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Parts simulation design and simulation training system combined with hardware-in-the-loop

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Abstract. In order to improve the simulation effect of automobile parts, this paper analyzes the simulation design of automobile parts with hardware-in-the-loop, and verifies the system through setting up a simulation system to improve the design effect and practical effect of automobile parts. Moreover, this paper proposes a dual-core HILoC architecture suitable for small-scale dynamic system simulation, and a dual-core data exchange architecture based on IPC mechanism communication, which solves the problem of dual-core shared memory utilization and improves the communication efficiency between dual-cores. In addition, this paper proposes a hardware-on-chip real-time simulation (HILoC) system based on dual-core technology. There are two ways to realize data exchange between two cores, and one is to store data in shared memory, which can be operated by both cores. After that, this paper takes the pure electric vehicle with direct drive structure equipped with reducer as the target to carry out experimental research. Based on the comprehensive analysis of the powertrain structure and forward simulation characteristics of pure electric vehicle, the longitudinal dynamic model of the whole vehicle is established by using modular modeling idea. Finally, this paper verifies that the method model proposed in this paper has good effect through experimental research.

Keywords: Hardware-in-the-loop / parts / simulation design / simulation

1 Introduction

With the improvement of material living standards and the continuous development of automobile technology, people put forward higher requirements for automobile performance, and more and more electronic controllers are applied to automobiles, which leads to more complex automobile control systems, so the development and testing of controllers are more arduous. The traditional vehicle controller development is mainly completed by real vehicle road test, but the real vehicle test cost is high and it is difficult to achieve for dangerous and extreme working conditions, which further increases the difficulty of testing and development. Hardware-in-the-loop simulation technology is introduced into the development of automobile control system, which can create a platform foundation for researchers' software development and testing, greatly shorten the development cycle and reduce the work intensity of developers and testers. The simulation technology of hardware-in-the-loop refers to replacing the controlled object with a real-time simulation model, and associating the hardware controller with the simulation model to form a control loop. By simulating the working conditions of the actual controlled object, simulation tests are carried out to verify the logic of the hardware controller.

In the current development process of automotive components and controllers, systems are becoming increasingly complex, and their performance requirements are also increasing. At the same time, it is required to minimize development time and costs as much as possible. Performance and functional testing is a very important part of the product design process [1]. At present, research on pure electric vehicles is mainly achieved through computer simulation tests, bench simulation tests, and road actual vehicle tests. The bench simulation test can not only load static loads, but also effectively dynamically simulate road conditions and electric vehicle driving conditions, accurately test the key components of electric vehicles (such as motors, batteries, and transmissions) and powertrain performance, verify the effectiveness of control strategies, and reduce product development time, risks, and costs. During the testing process, the temperature, humidity, load, etc. of the tested object can be well controlled, and the environment of the road surface (such as adhesion coefficient, slope, wind resistance coefficient, wind speed, etc.) can be controlled, making the test results more accurate and referential [2].

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In the traditional sense, hardware in the loop system refers to hardware in loop simulation (HIL), which means that during system testing, the controller is real (such as the electronic control unit ECU, TCU), and the rest can use actual products. If actual products cannot be used, real-time virtual models are used to simulate the external environment of the controller for system testing. The model-based hardware in the loop real-time testing platform is a fusion of traditional hardware in the loop testing systems and traditional real-time testing platforms. The testing objects are not only controllers and control strategies, but also real tested units, such as transmissions, powertrain, etc. The simulation model controls the testing platform to simulate the real environment faced by parts and strategies [3].

The hardware in the loop simulation system mainly consists of five parts: real-time target machine (lower computer), controller, upper computer, signal generation and measurement module, and interface module. The real-time target machine is mainly used for simulation calculation of real-time system models; The upper computer serves as a human-computer interaction interface, which allows for real-time modification of model parameters and execution of test cases. It is also used to monitor the operational status of simulation models and hardware controllers; The signal generation and measurement module is mainly used for sensor signal simulation and measurement; The interface module is used for signal transmission between the model and controller hardware. Using hardware in the loop simulation system for controller logic verification can simulate some extreme and dangerous working conditions that are difficult to achieve in actual vehicle tests. In addition, using automatic testing tools to execute test cases can greatly reduce work intensity and shorten development cycles [4].

Reference [5] applied HIL to photovoltaic power generation systems, verifying the correctness of the automation testing scheme proposed in the paper. Reference [6] built a simulation platform based on dSPACE and conducted simulation research on batteries. The results showed that this method can effectively simulate the dynamic characteristics of batteries in battery packs. Reference [7] designed a drive control integrated system for SCARA robots and applied HIL simulation technology to verify the system. It can shorten the development cycle of the system, improve efficiency and safety. Reference [8] introduces the structure, real-time simulation model, and application fields of the simulation system from the simulation of controller hardware in the loop and power hardware in the loop. Reference [9] focuses on the precise mathematical modeling of electric vehicle propulsion systems to build an HIL platform, describing a case of providing real-time experimental verification of HIL for the General Chevrolet Volt. Real time simulation of permanent magnet synchronous motor (PMSM) and power electronic hardware components was conducted, and the real-time simulation performance was studied under different load operation conditions to verify its robustness. Reference [10] designed an easy to install hardware in the loop inverter system, mainly used in university laboratories. Reference [11] introduces a high-precision real-time simulator that can be applied on the HIL testing platform, which can simulate permanent magnet synchronous motor drivers in real time. Reference [12] proposes a hardware in the loop real-time simulation test platform for physical security of electric vehicle powertrain networks. The test platform includes multiple physical fields of electric vehicle powertrain, including electric drive systems, mechanical transmission systems, and vehicle control units. At the same time, the article proposes an energy consumption monitor that can calculate the system's electrical energy and power information in real time. Reference [13] builds an HIL platform based on RT-LAB to conduct real-time simulation of the operation status of high-speed maglev trains, facilitating the development of train traction control strategies. Reference [14] also proposed a hardware in the loop testing method for a flexible DC distribution protection system based on the RT-LAB platform, which has certain reference significance for the construction of flexible DC distribution. Reference [15] applied hardware in the loop real-time simulation to PWM rectifiers in ship power electronic devices, and compared it with offline simulation to verify the correctness of the PWM rectifier controller.

Semi physical simulation is a simulation method that virtualizes the controller or controlled object in a circuit, enabling real-time simulation of the actual operating state of the system [16]. In the field of semi physical simulation, hardware in the loop simulation is a common application mode. It simulates the dynamic characteristics of the controlled object through a real-time simulator. The real controller in the loop is connected to the real-time simulator through an interface, and can obtain the same signal feedback as the real power converter [17]. This provides a safe way to test the effectiveness of the controller. The use of hardware in the loop simulation can greatly shorten the development cycle of power electronic systems and reduce the cost investment required for development. Meanwhile, hardware in the loop simulation can reduce various risks that may occur during the operation of actual systems, improve system reliability, and facilitate engineering and technical personnel to study and apply actual systems [18].

Currently, semi physical simulation can be divided into two simulation modes, namely Rapid Control Prototyping (RCP) derived from rapid prototyping technology in the manufacturing industry and Hardware in Loop (HIL) simulation optimized through control prototyping technology. Rapid control prototype technology is mainly used in the development of pre-designed control systems and algorithms, as well as real-time detection in current social production [19]. In the initial stage of controller development, developers first complete the construction of the controller simulation model, and then use the built controller simulation model to control the movement of physical devices. Through a sufficient number of offline and online simulation experiments, they verify whether the designed control system method meets the pre-proposed functional requirements. On the basis of completing the virtual controller verification of RCP technology development, a new semi physical technology simulation mode was proposed through further optimization work. Hardware in the loop simulation, which uses a real controller to control the motion of the virtual experimental equipment simulation model. Therefore, this article takes hardware in the loop simulation [20] as the research direction. Hardware in the loop simulation technology achieves real-time data exchange between virtual simulation models of real physical devices and physical device objects that need to be controlled through real-time data communication technology. Therefore, hardware in the loop simulation technology not only improves the shortcomings of pure digital simulation, but also enhances the reliability of simulation systems; In addition, as the controller of the simulation system is a physical device, it saves the modeling work of the controller model and reduces the programming time and energy of the experimental personnel; Compared to virtual controller models, simulation systems with physical controllers are more accurate. At the same time, compared to pure physical models, the controlled physical devices are virtual simulation models, which minimize the complexity of experiments.

The hardware in the loop simulation technology achieves synchronization between the operating cycle of the real controller and the simulation cycle of the simulation system, making the simulation results very close to the real pure physical simulation experiment results. Moreover, the use of virtualized simulation models instead of physical control objects for testing experiments increases the fault tolerance of the development process and reduces the time required for the entire product development. Hardware in the loop simulation technology is in between pure physical simulation technology and digital simulation technology. In the simulation process, there are both computer simulation systems and physical devices connected to form a closed-loop simulation loop, ensuring the normal operation of the entire simulation experiment. Hardware in the loop simulation not only utilizes the convenience of building models using computer technology, but also has strong operability. It can quickly and simply modify the input and output variables of the simulation model of the control object according to experimental requirements, and can also modify the parameters of the simulation model of the control object to intuitively analyze changes in system performance.

This article completes the functional design of the relevant sub modules in the rapid control prototype, and uses HIL to test and verify each sub module to ensure that the functions of the sub modules can be implemented normally. On this basis, encapsulate all sub modules, configure interfaces, compile and generate target code, and then download it to the rapid control prototype. Use upper computer software to integrate and test the entire system. The testing objective is to ensure that all functions of the system can be implemented normally after integration, including the interaction function between various submodules, as well as the fault response and self-protection mechanism of the controller under different working conditions.

On the basis of understanding the principles and applications of on-board chargers and hardware in the loop, this article designs an innovative HIL testing system solution. Establish a bidirectional vehicle charger model and comprehensively verify the various functions of the developed system using a rapid control prototype. The research objectives of this paper are as follows: Hardware in the loop testing is based on real-time processors, simulating the response characteristics of real controlled objects, obtaining I/O interface signals and feedback them to the real controller, and achieving the testing of the tested controller without actual controlled objects. HIL testing can ensure the safe and efficient execution of testing tasks by testers, reduce testing costs, save testing time, and as an indispensable part, further ensure product quality.

Hardware in the loop simulation technology is widely used in product modification, shaping, and factory inspection. The use of HIL technology in scientific research and industrial fields can avoid excessive investment in electromechanical hardware and safety hazards during the experimental process. The use of hardware in the loop simulation platform for development fills the gap between empirical design and actual products. Virtual objects can be used for product development at the lowest cost, greatly reducing the investment and risk of experiments.

This article analyzes the problems of high testing costs and long testing cycles in traditional power electronic system design, and combines the current development status of HIL simulation technology to consider using HIL simulation technology in system design testing and development. Under the premise of implementing simulation functions, develop a reliable dual core on-chip hardware in the loop simulation system for small-scale dynamic simulation systems.

Research iterative algorithms for real-time simulation object numerical modeling and dynamic system modeling, allocate model computing resources in dual core processors based on the system's time scale, and achieve real-time data exchange between dual cores. Design and select the core processor for system computing, and allocate the system's analog-to-digital input/output and communication resources to form a scalable interface architecture. Implement reliable hardware design for digital and analog IO interfaces, as well as software and hardware design for data exchange.

This paper combines hardware-in-the-loop to carry out analysis of parts simulation design, and through setting up simulation system to carry out system verification, so as to improve the design effect and practical effect of automobile parts.

2 Algorithm and model design

Traditional HIL simulation system includes real-time host, I/O interface board, signal conditioning module, load, program-controlled power supply and fault injection module. FPGA is usually used as the computing core of simulation platform. Considering the advantages of DSP processor, such as flexible solution and simple programming, combined with the cost and data transfer efficiency of HIL system, this paper proposes a dual-core HILoC structure suitable for small-scale dynamic system simulation, and a dual-core data exchange architecture based on IPC mechanism communication, which solves the utilization problem

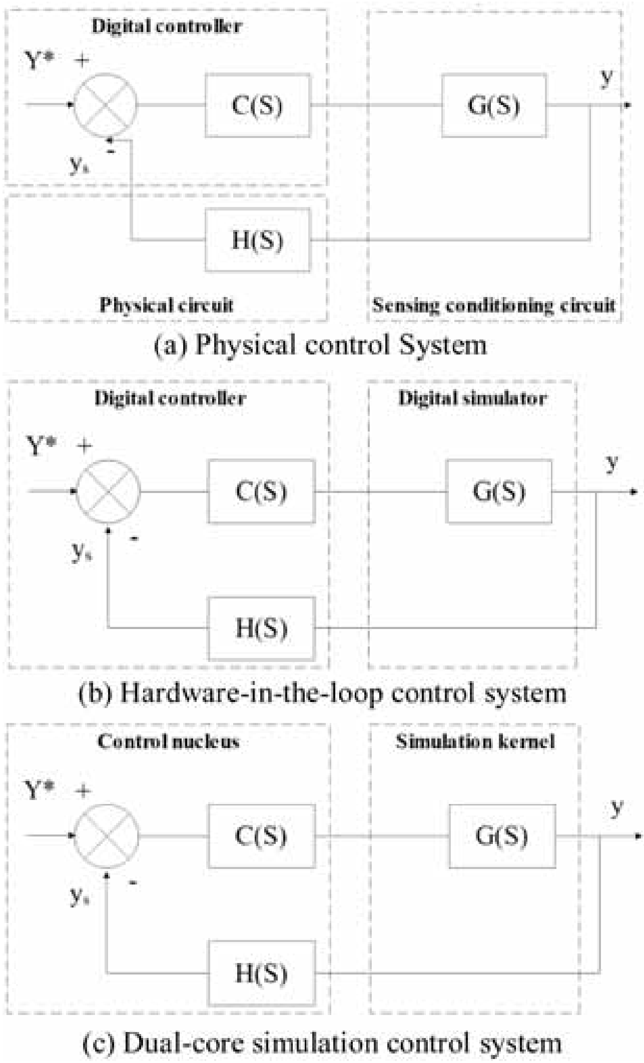

Fig. 1. Block diagram of loop control system.

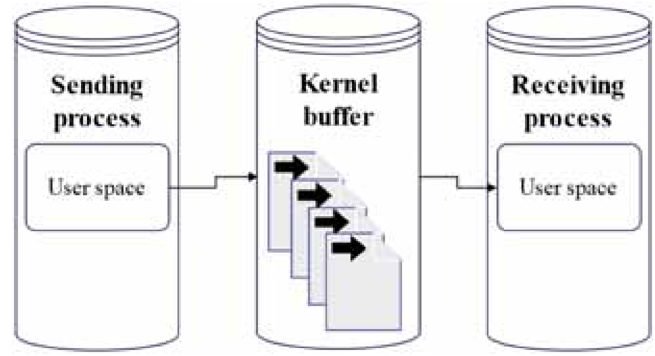

Fig. 2. Shared memory communication model.

of dual-core shared memory and improves the communication efficiency between dual-cores. Figure 1 shows the block diagrams of the traditional digital control platform and the hardware-in-the-loop simulation platform studied in this paper. The error calculation and controller $C(s)$ of the traditional digital control platform shown in Figure 1a are realized in a dual-core processor, and the sensing conditioning circuit is composed of voltage and current sensors and their conditioning circuits, and $G(s)$ is a real circuit. In the hardware-in-the-loop simulation system in Figure 1b, the circuit object $G(s)$ is realized by averaging model in the digital simulator, and the digital controller realizes the functions of sensing conditioning circuit, error calculation and controller. Dual-core simulation control system is shown in Figure 1c.

This paper presents a hardware-on-chip real-time simulation (HILoC) system based on dual-core technology. There are two ways to realize data exchange between dual-cores. One is to store data in shared memory, and both cores can operate on it. As shown in Figure 2, the sending process and the receiving process have corresponding user space, and the exchange of data must pass through the kernel cache. The sending process sends data from the user space to the kernel cache, and the receiving process reads data from the kernel cache.

Figure 3 is a schematic diagram of dual-core data flow based on IPC mechanism. It assumes that CPU1 sends data to CPU2, CPU1 applies for write permission, writes the data into the global shared memory, assigns the memory address to the IPC control structure, generates IPC interrupt, and resets IPC flag. After that, it informs CPU 2 to use the IPC control structure and assign the shared memory address to CPU 2 to receive the array pointer. After CPU2 inquires that the IPC flag is reset, it assigns the contents of the receiving array to the required variables, and sets the IPC flag to complete a transmission.

The simulation kernel and the control kernel work independently. In order to achieve the purpose of real-time, the simulation step is set to $1/10$ of the control period in the iterative calculation of the simulation kernel. The simulation kernel continuously carries out iterative operation, and transfers the state variables obtained after 10 iterative calculations to the control kernel. After AD conversion, the control variables updated by the control kernel are transferred to the simulation kernel, and then the simulation kernel is transferred to the control kernel after 10 iterative calculations.

The HILoC system clock PLLSYSCLK is set as equation (1).

$$PLLSYSCLK = (XTAL\ OSC) \times \frac{(IMULT + FMULT)}{(PLLSYSCLKDIV)}. \quad (1)$$

Among them, $XTAL\ OSC =$ 10 MHz, $IMULT =$ 40, $EMULT =$ O, $PLLSYSCLKDIV = 1$ (frequency division by 2), and system clock $PLLSYSCLK =$ 200 MHz.

HILoC simulation system iterates the discrete description equation of the target object in real time to generate the state quantity of the description object. In this study, an accelerated iterative algorithm is proposed. The simulation kernel takes the signal from the control kernel as the input according to the preset different simulation objects. After that, we take an example of an n-order system, where the system first discretizes an equation with n state variables to obtain an equation, which is

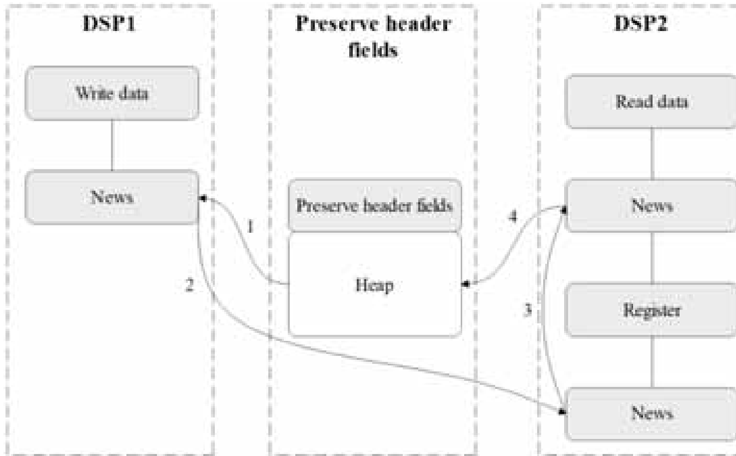

Fig. 3. Schematic diagram of dual-core data flow.

solved in an iterative manner. Within the k-h iterative operation on the state-variable equation, if the mth equation is solved for $x_m[k+1]$, then the $m+1$-th computation is performed using the initial value $x1\ \ [k+1], ..., x_m[k+1], x_m[k], ..., x_n[k]$.

$$\begin{cases} x1 = f\ \ (x1, ..., x_n, d) \\ x_n = f_n(x1, ..., x_n, d). \end{cases} \tag{2}$$

Among them, x_1– x_n is the state variables in the simulated circuit, such as the current of inductor and the voltage of capacitor. d is the control input of power electronic circuit, and d is the pulse width modulation wave in actual circuit. In an implementation of an on-chip hardware-in-the-loop simulation system, d is a floating-point number between 0-*1* and its derivative with respect to x on the left side of the equation forms the KCL or KVL equation describing the circuit.

In order to solve the disadvantage that DSP can't handle continuous variables, equation (2) is discretized to obtain equation (3):

$$\begin{cases} x1[k+1] = g1(x1[k], x2[k], ..., x_n[k], d[k]) \\ x2[k+1] = g2(x1[k], x2[k], ..., x_n[k], d[k]) \\ \quad\quad .... \\ x_n[k+1] = g_n(x1[k], x2[k], ..., x_n[k], d[k]) \end{cases}. \tag{3}$$

The accelerated iterative algorithm is used on the basis of equation (3), as shown in equation (4):

$$\begin{cases} x1[k+1] = g1(x1[k], x2[k], ..., x_n[k], d[k]) \\ x2[k+1] = g2(x1[k+1], x2[k], ..., x_n[k], d[k]) \\ \quad\quad ... \\ x_n[k+1] = g_n(x1[k+1], x2[k+1], ..., x_{n-1}[k+1], x_n[k], d[k]). \end{cases} \tag{4}$$

Among them, g is the discrete function, and $x[k]$ is the current sample value.

2.1 Design and Implementation of in-loop simulation experiment

The system software design includes PWM setting and PWM triggering ADC interrupt setting. The ultimate goal of HILoC system software design is to realize the migration of hardware-in-the-loop simulation and physical debugging at the same time.

The PWM waveform is generated by the digital signal controller TMS320F28379D, and the frequency of PWM is controlled by the time base period register (TBPIm) register and the mode of the time base counter. For increment and decrement counting, the period and frequency of the time base counter mode are calculated as equation (5):

$$\begin{cases} T_{PWM} = 2\ \times\ TBPRD\ \times\ T_{TBCLK} \\ f_{PWM} = \dfrac{1}{T_{PWM}}. \end{cases} \tag{5}$$

DC triggering and conversion sequencing are accomplished by configurable SOC (Start of Conversions), which are triggered by disable (software settings), CPU timer 0/1/2 triggering, GPIO triggering and ePWM triggering. The HILoC system selects to configure ePWM to trigger the ADC conversion. The ADC control logic will sample the ADCINA channel with the specified acquisition window width. Once the acquisition is complete, the ADC starts converting the sampled voltage to a digital value, and when the ADC conversion is complete, the result is provided in the ADCRESULT register.

The analog regulator designed in continuous control system is often expressed in the form of transfer function. For digital controllers, the transfer function of the controller should be expressed in discrete form, as shown in equation (6):

$$D(\mathrm{z}) = \frac{U(\mathrm{z})}{E(\mathrm{z})} = K_p + \frac{K_1}{1 - z^{-1}}. \tag{6}$$

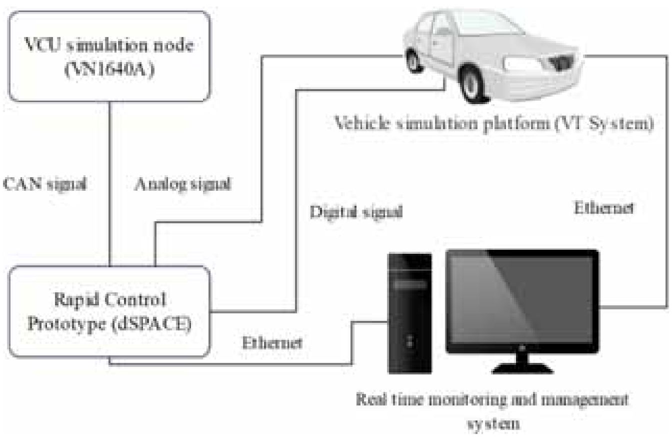

Fig. 4. Schematic diagram of overall design scheme of test system.

Among them, $E(z)$ is input, $U(z)$ is output, K_p is proportional coefficient and K_I is integral coefficient. By simplifying equation (6), equation (7) can be obtained:

$$U(z) = U(z)^{z-1} + \left(K_p + K_1\right)E(\mathrm{z}) - K_pE(z)^{z-1}. \quad (7)$$

The above equation is expressed in time domain as:

$$u(k) = u(k+1) + \left(K_p + K_1\right)e(K) - K_pe(k-1). \quad (8)$$

2.2 System environment construction

According to the overall hardware-in-the-loop architecture scheme designed above, it is clear that the HIL simulation system in this paper is mainly composed of the following software: CANoe, Simulink, Quartus, DSP Builder, ControlDesk. The overall block diagram of the software is shown in Figure 4.

Based on the hardware-in-loop system, the following functional modules are deployed: (1) The communication between signals is realized through CAN bus to send and receive data in messages, so as to realize the test of communication function. (2) It has the sensor model of signal interaction between on-board charger system and rapid control prototype, which can realize the input and output of digital signal and analog signal. (3) The two-stage bidirectional on-board charger model composed of the front stage PFC and the back stage CLLC can collect the PWM driving signal of the tested controller, and realize the output current and voltage close to the value required by the system. (4) The system should design a simple and effective upper computer interface, which can realize real-time reading of model parameters, support fault injection, and keep test results for further analysis. In addition to supporting manual testing, the system should have the call of automatic programs to realize automatic testing.

According to the overall hardware-in-the-loop architecture scheme designed above, it is clear that the HIL simulation system in this paper is mainly composed of the following software: CANoe, Simulink, Quartus, DSPBuilder, ControlDesk. The overall block diagram of the software is shown in Figure 5.

MicroLabBox and bus monitoring equipment VN1640A transmit messages through CAN signals, and collect analog signals output by VT board and send PWM digital signals to VT board. In addition to CAN signal communication between devices and digital signal and analog signal communication, the host computer is connected with VTSystem and MicroLabBox through Ethernet port, and also connected with VN1640A port through USB port. In addition, a 12V60W DC power supply is separately configured to meet the power requirements of VTSystem, and the overall block diagram of the built hardware platform is shown in Figure 6.

The quality of digital signal acquisition is one of the key factors that determine whether the scheme proposed in this paper can be realized, so it is necessary to test the function of digital signal acquisition. Because of the low data transmission frequency between CANoe and the board, it is difficult to verify whether the board has collected effective digital signals through the data monitoring function of CANoe. Therefore, a simple model is built in the board, which converts the digital signal collected by the measured digital signal channel into analog output, and confirms whether the measured digital signal channel works normally with the help of high frequency sampling of oscilloscope. The generation of digital signal is completed by means of single chip microcomputer. The modulation period of PWM wave is selected to be 10μs, and three different PWM duty cycle signals of 0.05, 0.06 and 0.07 are generated. The test results are shown in Figure 7. Comparing the three sampling results, the digital signal can be collected at this modulation frequency, and the pulse width of PWM wave with three duty cycles is significantly different. Therefore, it is considered to meet the needs of digital signal acquisition in HIL test system developed in this paper.

In this paper, the voltage and current sensor model should be implemented in simulation, and the analog signal acquisition function is tested. By building a simple model, the analog signal collected by the signal acquisition channel is directly output through the output channel, and the output is sampled by oscilloscope. The input signal is a 10 kHz excitation signal generated by the resolver decoding board, and the final sampling result is shown in Figure 8. It can be seen that the output sinusoidal signal waveform after acquisition is complete, so it is considered that the analog signal acquisition function is normal.

3 Simulation training tests

Direct drive means that the motor is connected with the drive axle directly or through the reducer to transmit power to the driving wheels, while variable speed drive means that the motor is connected with the differential through the multistage transmission to transmit power. Because the drive motor has the characteristics of wide speed range and strong speed regulation ability, most car companies gradually give up the variable speed drive

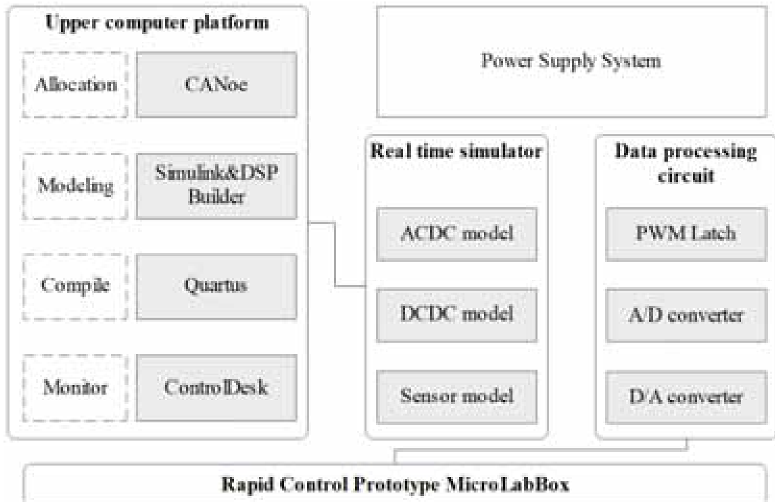

Fig. 5. Overall block diagram of software system.

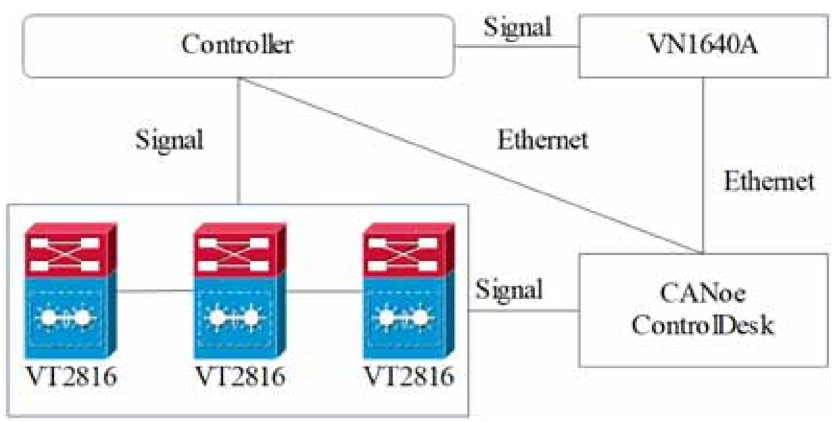

Fig. 6. Hardware platform of HIL test system.

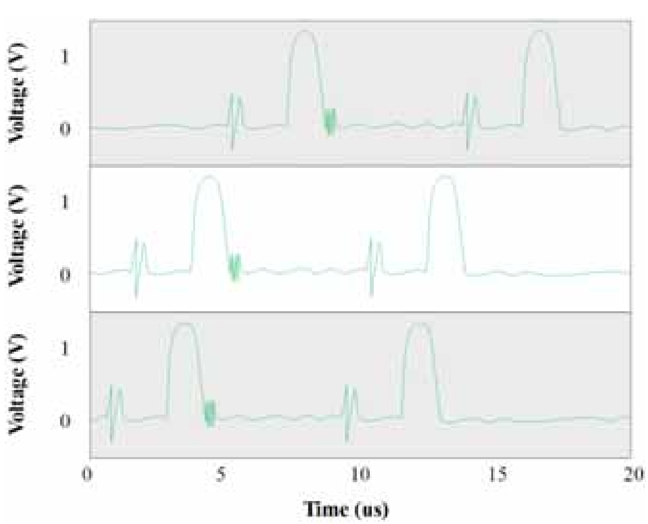

Fig. 7. THE rendering of digital signal acquisition.

powertrain and produce pure electric vehicles with direct drive structure powertrain. In this paper, the pure electric vehicle with direct drive structure equipped with reducer is studied, and its specific structure is shown in Figure 9.

On the basis of implementing real-time object simulation and closed-loop interaction between physical digital controllers and virtual (numerical simulation) objects in the on-chip hardware in the loop simulation system, comparative experiments were conducted with commercial Typhoon HIL simulators. We built a simulation model for Typhoon HIL and conducted experimental verification of the HILoC simulation system under input and load disturbances. The same component parameters were used for simulation to verify the reliability of the HILoC simulation system results.

Based on the comprehensive analysis of powertrain structure and forward simulation characteristics of pure electric vehicle, the longitudinal dynamics model of the whole vehicle is established by using modular modeling idea. The main modules include working condition module,

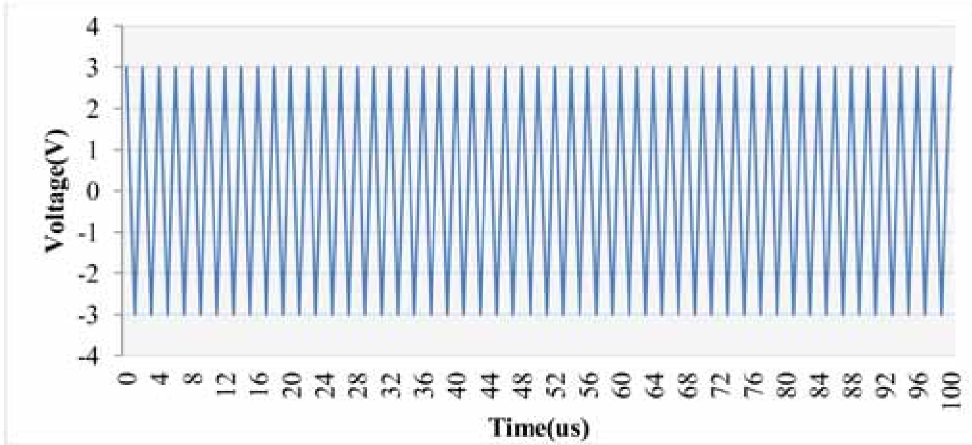

Fig. 8. The test effect diagram of analog signal.

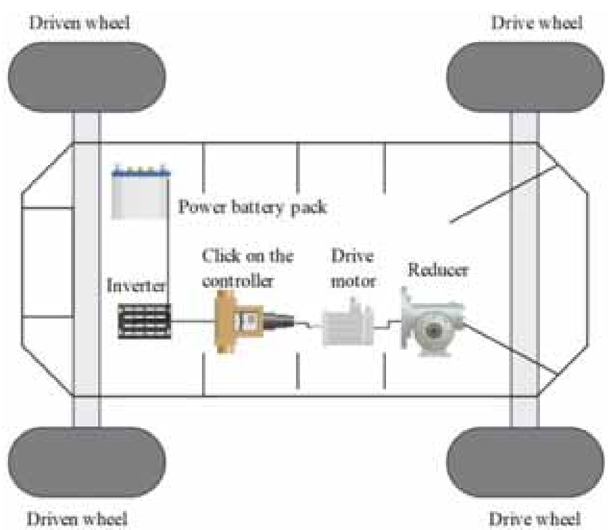

Fig. 9. Powertrain in direct drive configuration.

driver module, motor module, reducer module, battery module and whole vehicle dynamics module. The key parameters for establishing the vehicle model are shown in Table 1, and the model structure block diagram is shown in Figure 10.

Vehicle driving conditions are time and speed series describing vehicle driving characteristics in specific traffic environment. It is generally established through multiple driving experiments in the target traffic environment and a large number of data analysis by using multivariate statistical theory, which can reflect the typical driving characteristics of vehicles in the traffic environment. The driving condition is originally used for emission detection and fuel consumption test of traditional fuel vehicles. At present, the driving conditions adopted by automobile industry in the world are different, such as NEDC driving conditions in Europe, FTP75 driving conditions in America and JC08 driving conditions in Japan. In 2019, China National Standardization Administration released CATC (China Automotive Test Cycle), which is also the working condition selected in this paper.

Table 1. Main parameters of the whole vehicle.

Key parameters of whole vehicle	Parameter value
Curb mass (kg)	1428.14
Effective rolling radius (mm)	317.14
Rolling resistance coefficient f	0.01515
Windward area (m2)	1.8988
Air drag coefficient	0.3232
Rotational mass conversion coefficient	1.0605
Main reduction ratio	5.676:1
Battery capacity KW*h	55

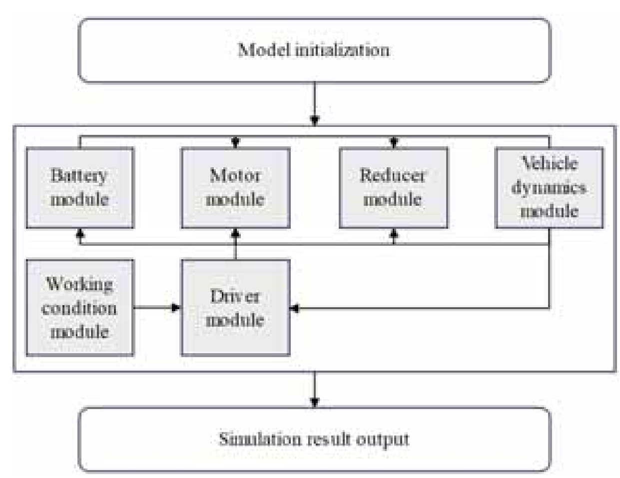

Fig. 10. Structural block diagram of longitudinal dynamic model.

Vehicle speed, motor torque and battery SOC are important parameters to validate the function of the distributed system in the next step. Therefore, in the off-line simulation of the integrated vehicle model, we should focus on the actual output of accelerator pedal and brake pedal after analysis by the driver module, the follow-up of the actual vehicle speed to the target vehicle speed, the

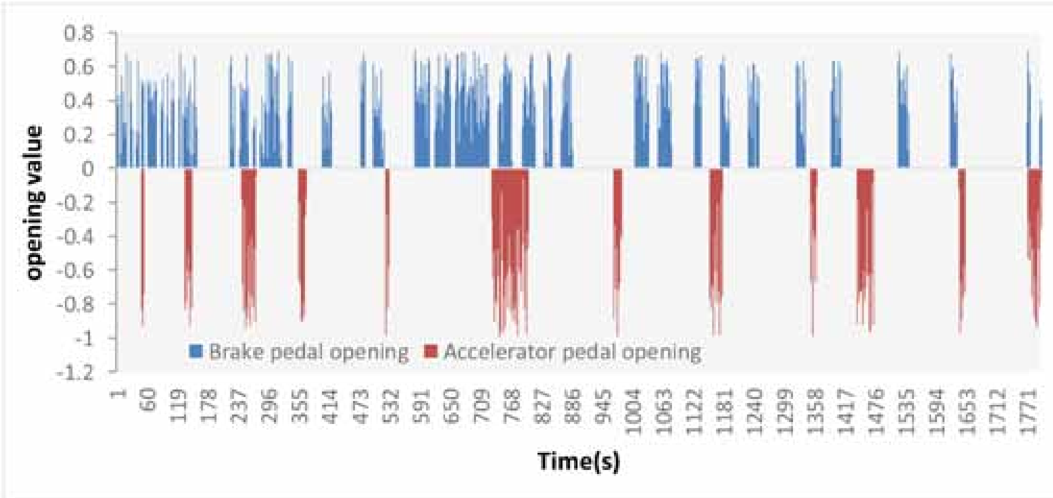

Fig. 11. Opening curve of accelerator pedal and brake pedal.

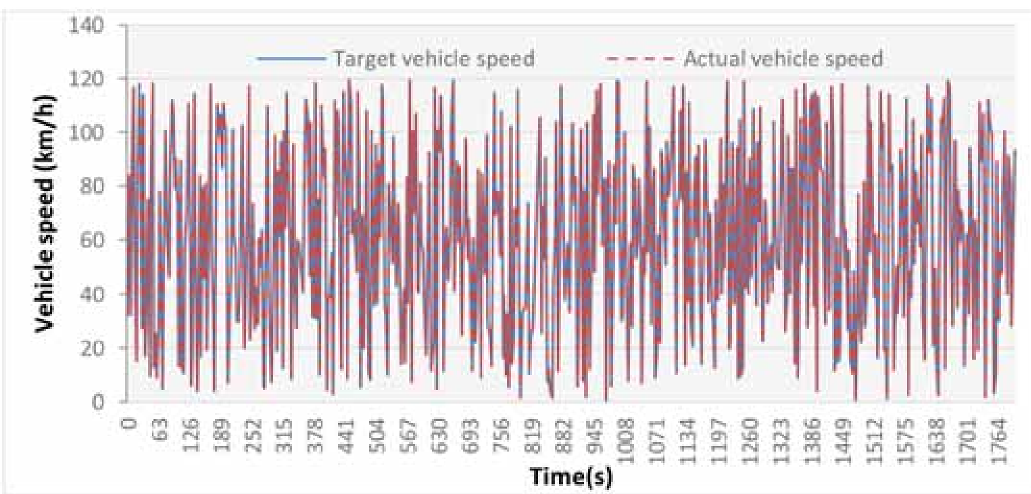

Fig. 12. Target and actual speed curves.

comparison between the actual output torque and the target torque in the motor module and the change of SOC value in the battery module. The off-line simulation uses NEDC driving conditions and CLTC-P driving conditions, and only the simulation results under CLTC-P conditions are shown here, as shown in Figures 11–14.

To further verify the effectiveness of the simulation system proposed in this paper, a comparison was made between the simulation system proposed in this paper and the systems proposed in references [10] and [11]. The performance of the system in automotive component simulation was statistically analyzed and evaluated through subjective evaluation by experts. The simulation effect, control effect, user experience, offline testing, and other aspects of these systems were evaluated, and the results are shown in Table 2.

From the above comparison, it can be seen that the model in this article plays an important role in automotive component testing and simulation compared to existing models, and has certain advantages.

It can be seen from the above figure that the actual speed follows the target speed well, the SOC value change under the change of pedal opening conforms to the actual situation, and the functional parameters of each module basically meet the design requirements. Therefore, the establishment of the model is reliable and effective, which can carry out the next research work on the basis of the whole vehicle model.

The hardware in the loop simulation system uses a real-time processor to run a simulation model to simulate the operating status of the controlled object. It is connected to the tested controller through I/O interfaces and conducts comprehensive system testing on the tested controller. Hardware in the loop testing is a semi physical and semi system testing (real controllers+virtual objects). Conducting hardware in the loop testing of developed control strategies can reduce the number of actual vehicle tests, greatly shorten the development cycle of control strategies, and also effectively reduce development costs.

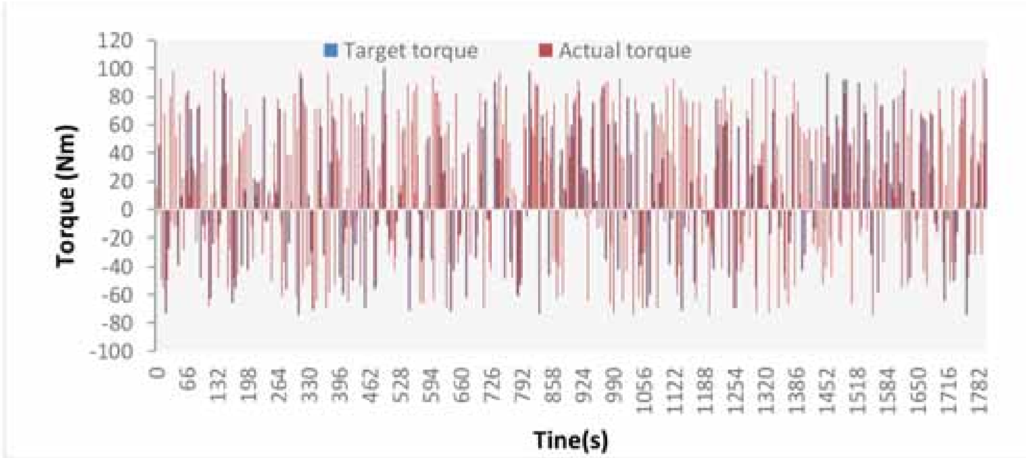

Fig. 13. Target and actual torque curves.

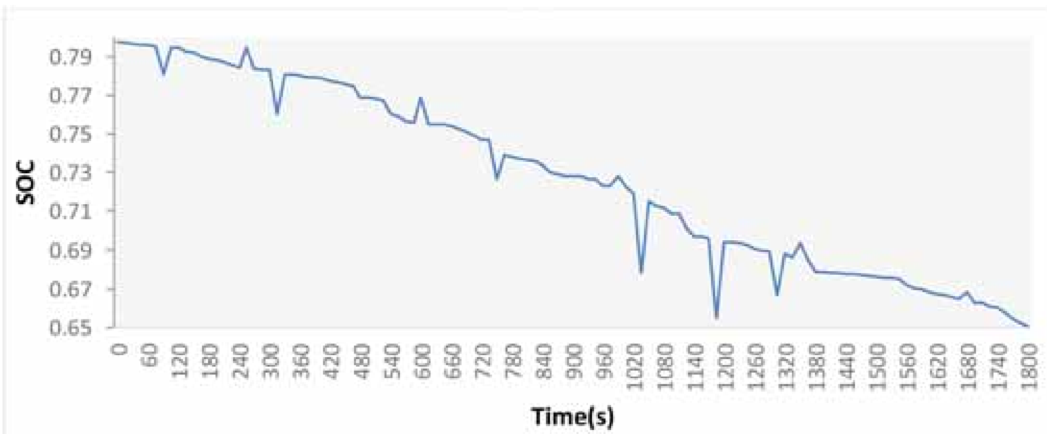

Fig. 14. Variation curve of SOC value.

Table 2. Comparative evaluation of the model in this article and existing research.

	Simulation effect	Control effect	User experience	Offline testing
The model of this article	93.52	91.24	94365	89.33
The model of reference [10]	83.94	81.28	83,159.57	80.07
The model of reference [11]	88.34	78.80	87,372.07	83.34

Firstly, the model construction and compilation of the hardware in the loop simulation system were completed, and the vehicle charger model code was successfully burned onto the FPGA board, achieving open-loop and closed-loop simulation of the system. Secondly, the automated testing development environment was introduced, and the automated testing development process was established. Subsequently, based on testing requirements and typical testing theories, corresponding test cases were written, and an automated testing program for input voltage protection strategy was developed based on the test cases. Finally, automated testing experiments were conducted and test reports were generated to verify the correctness of the automated testing scripts. The above research has verified the reliability of the method proposed in this paper.

The on-chip hardware in the loop simulation system designed in this article mainly studies dual core data exchange, utilizing the high-speed computing ability of dual core controllers to study the implementation of simulation object models and control in dual core systems, in order to achieve hardware in the loop simulation function and digital twin function of the simulation system.

A detailed analysis was conducted on the test results of the control strategy in both offline simulation and hardware in the loop systems, and the control effectiveness of the control strategy was summarized. The stability and compatibility of the test system were also verified. Experimental verification was conducted on the effectiveness of hardware design transfer from the loop to the physical object. The results showed that under the same controller parameters, closed-loop control of the physical object can be achieved, and the connected physical hardware circuit can be tested and tested in an operating environment that meets the performance indicators of the real system. The simulation effect is close to the real operating situation.

4 Conclusion

In order to realize the intelligent manufacturing of automobile parts and implement the product quality traceability system, this paper designs a hardware-in-the-loop simulation training system for automobile parts based on the popular intelligent simulation technology. The test content and test requirements of the diagnostic test of all the car body controllers are analyzed, and the overall design scheme of the diagnostic automatic test system is formulated on the basis of the functional requirements analysis of the test system. The automatic test flow of power level HIL test system is designed, and the automatic test experiment is carried out according to the automatic test flow. The results show that the test program in this paper can implement the test steps and generate the test report, the hardware-in-the-loop system is successfully built by using the vehicle controller communication interface model and simulation model, the hardware and software of the system run stably, and the control effects of the three control strategies can be further verified. Therefore, through experiments, it can be seen that the actual speed follows the target speed well, the SOC value changes in the case of pedal opening changes in line with the actual situation, the functional parameters of each module basically meet the design requirements, and the establishment of the model is reliable and effective.

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Conflicts of interest

The authors declare no conflict of interest.

Data availability statement

All relevant data are within the paper.

Author contribution statement

Zhanfu Ge wrote this paper, Youwei Xu designed Model, Baohai Zhang reviewed and revised the paper.

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