Flexible Joint Control System Design for Space Modular Robotic System with Torque Feedback

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Abstract
In this paper, a design of modularized flexible-joint servo control system for a space manipulator system is presented. First of all, the structure and sensor system of dual-joint is introduced. Next, the features of the hardware system of the dual-joint controller is described, as well as design details and fault tolerant mechanism. Moreover, the working principle of joint torque sensor is analyzed emphatically. The structural optimization design of the joint torque sensor is carried out with the help of the ANSYS program for weight minimization. After that, a position control strategy with joint torque feedback is provided to improve both precision and bandwidth of the control system. Finally, the performance specifications of the dual-joint control system are presented. Experimental results demonstrate the effectiveness of the compact joint servo controller for the space manipulator system.

Keywords: Space Manipulator, Flexible Joint, Torque Sensor, Position Servo System, Torque Feedback

1. Introduction

With the rapid development of space technology, the number of the human exploratory activities in space has constantly increased. Besides handling and assembling of large payloads, more precise and more dextrous space missions such as on-orbit maintainability, on-orbit capture appear in space, etc [1-4]. These space missions promote the development of high performance space manipulator systems, which could move as dextrous as the arm of a man.

In recent years, space manipulator systems appear the trend of light weight, modularization, high performance and dexterity. Modular design method was adopted in the Space Station Remote Manipulator System (SSRMS) from Canada, which was launched in 2001 [5]. ROKVISS was aboard the International Space Station in 2005, which aimed to validate the space qualification of the newest lightweight, modular robot joint technologies developed in DLR’s lab [6].

However, the use of space flexible manipulator is not as good as people expected, influenced by the structure and dynamic characteristics of the space manipulator system. In order to meet the requirement of driving capability, joints need to be fitted with reducer driven by harmonic gear or planetary gear, but the joint flexibility is also increased at the same time. Previous studies [7-9] have shown that the flexibility of joint cause problems as precision reducing and robust stability decreasing, becoming the main factors restricting the performance of the joint control system. So, how to design a joint of high performance, high integration and high reliability is a challenging work that must be resolved, and the research on this problem has vital realistic significance and applied value for the development of space robot.

This paper investigates a new modularized flexible-joint servo control system for a space modular robotic system, the objective of which is to improve both precision and bandwidth of the control system and obtain a dual-joint of high performance, high reliability, small mass and low volume. Based on SOPC (System on a Programmable Chip) technology, the hardware architecture and fault tolerant mechanism for dual-joint servo system will be discussed. Furthermore, the structural optimization design of the joint torque sensor will be carried out with the help of the ANSYS program for weight minimization. Then, a position control strategy with joint torque feedback will be proposed. Lastly, some experimental results are given.
2. The structure of dual-joint

At present, the space manipulator system (SMS) is designed to have six degrees of freedom with a length of about 2 meters, comprising two main arm booms, three identical dual-joints, an end effector at the tip and a camera on wrist. Each dual-joint serves two independent orthogonal axes enabling two degree-of-freedom. In order to obtain high bearing ability, small volume and light weight dual-joint, direct drive DC torque motors, harmonic drive gears and ELMO Digital Servo Drive are adopted as the drive module. The electronic module in the dual-joint consists of a FPGA control board, a power and sensor conditioning board, accomplishing the tasks as information collection form sensors, servo control, communication with trajectory planning computer. All the electric components are installed inside the joint internal space as shown in Figure 1. With the protection from the shielding effect of joint metal crust, the life-span will be prolonged and the reliability will also be enhanced.

![Figure 1. Construction of the modular dual-joint](image)

The whole sensors integrated in the modular dual-joint are listed in Table 1. Incremental optical-electrical encoder is used to obtain the motor position. The harmonic driver increases the flexibility of the dual-joint, and reduces the control precision. As a result, a two-speed electrical resolver is adopted as absolute joint position sensor, which is installed between the output of harmonic drive gears and the link. Two Hall-effect limit switches are also installed to increase the system reliability.

<table>
<thead>
<tr>
<th>Sensor Type</th>
<th>Quantity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Torque sensor</td>
<td>2</td>
</tr>
<tr>
<td>Joint position sensor</td>
<td>2</td>
</tr>
<tr>
<td>Motor position sensor</td>
<td>2</td>
</tr>
<tr>
<td>Temperature sensor</td>
<td>3</td>
</tr>
<tr>
<td>Limit position switch</td>
<td>4</td>
</tr>
</tbody>
</table>

3. Design of the joint control system

3.1. Hardware architecture based on SOPC technology

As is known, motor control is the key factor to the performance of the robot joint. Previous studies have shown that servo control system based on DSP is the typical hardware architecture of modular
joints. This control scheme has the advantages of simple circuitry, software control, and flexibility in adaptation to various applications, but more CPU time on the other hand. Architecture based on multi-DSP or a DSP with FPGA relieve the computation load of microprocessor. However, the design process will be complicated by this architecture. The increasingly number of electric components will lead to the disadvantages of integration and reliability at the same time. As the rapid evolution of microelectronics technology, a high capacity FPGA employed as motor controller becomes the primary trend. FPGA processes data in a way of pure hardware, which does not occupy the resources of CPU, making the system has better performance and higher Integration. Besides, recent researches [10-12] show that FPGA has the advantages on the aspects of signal processing, data acquisition and dynamic fault-tolerant, which are key technologies of joint control system as well. Moreover, FPGA could embed microprocessors and related peripherals to form a complete System-on-a-Programmable-Chip (SOPC), owning DSP and FPGA merit simultaneously.

As shown in Figure 2, the dual-joint provides an electrical power bus and a dual-redundant CAN bus as external connections. The input voltage is DC 24v. The dual-redundant CAN bus is designed to connect with other modules, such as the trajectory planning computer of space robotic system. The hardware architecture for dual-joint servo system is based on FPGA with Nios II processor, comprising main control unit, power management unit, signal processing unit, and drive unit.

![Figure 2. Hardware structure of the modular dual-joint](image)

### 3.1.1. Main Control Unit

Main Control Unit (MCU) consists of FPGA, SDRAM, configuration memory, external oscillator, restoration circuit. FPGA Chip adopts Cyclone 3 series manufactured by Altera Corporation. A Nios II processor is integrated in the FPGA, including 4Kbytes instruction cache, 2Kbytes data cache, 18 × 18-bit embedded multiplier. In order to improve floating-point operation performance, custom instructions of arithmetic floating-point operations is adopted in FPGA.

Moreover, customized IP cores programmed with the hardware description language of Verilog as CAN bus interface, resolver control module, torque signal processing module are integrated in FPGA, which connect with Nios II processor by Avalon bus as shown in Figure 3. This kind of design scheme has the advantages of better performance and higher integration. To prevent the occurrence of endless loop, A programmable watchdog timer realized by soft-core is also integrated in FPGA to improve the system reliability.
3.1.2. Signal processing unit

Precision of data Acquisition from sensors is one of the key factors, which can affect the control performance of servo system. However, the harmonic drivers and joint torque sensor increase the flexibility of the joint, and reduce the control precision. So two-speed electrical resolvers are adopted as absolute joint position sensors. The specific IC called resolver-to-digital converter (RDC) is usually used in typical resolver applications, and 4 RDC chips are needed to serve two two-speed electrical resolvers, resulting in larger volume, bigger power consumption, higher price and complicated debug methods.

In the designed dual-joint, FPGA with external component as A/D, D/A converters are used instead of specific RDC chips. Algorithms as resolver-to-digital conversion, coarseness-precision combining and its error correcting realized by soft-core are integrated in FPGA, and ADC, DAC are adopted as the interface between the analog system and digital system as shown in Figure 4. In order to reduce further volume and increase integration density, the TDM technique is employed through a analog switch, deciding which resolver output signal to be resolved at a time.

As shown in Figure 4, torque data acquisition module consists of bridge measurement circuit, A/D conversion circuit and digital filtering circuit. First of all, joint torque is converted into weak electrical signals through a full bridge circuit, which is made up of 4 resistance strain gages. Then, instrumentation amplifiers are utilized to amplify the transmitted signals with great accuracy and low noise. The signals are converted to digital form by the A/D conversion circuit and transferred to the digital filter circuit realized by Verilog HDL in FPGA. Numerical sliding average filtering algorithm is adopted in the digital filter circuit to preprocess the acquired data.

3.1.3. Drive unit

Drive unit, comprising driving circuit of servo motor and electromagnetic switch control circuit as shown in Figure 4, is a important part of the dual-joint hardware system, which can affect the joint motion performance and system reliability. A kind of servo drive for industrial applications called SimpIIQ servo drive from Israel is adopted in the design, which has the advantage of simple circuitry, standard communication protocol support, small volume, light weight, high power density and high reliability.

The function and the working process of the drive unit are as follows: the drive unit receives drive commands from MCU with the RS232 bus, and feedback the motor states as position, velocity and working current at the same time. Moreover, a relay is adopted in the electromagnetic switch control circuit to control the power supply of the driving circuit.
3.2. Fault detection and fault tolerant

Previous studies have shown that the key to practicability and commercialization of robotics lies in the reliability and security. Modular design approach means that robotics can be customized with more flexibility. It also means that the uncertainty and variability of tasks and working environment in space are increasingly going up. Once the robot failure or malfunction occurs, it will result in unpredictable consequences. Therefore, the research into reliability and security of dual-joint, which may avoid the body hurt and device damage, is of great practical significance.

Screening more reliable and stable electronic equipment, which could avoid breakdowns and accidents from taking place, and enable faults to eliminate hidden dangers stage, is an effective measure for resolving this problem. Pointed design of fault detection method and fault-tolerant strategies, achieving the purpose that timely detection, shielding and recovery of failure, is more important at runtime.

3.2.1. Fault detection and fault tolerance strategy of MCU

MCU is the core component of dual-joint module, undertaking the tasks as signal acquisition and processing, path planning in the joint space and servo control. So fault-tolerance capability of MCU at run-time has a direct impact on the overall reliability of the dual-joint module. The adopted methods to solve the problem are as follows.

Firstly, system power-on self-test is used in the system initialization stage, including auto detections of Nios II processor, SDRAM, and CAN bus. Then the system is under standby mode, uploading the self-test state to the trajectory planning computer of space robotic system. The trajectory planning computer would then be able to determine fault-tolerant strategies of the robotic system, such as hard reset to restore a transient failure, or system degrading at runtime, or promptly notify the manual processing to fix the problem.

Secondly, a programmable watchdog timer realized by soft-core is integrated in FPGA. In order to meet the requirement of long time continuous work, monitoring program state of the dual-joint control system is needed at runtime. When the watchdog timer detects fault conditions as software hangs, the entire FPGA device reset is triggered to avoid the unpredictable consequences and improve the system reliability.

3.2.2. Dual-redundant data bus structure and fault tolerance strategy

Communication network reliability is also considered. According to the factors of both real-time Performance of bus switching and complexity of fault-tolerant strategy, a design of dual-redundant CAN bus is adopted in the dual-joint module as shown in Figure 5. Data exchange can be
accomplished by either of two CAN bus between the trajectory planning computer and the dual-joint module without any special configuration.

The mechanism of the dual-redundant CAN bus, not only inherits fault-tolerant capability of single network node mistakes from CAN bus, but also supports the tolerant method for communication link failures, and thus has a higher reliability.

Datagram transmitted through CAN bus, comprising polling instructions of joint state information and joint position control instructions, is the basis for the joint servo control. If receive the wrong instruction, it may lead to unpredictable consequences. Therefore, in order to ensure the accuracy of instructions, the datagram transmission reliability needs to be taken into account. The physical layer protocol of CAN bus verifies datagram per frame using CRC algorithm, but only to ensure the correctness of the datagram transmission between the sender and the receiver of CAN bus node controller. There is no error detection before the received messages stored in the registers are read into MCU and complete high-level parse, may be subject to electromagnetic noise interference and cause data errors.

Therefore, the CRC checksum of the single frame message realized in software, including identifiers and data fields, is specified in the application layer protocol, and is transmitted to the receiver as a part of the datagram. This mechanism verifies the whole process of datagram transmission to ensure the data accuracy of transmission, and thus improve the overall reliability of the double-joint control system.

![Figure 5. Dual-redundant data bus structure](image)

### 3.2.3. Sensor failures detection based on information redundancy

The dual-joint control system obtained position information from the incremental optical-electrical encoder and two-speed electrical resolver. If the flexible deformation caused by harmonic gears is not taken into account, the relative motor shaft position can be transferred to the joint shaft position using normalization methods. Then the dual-joint control system could acquire 4 kind of position information, comprising optical-electrical encoder, coarse channel of resolver, fine channel of resolver, coupling between the coarse channel and fine channel of resolver. The independent failure analysis of sensing system is as follows:

Firstly, select the appropriate threshold, and contrast between position from optical-electrical encoder and coarse channel of resolver to obtain the fault detection results.

Then, taking further measures to locate faults is needed. Contrasting the ratio between the change rate of position from coarse channel of resolver and fine channel of resolver. If the ratio meets the poles of the resolver, the optical-electrical encoder is failed, or the resolver is out of order.

Finally, according to the fault location, degrade the position sensing system to maintain the operation of servo control system, and feedback the fault state to the trajectory planning computer.
3.2.4. Overload protection and overheat protection

Overload, locked rotor is one of the main reasons leading to motor failure, may cause too large current flowed through the motor winding, and finally burn out the motor. Therefore, in order to avoid the occurrence of over-current, current limiting strategy is adopted for the motor drive. Due to the high integration and small interior space of the dual-joint module, the heat dissipation efficacy is reduced. Temperature sensors are installed in internal space of dual-joint, monitoring the temperature of motor drive and control system, to prevent occurrence of over-heat. When temperature rises abnormally, the power management module could cut-off power supply timely, preventing the damage to the motor drive and control system from high temperature.

3.3. Position control strategy with joint torque feedback

Recently, the continuous development of space missions brings up higher standard for rapidity and precision of control system. As mentioned before, Direct measurement and feedback of joint angle by resolvers could compensate for the effect of drive flexibility that occur outside the motor control loop, providing an effective improvement on control precision. Then, since the flexibility is inside the joint angle feedback loop, how to obtain a closed-loop control system with higher bandwidth is still a challenge. Therefore, the joint torque feedback is required to be introduced in the control loop, and the joint torque sensor needs to be designed for the dual-joint module.

3.3.1. The structural optimization design of the joint torque sensor

A spoke-structure is adopted in the design of the joint torque sensor as shown in Figure 6, consisting of the internal rim, the external rim and the elastic body of the flange. The internal rim of the flange is connected with output of harmonic drive gear, and the external rim of the flange is connected with the link. The elastic body of the flange is made up of 4 equally distributed beams, used to stick strain gage forming a full-bridge circuit. BHF350-2AA is chosen as the resistance strain gage, having advantage of high precision, fully sealed, temperature self-compensation and creep self-compensation.

The analysis of stress distribution and deformation is carried out with the help of the ANSYS program to minimize the weight of the sensor within the certain range of stiffness. As shown in Figure 6, when the elastic beam has a thickness of 2.5mm, a torsion torque of 4NM results in a stress of 240MPa and a deformation of 10⁻³mm, lower than the yield limit of the hard aluminum alloy 2A12-T4, and thus satisfy the strength requirement.

3.3.2. The control strategy based on the full-closed loop PD control plus joint torque feedback

A position control system consisting of a conventional closed-loop PD control plus joint torque feedback is provided as shown in Figure 7. In this figure,
In Figure 7, the closed-loop transfer functions from the reference angle \( \theta_d \) to joint angular displacement \( \theta_L \), become

\[
\frac{\theta_L}{\theta_d} = \frac{NK_p \omega_m^2}{J_m s^2 (s^2 + \omega_m^2) + (NK_p + K_s) s (s^2 + \omega_m^2)}
\]  

(1)

When the joint torque signal is feedback, the antiresonance frequency \( \omega_L \) and resonance frequency \( \omega_m \) is expressed by

\[
\omega_L = \frac{K}{\sqrt{J_L}}
\]  

(2)

\[
\omega_m = \frac{K}{\sqrt{J_L}} \sqrt{\frac{N (NK - KK_T - K_p)}{J_m} + \frac{K}{J_m}}
\]  

(3)

The system property at the antiresonance frequency is directly related to the vibratory behavior, as seen from the fact that the antiresonance frequency is decided only by the system structure parameters shown in Eq.(2). The system gain characteristic at the antiresonance frequency can be obtained from Eq.(1)

\[
\left| \frac{\theta_L(j \omega_m)}{\theta_d(j \omega_m)} \right| = \frac{K_p}{K_p + K (K_T - N)}
\]  

(4)

As shown in Eq.(4), system gain characteristic at the antiresonance frequency is decided by \( K_p \) and \( K_T \). Usually, \( K_p \) is desired to be large, and lead to a high system gain, so system structure oscillation is easy to be excited by increasing \( K_p \). When the joint torque feedback is carried out, Both \( K_p \) and \( K_T \) can be adjusted to get a proper system gain, ensuring the system stability with a high control precision.

### 4. Performance evaluation

To testify the design concept of the dual-joint controller, a dual-joint module is developed. Then the performance of the dual-joint controller is tested, shown in Table 2.
### Table 2. Performance of the dual-joint controller

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Performance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Throughput</td>
<td>32bit Nios II core with float point</td>
</tr>
<tr>
<td></td>
<td>Near 113DMIPS@100MHz</td>
</tr>
<tr>
<td>Memory</td>
<td>8Mbytes SDRAM</td>
</tr>
<tr>
<td></td>
<td>8Mbytes CFI Flash</td>
</tr>
<tr>
<td></td>
<td>2Mbytes EPCS Flash</td>
</tr>
<tr>
<td>Dimensions</td>
<td>68 × 68 × 28 mm³</td>
</tr>
<tr>
<td>Mass</td>
<td>Less than 0.25Kg</td>
</tr>
<tr>
<td>Power consumption</td>
<td>Less than 5W</td>
</tr>
<tr>
<td>Supply voltage</td>
<td>+24V, ±12V, ±5V</td>
</tr>
<tr>
<td>CAN bus</td>
<td>512Kbps</td>
</tr>
<tr>
<td>RS232 bus</td>
<td>57.6kbps</td>
</tr>
</tbody>
</table>

After that, the basic parameters of whole dual-joint module are given, shown in Table 3.

### Table 3. Basic parameters of the modular dual-joint

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Data</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass</td>
<td>4.442Kg</td>
<td>Including the mechanical structure,</td>
</tr>
<tr>
<td></td>
<td></td>
<td>electronic circuit and servo systems</td>
</tr>
<tr>
<td>Power consumption</td>
<td>4.6W</td>
<td>Standby mode</td>
</tr>
<tr>
<td></td>
<td>about 15W</td>
<td>Nominal load</td>
</tr>
<tr>
<td>Torque output</td>
<td>14Nm</td>
<td>Max torque output</td>
</tr>
<tr>
<td></td>
<td>7Nm</td>
<td>Nominal torque output</td>
</tr>
<tr>
<td>Joint position range</td>
<td>±170˚</td>
<td>Limited by limit position switch</td>
</tr>
<tr>
<td>Joint positioning accuracy</td>
<td>±1.2˚</td>
<td>Nominal load</td>
</tr>
<tr>
<td>Torque sensor parameters</td>
<td>1.649%</td>
<td>Linearity</td>
</tr>
<tr>
<td></td>
<td>1.234%</td>
<td>Repeatability</td>
</tr>
<tr>
<td></td>
<td>2.894%</td>
<td>Hysteresis</td>
</tr>
<tr>
<td></td>
<td>0.383 V/(Nm)</td>
<td>Sensitivity</td>
</tr>
</tbody>
</table>

5. Conclusion

In this paper, a highly integrated flexible joint servo system with torque feedback has been built. After that, the joint fault tolerant designs have been described. Moreover, a position control strategy with joint torque feedback is provided to improve both precision and bandwidth of the control system. Experimental results have demonstrated the effectiveness of the compact joint servo controller for the space manipulator system. The future work will be concentrated on the control architecture considering the effects of both joint flexibility and link flexibility. More results will be available in the course of the project and their capability will be further proved in near future.

6. Acknowledgment

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7. References