Design of a Field Programmable Gate Array Based Test Launch and Control System for Hybrid Vehicle

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Abstract

In order to satisfy the throttling and multiple restart characteristics of the hybrid rocket engine and guarantee the controllability and security of hybrid rocket, the test launch and control system for hybrid vehicle needs to achieve ground power control, serial communication with the flight control computer and the telemetry system, onboard thermal battery activation, battery voltage acquisition, power conversion, pressure monitoring, valve control, booster ignition, power-off and remote pressure relief in emergency. Considering the complexity of the test launch and control system for hybrid system and the advantages of Field Programmable Gate Array (FPGA), such as, a large number of I/O ports, ability to efficiently implement large-scale systems and programmability, a **FPGA** based test launch and control system for a type of hybrid vehicle was designed. Many conducted ground and flight experiments have proved that the system has superior performance in integration, universalization, miniaturization, automation and can perfectly meet the needs of the hybrid vehicle.

Keywords-hybrid vehicle, test launch and control system, **FPGA**, internal logic

Introduction

Hybrid rocket engines use liquid oxidizer and solid fuel as propellants, which have advantages such as safety, low cost, throttling and multiple restart capabilities [1-2]. The hybrid rocket engine presents extensive application prospects in the fields of sounding rocket, launch boost, small satellite propulsion system, and manned space-ship [3]. As the representative, US Lockheed Martin Company and NASA combined to develop “HYBRID Sounding Rocket” (HYSR) project in 1995 to verify rocket performance with high thrust, break through key technologies in pressure boost with helium and transmission system, in experimental system and so on to advance maturity of its engineering technique. In 2002, they launched the largest hybrid rocket to this day, whose length was 17.4m, diameter was 0.6m, valid loading was 360kg and flight time was 219s, which proved to the world the hybrid vehicle’s development potential, sparked a research boom all over the world. In China, Beihang University launched China’s first hybrid vehicle “buaa.2” successfully on December 5, 2008 and “buaa.3”, which realized the variable thrust during flight on April 25, 2012 [4-6].

To our best knowledge, there is no research work on the **FPGA** for solving problems of the complicate test launch and control system design of a hybrid vehicle, so considering the complexity of the test launch and control system for a hybrid vehicle and the advantages of **FPGA**, we designed a **FPGA** based test launch and control system for a hybrid vehicle. As a fiendishly complicated system, the test launch and control system for a hybrid vehicle needs to achieve ground power control, RS-422 serial communication with the flight control computer and the telemetry system, onboard battery activation, battery voltage acquisition, power conversion from ground power supplies to onboard batteries, booster ignition, emergent power-off, especially pressure monitoring, valve control and remote pressure relief in emergency.

Because of its advantages such as low cost due to the small quantity, rapid running speed, a large number of I/O ports, ability to efficiently implement large-scale systems, high reliability and programmability [7-10], **FPGA** is extensively used in rapid prototyping and verification of a conceptual design and also used in electronic systems and has already demonstrated its good performance in a large amount of complicate system. In [11], N. Chettibi discussed the real time simulation and control of grid-connected photovoltaic systems based on **FPGA**. An instrument based on **FPGA** was proposed in [12] for power measurement in DVB-T systems. In [13], an **FPGA**-based reconfigurable system was designed for tool condition monitoring in high-speed machining process. In [14], Stephan Zschäk studied the control of nanopositioning and nanomeasuring machines with a modular **FPGA**. A Real-time Updatable **FPGA**-based Architecture was proposed in [15] for fast regular expression matching. More systems were designed based on **FPGA**, like a digital coincidence measurement system [16], a chlorophyll fluorescence measurement system [17], power flow monitoring system in a microgrid [18], human detection system [19], an image analysis system for automatically controlled pan-tilt smart camera [20], etc.

The remainder of this paper is organized as follows. In section 1, the overall design of the test launch and control system is introduced, which includes signal isolation and adjustment, launch and control, data acquisition, remote communication, signal transfer and safety control. In section 2, the internal logic design of **FPGA**, especially the RS-422 serial communication module and the A/D sample control module, is discussed and analyzed in details. In section 3, the software design of the test launch and control system is illustrated. In section 4, a number of ground and flight experiments are introduced to prove that the system can perfectly meet the needs of the hybrid vehicle. Finally, the conclusion is given in section 5.

1 Overall Design of the Test Launch and Control System for a Hybrid Vehicle

To meet the integration needs of a hybrid vehicle, a remote automatic testing scheme was developed based on **FPGA** for a hybrid vehicle. The general structure of the test launch and control system is shown in Figure 1.

Fig.1. the general structure of the test launch and control system

As shown in Figure 1. The hybrid vehicle consists of **onboard control devices** (including the flight control computer, navigation system, rudder system, telemetry system, remote pressure relief valve and pressure sensors), solid boost and the hybrid rocket engine. **The hybrid rocket engine consists of** high-pressure gas reservoir, liquid oxidizer reservoir, startup valves, solid propellant, nozzle, and blasting bolt. Having a distributed structure, **the test launching and control system** consists of the front-end equipment near the rocket and the back-end main control console [21]. Wherein, the front-end equipment includes **FPGA** control board, ground power supplies, Electrical explosion component tester, etc. The front-end equipment is mainly designed to achieve power supply, launch control, signal isolation and adjustment, data acquisition, remote communication, signal transfer and safety control. The back-end main control console includes the main computer and **two remote manual control switches**. The main computer can achieve RS-422 communication with XC3S250E, data display, storage and analysis. **The remote manual control switches are used for safety control as a backup**. The front-end equipment is located below the launcher, the back-end equipment located at a safe distance.

The system uses XC3S250E of Xilinx Spartan3E as the core control chip. By configuring the internal logic function of XC3S250E, we can integrate board product in chip product to reduce the difficulty of the design of printed circuit board, which enhances the reliability and maintainability of the test launch and control

system. The functions of launch and control, **isolated and adjustment**, data acquisition, remote communication, signal transfer and safety control are as follows:

Launch and control: The system needs to provide **the hybrid vehicle with excitation signals** to complete power distribution control, mainly including thermal battery activation and power conversion (converting ground power supplies to batteries on board). **FPGA** needs to provide **control signals** for ground power supply control, valve control, booster ignition, power-off and remote pressure relief. **When receiving commands from the main computer**, XC3S250E will output validation signal to drive relays. Then excitation signals are output.

Isolated and adjustment: The **isolated and adjustment module** has two functions: one is to isolate XC3S250E from peripheral driving circuits for decreasing interference influence. The other is to boost the driving voltage of XC3S250E from 3.3V up to 5V. We choose 74LVC164245 as the isolation and adjustment chip. Figure 2 shows the details of the circuit. Wherein, 16 voltage signal inputs (1A1-1A8 and 2A1-2A8) are 3.3V driving signals from XC3S250E. 16 voltage signal outputs (1B1-1B8 and 2B1-2B8) are 5V driving signals used to drive corresponding peripheral circuits.

Fig.2. Isolation and adjustment circuit of 74LVC164245

Data acquisition: This module is designed to acquire the key parameters in real time, **including** the resistance of Electrical-explosion Devices (EEDs) and the thermal battery voltages.

As EEDs are sensitive devices, which have strict restrictions on current size and power-on time, the resistance of EED must be measured by Electrical Explosion Component Tester (EECT) before launch. The EECT **sends** the result to XC3S250E through its serial interface. Then XC3S250E **sends** the result to the main computer. In order to test multiple EED, the multi-channel control circuit is designed as showed in Figure 3.

Fig. 3 Multi-channel resistance test of EED

The function of multi-channel resistance test of EED can be realized by switching the relays group, which constitutes the EED test control circuit. Besides, to enhance the accuracy of the detection of EED, the test results must subtract the resistance of the cable from the EED to EECT. The resistance of the cable can also be tested with the EECT.

There are five thermal batteries on board, **one of which is for control devices**, one is for EEDs on board, and three are for the rudder system. To insure the status of the thermal batteries is normal after activation, it is necessary to acquire the voltage of batteries. This function is achieved by A/D sample circuit based on relays group as illustrated in Figure 3. **Firstly**, by switching the relay group, **multi-channel voltages of batteries are** led into A/D sample circuit with the AD7895 as the core chip. **Secondly**, after the RC filter circuit, the differential signals **are** converted to single-ended signals through the amplifier. Then single-ended signals **are** sent to the chip AD7895 and converted to digital signals. **Thirdly**, the chip AD7895 **sends** the data to XC3S350E through the isolated and adjustment module. **Finally**, when receiving the voltage data, XC3S350E **sends** the data to the main computer through the RS-422 serial communication.

Remote communication: The remote communication circuit is designed to achieve remote RS-422 communication between XC3S250E and the main computer. It can provide instruction and data channels for achieving unattended operation in the front equipment and remote control in the back-end.

Signal transfer: To achieve reliable remote RS-422 serial communication between the main computer and the onboard electrical devices, including the flight control computer, the telemetry transmitter and the telemetry receiver, the RS-422 signal repeat circuit is designed. The RS-422 signal repeat circuit can auto-achieve signal transfer and isolation without the main chip's participation. Through the communication with the flight control computer, the system can achieve real-time monitoring of devices on board, data bookbinding and pressure acquisition. Through the communication with the telemetry transmitter and the telemetry receiver, the transmitter and receiver parameters can be set. Besides, any two channels are isolated, and shielded twisted-pair cables with 1500V electrical isolation are used as the communication cables, which **increases the reliability**.

Safety control: when faults occur, to effectively ensure the human safety and reduce the losses, **the test launch and control system needs** to realize the function of safety control including cutting off the power supply and opening the remote pressure relief valve to release the gas in the high pressure vessel. The schematic of the remote pressure relief valve control circuit is shown in **Figure 4**.

Fig.4. Schematics of safety valves' control circuit

As shown in Figure 4, the circuit uses redundant design with dual control to enhance the reliability. The valve will be opened when XC3S250E receives the control command of safety valves or S1 is closed.

In summary, the system uses an integrated design principle and takes full advantages of the wealth I/O interface of **FPGA**. The remote communication circuit enables XC3S250E to receive control commands from the main computer at any time and auto-complete the corresponding test, control, and firing mission, which greatly improves the automaticity of the system and makes the system more reliable. Figure 5 is the physical picture of the printed circuit board of **FPGA**.

Fig.5. Physical picture of the printed circuit board of **FPGA**

2 Internal Logic Design of **FPGA**

Hardware programming of **FPGA** is the key step of the system. It is mainly designed to achieve remote serial communication with the main computer, command parsing, A/D sample control and information processing. RS-422 serial communication module and A/D sample control module are designed by VHDL (Vhsic Hardware Description Language) as follows.

RS-422 serial communication module: RS-422 serial communication module aims at completing intelligent RS-422 serial communication with the main computer, which is the basis of the entire control system. According to the requirements of the test launch and control system, the module **is** designed as in Figure 6.

Fig.6. the RTL (Register Transfer Level) Schematic of RS-422 serial communications module

As shown in the figure, 'clk' is external clock input, 'rst' is reset signal, 'rxd' is data input terminal, 'txd' is data output terminal, 'DE' is data output enable, 'clkout' and 'rxd_clk' are all output test terminal. The system uses a baud rate of 38400 with a data frame of 10 data bits (one starting bit, eight data bits and one ending bit).

When receiving data from 'clk', the serial data will be sampled after the starting bit is received. The serial data will be stored by the shift register. The module starts judging the ending bit as soon as eight data bits are received. When transmitting data to 'txd', 'DE' will be high first and then the module starts sending the starting bit, eight data bits and the ending bit at last. Figure 7 is the simulation waveforms of receiving 0x55 with 0xAA feedback.

Fig.7. Simulation waveform of RS-422 serial communications module

AD sample control module: This module is designed to control the A/D sample circuit and read data from AD7895. It will transport voltage data to the host computer through RS-422 bus.

AD7895 is a fast 12-bit ADC that operates from a single +5V supply and contains a 3.8μs successive approximation A/D converter and a high speed serial interface. Figure 8 shows the timing and control sequence required to obtain optimum performance from the AD7895.

Fig.8. Timing and control sequence of AD7895

As shown in the figure, conversion is initiated on the falling edge of $\overline{CONVST}$ and new data from this conversion is available in the output register of AD7895 3.8μs later. Once the reading operation takes place, a

further 300ns should be allowed before the next falling edge of $\overline{CONVST}$ to optimize the settling of the hold amplifier.

Fig.9. Data reading operation

Figure 9 shows the timing diagram of the AD7895 reading operation. The serial clock input (SCLK) provides the clock source for the serial interface. Serial data is clocked out from the SDATA line on the falling edge of this clock and is valid on both the rising and falling edges of SCLK, which provides the user great flexibility.

According to the characteristics of the AD7895, the control logic has been designed as shown in Figure 10.

Fig.10 the RTL (Register Transfer Level) Schematic of AD acquisition control module

The function of A/D acquisition is realized by state machine. When XC3S250E receives the command of A/D sample from the main computer, A/D state machine will get started and automatically complete voltage acquisition one by one according to the timing sequence. The simulation waveform of A/D acquisition is shown in Figure 11.

Fig. 11 Simulation waveform of AD acquisition control module

3 Software Design of the Test and Launch Control System for a Hybrid Vehicle

The test launch and control system **software**, including the main computer man-machine interface, and the telemetry system parameter setting interface software are designed to communicate with XC3S250E, the flight

control computer and the telemetry system. The main computer man-machine interface communicates with **FPGA** to achieve ground power control, thermal battery activation, battery voltage acquisition, power conversion, valve control, booster ignition, power-off and remote pressure relief. The main computer man-machine interface communicates with the flight control computer to realize pressure monitoring, onboard devices monitoring and flight parameters bookbinding. The telemetry system parameter setting interface software is used to set the parameters of the telemetry transmitter and receiver.

3.1 Software Development Environment

The man-machine interface software of the main computer is developed by VC ++ 6.0 based on MFC (Microsoft Foundation Classes) provided by Windows. Windows provides more than 1,000 kinds of application programming interface, through whose MSDN (Microsoft Developer Network) the required function and function usage can be easily found. The man-machine interface, shown in Figure 12, needs a total of **four-channels of the** RS-422 signals, to realize serial communication with XC3S250E, the flight control computer, the telemetry transmitter and the telemetry receiver. Serial communication programming mainly uses MSComm controller provided by Microsoft, multithread serial programming CSerialPort class and Windows API functions. In fact CSerialPort class is also written by API functions, just packaging the main API functions about serial programming and reserving external interface to convenient customer's operation. **To guarantee the real-time and security**, we choose Windows API to program.

Fig.12. Man-machine interface of the host computer

In addition, **to display** the pressure data and the voltage data collected in real time, we use a chart controller **named** TeeChart developed by the Spanish Steema company, which can be directly embedded into the dialog box, and programmed by API functions it provides. The software is designed based on multithread. The modular structure design can effectively speed up development time and result in more maintainable code. After a simple combination of modules the software can be applied in similar tasks.

After getting powered, the **telemetry** transmitter and receiver can be set by telemetry transmitter parameter setting interface software and telemetry receiver parameter setting interface software according to the parameters (carrier frequency, PCM(Pulse Code Modulation) rate, modulated frequency deviation, input

mode, and modulation mode) given on site. The parameters set can be saved in the telemetry system to be read when necessary.

3.2 Software Running Process

After the main computer and **FPGA** control board are powered, the software of the ground test launch and control system can be run.

Firstly, the man-machine interface software is run. The emergency power-off switch is turned on to reset the relays on the vehicle and the ground power supply for onboard control devices and the ground supply for the rudder system are then turned on.

Secondly, **the control devices are initialized**. When powered on, the flight control computer will have its self-checking program run automatically. After receiving the communication confirmation command from the main computer, **the flight control computer packages the result and sends it to the ground**. Based on the communication protocol the self-checking data **is** analyzed and displayed. The main computer sends pressure acquisition command to the flight control computer to monitor the pressure in real-time. **When** powered on, the navigation system needs a period of time to preheat. Then the main computer sends self-checking command through the flight control computer to the navigation system. After receiving self-checking result of the navigation system, the main computer binds initial parameters of the navigation system, including geographical longitude, latitude, altitude, pitch angle, yaw angle and roll angle through the flight control computer. Selecting East-North-Up coordinate as navigation reference coordinate system, when the navigation system's body coordinate system are biased against reference coordinate system, the attitude angles need to be bound within the system to achieve accuracy alignment. The main computer sends the rudder self-checking and zero commands to the rudder system and receives the feedback message through the flight control computer. The telemetry transmitter and receiver are set by telemetry transmitter parameter setting interface software and telemetry receiver parameter setting interface software .

Thirdly, after the system initialization is the procedure of launch-control. **During the test phase**, the onboard devices are powered up by the ground power supplies. **During the flight phase**, the devices should be powered up by the thermal batteries. The main computer sends an activation command to **FPGA**, and then a 28V ground power supply generates a 28V pulse lasting 300ms to **activate** the thermal batteries. After the thermal batteries are activated, the main computer sends voltage acquisition command to **FPGA** and receives the voltages of the thermal batteries per second. The main computer displays, and stores the voltage data. If the battery voltages meets the requirements, the main computer sends power conversion command to **FPGA**.

Finally the verification code is entered to unlock the ignition button and fire. As the plug is not in position, this means the vehicle is launched after ignition. The status of the plug is checked to ensure the flight control computer starts sequence [22]. In addition, when emergency occurs, the power supply is cut off and the remote pressure relief valve is opened to release the gas in the high pressure vessel.

4 Testing of the Test Launch and Control System for a Hybrid Vehicle

To evaluate and verify the designed functions of the test launch and control system, **testing with hardware has been done**. The test results are observed by an oscilloscope as shown in Figure 13-17. Figure 13-15 show the testing waveforms of ground power supply for onboard control devices and the rudder system and the remote

pressure relief valve control. Figure 16 shows the testing waveforms of the excitation source of battery activation and booster ignition, Figure 17 shows the testing waveforms of the power conversion driving signal and power-off driving signal.

Fig.13. Ground power supply for onboard control devices on (left) and off (right)

Fig.14. Ground power supply for the rudder system on (left) and off (right)

Fig.15. Testing waveforms of remote pressure relief valve on (left) and off (right)

Fig.16. Testing waveforms of the battery activation output (left) and booster ignition output (right)

Fig.17. Testing waveforms of the power conversion signal (left) and power-off signal (right)

From Figure 13, it is easily seen that the test launch and control system can achieve the on-off control of the 28V ground power supply for the onboard control devices and the 48V ground power supply for the rudder system. Figure 15 illustrates the designed system can control the remote pressure relief valve on/off with a fast response time. From Figure 16, the battery activation output voltage is 12V and the booster ignition output voltage is 27V with duration longer than 200ms, which satisfied the analysis request. In addition, the real object experiment shows that the system can rapidly and reliably fire common electric ignition head and achieve the onboard thermal battery activation. From Figure 17, it is seen that that the designed system can normally produce the 28V power conversion pulse signal and 28V power-off pulse signal, which last longer than 200ms.

Conclusion

By analyzing the requirements of the hybrid vehicle test and launch, an integrated test launch and control system is designed based on **FPGA**, which has the functions of ground power control, serial communication with the flight control computer and the telemetry system, onboard battery activation, battery voltage acquisition, power conversion from ground power supplies to onboard batteries, booster ignition, power-off and remote pressure relief. The core internal logic module of XC3S250E is illustrated and solved in detail. According to the integrated design

and the actual engineering validation, the system has been successfully developed and tested in hybrid vehicles. The application can fully show that the system has the advantage in the aspects of integration, miniaturization, automation, versatility and high reliability. The system also has powerful data acquisition and display capabilities, which can ensure the launch mission of the type of hybrid vehicle to be successful.

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