Transactions on Computer Science and Intelligent Systems Research
ISSN: 2960-1800, eISSN: 2960-2238 | Volume 6
ISET 2024

A Survey of Real-time Simulation and Hardware-in-the-loop Technology

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Abstract. This paper introduces the definition and background of real-time simulation and hardware-in-the-loop technology, and explains the concept, development process and application field of real-time simulation and hardware-in-the-loop technology, as well as its importance and advantages in practical applications. The research methods and technologies for real-time simulation and hardware-in-the-loop technology include commonly used methods and technologies for model establishment, control algorithm design, system integration, and experimental verification. For the application of real-time simulation and hardware-in-the-loop technology, specific cases in different fields are also listed, such as the design of distribution automation terminal in the kernel, the research of virtual test system of hardware-in-the-loop for unmanned vehicles, etc. Finally, the current challenges of real-time simulation and hardware-in-the-loop technology are stated, and the future development trend of the technology is summarized.

Keywords: real-time simulation technology; hardware-in-the-loop; control system; embedded system

1. Introduction

Real-time simulation technology can be considered as a system or process that uses computers to simulate and imitate the real world. In terms of simulation hardware, digital computers have gradually been used more than analog computers since the 1960 s. The hybrid computer system stagnated in the 1970s, and has been developing since the 1980s.Due to the development of minicomputers and microprocessors, as well as the use of pipeline principle and parallel computing, the improvement of digital simulation operation speed has made new breakthroughs. In terms of simulation software, in addition to the further development of interactive simulation language and more powerful simulation software system, another important trend is to combine simulation technology with artificial intelligence to generate simulation software with expert system function. At the same time, the scale and complexity of simulation models and experimental systems are constantly increasing, and the research and application of this technology will also continue to deepen.The hardware-in-the-loop technology is a means of testing the controller, and its name has revealed its meaning : hardware, that is, the object under test, is generally the controller object ; in the loop, it is emphasized that the controller under test should be in a closed loop, that is, the process of the controller receiving the state of the controlled object and issuing the control command, getting the feedback of the controlled object and issuing the control command again. In China, the hardware-in-the-loop simulation industry started late, and the market is still in the development stage. There is still a gap between domestic enterprises and international enterprises in terms of software / hardware development, R & D capabilities, and technical levels. The hardware-in-the-loop simulation system is mostly used in the automotive field. China is also a global manufacturing power. Under the development trend of intelligent manufacturing, the hardware-in-the-loop simulation market has great potential for development.

Real-time simulation technology can not only be applied to the analysis, research and design of control systems, but also can be widely used in the training and education of large-scale control system operators, so as to avoid the danger and high cost caused by improper operation in the actual control system. In addition, with the rapid development of microcomputers, a variety of new microcomputer control devices continue to appear. These devices must be strictly debugged and

tested before use. Therefore, it is particularly important to carry out the reality to test the practicability and safety of the control device in the whole control system. At the same time, if the simulation system is used in the power industry to debug, maintain and troubleshoot nuclear power plants, the cost of building the simulation system can be recovered in one year, which has high economic benefits.

2. An Overview of Real-time Simulation and Hardware-in-the-loop Technology

Real-time simulation and hardware-in-the-loop technology is a technology that combines real-time simulation and actual hardware to simulate embedded systems in real operating environments. Real-time simulation refers to the real-time simulation of the embedded system by simulating the actual hardware environment in the computer through simulation software, while hardware-in-the-loop refers to the transmission of the output results of the actual hardware to the embedded system in the real-time simulation process, and the output results of the embedded system are fed back to the actual hardware to form a closed-loop control.

2.1. Real-time Simulation Technology

Real-time simulation technology is a technology that can simulate the real environment, including system modeling, control strategy development and real-time simulation. Specifically, the time proportion of the simulation model is exactly the same as that of the real system, which requires the simulation system to receive dynamic input in real time and generate real-time dynamic output. The specific process is to use the computer to continuously calculate the motion equation of the object and the environment, and then express the real-time motion of the simulated object through the motion system, visual system, sound system and instrument system. The simulation trainer of thermal power station is an example of an actual real-time simulation system. The environmental simulation output device of the system includes a console, a display instrument panel, and an operation monitor. They are almost the same as the actual equipment in the control room of the thermal power station. The difference is that the operation signal from the console is not the actuator that goes to the scene, but goes to the computer through the data interface. The signals of various display instruments and operation monitors do not come from the on-site transmitter but also from the computer. In addition, an instructor desk is added to the system to control the operation of the entire simulator. It can set faults and record the operation process of the operator, which can replace the local operator in the actual power station to do local operation.The computer of the simulation trainer mainly completes the model calculation task of the boiler, steam turbine, electrical part and the model calculation of the operation monitoring system.

2.2. Hardware-in-the-loop Technology

Hardware-in-the-loop technology is to apply the real-time control strategy directly to the actual system to achieve higher performance and accuracy. Hardware-in-the-loop technology mainly includes three aspects: hardware design, real-time control and system integration.

2.3. Hardware Design

Hardware design is the basis of hardware-in-the-loop technology. It is the process of designing the controller into a hardware circuit that can be directly applied to the actual system. The hardware design needs to consider the computing power, communication ability and real-time performance of the controller. The hardware design includes FPGA, DSP, ARM and so on.

2.4. Real-time Control

Real-time control is the core of hardware-in-the-loop technology, which is the process of applying the control strategy to the actual system in real time. Real-time control needs to consider the communication mode between the controller and the controlled object, the real-time performance of the control algorithm and the stability of the system.

2.5. System Integration

System integration is to integrate the hardware controller with the controlled object to realize the operation of the control system. System integration needs to consider the interface standards, signal transmission and data processing of the hardware controller and the controlled object.

3. Application Scenarios of Real-time Simulation and Hardware-in-the-loop Technology

Real-time simulation and hardware-in-the-loop technology are widely used in many fields, including aerospace, unmanned vehicles, automotive control and power automation.

In the field of aerospace, real-time simulation and hardware-in-the-loop technology can be used for aircraft control and navigation system development. Through real-time simulation technology, various flight environments and system failures are simulated to optimize the control strategy. At the same time, the hardware-in-the-loop technology can directly apply the optimized control strategy to the actual aircraft system, thereby improving the flight performance and safety of the aircraft. Among them, the aerospace human-embedded software is a typical high-confidence software. The entire development process uses a model-based method, follows the MBD development process, and uses MBD tools for modeling, model verification, testing, and automatic code generation. Engineering practice has proved that it is effective and executable. It can be seen that the MBD method is to advance the design verification work, so that the demand analysis, design and test verification links are quickly iterated, and the automatic code generation reduces the human error. At the same time, it is also the embodiment of the advanced nature of software engineering technology.

In the field of unmanned vehicle research and development, real-time simulation and hardware-in-the-loop technology can be used for effective testing, verification and evaluation of unmanned vehicle driving. Through the real-time simulation system, different types of traffic scenarios are preset, and the software of the hardware-in-the-loop virtual test system of the unmanned vehicle is designed. It can realize the collection of various traffic data states by the unmanned vehicle, and can also complete the large-scale car-following test, automatic emergency braking test, lane keeping test and traffic sign recognition test. It provides a complete, fast and efficient solution for the overall test of unmanned vehicles.

In the field of vehicle control, real-time simulation and hardware-in-the-loop technology can be used for vehicle control and safety performance optimization. By simulating the dynamic response and stability of the vehicle under different road conditions and driving conditions, the control strategy of the vehicle is optimized. At the same time, the hardware-in-the-loop technology can apply the optimized control strategy to the actual vehicle control system, thereby improving the safety and performance stability of the vehicle. For example, in the intelligent connected vehicle industry, real-time simulation technology can realize the real-time synchronous simulation of intelligent vehicles in cross-platform and multi-software by constructing a cross-platform real-time simulation system architecture of intelligent connected vehicles, which improves the effectiveness of intelligent vehicles in dealing with complex verification requirements.

In the field of power automation, real-time simulation and hardware-in-the-loop technology can be used for the control and optimization of power automation systems. Through real-time simulation technology, the operation of power automation system under different working conditions can be simulated, so as to optimize the control strategy and control algorithm. At the same time, the hardware-in-the-loop technology can apply the optimized control strategy and control algorithm to the actual power automation system, thereby improving the performance and efficiency of the power automation system. For example, based on real-time simulation technology, a multi-port power electronic transformer topology of hybrid modular multilevel converter is proposed. Through the targeted research on the system structure and working principle of power electronic transformer, the simulation model is built and the demonstration project is studied to minimize the possibility of bringing the defects of control and protection system to the field. At the same time, it provides

comprehensive technical support for equipment development and engineering field equipment debugging. In the distribution industry, a distribution automation terminal device with ARM Cortex-M7 core is also proposed. The terminal design includes hardware design and software design, which realizes centralized and real-time monitoring and management of power distribution, and meets the automation requirements of power distribution system.

Real-time simulation and hardware-in-the-loop technology can be applied to all stages of embedded systems, including design, development, testing and maintenance. In the design phase, developers can verify and debug the function and performance of the system through real-time simulation and hardware-in-the-loop testing, and find and solve problems early, so as to improve the reliability and stability of the system. In the development phase, developers can use real-time simulation and hardware-in-the-loop technology to verify the performance and stability of the system, and find and solve problems early, so as to reduce the occurrence of system failures and errors and accelerate the development process of the system ; in the testing phase, developers can use real-time simulation and hardware-in-the-loop testing to simulate the system behavior in the real operating environment, so as to test the real-time, stability and reliability of the system. In the maintenance phase, developers can use real-time simulation and hardware-in-the-loop testing to verify the functionality and performance of the system, as well as early detection and problem solving, thereby improving the maintainability and maintainability of the system.

4. Advantages of Real-time Simulation and Hardware-in-the-loop technology

(1) Improve the reliability and stability of the system

(2) Through real-time simulation and hardware-in-the-loop testing, developers can test the performance and stability of the system in a real environment, find and solve problems in the system in time, so as to improve the reliability and stability of the system.

(3) Accelerating the system development process

(4) Real-time simulation and hardware-in-the-loop technology can quickly verify and debug the system, reduce the time and cost of trial and error and debugging, and accelerate the development process of the system.

(5) Improving development efficiency and quality

(6) Through real-time simulation and hardware-in-the-loop technology, the system behavior under extreme conditions can be simulated, such as high load, high temperature, low temperature, etc., which helps developers find and solve problems before the system runs, thereby improving the development efficiency and quality of the system.

(7) Reducing development costs and risks

(8) Through real-time simulation and hardware-in-the-loop testing, developers can find and repair problems in the system, improve the maintainability and maintainability of the system, thereby reducing development costs and risks.

(9) High real-time

(10) Real-time simulation and hardware-in-the-loop technology can simulate the system behavior in the real operating environment, and can monitor and record the running state and output results of the system in real time, so it has high real-time performance.

5. Real-time Simulation and Hardware-in-the-loop Technology

The combination of real-time simulation and hardware-in-the-loop technology refers to the combination of real-time simulation technology and hardware equipment to achieve a more realistic and accurate simulation and experimental environment, including hardware interface design and

development, data transmission and synchronization, real-time control and feedback. Firstly, the hardware interface, which is a key component of real-time simulation and hardware-in-the-loop technology, is introduced. It connects the simulation system and hardware equipment to realize the input and output of data. The design of the hardware interface usually needs to consider the interface type, data format and transmission rate of the hardware device to ensure the accuracy and real-time performance of the data. At the same time, the development of the hardware interface involves the design of the hardware interface circuit, the preparation of the driver and the formulation of the interface protocol.Second, real-time simulation and hardware-in-the-loop technology require that the data transmission and synchronization between the simulation system and the hardware device are real-time. In this process, data transmission can be realized through various communication methods, such as Ethernet, serial port, USB, etc., and the selection of appropriate communication methods should consider factors such as data transmission rate, real-time performance and stability. Data synchronization refers to ensuring data consistency and timing consistency between the simulation system and the hardware device. Data synchronization can be achieved through time stamps, handshake protocols, and data validation. Third, real-time simulation and hardware-in-the-loop technology also require the simulation system to control hardware devices in real time and receive real-time feedback from hardware devices. Real-time control can be realized by control algorithm and control interface. The control algorithm can generate control instructions in real time according to the state and target of the simulation system, and the control interface sends the control instructions to the hardware device. Real-time feedback can be realized through sensors and feedback interfaces. Sensors can collect the status information of hardware devices in real time, and the feedback interface transmits the status information to the simulation system for real-time feedback.

6. The Challenges and Future Development of Real-time Simulation and Hardware-in-the-loop Technology

In the context of the intelligent development of the global industry, the development and research potential of real-time simulation and hardware-in-the-loop technology in applications is huge. But at the same time, the application of technology also faces many difficulties and challenges, which can be embodied in the following points :

Hardware cost and complexity : Real-time simulation and hardware-in-the-loop technology need to use specialized hardware devices to interact with the simulation system, which undoubtedly increases the cost and complexity of the system. Enterprises and related R & D personnel also need to carefully measure the cost increment generated by the development of real-time simulation and hardware-in-the-loop system and the income increment brought by the implementation of the technical system. Most enterprises or industrial factories are not willing to bear the cost of system design failure.

Real-time performance and accuracy : Real-time simulation and hardware-in-the-loop technology require high real-time performance and accuracy of data transmission and processing, and need to solve the problem of delay and synchronization of data transmission. Real-time performance and accuracy are two important indicators in real-time simulation and hardware-in-the-loop technology, which have a key impact on the effect of real-time control and feedback. In real-time simulation and hardware-in-the-loop technology, real-time requires the system to obtain sensor data, calculate and process in time, and transmit the results to the control system for real-time feedback. The real-time requirements are mainly reflected in the real-time data transmission and control feedback. In real-time simulation and hardware-in-the-loop technology, there are also high requirements for accuracy. It is hoped that the system can accurately simulate and reflect the behavior of the actual system, and can provide accurate control instructions and feedback. It not only needs accurate simulation model, but also has high precision control instructions and feedback.

System stability and reliability : In order to avoid system crash or failure, the improvement of algorithm and control technology is an important means to improve the real-time performance and

accuracy of real-time simulation and hardware-in-the-loop technology, which will directly affect the control effect and real-time performance of the system.

Data security and privacy protection : Real-time simulation and hardware-in-the-loop technology involves a large amount of data collection, transmission and processing, which may contain sensitive information and personal privacy. Measures need to be taken to ensure data security and privacy protection. Therefore, data security and privacy protection is an indispensable part of real-time simulation and hardware-in-the-loop technology. In order to effectively protect the security and privacy of data, reduce the risk of data leakage and abuse, improve the trust and acceptance of users and participants in real-time simulation and hardware-in-the-loop technology, more efforts have been made in encryption and secure transmission, data backup and recovery, anonymization and desensitization processing, access control and rights management.

It is undeniable that there is also a good prospect for the future development of this technology. With the continuous advancement of hardware technology, the cost of hardware devices will gradually decrease, and performance and functions will also be improved, providing better support for real-time simulation and hardware-in-the-loop technology applications.At the same time, the development of network communication technology drives the improvement of the speed and stability of data transmission, which can better meet the requirements of real-time simulation and hardware-in-the-loop technology for data transmission. The improvement of algorithm and control technology will also make the control algorithm and control strategy of real-time simulation and hardware-in-the-loop technology more efficient and accurate, and provide better real-time control and feedback effect. In the scientific community, interdisciplinary cooperation has become the mainstream trend, so the strengthening of interdisciplinary cooperation can promote the development and innovation of real-time simulation and hardware-in-the-loop technology. Real-time simulation and hardware-in-the-loop technology involves the knowledge of multiple disciplines, including computer science, control engineering, etc., and its advantage is that it can comprehensively utilize the professional knowledge of various disciplines ; promote the cross-integration of innovative thinking and methods, and bring new breakthroughs to the development of technology ; improve the ability to solve complex problems ; promote the development of science and technology.

7. Summary

Real-time simulation and hardware-in-the-loop technology are important research directions in the field of modern control engineering. Real-time simulation technology can simulate the real environment and be used for system modeling and control strategy development. Hardware-in-the-loop technology can directly apply real-time control strategies to actual systems to achieve higher performance and accuracy. The downstream of the industrial chain is the application layer. Hardware-in-the-loop simulation has a wide range of applications, including aerospace, electronic power, automobiles, unmanned vehicles and other scenarios. Automobile is still its main application field. The global hardware-in-the-loop simulation market competition is fierce. China 's hardware-in-the-loop simulation industry started late. At present, the market is still in the development stage. There is still a gap between domestic enterprises and international enterprises in terms of software / hardware development, R & D capabilities, and technical levels. However, China is a big manufacturing country in the world. Under the development trend of intelligent manufacturing, the hardware-in-the-loop simulation market has great potential for development and is developing in a more automated direction. At the same time, the requirements of intelligent manufacturing on the complexity, accuracy, fidelity, integration and scalability of hardware-in-the-loop simulation technology will continue to increase. In the future, the development opportunities and challenges of the hardware-in-the-loop simulation market coexist.Therefore, on the basis of mastering the implementation of real-time simulation and hardware-in-the-loop technology and the current research orientation, it is necessary to rationally apply the existing real-time simulation and hardware-in-the-loop technology software, give full play to the advantages of various developed systems, and train and invest in

professional and innovative researchers to promote the sustainable development of science and technology in China.

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