Hot-swap and hot redundancy technology for high-availability Compact PCI system

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Abstract: Motivated by the challenging requirements of optimal fault tolerance and real-time response in the Compact PCI (CPCI) measurement and control systems, a design of a high-availability hot-swap system based on VxWorks operating system is proposed. In addition, multiple methodologies are designed and applied to guarantee operational safety during the hot-swaps. An external experimental measurement platform is developed to analyze the reliability of the controlled entity in the hot-swap hot redundancy experimental system. The experimental results prove that this hot-swap hot redundancy system achieves highly stable performance as designed.

Keywords: hot-swap, hot redundancy, Compact PCI, high-availability

References

1 Introduction

Nowadays, aerospace measurement and control tasks have strict requirements for computer systems. Large scale measurement systems used in the aerospace field have major application requirements for system-level hot-swap and hot redundancy technologies such as multiple redundancies and backups. With the improvement of integration and intelligence of on-board equipment on launch vehicles, demands for test and diagnosis of them have been increasingly complex. As multiple functions like high-speed data bus interface, control and self-testing are integrated into the on-board rocket equipment, problems such as various kinds of interfaces and increased test data information amount are brought about. Therefore, how to construct a high performed and superior integrated measurement and control system of the on-board equipment on launch vehicles is becoming a topic that is explored currently.

In recent years, the measure and control signal processing systems that are standard on the Compact PCI (CPCI) have drawn increased attention, especially in accurate testing fields [1]. However, the traditional CPCI bus product can no longer satisfy the need for high stability hot-swap and hot redundancy. As a result, a bus structure calculation control platform with the features of hot-swap and hot redundancy as well as high stability and reliability has become the prerequisite of developing modern measure and control systems. Danny Lee and Joe Zhou [2] have designed an automatic refueling system. The system uses an autonomous hot-swap system that enables battery swapping for a quadcopter on the ground charging station to minimize its down time. This system also uses hot-swap on the battery to ensure no data loss during the swapping process. Sheng-Yan Ou and Fu-Sung Chen [3] proposed an adaptive current-sharing control strategy for multiple power modules to solve the output current imbalance problem caused by hot-swap. In this paper, we propose a solution based on a CPCI bus for hot-swap and hot redundancy of both software and hardware. This solution is stimulated by the requirements for high reliability and high real-time response in the aerospace measurement and control systems. An experimental measurement platform was developed to perform verification of this device-level hot redundancy technology.

2 System architecture

Aiming at actual testing requirements for on-board system of launch vehicles, a software and hardware implementation scheme based on CPCI bus is proposed in this paper to enhance reliability of the measurement and control system, in which independent research and development is achieved in every component modules. Fig. 1 shows the architecture of the high-availability CPCI measurement and control system which is proposed in this paper. It is composed of three layers: an upper computer system, a lower computer system and an experimental measurement platform. The upper computer runs Windows operating system. The lower computer is a dual-core PC from NI and runs VxWorks embedded real-time operating system. Four different kinds of self-developed Compact PCI cards work in the lower computer. There are two switching value input cards, two analog collecting cards, two serial communication cards and one switching value output
card in the lower computer system. Among them, these two identical cards constitute a hot redundancy devices system and all the cards can achieve the hot-swap function.

The design uses the CPCI hot-swap technology to effectively limit the inrush current generated when the card and peripherals are inserted or pulled out of the charged plate. This design solves problems such as components burnout, backplane supply voltage reduction and other issues caused by hot-swap. It can provide effective control and protection for the cards and peripherals during a hot-swap application. At the same time, users can upgrade, change and add function modules without suspending the operation of the main system. Such system has a complicated structure. Hence great attention should be given to coordination of the physical, hardware and software layers. The physical layer needs to ensure absolute safety of the circuit structure during the hot-swap process. Therefore, it is necessary to adopt variety of security measures to ensure that the comprehensive process prevents an inrush current due to instantaneous electrostatic discharge to the testing facility. The hardware layer ensures the stability and security of a smooth control by using a multi-channel power supply to achieve isolation between powers. A MOSFET device is used as an isolation buffer for power source when the hot-swap occurs [4]. For the software, the operating system needs to have plug and play.

Fig. 1. System architecture.
functions. It should be configurable for different system requirements and coordinate the core functions of the system resources.

3 Design and safety guarantee of hot-swap

Hot-swap systems are divided into three grades. A basic hot-swap system supports the physical and hardware systems connections process, but the aspects of the software should be handled by the operator. A full hot-swap system supports the physical, hardware and software levels of the connection process. In this system, the card interfaces with a micro switch. When the card is inserted or removed, a signal is sent to the host processor. This high-availability hot-swap system is based on a full hot-swap system that has a higher grade of control. In this level, not only the mechanical aspects and hardware but also the support redundant components are controlled by the replacement of the software itself. This feature makes the designed system achieve the highest level (i.e., the high availability) hot-swap.

3.1 CPCI connector design

Based on the requirement of a common interface on the hardware layer for the hot-swap functions, the Compact PCI connector uses different grade pins from the conventional, as shown in Fig. 2. It can make all pins connected or disconnected in accordance following certain sequence when the CPCI card is inserted or pulled out of the machine slots. The length of the grade pin includes long, medium and short stages. Long pins are used for the power and ground pin, medium pins connect to CPCI signals, and the short pins are connected to access the signal to enable the module. When the card is inserted, the power pin and ground pin firstly connect to the CPCI bus system through a hot-swap controller in order to finish the pre-charge process for device. Then the bus of signals system is connected with the medium pins. The purpose of pre-charge is to reduce the impact on bus data and control signals due to the capacitive effect during the progress of inserting or pulling the CPCI card. The measures must be taken to prevent any negative impact of an instantaneous current on the bus signals. The short pins connect to the enable signals (BD_SEL#, INSEL#), and meanwhile, send out the enable signals to system. Then the system can recognize a new device that has been inserted into the system, and began its initial configuration. Similarly when the module has been pulled out, the system executed contrary to the process of above.

![Fig. 2. CPCI connector.](image-url)
3.2 Electrostatic bar

The insertion of CPCI card into the computer can be understood as a process of mechanical connection. In the process of mechanical connection, the card is required to pre-charge for the signal pins. Only when the pre-charge is completed, can the bus signal pins finish the connection. However, a large amount of electrostatic charges is created during the pre-charge process, which can easily damage the equipment. To prevent the damage, the card is required to discharge electrostatic charges before pre-charge for the signal pins. Fig. 3 shows the electrostatic discharge bars designed to discharge electrostatic charges in time to protect the hot-swap module from the static shock during the process of pulling or inserting the card.

![Fig. 3. Static electrostatic bars of CPCI card.](image)

3.3 Connection states

Fig. 4 shows the specific schematic diagram of the state nodes in the hot-swap connection process. Ordered management to the hot-swap process of CPCI card is essential to achieve high availability hot-swap. The connection process is divided into the physical connection state, hardware connection state and software connection state. P0 means the module has not been installed in the system yet. P1/H0 means the module has been inserted into the slot and all the function pins have been completely connected to the CPCI bus successfully but not powered on. The bus has not been activated. H1 means the module connects with the bus after power-on initialization. The corresponding initialization proceeds after the module powers on. If the initialization fails or the module breaks from the bus after detecting a fault, the system will indicate that the bus is not suitable to be used with the state H1F. H2/S0 means the module powers on. The bus can only visit the configuration space, and the configuration register has not yet been configured. S1 means the system has finished configuring the module. S2 means the module can be used by the operating system and the application software after loading the necessary
drivers. However, all the operations have not yet started. S2Q is same as S2 but it does not allow new operations, and the module is in a static condition. S3 means the module joins the system and operates normally. S3Q means the software has finished the current operation but does not allow initiating new operations. The module is in a static condition.

3.4 Hot-swap controller and circuit

The MIC2580 integrated circuit is designed based on the CPCI bus structure and accomplishes the control process by cooperating with MOSFET [5, 6]. It imposes restrictions on the surge current by slowly decreasing or increasing the on-resistance of MOSFET by the N-channel. When the card is inserted into slot, the controller opens and the gate drive of MOSFET are enhanced slowly. The drain voltage increases slowly from 0 V because opening the conducting channel requires a sequential process. The sampling resistance interface is reserved in the power interface to monitor the current of the main power paths. When the voltage of the sampling resistance is greater than 50 mV, the hot-swap controller determines that the current is too large and cuts off all the power in response. This configuration can prevent excessive current from destroying the card devices.

In this paper, the control interface connects with the logic controller serial communication on the card. The software can control the power and manage power supply and outage in the redundant equipment [7, 8, 9]. However, the power of the logic controller and bridging controller come from the 3.3 V power supply of the bus interface. So inserting or pulling the card can cause the software system to obtain the control interface of the power of card. The power control demand can arrive at the logic controller by the bus writing operation through the bus bridging controller. Then, the redundancy management of the test system can be controlled according to the requirements at any time. Hence the high availability hot-swap level defined by the PICMG standards is achieved. The system also provides the foundational technical support for testing the hot redundancy and designing the hot backup structure.

The principle block diagram based on the hot-swap circuit design of MIC2580 is shown in Fig. 5. IRF7413, PCI9054 and EP2C8Q208 are designed to be coordinated in the hot-swap interface circuit.

The hot-swap controller has an internally integrating manager of the 12 V and −12 V power supplies. The management of the 3.3 V and 5 V power supplies depends on the external MOSFET. The MIC2580 integrated circuit of the hot-swap controller provides a gate pole control signal for exterior control. Note that the FAULT signal can affect the circuit switch. Therefore, this pin must be guaranteed to stably supply power during normal operations. So a resistance of 2K is used to pull up the power to the CPCI bus interface VIO pin. In addition, the activation and outage of the whole circuit can be controlled using the ON signal. Hence the control interface is reserved. As mentioned previously, it is possible to use software to control power connection and disconnection. In Fig. 6, there are four different types of CPCI cards including the one we developed. All of these CPCI cards can achieve high-availability hot-swap. In Fig. 6, M1s are the power management modules, and they use MIC2580 as their cores. MIC2580 is employed in these
modules to achieve power supply management function of the card. M1s are the core parts where the hot-swap can be realized. The specific design of the MIC2580 circuit is described in detail in Section 3.4. M2s are the functional modules in all cards. There are different designs of M2s for the different functional requirements of different cards. M3s are the pull resistances of the CPCI bus control signals. There are totally 12 row resistances for 48 roads in each card. M4s are the electrostatic discharge bars, and they have the same layout on the back of the card. The specific design is described in detail in Section 3.2.

3.5 VxWorks system design for the hot-swap
Considering the hardware structure of a typical hot-swap system, WINDOWS operating system is chosen as the mainframe for designing the human-computer interface. However, WINDOWS itself is not a real-time operating system. In a typical hot-swap system, some applications require high instantaneity and stability,
such as the aerospace test field. So the lower computers are used to operate in the embedded system (for example, the VxWorks and Linux operating systems are used most often). Although Windows has the added function of supporting hot-swap in its earlier version, these embedded operating systems often have simple file systems and hardware driving functions only. The system itself does not support hot-swap, which is an urgent matter when developing a typical hot-swap system [10]. The open source code of the embedded system, such as VxWorks, is modified by extending the function and creating the function of the CPCI card hot-swap.

BSP (Board Support Package) is between the mainboard hardware and the operating system. BSP belongs to one part of the operating system. Its purpose is to support the operating system and improve its operation in the mainboard hardware. BSPs for different operating systems use different defining forms. For example, VxWorks BSP and Linux BSP have the same functions, but their writing methods and interface definitions are totally different. Therefore, a BSP should be written according to the definitions for a specific system. The programming process of a BSP is mostly modified using a molded BSP template. The CPCI drive of the default BSP in VxWorks does not support hot-swap of the hardware card. Therefore, the following parts of the BSP drive must be remolded: 1) Modify the initialization function to make original BSP handle the CPCI equipment which is not in the CPCI slot. 2) Modify the interrupt chain management to make it selectively add or delete a specified ISR. 3) Increase the driving part of the hot-swap equipment, which includes dynamic detection to the CPCI equipment, the management of insertion or removal of a card, and the setting process of hot redundancy.

4 Experimental results

4.1 Performance test of the hot-swap controller

After the ON pin of the hot-swap controller, MIC2580 receives a reset instruction signal. The gate pole control sites of MOSET corresponding to 5 V and 3 V power supplies are synchronously charged with the CSLEW pin connecting the capacitance, which lifts the voltage. Fig. 7 shows the theoretical lifting rate of the three pins. When the configuration capacitance is 0.03 µF, the rise time is approximately 10 ms.

![Gate-voltage response frame.](image)
Fig. 8 was the waveform record of the hot-swap power gate pole control signal for the 5VGATE and 3VGATE recorded during the practical test. The rise time of the gate pole control site was 30 milliseconds. Under the condition of $CSLEW = 0.1 \, \mu F$, the rise time triples the original time (10 ms) as given in the datasheet of Fig. 7, which was roughly equal to the ratio of the two capacitances. This verifies that the function of the opening rate of the gate pole was controllable.

4.2 System experiment of hot-swap and hot redundancy
The reliability of the Compact PCI bus hot redundancy can be verified through experiments. The experimental system is composed of an upper computer, a lower computer and a self-developed experimental measurement platform, as shown in Fig. 9. The upper computer is a Windows PC and the lower computer runs VxWorks embedded real-time operating system. While conducting the experiment, two identical self-developed 16-channel serial communication cards and a self-
developed 32-channel switching value output card were inserted into the CPCI slot of the lower computer. Once the system began to operate, the switching value output card outputted the switching value to the platform using the upper computer. One serial communication card was set to the working condition (main card), and another was set to the hot standby state (backup card). The serial communication card procured and collected the high 16-bit data of the switching values from the experimental platform.

In the experiment, the upper computer connected with the operation system of the lower computer, and then, the three cards were inserted into the case of the lower computer using operations in VxWorks. Instructions were sent from the upper computer to the lower computer to direct the switching value output card to input data 0x90000, 0x9090000 and 0x190f0000 into the experimental platform.

To verify the redundancy characteristic of the system, when the serial communication main card read the data, the main card was suddenly removed from the computer case to simulate a breakdown of the main card. The main card was isolated into a safe state immediately, and the backup card started to perform its function, as shown in Fig. 10. Hence, the data read by the serial communication cards were not corrupted when the main card was pulled off. The interface of the VxWorks is shown in Fig. 11.

Next, to simulate the situation when maintenance on the main card was finished, the main card was inserted into the computer. The main card was identified immediately by the system, and then it took the work of the backup card. The above experiment proves that the system is qualified to achieve hot redundancy related operations. The reliability of the CPCI system can be improved by utilization of this hot-swap and hot redundancy system.
5 Conclusion

This paper analyzes the implementation processes of three types of hot-swap techniques, and a new implementation method and an application scheme of the high-availability mode of the hot-swap hot redundancy technique is proposed. Various design measures for guaranteeing safe operation of hot-swap equipment are established. Based on these requirements, a physical verification platform system of the high-availability mode of hot-swap hot redundancy technique is designed. Accordingly, the equipment is designed and manufactured to provide the hot-swap management. The all-round function tests and verifications are conducted using this self-developed experimental measurement platform.

The CPCI bus system mentioned in this paper, which has the most complex bus and is widely used in aerospace measurement and control systems, has the highest application requirement of achieving high level hot-swap and hot redundancy. The design and application method in this paper not only can be applied to redesign and upgrade relevant equipment but also can be applied to integrated system design at higher levels.

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