Design and Implementation of Hardware in the Loop Simulation Operation Simulator for Complex Mechanical Equipment

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Abstract: Hardware in the loop simulation technology is an important branch of system modeling and simulation. With the development of artificial intelligence, big data, virtual reality and other technologies, more and more advanced technologies are integrated into it, and the economic and military benefits are constantly highlighted, which attracts the attention of all parties. In view of the complex structure of modern large-scale mechanical equipment system and the high cost-effectiveness ratio of carrying out practical operation training, an operation simulator is developed by using hardware in the loop simulation and virtual reality technology. The simulator can complete the daily training of mechanical equipment and the interactive operation, maintenance training, assessment and operation data recording of other equipment, and can popularize and update equipment knowledge Improve the technical level and maintenance skills of operators and technical support personnel as soon as possible.

Keywords: Hardware in the loop simulation; mechanical equipment; simulator; economic benefits.

1. Introduction

Modern mechanical equipment has the characteristics of high information level, complex system structure and large configuration area. In the process of mechanical equipment training and scientific research, the number of actual equipment is small, and the personnel can not participate in the actual training, which leads to the problems such as high intensity, long demonstration time and short service life of equipment [1]. When mechanical equipment breaks down in the process of operation and use, it will seriously affect the progress of production and scientific research [2]. Hardware in the loop simulation, also known as hardware in the loop simulation, is an important aspect of system simulation, which is widely used in industrial and military fields. Using the mode of "practical hardware simulation platform" to build the simulation operating system has better real-time performance and smaller difference with the actual operation, which can replace the actual installation to complete the training and research of related subjects. Using simulator instead of actual installation system for operation training can overcome the adverse effects of time, site, weather and other factors. Taking the development of mechanical equipment vehicle simulator as an example, the operation training of related subjects can be carried out without actual installation, so as to reduce the actual loading loss and improve the efficiency. In the working process, the simulator and other equipment constitute a whole.

In addition to completing its own work, the simulator can also be interconnected with other simulation equipment to build a comprehensive operation platform of the whole system for operation training. Fig. 1 shows the simulator of oil and gas equipment vehicle.

Fig. 1. The simulator of oil and gas equipment vehicle.

2. Hardware in the Loop Simulation

Simulation is the activity of experiment, analysis and simulation training by replacing the original equipment or imaginary things with models. With the same principles, modeling ideas and computer technology, models are generated by using real objects or simulators with the support of simulation related technologies and combined with the effectiveness of equipment. Simulation technology is widely used in today's society. The integration of modeling and Simulation in simulation operation process can change the traditional training mode [3].

According to the classification principle of differentiation, the system simulation can be classified into different categories according to the classification standards such as the computer used in simulation test, the characteristics of test system, the consistent relationship between simulation system clock and astronomical clock, mechanism and implementation method. Classification of simulation: simulation is an organic combination of hardware and software for model experiment [4]. Through calculation and solving the generated requirements, targeted research on the internal composition and efficacy of experimental objects, clear methods and steps, can reproduce the original scene model, and analyze the results with this model. From the macro point of view, simulation can be divided into four categories: one is the model simulation of physical device replacing the prototype, such as training simulator and simulator; the second is the analog simulation of the results obtained through experimental analysis, with the help of computer operation technology, the ordinary differential equation is used to describe the dynamic change model of the system, and then compared with the real object; the third is the digital simulation using numerical calculation Logic calculation, queuing problem, etc [5]. will be studied by such simulation; fourth, the compound simulation generated by analog simulation combined with digital simulation is used to model and analyze, which is often operated to find the optimal solution. Hardware in the loop (HILS) is a combination of mathematical simulation and physical simulation, and the hardware part of the test object is connected in the system simulation loop to construct the simulation test system, referred to as HILS. The hardware in the loop simulation system uses mathematical modeling for the simple part of the system, and uses the actual hardware directly for the part with complex system structure, which avoids the difficulty of modeling. Compared with other simulation systems, it can better reflect the function, performance or other indicators of the actual system [6]. Hardware in the loop simulation is a simulation test system between mathematical simulation and physical simulation, and its composition depends on the research object.

2.1. System Hardware and Software

Hardware can be divided into simulation computer, signal generation and excitation equipment, data acquisition and recording display equipment, communication monitoring equipment, power equipment, test object components and other interactive and connecting equipment [7]. The software includes system model software, general software, special software and database. The system model software includes the mathematical model of the test object, the simulation algorithm and the running process of the simulation system [8]. The general software includes operating system, programming language, running environment, graphic development program, general interface communication program, data acquisition and display, etc. The special software includes special algorithm, special interface communication program, etc. The database contains the data development system and various equipment [9].

2.2. System Evaluation and Verification

The evaluation is divided into software evaluation and hardware evaluation. Software evaluation object includes system algorithm, implementation method, running program, test index, etc. hardware evaluation object is mainly test equipment in hardware in the loop simulation system. The evaluation contents include simulation system performance, test index selection, system reliability, availability and confidence. According to the system evaluation results, the hardware in the loop simulation system is adjusted and coordinated to determine the test process [10]. Through the simulation test, whether the hardware in the loop simulation system meets the simulation requirements, whether it meets the simulation requirements, and whether the simulation results have good credibility.

2. Research Status of Hardware in the Loop Simulation

Since the hardware in the loop simulation technology is mature, the performance and real-time performance of several hardware in the loop simulation platforms widely used in the world have been verified [11].

Matlab appeared in the late 1970s. It was originally an interface program written by clever moler, director of the computer department of the University of New Mexico in the United States, to teach students to use EI spark and Li npack program library. It is named matlab (Matrix Laboratory), which is the combination of matrix and laboratory. MATLAB has good openness and reliability, and is highly praised by more and more scientific and technological workers after its commercialization. It has a friendly user interface, rich model library and convenient call process. Users can quickly create the required model block diagram by simply dragging the mouse, and change the parameter configuration according to the test requirements [12].The operation results will be visualized through the oscilloscope or display screen, even if you do not write code, do not understand the computer language, can also carry out modeling analysis and simulation. Up to now, MATLAB has released dozens of versions. It is no longer a simple matrix laboratory, but has developed into a high-level computer programming language integrating real-time control, dynamic simulation, signal processing and other functions. It also has the functions of numerical analysis, graphic (image, text) editing, symbol calculation and mathematical modeling. However, Matlab is a mathematical application software, which needs other tools to complete the construction of hardware in the loop simulation system [13].

DSPACE system is developed by dSPACE company of Germany. It is a hardware in the loop simulation platform based on MATLAB / Simulink. It is committed to the development of control system and realizes the seamless connection with Matlab / Simulink / RTW. DSPACE system has the characteristics of strong combination, good transition, good rapidity, good real-time, strong flexibility and easy to master. Its hardware system is computationally efficient and has a convenient software test environment. It can provide a variety of options for different user needs. It has been widely used in aerospace, automobile, engine, electric locomotive, robot, drive and industrial control fields.

RT-LAB real-time simulation system is a distributed real-time platform developed by opal RT company in Canada. It is also a model-based engineering design test application platform. In general, there are three kinds of system configurations in which RT-LAB is widely used. This configuration is mainly used in fast control principle, hardware in the loop (HIL) control, using virtual object model for hardware controller design and testing, fast simulation, etc. Distributed node system, which divides the complex system model into multiple hosts and performs calculation, is mainly used in hard real-time distributed HIL control, hardware controller design and test using virtual object, and rapid simulation of complex model. Embedded target machine, which runs the tested controller model on the target host, connects external hardware devices, tests and improves the performance of the model. It is mainly used in high-precision simulation, control system prototype, embedded data acquisition and control, etc.

LabVIEW is a kind of virtual instrument software tool based on graphical programming language, which is introduced by national instrument (Ni) Company in the United States. LabVIEW is the core of Ni platform. It uses graphical programming language instead of traditional programming language. It saves about 80% of program development time while running speed and real-time performance remain unchanged. Modular program has better expansibility and interactivity, and is an ideal choice for developing measurement and control system. In order to meet the increasing real-time requirements, Ni is integrating real time (RT) components into the platform. LabVIEW RT is widely used in hardware in the loop simulation system because of its good development interface.

YH astar high-performance real-time simulation platform was developed by Chinese experts for three years. The YH astar simulation platform is based on Intel platform and windows operating system, with yhsim integrated simulation modeling software as the core, and yhsim as the simulation language. It has developed Galaxy simulation model I machine, type II computer and Galaxy super small simulator successively. The advantages of using computer in hardware in the loop simulation, at the same time considering the requirements of scalability and versatility, it is easy to maintain, use and upgrade. YH astar uses special simulation language and is designed for simulation professionals. It has powerful modeling function and high efficiency, and can directly connect external things. The operation of I / O interface has the characteristics of powerful function, rich and friendly interface, easy to use, simple modeling, strong scalability and versatility. The platform supports the construction of continuous system simulation, discrete system simulation and distributed hardware in the loop real-time simulation model, which has been well applied in many large-scale task simulation experiments of many units.

Sea Hawk simulation integrated development environment (Hyside) is developed on the basis of Sea Hawk simulation workstation (hy-rts). Similar to the integrated development environment of other programming languages, Hyside can integrate the pre-processing work, operation interaction and post-processing of simulation language, such as editing, compiling, linking and running of simulation language. The error information can be fed back and displayed through a special window. Hyside preprocesses HYSIM simulation language source program files and interpolation function source files, translates them into FORTRAN program, forms object code file and executable code, and uses macro assembly language of open VMS. The clock function is designed by ourselves, and the absolute time scale is used to delimit the absolute time of the start and end of each frame to ensure the real-time requirement; based on the X font expansion function of X windows, the software core is processed in Chinese, so that Chinese characters can be recognized by the system.

At present, most of the simulation software is based on Windows operating system, Intel processor and MATLAB modeling software. One idea of developing simulation platform based on galaxy Kirin operating system provides reasonable solutions for three key technical problems in the construction of Kirin real-time simulation system, which can be used for reference to the mature construction ideas and methods of YH astar real-time simulation platform to design kylin system The simulation framework of SCW based on shared memory, cyclic cache and real-time disk writing is proposed; the model code of Simulink model library is modified in real time, and the initialization, step, and termination functions of the modified model are embedded into the simulation framework, and the graphical modeling of simulation is realized by combining high-precision time control algorithm, and three key technologies are tested The verification and test provide a method for the research of autonomous hardware in the loop simulation technology [14].

4. Development Scheme of Hardware in the Loop Simulation Simulator

4.1. Design Ideas

The overall idea of the simulator development scheme is: using the combination panel consistent with the actual installation, constructing the basic hardware environment of the system, simulating the internal circuit function of the combination, realizing the logic control of each combination, establishing a realistic human-computer interaction interface (environment), realizing the daily operation and maintenance operation of the equipment. It is composed of hardware in the loop operation subsystem, virtual device subsystem, hardware in the loop component subsystem, interaction subsystem and control center. Each subsystem is connected to form an organic whole through the control center and works under the unified and coordinated control of the control center. The control center is connected with the distributed interactive platform. Fig. 2 shows the composition principle.

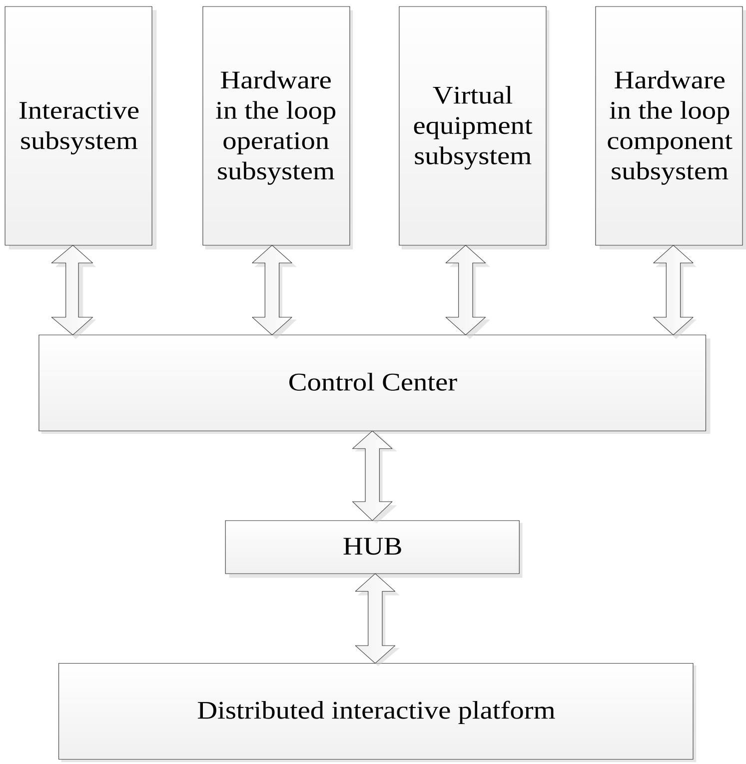

Fig. 2. The composition principle.

4.2. Functions of Each Subsystem

Control center. The control center is the "brain" of the whole system. When the equipment system works normally, the internal relationship of the system is diverse, the fault types are many, and the relationship between them is complex. Therefore, it is necessary to simulate the normal operation state of the control system and the phenomenon when the fault occurs on each simulation subsystem in an all-round and accurate way [15]. The design idea is to divide the whole simulation system into different units with each subsystem as the module, and the units are independent. The control center is the hub of the simulation system. The central control board outputs commands and supervises the switching values and adjustable variables of the operation panel of each subsystem through the network interface to control the operation status of each subsystem and the whole system.

Hardware in the loop operation subsystem. The internal circuit connection of the system is complex, and the functions of different control panels are different. Therefore, the personnel need strong operation ability when they carry out daily operation. When the equipment fails, it will be caused by different reasons. According to the fault phenomenon, it is difficult to eliminate the fault causes in time. When carrying out maintenance operation, it is more necessary to approach the operating environment of the actual equipment [16]. The hardware in the loop (HIL) operation subsystem uses hardware in the loop simulation technology. The control panel is almost the same as the actual equipment in appearance and function, creating a real operating environment. The hardware in the loop operation subsystem is composed of hardware and software according to the operation law of the equipment system. The hardware part is mainly based on the actual operation panel; the software part is mainly concentrated on the terminal to complete the information processing [17].

Virtual device subsystem. Virtual device subsystem is based on virtual reality and computer simulation technology to achieve the structure and composition of the system, the logical operation relationship between control panel and components, so as to build the entire operating environment. Combined with the data recording function, a large number of operation data can be stored to evaluate the operation effect. It can also realize the fault simulation, reproduce the real fault phenomenon, and facilitate the virtual maintenance operation. Virtual reality technology has three characteristics: immersion, interactivity and imagination. Immersion: it is the essential attribute of virtual reality. In the virtual battlefield environment, the feeling, listening, hearing, asking and perception of personnel are the same as in the real environment, as if they were in the real environment. Interactivity: instead of accepting passively in the constructed environment, personnel can interact with the equipment or personnel in the virtual environment by immersing themselves in the environment, and generate corresponding perception. Interactivity mainly depends on some specific devices, such as 3D helmet, VR glasses, etc. Imagination: in order to achieve certain operational purposes, the constructed environment is designed by the imagination of personnel. Through interaction and immersion, personnel can acquire new knowledge and methods, improve the adaptability and level of personnel, and master the operation and use of new equipment skillfully [18].

Hardware in the loop component subsystem. The main function of the hardware in the loop component subsystem provides the real working environment of the control system. Therefore, each part of the system is composed of actual components. The components of each part are connected by control modules and cables with different functions, so as to simulate the normal operation of the system and output different signals. According to different signals, it can be operated, detected and maintained.

Interaction subsystem. The interaction subsystem is mainly to interconnect the simulator with other equipment on information, and control the information on the link purposefully. There are two parts in the interface of the interactive subsystem, one is with the actual equipment, the other is with other simulation systems (devices). From the whole system level, the working mode of the simulation system is mainly divided into independent working mode and linkage working mode.

In this mode, on the one hand, the simulator completes the work of the machine, on the other hand, it also needs to complete the interaction with other equipment, so as to establish the operation platform of joint debugging and joint test. The information flow of linkage working mode is shown in Table 1. The working process of single equipment simulator is as follows: the main control module receives the subject setting information (normal operation and maintenance), monitors the operation status according to the status of the front panel of the subject control and the working mode of the data processing module, and sends the operation status information to the control center; the data processing conversion module completes the normal data replacement and port fault state under the control of the main control module Simulation and fault data generation and other functions; the wireless data transmission module realizes the networking communication of each single device simulator, and each single device simulator is distinguished according to the work ID. Table 1 list of input and output information of subsystems in linkage mode.

Table 1. List of Input and Output Information of Subsystems in Linkage Mode

Serial number	name	input information	output information
1	Hardware in the loop operation subsystem	1. Relevant information of control command and linkage command of control center 2. Operation information of actual panel and interactive equipment 3. Operation information of hardware in the loop component subsystem 4. Operation information of virtual device subsystem	1. Linkage, equipment status, operation information and target related information of control center 2. Operation information of hardware in the loop component subsystem 3. Operation information of virtual device subsystem
2	Virtual device subsystem	1. Control command and linkage command of control center 2. Equipment status information of hardware in the loop operation subsystem 3. Standby status information of hardware in the loop component subsystem	1. Related information of virtual equipment in control center 2. Equipment related information of hardware in the loop operation and hardware in the loop component subsystem
3	Hardware in the loop component subsystem	1. Control command and linkage command of control center 2. Equipment status information of hardware in the loop operation subsystem 3. Equipment status information of virtual device subsystem	1. Related information of components in actual installation Department of control center 2. Hardware in the loop operation, virtual device subsystem assembly status information

Independent working mode. In the independent working mode, the simulator can work independently. The difference with the linkage mode is that the simulator does not need to interact with the system comprehensive simulation interactive platform, and the control center coordinates the hardware in the loop operation subsystem, virtual device subsystem and hardware in the loop subsystem to work independently or cooperatively.

5. Research on Simulator Hardware System

The research based on hardware refers to the hardware design and implementation of each subsystem. The whole process of operation is the effect of stimulating each simulator. The hardware design of simulator refers to the hardware design of each subsystem. Based on the implementation process of the simulation system, the hardware in the loop operation subsystem, hardware in the loop component subsystem and virtual device subsystem are mainly introduced [19].

5.1. Hardware in the Loop Operation Subsystem

This part adopts the control mode of main control computer + display control computer + fault diagnosis computer.

According to the characteristics of the system equipment, the hardware in the loop operation subsystem is based on the actual equipment and the working principle, and the operation panel developed is the same as the actual equipment in appearance and function. So as to achieve the authenticity of the simulation operation. In actual operation, it is mainly to complete the operation of the operation panel and related parts. The hardware consists of two parts: one is the main control computer system, which inputs operation instructions and the computer related programs run. On the one hand, it can carry out relevant operation; on the other hand, it carries out fault simulation, aiming at the fault phenomenon, the personnel completes the fault diagnosis, so as to realize the maintenance operation; the other is the display control computer, which transmits the program generated by the main control computer through network protocol For the display control computer, the display computer presents the system.

5.2. Hardware in the Loop Component Subsystem Running Scene

The main function of the hardware in the loop component subsystem provides the real working environment of the equipment subsystem. Therefore, the components of the control system are assembled components, which are connected between the components and integrated units to ensure that the components and functions are consistent with the actual installation. On the other hand, in order to operate, test and maintain on the basis of the hardware in the loop component subsystem, it is necessary to modify the hardware in the loop component according to the actual needs to complete the connection with the actual installation. The hardware is composed of practical module, control module, connection and integration module. The composition is shown in Fig. 3.

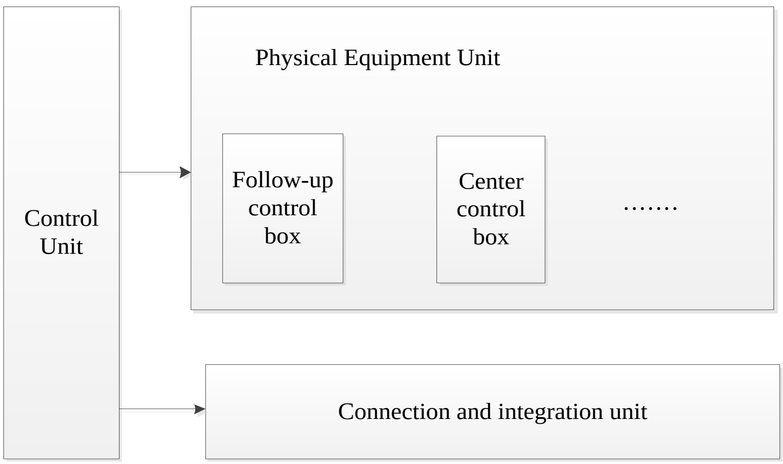

Fig. 3. Hardware composition of hardware in the loop.

Hardware implementation process of hardware in the hardware component subsystem: the connection and integration module through mechanical and electrical connection, under the control of the control module, provides various power supply, excitation and control signals required for the normal operation of the actual assembly module, so as to realize the normal function of the on-board equipment. Connect the actual components of the equipment to make the equipment work normally; the switch controls the signal generated by the link part to facilitate the observation and isolation of faults; indicate the test position through the indicator light for observation; control the large screen LCD display to show the test position through the key. The above three parts are organically combined together through the rack to form a convenient and practical operating environment [20].

5.3. Virtual Device Subsystem

The implementation of virtual device subsystem is based on various virtual equipment, which is mainly composed of virtual test instrument, real test instrument and special signal generator. In this subsystem, the trainees can complete virtual operation of equipment, virtual test after fault diagnosis, virtual maintenance operation, etc. Based on the above operation, the virtual device subsystem, control center and interaction subsystem are required to interact with each other. The virtual device subsystem can interact with the hardware in the loop operation subsystem, and also can operate with the actual operation subsystem, so as to realize the operation synchronous perception. The virtual device subsystem can also perform virtual maintenance operation independently.

6. Research on Simulator Software System

6.1. Software Design and Implementation

The tree software architecture is adopted in the simulator design, and the programming method is object oriented programming (OOP).

a) Computer Operating system: Windows XP, Windows 2000; Memory: 3gb; Graphics card: GF series video card.

b) Tool software. Distributed simulation support software: pRTI 1516 / KD RTI; Three dimensional modeling software: Softimage, Cinema 4D;Virtual simulation software: PLC simulation; Programming environment: Visual Studio 2003 / 2005 / 2008, database: MySQL / MariaDB.

6.2. Subsystem software design

a) Hardware in the loop operation subsystem: supporting software: the software layer can be divided into application layer, simulation layer, network and communication layer, hardware control layer and system layer. The hardware in the loop operation subsystem can simulate the normal operation and common fault phenomena of the system. It is designed on the basis of comprehensive consideration of programming language, user needs and engineering practice. The top layer of the system is the application layer, which is responsible for the management and control of the whole system, and completes the necessary human-computer interaction and interface management; the second is the data layer, which is responsible for information acquisition, output and communication control; the third layer is the logic layer, which is responsible for the normal logic control of each combination and the logic control of fault phenomena.

b) Interactive subsystem: in addition to professional operation, the simulator also needs to interact with other equipment. Two levels of integration should be considered in simulator design. One is to consider the input and output information of the simulator according to the information flow of the system. On the one hand, it can receive the information from other simulators, on the other hand, it can output the information to other simulators; the other is to set up the data interface to realize the link based distributed interconnection between simulation systems.

c) Virtual device subsystem: From the view of software design, the frameworks of "virtual operation", "virtual maintenance" and "joint maintenance" are similar: all components adopt consistent message based interaction. The software parts of "virtual operation ", "virtual maintenance operation" and "joint maintenance operation" adopt the same design pattern: the "component framework" interaction mode with "message management component" as the core and the component interoperability mode based on message. The running of the three tasks can be regarded as software instances under the unified framework. The running of the three tasks can be regarded as software instances under the unified framework. The data flow related to the virtual subsystem is shown in Fig. 4.

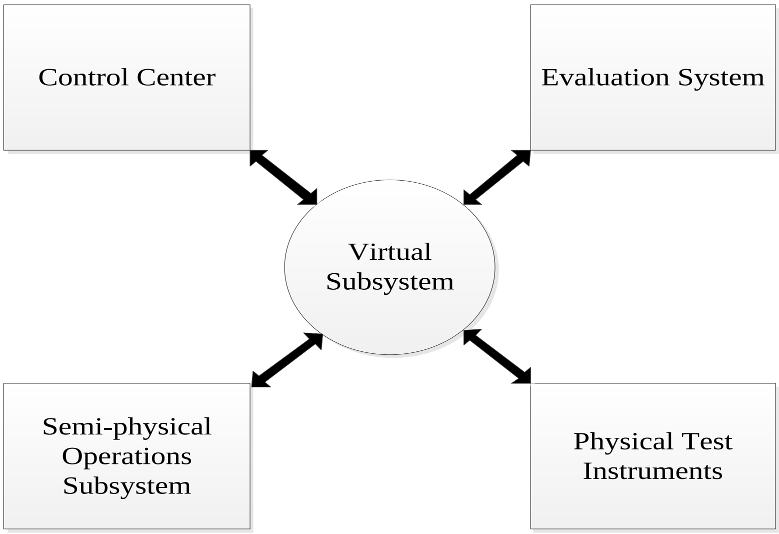

Fig. 4. The data flow of the virtual subsystem.

6.3. Core Technology

The core technologies of the simulator are as follows

a) State mapping method design of simulation equipment and actual equipment. State mapping is an important function of simulation equipment structure: first, the simulation equipment structure can fully reflect the working state or fault phenomenon of equipment; second, the state switching, working mode control, fault setting and signal injection on simulation equipment can be expressed in actual equipment. The state mapping method of simulation equipment and actual installation is mainly realized by node monitoring, distributed control and other means. The simulation technology with the same structure and size as the real object is used to make the operation demonstration of the whole system, disassembly and debugging of various components, which can completely replace the actual installation operation of the system.

b) Failure mode and failure mechanism modeling. Fault simulation is the difficulty of virtual maintenance in operation simulation system. There are two preconditions for fault simulation, one is to analyze the failure mode of equipment, the other is to establish the mechanism model of equipment failure.

The fault mechanism modeling is realized through the principle research and the actual installation experiment. Starting from the function and composition of single equipment, this paper analyzes the possible faults of single equipment and its software modules by using RCM and FMEA theory, determines the failure mode, phenomenon and output fault signal form of each single equipment; then, studies the connection relationship and working principle of single equipment, and analyzes the type of transmission signal, data composition, receiving and sending sequence and so on.

c) The mode of generating signal and operation state is synchronous. When the fault occurs, the influence characteristics between individual devices are clear, and the fault mechanism model is built to realize the fault simulation. With the help of the diagnosis technology of deep learning, for the simulation of different signal forms, the signal generation equipment is constructed, and a variety of special signal generation modules are embedded inside, which can generate the signal form matching with the actual installation. The fault test is carried out on the actual equipment, focusing on recording the fault phenomenon of the single operation panel, collecting the signal characteristics of the input and output ports of the single equipment, and correcting and improving the fault mechanism model. When the equipment is in normal operation, it will output normal signal. When the equipment is in fault state, the signal of this port will be interrupted without output.

7. Conclusion

With the help of hardware in the loop simulation technology, the simulator of complex mechanical equipment adopts the integrated comprehensive simulation design method, which can replace the actual structure and action teaching, and can also complete the structure decomposition and combination, fault setting and troubleshooting and other maintenance. At the same time, the principle of the system is separated from the system to make the abstract principle intuitionistic. The simulator has the characteristics of comprehensive function, good simulation effect and high visualization degree, which can be used in the ordinary teaching operation of enterprises and scientific research institutions.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Author Contributions

Siyu Li, Shaoluo Huang conducted the research; ,Shuo Meng analyzed the data; Siyu Li，Weiyi Wu wrote the paper; all authors had approved the final version.

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