUCTION OF DIGITAL TWIN SYSTEM FOR LATTICE GANTRY CRANES

The physical space consists of the physical entity of the truss gantry crane, the basic control unit, the communication lines and the data acquisition equipment. The components of the truss gantry crane are analyzed to determine their inter-relationships and movement patterns. By arranging sensors to collect the position of each component and the physical information of key parts, it provides data support for real-time monitoring of the position of truss cranes and the performance of key parts.

A. SYSTEM ARCHITECTURE DESIGN

The digital twin system of truss gantry crane is to monitor the real operational status of this equipment in real time in the digital space through digital twin technology, and to achieve the purpose of controlling the physical entity through the mapping model of this equipment. The structure of the system as shown in Figure 1 is mainly divided into three parts: physical space, communication system, and digital space.

In the physical space, the real-time operational data of the truss gantry crane is collected by arranging sensors to obtain the position information of each component. This includes analyzing the fit and motion relationships of each component to achieve reliability monitoring of truss gantry cranes. A communication interface is reserved in the control system of the truss gantry crane to receive control commands from the digital space.

The role of the communication system is to connect the physical space with the digital space. By establishing high-speed network communication, the collected data can be transmitted to the digital space, and the control commands from the digital space can also be sent down to the control system of the truss gantry crane. Create different masters based on different functions as well as different data sources. Data transfer between the master station and the physical devices is carried out via the MODBUS-RTU communication protocol. Supports one master to control multiple slaves and can realize continuous data collection. A routing program is used between the master and each port of the server to pass the data from the master to the specified port of the server. The server can also issue commands to specific masters, which in turn control the device. The server and the digital space are connected via the WebSocket protocol and allow the server to actively push messages to the browser side for real-time data transfer.

The digital space mainly consists of a digital twin model of a truss gantry crane and a remote control panel. Therefore, the geometrical position of the components should be constrained in the digital space, and their mutual cooperation relationship should be set so that the twin model can completely map the real operation state of the truss gantry crane. The twin model also includes data analysis of its structural properties, using 3D rendering techniques to characterize its structural performance information using 3D cloud maps. Stress data collected through sensors at critical locations will

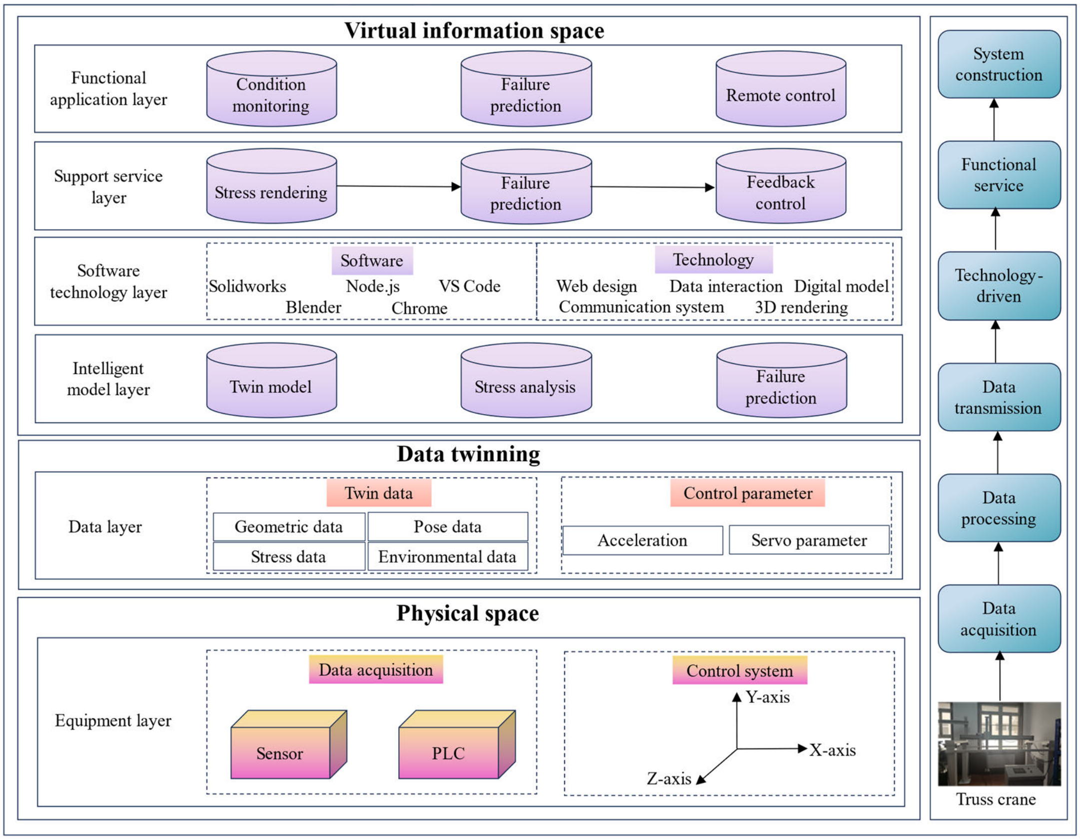


FIGURE 2. Six-layer architecture of digital twin system.

be visualized in digital space. It is also possible to issue control commands through the remote control panel in the digital space within certain permissions, which are transmitted to the control system of the truss gantry crane to complete the operation of the truss gantry crane.

B. SYSTEM ARCHITECTURE

Through the design of digital twin system architecture for truss gantry cranes, the two-way mapping between digital space and physical space is realized. The system adopts a B/S architecture model, based on which the system developed has good compatibility, scalability and portability. Users can manipulate the digital twin model for the purpose of manipulating physical entities, as well as monitor the entire lifecycle of a truss gantry crane, utilizing the advantages of the digital twin as much as possible. Users only need to install a browser to log into the system anytime, anywhere to carry out the corresponding operations, and the system upgrade and maintenance can be realized only on the corresponding server operation, greatly reducing the maintenance costs.

From the overall analysis, the overall architecture of the digital twin system for truss gantry cranes is divided into three parts: physical space, data twin and virtual information space. The six-layer architecture of the digital twin system for truss gantry cranes is shown in Figure 2.

The first is the physical space layer. The device layer consisting of the truss gantry crane body as well as the sensors is the basis for building the digital twin, which is the underlying object and data source of the system. The device layer has the function of real-time data acquisition and transmission, senses the structural state of the equipment, operational performance and other parameters, and also receives commands from the model layer to complete the feedback control of the digital space to the physical entity.

Next is the data layer. The truss gantry crane data platform composed of geometric data, position data, control system parameters, performance parameters, etc. is the core of the whole twinning system and the key to the normal operation of this system.

The third layer is the virtual information space. It consists of intelligent model layers, software technology layer, support service layer, and functional application layer. The intelligent model layer is integrated with the twin model of the truss gantry crane, the twin model simulation data, and the twin model warning module. The software technology layer provides technical support for the digital twin system, mainly including digital twin web interface design, virtual model modeling technology, 3D rendering technology, virtual reality data interaction technology, and communication technology. The software required includes Node.js, Visual Studio Code, etc., to support the program writing and running environment of the twin system. The data communications-based support service layer is the basis for realizing virtual reality simulation interaction. The functional application layer integrates and encapsulates the above service layers to form a set of user-oriented digital twin interfaces that provide users with visualization and functional services.

C. PHYSICAL SPACE CONSTRUCTION

The physical space consists of the physical entity of the truss gantry crane, the basic control unit, the communication lines, and the data acquisition equipment. The components of a truss gantry crane are analyzed to determine their mating relationships as well as their movement patterns. By arranging the sensors to collect the information on the position of each component and the physical properties of the key parts, it provides data support for real-time monitoring of the position of the truss crane and the performance of the key parts.

The truss gantry crane is mainly used for the handling of objects, which has the advantages of large load, high displacement accuracy and short operation reaction time. This paper takes the experimental truss crane as the research object, and its various component structures are shown in Figure 3.

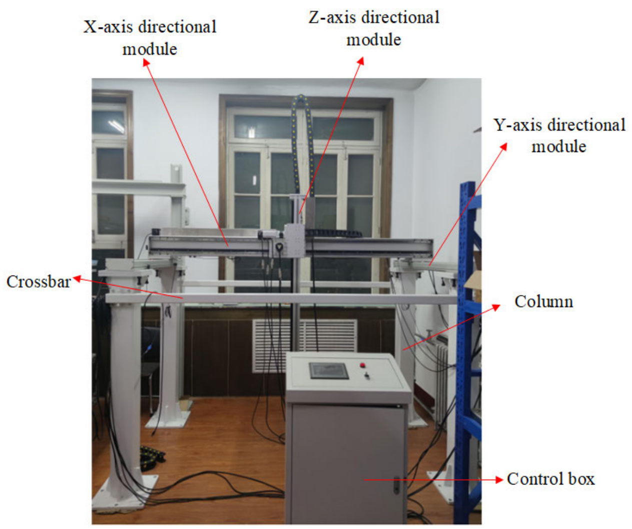


FIGURE 3. Structural composition of truss crane.

From the above analysis, it can be seen that the truss gantry crane completes the lifting and moving operation by controlling the corresponding motor during the lifting and handling process. The slide of the Z-axis direction module is fixed to the slide of the X-axis direction, and the guide rail of the Z-axis direction module moves to complete the lifting operation. The slider in the X-axis direction drives the Z-axis for the X-direction handling. The module in the X-axis direction is fixed to two Y-axis sliders. Two Y-axis slide modules are connected to the column.

Sensors are installed in the appropriate locations for data collection throughout the entire process of handling the operations of truss gantry cranes. The motion of the truss gantry crane is analyzed, and the type of sensors selected and their distribution location in the crane are shown in Figure 4.

The positional information of the truss gantry crane is collected in three directions. The X-axis direction and Y-axis direction use a pull-wire type displacement sensor. The X and Y axes require low displacement accuracy, with ranges of 2000mm and 1000mm respectively. The pull-wire sensor is fixed at the origin of the X and Y direction module. Z-axis direction due to the special structure, the use of laser distance sensor, the sensor high precision, the range of 1500mm, to meet the data collection accuracy at the same time, to ensure the smooth operation of the lifting action.

The performance of the X-axis direction module was monitored due to its large span and asymmetric forces. By analyzing the force of the connection of the module in the X-axis direction, the structure is simplified for the convenience of calculation, and the simplified cross-section is shown in Figure 5.

Through the finite element analysis of the simplified X-axis direction module, the force deformation of the module can be visualized. Strain gauges are attached to stress collection to the places with the largest force deformation. As shown in Figure 6, it shows the stress cloud of the X-axis direction module when the Z-axis direction module moves to the mid-span position with a total load of 800N and the stress cloud of the cross-section at the mid-span position.

It can be seen from the stress cloud in the mid-span cross-section that the maximum stress is applied at point A. In order to monitor the performance of the X-axis directional module more comprehensively and accurately, strain gauges are arranged at point A in the span of the X-axis directional module to collect the stress changes at this point. The collected stress changes are displayed in the form of a line graph in the digital space on the one hand, which is convenient for the user to observe; on the other hand, the X-axis direction module is monitored by comparing it with the result of stress calculation at that point under the same working condition.

III. DESIGN AND CONSTRUCTION OF COMMUNICATION SYSTEMS

The digital twin model emphasises the interaction between reality and virtual reality, which can be updated in real time and evolve dynamically. The realisation of digital twin requires the integration of massive data of multiple sources, types and structures generated at high speed, such as physical perception data, model generation data, and virtual-reality fusion data. Therefore, in order to realise the dynamic and realistic mapping of the digital twin model to the physical world, it is necessary to solve the problem of compatibility of high-speed generated multi-source data [34].

In this paper, the Express module is used to build the server, and after the server is built, it is necessary to mount the route file in the server port master programme so that the browser side can quickly and correctly obtain the corresponding server data. Due to the numerous twin data, and has the

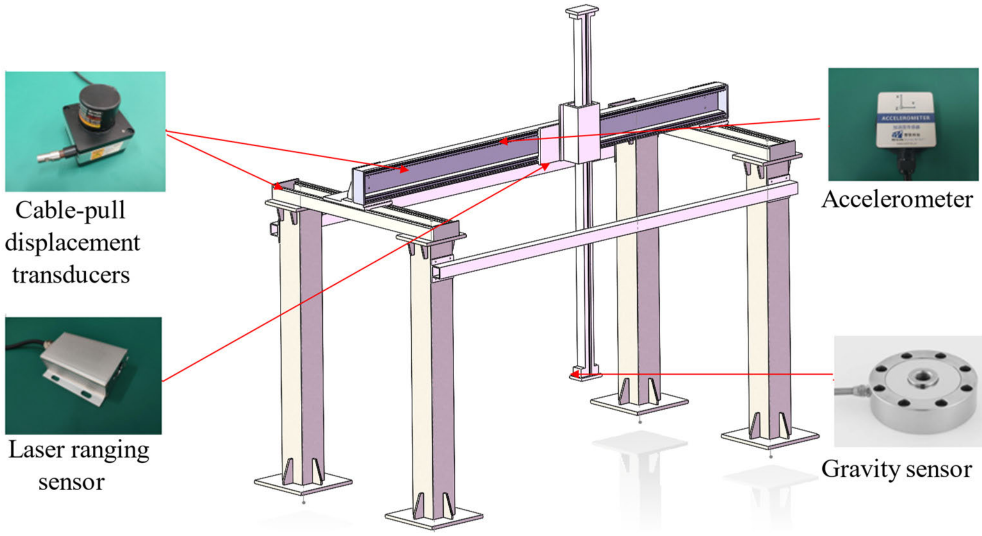


FIGURE 4. Sensor distribution.

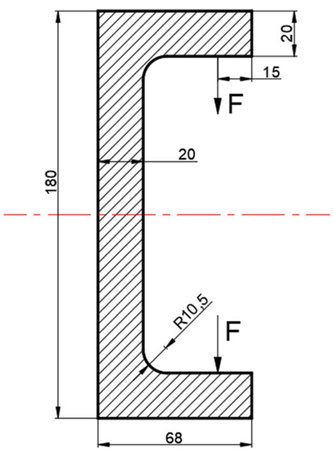


FIGURE 5. Simplified cross-section of X-axis directional module structure.

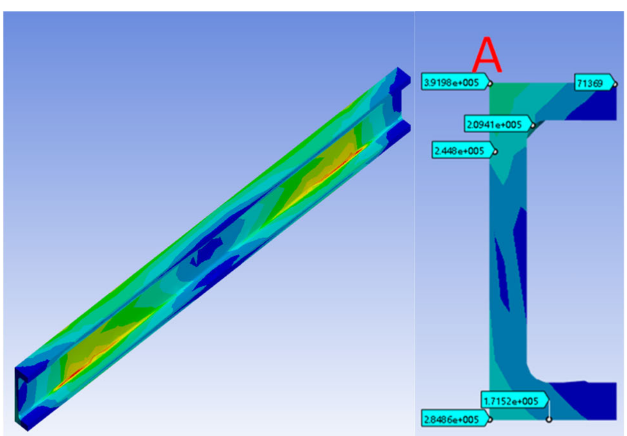


FIGURE 6. Stress cloud of the module in X-axis direction.

characteristics of multi-source heterogeneous. In order to make the procedure more concise and clear, and also to facilitate the later modification and expansion of the project, a server is built for each data source, and a route is mounted on the server port to handle different requests, and multiple servers and routing packets are used to deal with the corresponding data sources, so that data of multiple different types and sources are processed. After the browser side equipped with the digital space twin model establishes a connection with the server side port, the twin model can continuously obtain the data continuously transmitted back from the specified server, thus realising the real-time mapping of the twin model to the physical entity model. Solve the problem of compatibility of massive data from multiple sources, types and structures of digital twins.

A. COMMUNICATION SYSTEM DESIGN

The design of a digital twin communication system for truss gantry crane is shown in Figure 7. It consists of four parts: physical entity, master, server, and client.

There are three main components in the communication system, first, the serial communication between the physical entity and the master, second, the routing communication between the master and the server port, and third, the WebSocket protocol communication between the server and the digital space, which is centered on multiple Express servers. Servers and browser web pages interact with data by using the WebSocket protocol, which undertakes different tasks such as data computation, data transmission, and instruction issuance, and is an important part of data interaction between physical entities and digital space. Clients include computers, cell phones, etc. Users can open the Web-based digital space human-computer interface through the browser, and conduct remote monitoring and remote control of truss gantry cranes through the visualization interface and remote control panel.

Each sensor distributed on the truss gantry crane is connected to the master station through serial communication,

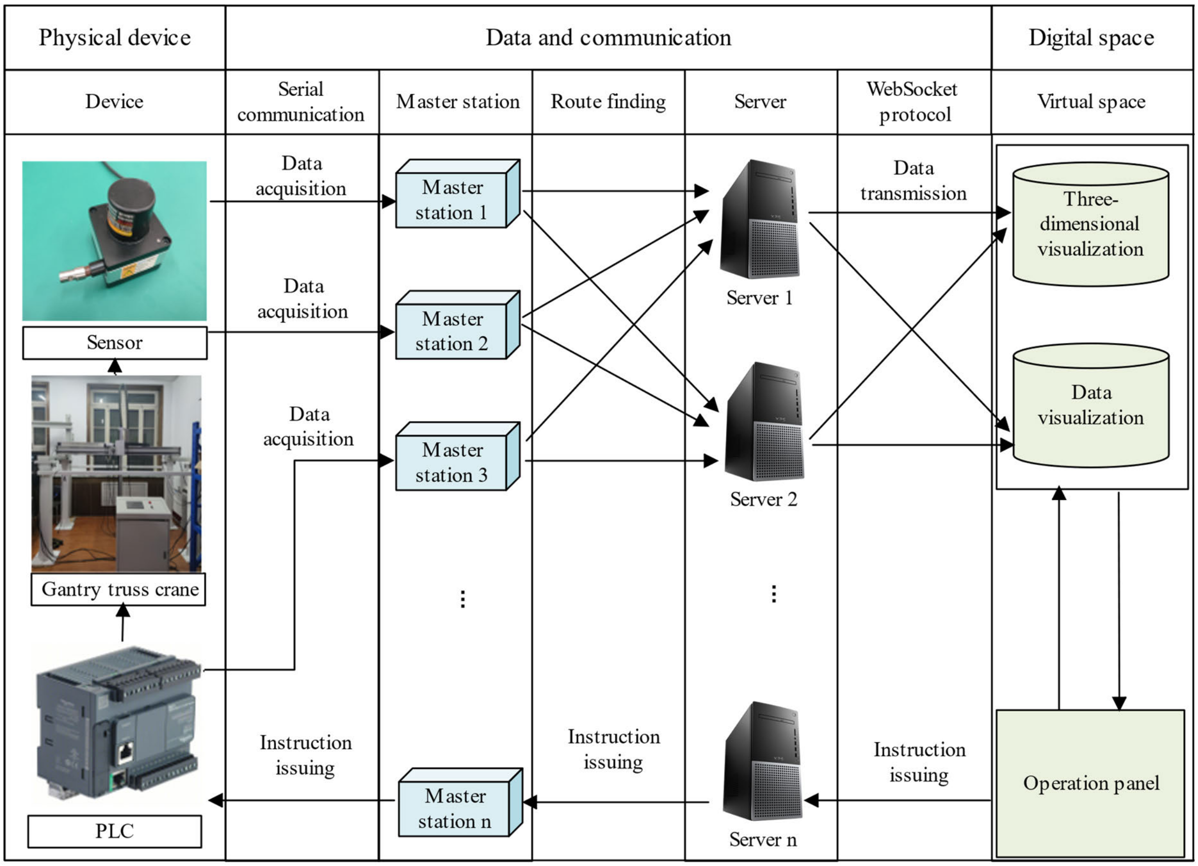


FIGURE 7. Digital twin communication system.

and the parallel master station with multiple channels is set up to make the communication data transmission stable. The multi-directional displacement data collected by the sensor and the X-axis direction module stress data are processed and transmitted. After furthering processing and format conversion of the collected data, the master station transmits the heterogeneous data from multiple sources to the designated ports of the server through routing pathfinding. The server will receive the data through the WebSocket protocol to the digital space to synchronize the operation and displacement control. Users can give motion commands to the digital twin model and the control system of the truss gantry crane from the remote control panel of the human-computer interaction interface in the digital space, and then control the truss crane to form a closed-loop control process, so as to realize the virtual-real interactive communication in the process of digital twin.

B. DEVELOPMENT ENVIRONMENT FOUNDATION

Node.js is a runtime environment for the JavaScript programming language, and its core language interpreter uses the Google V8 JavaScript engine. The platform is event-driven, and the asynchronous non-blocking I/O interface greatly improves the efficiency of program operation. The processing technology of asynchronous event-driven I/O mode in Node.js solves the problem of slow network data transfer and greatly improves server-side performance. The platform's main thread running mode is a big loop that handles various events. The developer analyzes the logic of event occurrence and registers the callback function for each event, and its callback function is put into the execution queue after the event occurs. I/O operations are run using asynchronous events and multi-threading. When the developer performs an I/O operation, it will be actually executed in the internal I/O operation thread, and then its callback function will be put into the event queue when the execution is finished. I/O operations do not block the main thread, avoiding operational inefficiencies caused by reading and writing data, and fully utilizing the server's capabilities. In summary, the Node.js platform based on event-driven and asynchronous non-blocking I/O is suitable for the development of servers with a large number of user connections and real-time reads and writes.

Express is a Node.js-based Web application framework. Express not only in the original HTTP module based on the expansion of more basic features, but also provides a framework for the development of network applications. Using this framework for development, there is no need to write code for routing, requests, and so on. On the basis of the framework, it is possible to focus more on the code writing of the application function implementation program.

Due to the Express framework design is simple, flexible and functional, can be quickly developed modular Web applications, and the use of JavaScript will be the server architecture.

The digital twin system for gantry truss crane is built based on the B/S architecture to achieve two-way communication between digital space and physical entities. Calling serialport package in node.js environment to establish different masters based on different functions and different data sources, the master is deployed on express server. Various types of sensors are different slaves. The master creates the corresponding query message and sends it to the slave devices, which perform the corresponding operation according to the function code and generate the corresponding response message back to the master. In order to meet the needs of two-way communication and real-time, the data collection and transmission method based on Modbus and WebSocket protocols is used to achieve data interaction from the truss gantry crane to the twin model. The communication timing between the twin model and the lattice gantry crane based on Modbus and WebSocket is shown in Figure 8. Modbus is a kind of stateless communication with request/response frame function between master and slave. Modbus RTU is one of the master-slave communication modes, and the communication interfaces adopt RS485 and RS232, and the communication content adopts formatted hexadecimal word messages. The transmission is carried out in data frame transmission mode, where each frame starts with an address code and ends with a parity bit [3]. The protocol covers two communication stations, master and slave, and there can be more than one slave. The slave station transmits the real-time operational data collected from the truss gantry crane back to the server. After the Chrome V8 browser side equipped with the digital space twin model establishes a connection with the server port, the corresponding routing file is configured between the port and the master station, and the twin model can continuously obtain the data continuously transmitted back from the specified master station, so as to realise the real-time mapping of the twin model to the physical entity model. Add a function to the digital twin space in the node.js environment to establish the maximum travel of the crane and the maximum permissible stress value of the main beam in the function. When the limit sensor is triggered and the stress data collected by the strain gauges at the danger point of the main beam exceeds the maximum permissible stress, the colour in the web model will change, and at the same time the program pops up an alarm message to achieve the limit position of the crane and the overload warning.

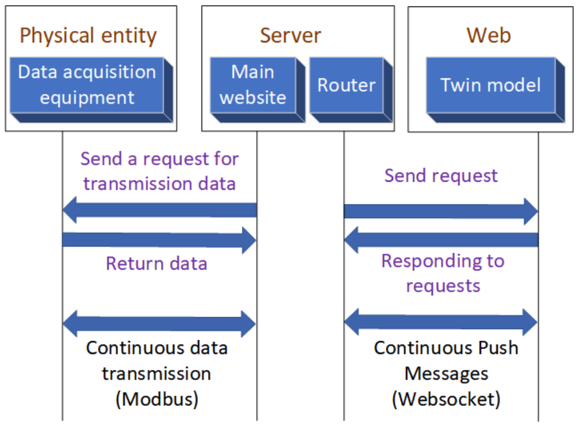


FIGURE 8. Data acquisition transmission based on.

C. DIGITAL TWIN NETWORK COMMUNICATION CONSTRUCTION

The implementation of digital twin network communication mainly includes server building and configuration of routing files, data collection and transmission based on Modbus and WebSocket, and remote synchronization and control of communication network. The core of the digital twin network communication system is the server module, which can provide HTTP request service with customized ports. Configuring the information interaction between the server port and the master station through the routing module can solve the path problem of request and response in a more convenient and concise way. The flowchart of the server building process is shown in Figure 9 below.

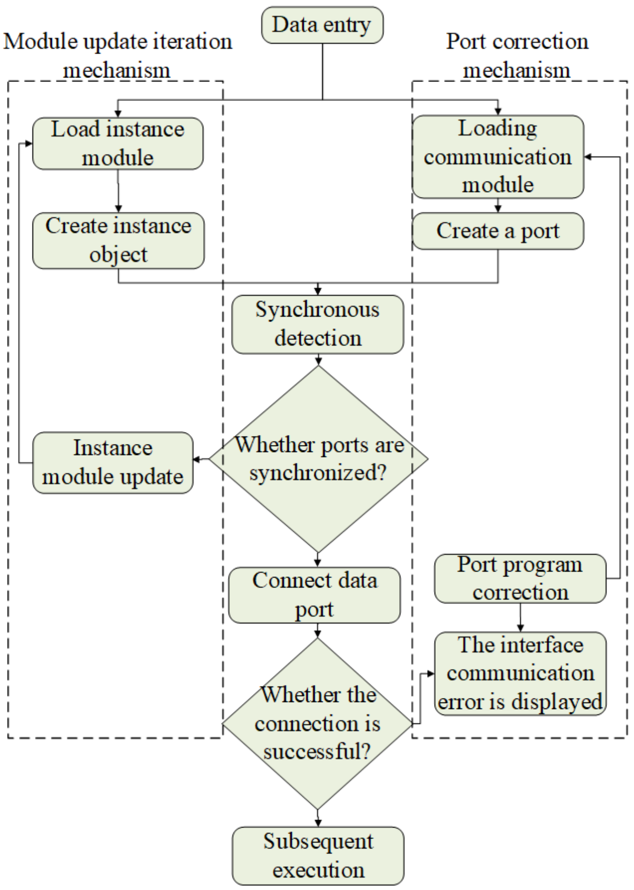


FIGURE 9. Server building process.

- Load modules:

First download the modules used. After the download is complete, the downloaded file is called by a wrapped require function. The modules used for the server module are:

a)Express module: Express has a powerful server building capability, using the express framework for development.

b) Express-ws module: Express-ws is an extension of the express module, based on the express framework, the Web-socket protocol is encapsulated, making it faster and easier to build servers.

c) Router module: mainly used to monitor the request for path resolution and event processing.

- Creating instance objects:

Create a server instance object and then execute the loaded express-ws module, passing in the instance object app, which allows calls to the WebSocket protocol wrapper functions in the current instance.

- Create ports, configure HTTP request methods:

Developers can choose to create one or more ports. Configuration for handling HTTP requests after port creation is complete. Since express provides modular routing, it is sufficient to mount a custom routing module on the instance object, and the response to the corresponding request is done in the routing module.

- Start the server:

After completing the above steps, listen to the created port. Set up a callback function that can send data to the browser side or read commands from the browser.

After the server is built, the route file is mounted in the server port master program so that the browser can quickly and correctly obtain the corresponding master data. Due to the large amount of twin data and the characteristics of multi-source heterogeneity, in order to make the program most concise and well-organized, it is also convenient to modify and extend the project at a later stage. Mount a route for each server port for handling different requests. Here to request the X-axis direction position data as an example, the entire request response process is shown in Figure 10. The browser accesses the specified server and port number, and the corresponding routing module passes the request to the specified routing instance object based on the resolved path. The routing object loads the location routing file and sends the location data, which is set as a global variable, to the browser via a function for assignment.

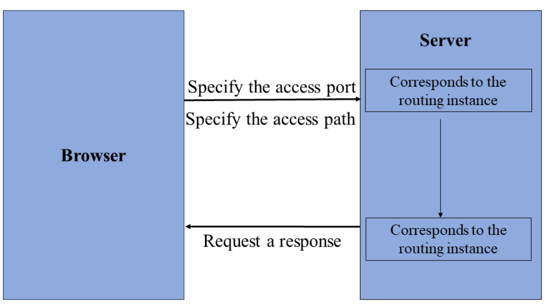


FIGURE 10. Request response process based on routing module Modbus and WebSocket.

D. REMOTE SYNCHRONIZED CONTROL COMMUNICATION NETWORK FOR TRUSS GANTRY CRANE

Remote control of truss gantry cranes is an important part of realizing the interaction between reality and reality. Considering that a server with the function of parsing commands is required for remote control of truss gantry cranes, the communication network architecture for remote synchronized control of truss gantry cranes is shown in Figure 11.

Remote synchronized control communication network for lattice gantry cranes is mainly composed of digital space human-machine interface, control server and lattice gantry crane control system. The digital space Human-Computer Interface (HMI) is a combination of a digital twin model and a remote control panel for truss gantry cranes. The operator transmits operational commands to the control server by operating the remote control panel in the HMI.

The control server mainly realizes listening to remote control commands and sending commands to the truss gantry crane control system. The realization of remote control is mainly accomplished in three steps:

- Clicking on the control button sent by the remote control panel is recognized by the information, and commands are generated and sent to the control server;
- The control server analyzes the control commands it receives;
- After the analysis of the control commands is completed, the master station sends specific control commands to the control system of the truss-type gantry crane.

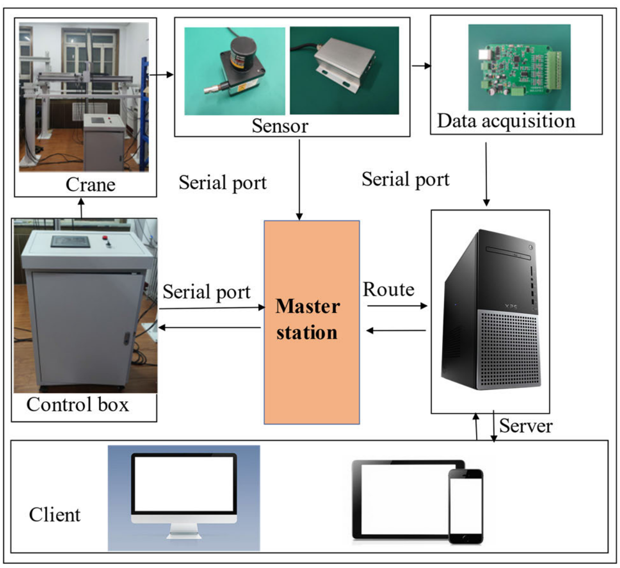


FIGURE 11. Structure of remote synchronized control communication network for lattice gantry crane.

The specific control commands in the control server are determined by the protocols supported by the PLC interface and the communication address of the program.

IV. CONSTRUCTION OF A WEB-BASED DIGITAL SPACE

The digital space is mainly a mapping of physical entities through a variety of information, including the dimensions, properties, and locations of the entity model. Based on twin data, with the help of the browser engine, using the third-party library Three.js, which integrates the WebGL API. A 3D visualization space was quickly constructed and an error analysis of the virtual and real synchronization was performed. Use JavaScript scripting language to build a human-computer interface that integrates 3D visualization, data visualization, on-site screen, and remote control panel.

A. DYNAMIC LOADING OF TWIN MODELS

Three.js mainly through the direct creation of geometric objects and import 3D models to achieve 3D visualization. Building geometric objects directly is done by creating a geometric model internally and loading that model into the scene as a 3D model. The geometric model is rendered using a 3D rendering engine and the results are presented graphically. The advantage is a better display of the details of the objects and materials in the scene. This approach is applicable to the authentic reproduction of real physical world data of the digital twin system, which requires full consideration of the mapping relationship between the digital space and the physical entity data, and full consideration of the data authenticity in the digital space. Therefore, the X-axis directional module adopts this approach to load the 3D model and endow it with performance information, rendering in real time in the 3D scene the state of change of the component's performance in the digital space. External model import refers to importing a 3D model directly from the outside into the scene for observation. Utilizing the object rendering mechanism of Three.js, 3D models in the digital space are dynamically loaded into the 3D scene for observation. The base, columns, and modules other than the X-axis direction module of the twin model of a truss gantry crane are created by importing the model externally. Use the scene editor provided by Three.js for scene creation, and use the GridView component to visualize the digital space.

After the model loading is completed, the mapping of the twin model to the truss gantry crane is achieved by designing its relative position in space as well as the fit relationship. The result of dynamically loading the twin model in the basic scene is shown in Figure 12.

B. DATA-DRIVEN DESIGN FOR TWIN MODELS

The twin model in the digital space is updated in real-time driven by the data obtained from the acquisition and computation. As shown in Figure 13, there exists a script-controlled connection mapping manager under the digital twin space that is used to combine the data table connections in the database and read the data collected from the physical space

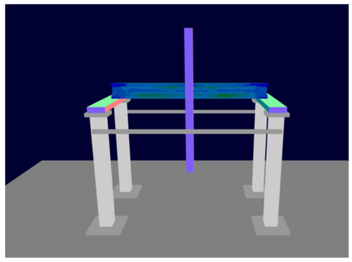


FIGURE 12. Importing 3D models in digital space.

for unified management. Associate the data with the twin model according to the device attributes corresponding to the data table and the connection configuration selected by the user when loading the model to drive the motion simulation of the twin model. The position information is measured by the sensors, the speed information is obtained from the truss gantry crane control system parameter acquisition, and the performance information is analyzed by the finite element analysis of Ansys software, which will export the data and process them.

After establishing the 3D scene of the crane in the form of internal creation and loading GITF model, the dynamic process of moving the crane in three directions is demonstrated. The realization of the animation relies on the Tween.js library.

After the dynamic loading of the twin model in the digital space is completed, the relevant settings are made for the motion of its simulated physical entities. After the communication system program is run, the connection for data acquisition and transmission based on Modbus and WebSocket is established. The collected data are transferred to the digital space in real time to realize the virtual-reality synchronization between the twin model and the physical entity model. And the twin model renders the stress data under the current operating conditions as a cloud map through a custom model shader. Figure 14 (a), (b) and (c) shows the mapping diagrams corresponding to the digital twin model when the truss gantry crane performs moving actions in the X-axis direction, Y-axis direction and Z-axis direction, respectively.

C. VIRTUAL REAL SYNCHRONIZATION TIME ERROR ANALYSIS

The time error is analyzed by calculating the time used by the module in the Z-axis direction to move a certain distance in the X-axis direction, the time used by the digital twin model to map the solid model to update the loading, and calculating the difference for comparison to carry out the analysis of the time error in the virtual-real synchronization. The time used by the module in the Z-axis direction is found by dividing the distance traveled by the current travel speed. The time it takes for the digital twin model to update and load With Chrome's Page Performance Analysis feature, all files and functions on a web page can be recorded in chronological order from the time the feature is opened to the time it finishes executing.

As an example, we calculate the time required for the digital twin model to update and load when the mapped solid

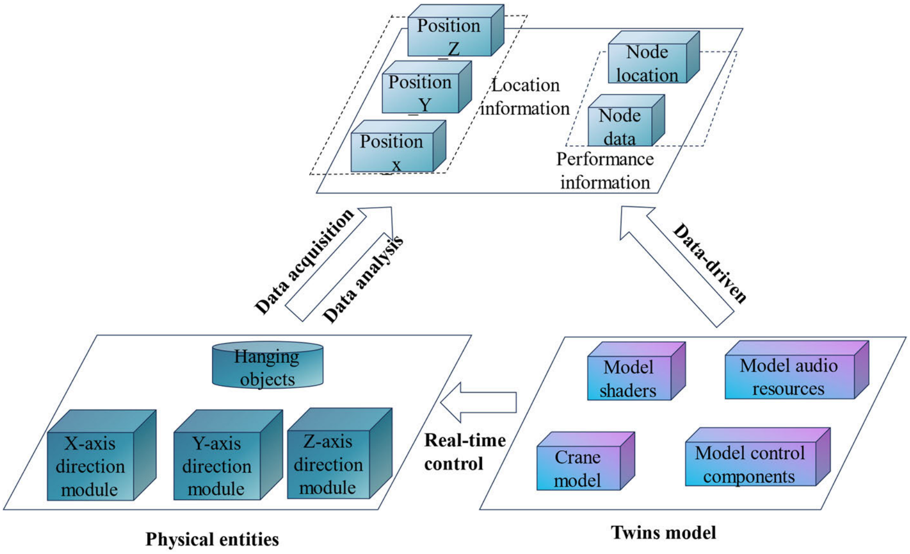


FIGURE 13. Data-driven digital twin model.

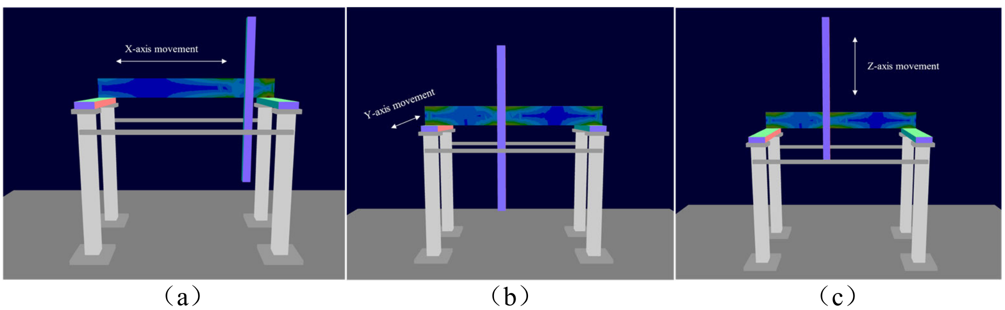


FIGURE 14. Basic motion of the 3D model in the digital twin space1.

model is moved by 1000mm at a speed of 100mm/s. Before generating the performance analysis report, the callback function is set when the X coordinate of the digital twin model of the module in the Z-axis direction is at 100mm and 1100mm, respectively. The first callback function records the time when the motion command is received from the tower, and the second callback function records the time when the motion of the twin model is finished. The time interval between the two callback functions being executed in the performance analysis report is the requested time. The time at which the two callback functions were executed is shown in Figure 15. From the figure, it can be seen that the execution time of the first callback function is 541ms recorded by the performance analysis, and the second time is 11.12s, which can be obtained that the time used when the Z-axis direction module maps the solid model to move 1000mm is about 10.58s.

According to the above method, the time required to collect the Z-axis direction module twin model mapping solid model moving distance of 250mm, 500mm, 750mm, 1000mm, 1250mm, 1500mm, and 1750mm is collected at the moving speed of 100mm/s, 200mm/s, and 300mm/s, respectively. The data results are shown in Table 1 below. The results of the comparison with the actual time taken by the solid model are shown in Figure 16.

From Figure 16, it can be seen that the error time of virtual-real synchronization increases with the increase of moving distance, and the faster the speed, the larger the error time. The time response error at a maximum speed of 300mm/s and a movement of 1750mm is about 0.73 seconds, achieving virtual synchronization in the crane operating environment.

D. LIMIT POSITIONS AND OVERLOAD WARNING

The digital twin system for lattice gantry cranes provides automatic warnings of extreme operating positions and warnings of structural performance failures. The system analyzes and processes the data in the background based on the collected locations. When the crane is overloaded, the limit sensor is triggered or the control system is abnormal, the system actively pops up the corresponding Overload warning, and saves and pushes this warning to the maintenance management personnel. As shown in Figure 17 (a) and (b) are the warning situations when the truss gantry crane triggers the limit switch in the X-axis direction and when the

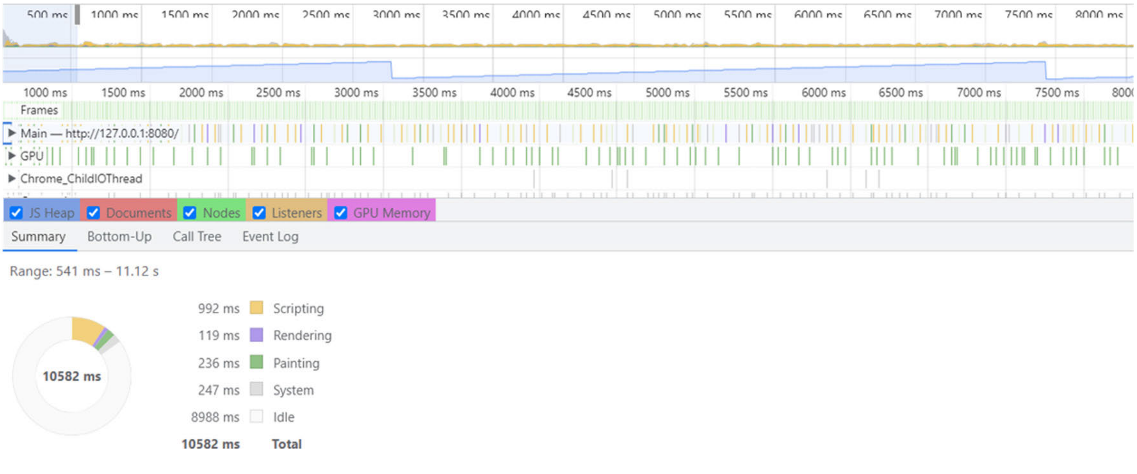
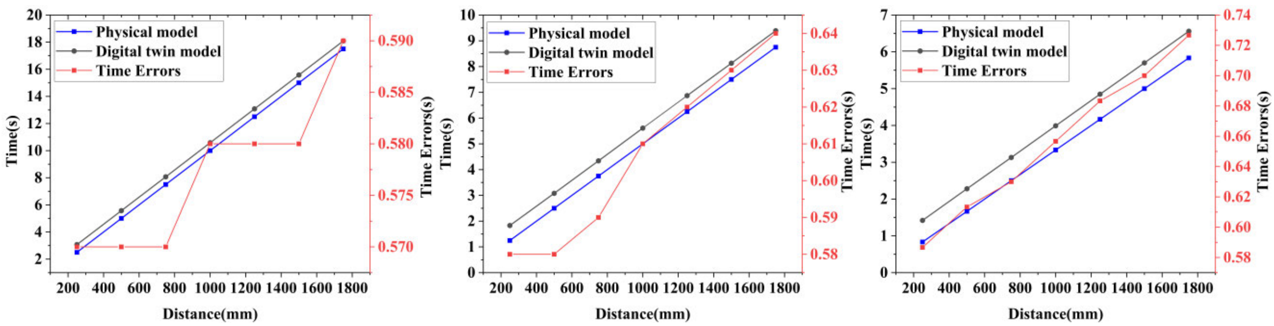


FIGURE 15. Time of execution of the two callback functions.

TABLE 1. Twin model motion time data acquisition results (Unit: seconds).

speed (mm/s)	distance (mm)						
	250	500	750	1000	1250	1500	1750
100	3.07	5.57	8.07	10.58	13.08	15.58	18.09
200	1.83	3.08	4.34	5.61	6.87	8.13	9.39
300	1.42	2.28	3.13	3.99	4.85	5.70	6.56



(a) 100mm/s comparison results (b) 200mm/s comparison results (c) 300mm/s comparison results

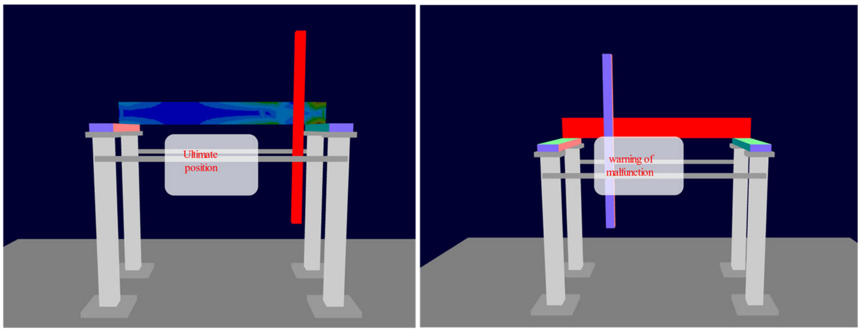
FIGURE 16. Comparison results of runtime between the solid model and the twin model.

current load exceeds the maximum load, respectively. When the truss gantry crane reaches the condition of early warning regarding use, it will automatically pop up a message box in the visualization area of the twin model for the corresponding voice warning. The system uses a combination of HTML5 and JavaScript language to realize the function. Define an audio tag on the web page, when the crane has a security problem, by reading the data file and sound file in the browser, to determine whether it is a dangerous event, if it is a dangerous event, then trigger the corresponding warning sound.

E. WEB-BASED HUMAN-COMPUTER INTERFACE

The UI interface of the digital twin system for truss gantry cranes selects the classic Holy Grail layout in the layout structure, as shown in Figure 18. It is divided into the header title bar, the system management area, the twin model display area, and the virtual reality interaction area.

The header title bar contains the title, the time display control, and the Exit System button. The system management area mainly has functions such as stress display, live screen opening on site, customer feedback, maintenance records, and system settings. The virtual-reality interaction area includes a real-time monitoring bar, a data visualization bar, and a remote control panel bar. Real-time monitoring is achieved by designing an HTML5 client to parse the video data and eventually render the image onto a canvas to display the monitoring screen. The system chooses to use the WebSocket protocol as well as the real-time streaming



(a) Limit position reached (b) Crane overloaded

FIGURE 17. Digital space alert module.

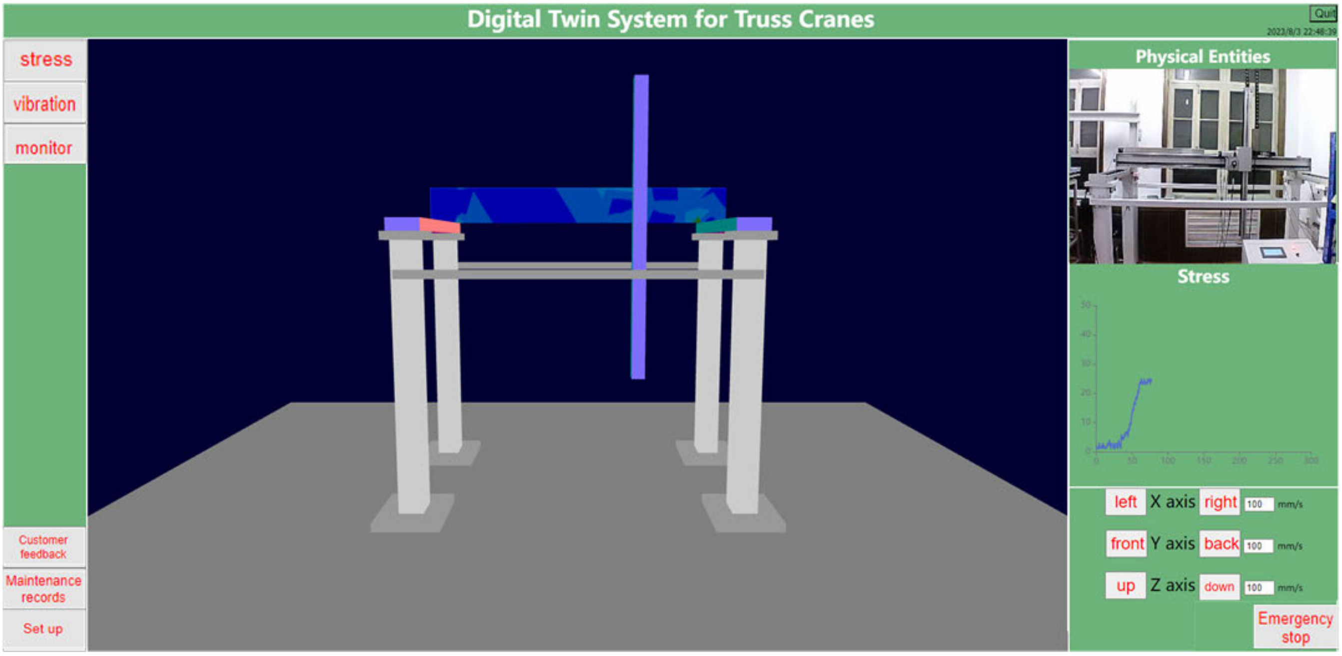


FIGURE 18. Digital twin system UI interface.

media transport protocol RSTP for video data transmission. In the Data Visualization column, use the Echart.js data visualization icon library. The sensor monitors the stress of the X-axis direction module at the mid-span position, analyzes and processes the collected data and converts the format, and then the server transmits the data to the Web visualization interface to display it in the form of graphs. Finalize the design and construction of the UI interface of the digital twin system for truss gantry cranes.

Based on the concept of digital twin, the digital twin system of lattice gantry crane ensures the operation safety of lattice gantry cranes as much as possible by applying the technologies of sensor technology, remote control technology and three-dimensional visualisation technology to record the past data, monitor the present data and plan the future operation trajectory. Construct a virtual display scene that simulates the reality, and make safety warning according to the background judgement by monitoring the real-time position change and performance information, change of the lattice gantry crane in the operation. And through the remote control panel, using remote control technology, you can carry out real-time remote control of physical entities. It greatly improves the informatisation level of the truss crane and provides a new method for realising the digitalisation and intelligence of the truss crane. By building a server multi-access data acquisition, processing and command sending functions of the master station, with rich development interfaces, the system with more functions can be developed quickly. Moreover, by reasonably assigning the correspondence between the master and the port and mounting the corresponding routing file, the system has a good computing and data transmission capability. In addition, the digital twin system based on Web can realise web remote monitoring and control without the constraints of the client.

The system builds 3D visualisation scenarios with an HTML5-based browser engine and the Three.js 3D graphics library for WebGL. The physical model of the truss crane can be replaced with various engineering machines, and its twin model can be built and imported. The real-time mapping between the twin model in the digital space and the solid model in the physical space is realised by combining the real-time operational state data collected from the physical entities by sensors and PLCs, and the structural performance rendered by the twin model in real time. The dynamic load and virtual-real synchronisation errors of the twin model were tested and analysed. The human-computer interaction interface in digital space was designed through JavaScript scripting language, including a remote control panel, which can send commands through buttons, and the synchronous operation of the remote engineering machinery physical model and the twin model. The system is highly versatile in construction machinery.

V. CONCLUSION AND PROSPECT

This paper focuses on the truss gantry crane as the experimental object, with the main research centered around the construction of the components and key technologies of the truss gantry crane digital twin system. The practical application of digital twin has been achieved. To meet the real-time monitoring and control needs of the truss gantry crane, the various components and structures of the digital twin system were planned. A six-layer architectural framework for the digital twin system was established. By analyzing the components of the truss gantry crane, their interrelationships and motion patterns were determined. Sensors were positioned to collect data on the key component poses and load information, and strain gauges were strategically placed based on finite element analysis to gather stress information from critical parts in the X-axis direction module. This provides data support for real-time monitoring of the operating status of the truss gantry crane.

To address the issue of poor real-time performance and compatibility in transferring data between physical space and digital space, a data communication method based on server and configuration routing files is proposed. By configuring the interaction between server ports and the main station through the routing module, it offers a more convenient and streamlined solution to address request and response paths. By setting up the Express server and mounting routing files, the communication system's data collection, transmission, and processing are completed, avoiding efficiency reduction due to data read/write operations and fully leveraging the server's capabilities. The Chrome V8 engine is utilized, and a three-dimensional visualization model is established based on HTML5 and the third-party library Three.js, which encapsulates WebGL API functions. Users can easily log into the system anytime and anywhere with just a web browser. System upgrades and maintenance are achieved through corresponding server operations, significantly reducing maintenance costs. Testing and analysis of dynamic loading of twin model and synchronization error between virtual and real scenarios were conducted to meet the real-time requirements of the digital twin system. Finally, an interactive action involving integrated digital space within the Web environment is designed. This includes presenting stress data from key components of the X-axis module in graphical form, functions for limit poses and Overload warnings, and real-time viewing of on-site scenes, all within a human-machine interaction interface.

In the subsequent research work, various intelligent inspection and maintenance modules, such as a fault diagnosis module, predictive maintenance module and life prediction module, will be gradually added to this system to enhance the data analysis capability of the system and completely solve the technical problem of digital islands. The system will also be gradually applied to different industrial equipment to provide a new direction for future research on industrial digital twins.

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