The Design and Implementation of Refuelling Machine Simulator Control System Based on FPGA

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Abstract: Refuelling machine simulator (simulator for short) has been used for operators to learn refuelling operation steps or periodic inspection. Refuelling machine is working in critical path of pressurized water reactor (PWR) nuclear power plants (NPPs), which has complicated control functions and interlock protection for refuelling operation. After finishing the refuelling, the control console of refuelling machine will be removed to a special room outside of reactor building. Then the simulator can be conveniently interconnected with control console for learning operation steps or making sure the control console in good condition before next reactor outage. The paper introduces the design and implementation of simulator control system, including requirements analysis, electrical product selection, control software development, HMI configuration and test validation. For designing and developing the simulator, the paper puts forward an innovative scheme that uses virtual simulation tools instead of physical instruments and electrical components by combining LabVIEW software platform with NI hardware platform based on FPGA. According to control requirements, the paper establishes mathematical simulation models of encoders, motors, load sensors, etc. Finally, the simulator has been validated by lots of tests to ensure the scheme is satisfied with design specification. In fact, the simulator control system has good performances in real time and expansibility. The simulator has been applied in the automatically controlled and digital refuelling machine of 1000MW PWR NPPs in China.
Keyword: Control system design, FPGA, LabVIEW, Simulation, PWR

1 Introduction

Refuelling machine is one of critical equipment in PWR NPPs, which is located over the pool of reactor building and responsible for transferring fuel assembly (FA) during reactor outage. Its reliability and security will directly affect the economic benefits of NPPs. Now the refuelling cycle of unit has been extended to 18 months, so it is the optimal period for operators to train operation and ensure the control console of refuelling machine in good condition before next reactor outage.

At present, the simulator in NPPs has mostly been designed by using physical hardware components (such as motors, encoders). This design scheme has made its control system difficult to be arranged and extended its functions. Besides, it has not good performance in economic efficiency.

Based on the above analysis, the paper puts forward an innovative design scheme that uses virtual simulation tools instead of physical instruments and electrical components by combining LabVIEW software platform with NI hardware platform based on FPGA.

Considering the training requirement and radiant sensitivity of electrical components, the control console will be removed to a special room outside of reactor building after refuelling. For the convenience of removal, all cables through control console are implemented by fast connectors. The simulator can be conveniently interconnected with control console by prefabricated cables. Operators handle joysticks and buttons of control console, and then the simulator control system will process commands from control console and feedback simulative running data and parameters in the absence of physical hardware components. It looks like realistic operation environment for operators.

2 Simulator requirements analysis

Requirements analysis must ensure that the simulator control system satisfies the control requirements and electrical interfaces of refuelling machine. As a typical bridge crane, refuelling machine can move on X (bridge), Y (trolley) or Z (hoist) direction to finish different operations according to the limited conditions of commands, position, load, etc. The operations of refuelling machine are summarized in table 1 and table 2.

Table 1 Operating mechanism of refuelling machine (manual mode)

Operating mechanism	Control method	Position measurement	Motor driver	Interlock protection
Bridge (B)	Joystick	Mechanical ruler/Dual encoders.	Dual servo drivers	Synchronous /Movement fault.
Trolley (T)	Joystick	Mechanical ruler/Dual encoders.	Single servo driver	Movement fault.
Hoist (H)	Joystick/ Buttons.	Dual encoders	Single servo driver	Gearing chain break/ Load limit/ Movement fault.
TV pole (TV)	Buttons	Single encoder	AC motor	Load limit/ Movement fault.

Table 2 Operating mechanism of refuelling machine (semi-atuomatic and automatic mode)

Operating mechanism	Control method	Position measurement	Motor driver	Interlock protection
B	Input coordinate	Dual encoders	Dual servo drivers	B&T can run at the same time.
T	Input coordinate	Dual encoders	Single servo driver	B&T can run at the same time.
H	Input coordinate	Dual encoders	Single servo driver	Same as table 1.
TV	Buttons	Single encoder	AC motor	Same as table 1.

Based on the above analysis of refuelling machine, the function requirements of simulator can be resolved into single function as follows [1].

a) Provide power supply to control console;

b) Quickly interconnect with control console by prefabricated cables;

c) Complete the simulation of absolute encoders;

d) Complete the simulation of motor resolvers;

e) Complete the simulation of load sensors;

f) Complete the simulation of faults alarm and other operation steps;

g) Display running states and adjust parameters on HMI of simulator;

h) Periodic inspection for control console.

3 Hardware design

The core of simulation system design and development is how to integrate signals generation and I/O acquisition devices with the simulation system software. The main challenge is how to synchronize a large number of I/O devices at high speed, and how to quickly convert the simulation signal data into input and output information, and convert the input and output information to data that can be correctly identified by signal receiving devices. These are the problems that need to be solved in the design of simulator.

In the simulation of control system, one of the important tasks for the simulator is to establish dynamic mathematical models. To make the simulation as realistic as possible to the actual operation conditions, it needs to be done in a fast and accurate controller, and the running speed of the simulator control system should be equal to or greater than the controller's sampling speed. Therefore, the simulator control system is a fast dynamic simulation system and hardware in the loop (HIL) simulation system. It is based on the real-time processor to simulate running states of refuelling machine. The following critical factors need to be considered when designing HIL systems.

- The system should be compatible with multiple control units.
- Minor changes to control units do not result in the completely different design.
- The system should be able to perform both open-loop and closed-loop tests.
- The system should be open and extensible.
- The most important point is that the system cost in terms of components and development time should be reasonable.

Above all, the simulator uses the control platform of National Instruments (NI) CompactRIO based on FPGA. NI CompactRIO is a rugged, reconfigurable embedded system. It consists of three components - a real-time controller, a reconfigurable field programmable gate array (FPGA) and industrial I/O modules.

The real-time controller contains an industrial processor that reliably and deterministically executes LabVIEW Real-Time applications and offers multi-rate control, execution tracing, onboard data logging and communication with peripherals.

The reconfigurable FPGA chassis is the center of the embedded system architecture. FPGA is directly connected to the I/O modules for high-performance access to the I/O circuitry of each module and unlimited timing, triggering, and synchronization flexibility. Because each module is connected directly to the FPGA rather than through a bus, there is no control latency for system response compared to other industrial controllers [2][3].

I/O modules contain isolation, conversion circuitry, signal conditioning, and built-in connectivity for direct connection to industrial sensors/actuators. By offering a variety of wiring options and integrating the connector junction box into the modules, the CompactRIO system significantly reduces space requirements and field-wiring costs.

One chassis of the CompactRIO system supports eight I/O modules at most, and it can be extended as required. The main chassis communicate with extended chassis through Ethernet or EtherCAT network protocol.

The hierarchic hardware architecture of simulator control system is shown in Fig.1.

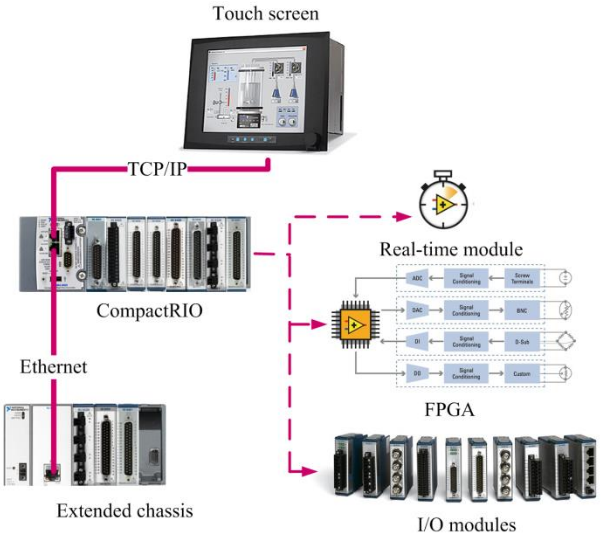

Fig.1 Hierarchic hardware architecture of simulator

4 Software design

The software design of simulator control system mainly includes two parts: human machine interface (HMI) configuration and control programs development, which are developed by NI LabVIEW software platform. The HMI is running on the touch screen computer with windows system. NI LabVIEW comes with a library with a large number of reusable codes. These reusable codes provide hundreds of built-in functions for control, analysis, communication, file I/O, and so on. In addition, NI LabVIEW introduces a new reusable code type called function block. These functional blocks are real-time applications and comply with the IEC 61131-3. Users can easily use these blocks with other LabVIEW codes [4][5].

The detailed software architecture diagram of simulator is summarized as Fig.2.

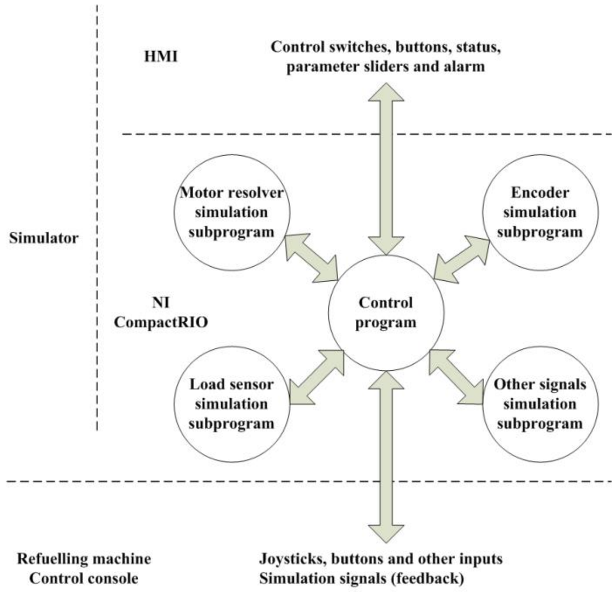

Fig.2 Software architecture diagram of simulator

As shown in Fig.2, the HMI can monitor and display control console states in real-time, but also can adjust initial parameters and send out relative control signals to control console. The control programs of simulator are mainly responsible for the simulation of various operation conditions, such as encoders, motor resolvers and load sensors.

The communication between HMI and NI CompactRIO controller use TCP/IP network protocol. The switches and buttons on HMI can send out commands to control programs in NI CompactRIO controller. The control programs of simulator not only take charge of simulation, but also transfer the device information to HMI for operator.

5 Control programs development

Control program development of the simulator is based on NI LabVIEW software, which has a set of tools for the collection, analysis, display and storage of data. The LabVIEW program is called virtual instrument (VI), and its appearance and operation are similar to real physical instruments (such as oscilloscope panel) [3].

5.1 Control programming

Based on control requirements of the simulator, the paper establishes mathematical simulation models of encoders, motors, load sensors, etc. Firstly, the simulator control system collects signals from the control console (e.g. speed and control commands). Secondly, the simulator control system simulates physical instruments and electrical components according to mathematical models in real time and outputs simulative signals to the control console. Finally, the simulator control system completes simulation of encoders, motors, faults and other operation steps.

According to the software architecture diagram in Fig.2, control programs are divided into four parts as follows.

- Encoder simulation subprogram
- Motor resolver simulation subprogram
- Load sensor simulation subprogram
- Other signals simulation subprogram

5.1.1 Encoder simulation subprogram

Encoder simulation subprogram consists of clock signal acquisition module, speed acquisition module, simulation signal generation module and simulation signal output module. The detailed flow diagram of encoder simulation subprogram is shown in Fig.3.

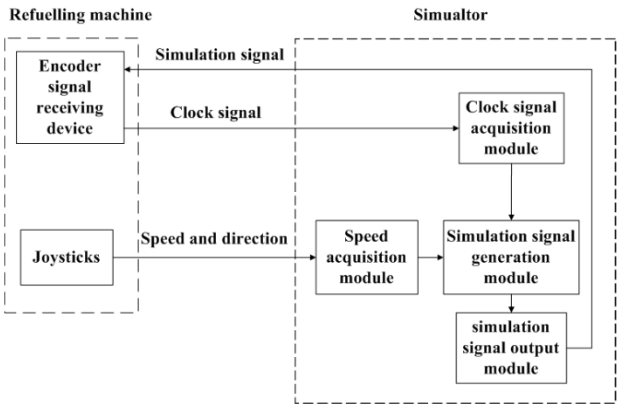

Fig.3 The flow diagram of encoder simulation subprogram

As shown in the figure above, when refuelling machine operator is in the operation training, operator handles joysticks on control console and control system of refuelling machine sends out speed and direction signals to simulator. Speed signal is used to simulate the numerical change rate of encoder. Directional signals are used to determine the increase or decrease of encoder value. Then simulator completes the logic and numerical computation according to pre-set mathematical model in controller and generates encoder simulation signals that will be fed back to control console. An illustration of encoder simulation data is shown in Fig.4.

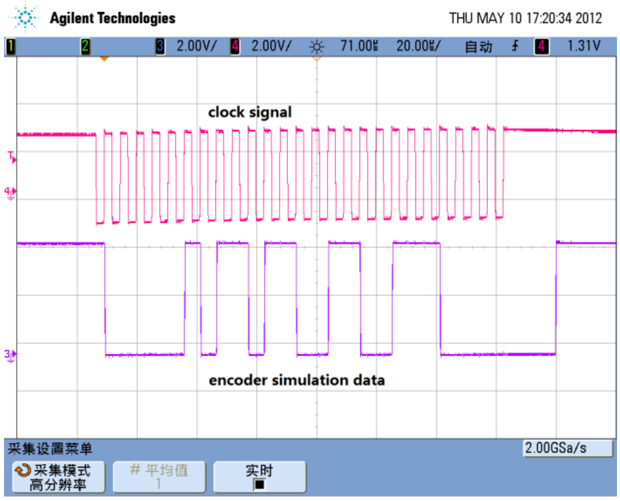

Fig.4 Illustration of encoder simulation data

5.1.2 Motor resolver simulation subprogram

Motor resolver simulation subprogram consists of excitation signal acquisition module, speed acquisition module, simulation signal generation module and simulation signal output module.

The subprogram architecture diagram is similar to Fig.3. The difference is that excitation signal acquisition module takes charge of receiving excitation signal from motor driver. Speed signal from speed acquisition module is used to simulate the speed of motor rotation in the simulation. Direction signals from speed acquisition module are used to judge the motor rotation direction.

Similarly, the simulator completes the logic and numerical computation according to pre-set mathematical model in controller and generates motor resolver simulation signals that will be fed back to control console. The motor driver receives resolver simulation signals and displays motor speed which is a part of the closed loop control. An illustration of motor resolver simulation data is shown in Fig.5.

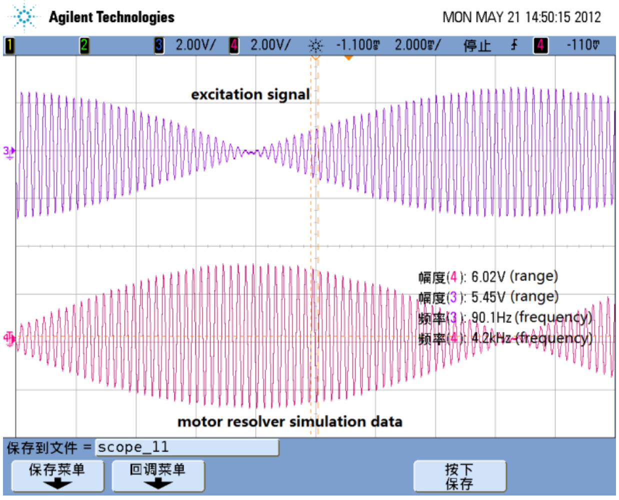

Fig.5 Illustration of motor resolver simulation data

5.1.3 Load sensor simulation subprogram

Refuelling machine is equipped with four load sensors (two for hoist and two for TV pole). When load sensors are being simulated, Control console needs to provide input signals as follows.

Table 3 Input signals of load sensor simulation

Item No.	Signal name
1	Hoist moving direction (up/down)
2	Hoist elevation
3	Gripper latch/unlatch limit switch
4	FA selection switch
5	Numerical deviation between two load sensors (HMI slider)
6	Load adjustment (HMI slider)

Based on the above input signals, simulator control system complete numerical and logic calculation and generate simulation signals of load sensors. Simulation signals will be sent back to control console for logic interlock. Over load or under load alarm can be easily simulated by adjusting slider on HMI. The simulation results of load sensors are shown in Fig.6.

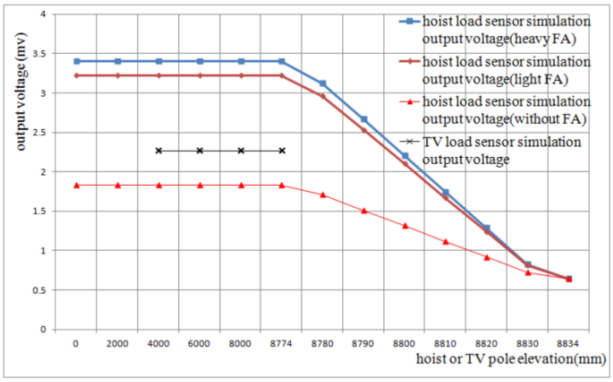

Fig.6 The simulation results of load sensors

5.1.4 Other signals simulation subprogram

According to the control requirements, simulator needs to simulate some operating conditions of refuelling machine. Other necessary simulation signals are shown in table 4.

Table 4 Other necessary simulation signals

Item No.	Signal name
1	Upper limit of TV pole
2	Upper limit of hoist
3	Gripper latch/unlatch limit switch
4	Brake open (emergency brake and safety brake)
5	Brake wear (emergency brake and safety brake)

5.2 HMI program development

According to the requirements analysis of simulator, HMI is divided into three parts, including the upper, middle and lower parts. It is very friendly and overall. The upper area is software function area, including company LOGO, software copyright, start/stop button, and communication indicator. The middle area is operation control area with responsibility for sending out commands to control console, involved with bridge, trolley, hoist, etc. The lower area is information display area, mainly including encoder position, states of limit switches and sensors, as well as the animation display of refuelling machine.

HMI can be configured by input controls and display controls. Input controls include knobs, buttons, switches, and other input devices. Display controls have graphics, indicator lamps, textboxes etc. When HMI configuration is finished, the corresponding control program code can be added. The objects on HMI can be controlled by using VIs, loop structures and timers. HMI program can be made as an .exe installation program and easily installed on the touch screen with windows system.

6 Test validation

The purpose of simulator tests is to ensure that the functional performances meet the specification requirements. The simulator tests are summarized as follows.

- Appearance inspection
- Insulation resistance test
- Ground continuity test
- Functional tests

Appearance inspection includes checking electrical components layout and installation, wire connection, cabinet dimensions and painting. Insulation resistance test is to check that the insulation resistance value of circuits meets the criterion of acceptability. Ground continuity test is to check that the ground resistance value of cabinet meets the criterion of acceptability. Functional tests consist of system start/close test, DI functional test, DO functional test, operation simulation test [6].

Base on the above test validation, the performances of simulator meet the specification requirements.

7 Conclusion

Using VIs can develop innovative solutions for challenging design problems and get rid of the shackles of traditional solutions. This paper firstly analyzes the functional requirements of the simulator. Then the paper puts forward an innovative scheme that uses VIs instead of physical instruments and electrical components by combining LabVIEW software platform with NI hardware platform based on FPGA. The design scheme makes full use of FPGA's speed and synchronization ability, and successfully develops the simulator control system.

Through the test and validation, the performances of simulator control system are satisfied with the specification requirements. In fact, the simulator control system has good performances in real time and expansibility. The design scheme not only shortens the design and development time, but also saves costs. The practicability and reliability of simulator can directly improve the training efficiency for operators and provide security for the refuelling process of NPPs.

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