STUDY ON FAULT-TOLERANT ARCHITECTURE OF MOTION CONTROL COMPUTER FOR SPACE ROBOT

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ABSTRACT

The motion control of space robot requires high processing capability while available high-reliability and anti-radiation processors generally have low performance in computation. In order to solve this problem， a master-slave fault-tolerant motion control computer architecture was proposed in this paper according to the analyzing of the motion control algorism. The CPU of the master module was a high-reliability and anti-radiation processor while the slave module was a COTS(Commercial Off The Shelf) processor. The master module was in charge of task management, health management and voting of the slave module whose main task was motion control computation. The number of the master modules and the slave modules can be configured according to different requirement. The architecture introduced in this paper has been proved with high-reliability, high processing capability and flexibility which will have extensive application potential for space robot.

1 INTRODUCTION

Space robots have been playing an increasingly important role in future space activities and space robotic technologies have been emphasized in many countries[1]. As a key component of the robotic system, motion control computer is in charge of motion plan, information fusion, health management and so on. Among the above tasks, motion plan required high processing capability[2]. Also the motion control computer of the space robot is a typical On-board computer which should have functional radiation resistance to enhance the reliability[3]. Traditional anti-radiation processor only have low performance in computation which can't meet the requirement of the robotic system. In order to solve this problem， Researchers have proposed various methods. Coprocessor based on Field Programmable Gate Array (FPGA) was realized[2], but the motion control algorism is very complicated while the FPGA is hard to be designed and modified. Besides FPGA is a kind of single-event sensitive device[4]， some special design such as Triple-Mode Redundant (TMR) should be adopted. Motion control computer based on COTS (Commercial off-the-shelf) was also proposed[5]. Although it has high processing capability, it can't correct errors, so it has to be stopped when errors were detected.

In accordance with analyzing of the work mode and the motion control algorism of the space robotic system， a fault-tolerant motion control computer architecture was proposed in this paper.

2 ANALYZING OF MOTION PLAN ALGORISM

Take Cartesian space motion planning for instance, the end-effector of manipulator is commanded to move from one pose to another under the provided speed. Figure 1 showed is the flow chart of Cartesian space motion planning. When motion control command comes, motion control computer calculates total time and up-speed time periodically at the input of initial joint angle, desired target pose, desired end-effector speed and acceleration speed. At the end of the period the planned joint rate is output.

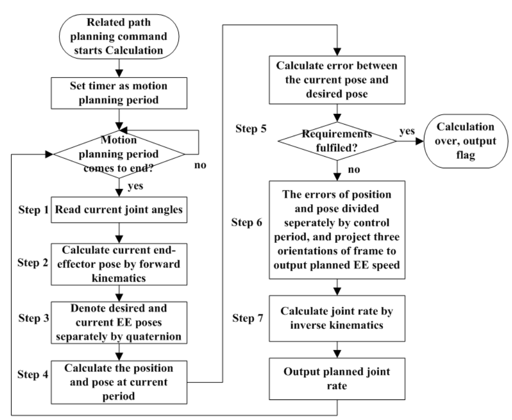

Figure 1: Flow chart of Cartesian space motion planning

The most obvious character of motion control algorism is that it is periodical. One complete mechanical movement includes numerous single step movement whose period is between 50ms and 200ms. And the speed of the end-effector is very slow. Take the SSRMS of the International Space Station for example, the speed of the end-effector is only 0.36m/s, the distance moved in one single step is very short. That means there is no requirement for the high precision of the period.

The space robotic system works intermittently. In Most time after it is launched, it just works in standby mode. In the standby mode, the space robot doesn't perform mechanical movement but just conducts health management such as telemetry, telecontrol and thermal control which just need low performance in computation. Mechanical movement just occupies a little portion of its life period.

As the space robotic system works intermittently, it is possible to design a configurable motion control computer which can work in different modes in accordance with different task. This can increase the flexibility of the task management.

3 DESIGN OF MOTION CONTROL COMPUTER

3.1 System Design

The system is composed of master module and N-backup slave modules, the schematic of the motion montrol computer is illustrated as Figure 2.

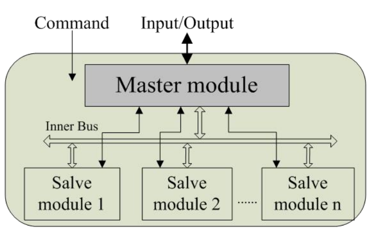

Figure 2: Schematic of Computer

The processor of the master module is high-reliable and anti-radiation while the slave module is a COTS processor. In standby mode, only the master module is working while the slave module is power off. When the robot needs to conduct mechanical movement, the master module and the slave modules work simultaneously. The master module is in charge of task management, health management and voting of the slave module whose main task was motion control computation. The master module and the slave module can realize data transfer through inner bus. The master module can also monitor the state of the slave modules and change the work mode of the slave modules, such as reset, power off/on and so on.

3.2 Principle of the System

The master module is time-triggered in every period of motion planning(50ms to 200ms), it should send data of joints of the robot to slave modules, such as current angle and speed, and start the computation of slave modules and vote the result of the salve modules after the computation is over.

The slave modules are task-triggered. After power on or reset, the slave modules will wait for the command of the master module. They will start one single step computation after receiving the start signal of the master module. When the computation is over, they will set flag to inform the master module.

The flow chart of motion planning is illustrated as Figure 3.

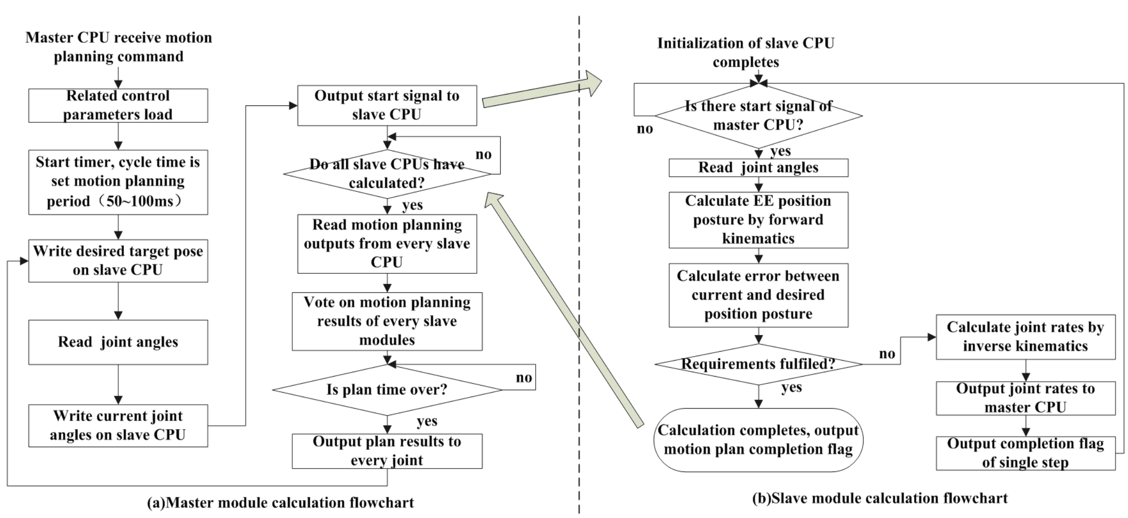

Figure 3: Flow chart of motion planning

The information flow of the system is illustrated as Figure 4.

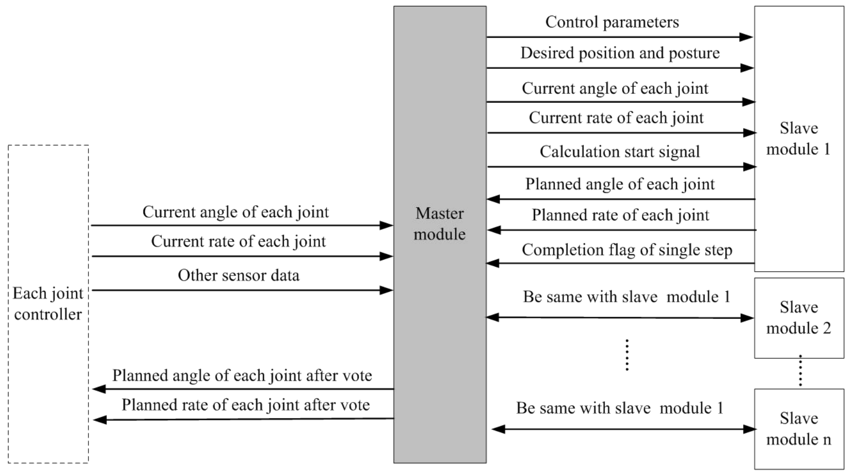

Figure 4: The information flow of the system

According to the work flow showed in Figure 3, the time distribution of the system is illustrated as Figure 5.

The definition of every symbol:

(1)*Tp*：Time to complete one whole path plan;

(2)*Tm1*：Time for the master module collect joint data and send to slave module;

(3)*Tcd*：Time for the slave module complete one single step path plan computation;

(4)*Tm2*：Time for the master module collect data of slave module, vote and output.

In order to satisfy the period of the path plan, $Tm1+Tcd+Tm2 < Tp$, Tm1 and Tm2 are the time of the data transfer between the maser module and slave module. The data must be transferred include the angle and rate of every joint, the target data from the camera and so on. The quantityof the data is estimated as dozens of bytes approximately. The master module and slave modules communicate through parallel data bus, the data rate can be *Mbps* or faster. So the data can be sended or received in 1ms. In consideration of margin, it is supposed 5ms. Generally, *Tp* is 50ms to 200ms, given *Tp* 50ms. So the time for slave module to conduct path plan computation is 45ms, the system can work normally if *Tcd*<45ms. There is no restrict to the synchronization of slave module except the time limit. Also in every period of path planning, the master module will synchronize the slave module utilize the start signal, so the error of the time will not cumulate. The slave module can adopt different architecture which improve the flexibility of the system design.

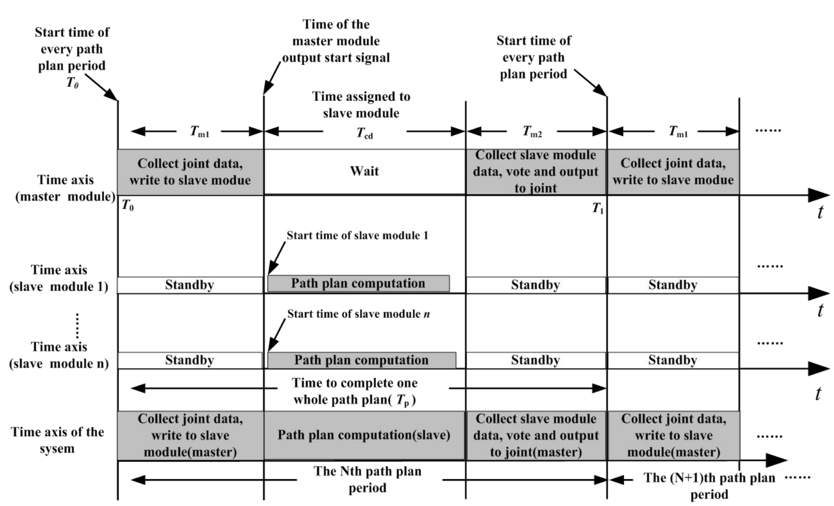

Figure 5: Time distribution of the system

4 COMPARISON OF DIFFERENT CONFIGURATION

Different configuration of the system can be adopted which depend on the requirement. The master module can be cold-backup or hot-backup, the number of slave modules can be chosen.

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4.1 Double Cold Backup Without Data Interactive

The architecture of double cold backup without data interactive is illustrated as Figure 6. The motion control computer is composed of two identical computers which don't work simultaneously and there is no data interactive between them. External commands control the switch of the two computers. Every single computer is composed of one master module and several slave modules. This architecture is easy to design, the connection is very simple. But the disadvantage is the high requirement of the hardware. For example, at least 6 slave modules are needed to realize error correction and 4 slave modules are needed to realize error detection. Also there is only one master module to vote the slave module, so the reliability of the master module should be very high which will increase the design difficulty.

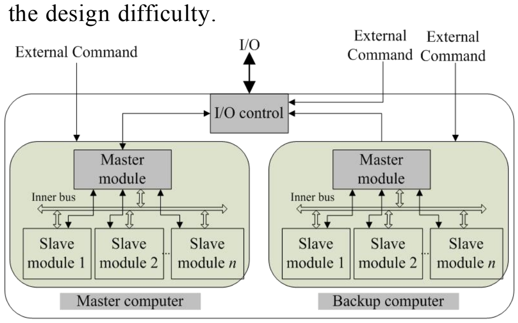

Figure 6: Double cold backup without data interactive

4.2 Double Hot Backup With Data Interactive

The architecture of double hot backup with data interactive is illustrated as Figure 7. Compared to double cold backup architecture, extra data path between the two computer which can be used to transfer data is added. The tasks of the two master modules are different, only one is in charge of data voting and input/output and another one just receive data from external device. Compared to double cold backup, this architecture has higher reliability because it can detect error of master module but it's more complicated because of the data path.

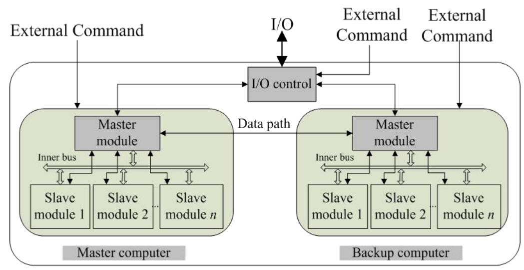

Figure 7: Double hot backup with data interactive

4.3 Double Backup With Cross Data Channel

The obvious disadvantage of the architecture above is the high requirement of the hardware. That's because there is no cross data channel between the master module and the slave module of another computer. If the cross data channel was added, it would decrease the requirement of the slave module. The architecture is illustrated as Figure 8. To achieve thesame ability(error detection or correction), the requirement of this architecture is only half of the architecture which don't have cross data channel. The disadvantage of this architecture is its complexity. The data interactive is very frequent, and some special method should be adopted to guarantee fault isolation and avoid single point of failure which has rigorous requirement for the designer.

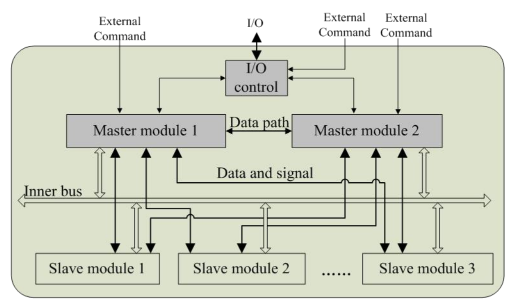

Figure 8: Double backup with cross data channel

4.4 Analyzing of Different Configuration

(1)Architecture without cross data channel: Easy to design but demand more hardware, can be used in application which has no restriction to the mass and power or the module has high integration density；

(2)Architecture with cross data channel: Demand more hardware but complicated, can be used in application which has high restriction to the mass and power.

(3)For the master module, if cold backup is adopted, the design will be simple and has low power demand but the master module should have high reliability. Cold backup is fit for the application whose master module has high reliability, such as anti-radiation processor adopted and the software has conduct reliability design and so on.

(4)For the master module, if hot backup adopted, there will be low reliability requirement for the master module, but it is more complicated. Hot backup is fit for the application whose master module just has low reliability.

The configuration of the motion control computer depends on the reliability requirement of the system and the master module and the resource constraints such as mass and power.

As to the number of the slave modules, at least 2 slave modules should be adopted in order to conduct error detection and 3 in order to correct error. Analyzing showed that if triplication redundancy is adopted, the failure rate of slave module is twice of the master module, the reliability of the voting system is higher than the master module. With the increase of the failure rate of slave module, the reliability of the voting system becomes lower, even lower than the master module. To increase the reliability of the system, some methods should be adopted to decrease the failure rate of slave module, such as preferment of high reliable device which will decrease the number of the slave modules.

5 CONCLUSION

In accordance with analyzing of the work mode and the motion control algorism of the space robotic system， a fault-tolerant motion control computer architecture was proposed in this paper. The architecture just needs the slave module to complete one single step path plan in specified time while has no restriction to the internal constitution and the synchronization of the slave modules. The architecture introduced in this paper has been proved with high-reliability, high processing capability and flexibility, it will have extensive application potential for space robot.

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