Proceedings of the 2010 IEEE
International Conference on Information and Automation
June 20 - 23, Harbin, China

Joint Driver and Control Design for Large Torque, Long Arm Space Remote Manipulator

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***Abstract* - This paper presents an overview of the structure and requirements of a ground engineering model for a space remote manipulator system, with long arm and large torque driver capacity. The system consists of a 6 DOFs robot arm composed of six identical modular joints, and a large-error tolerated end effector. A FPGA based joint controller hardware structure is built to form a distributed control scheme of the robot arm, while a fourth-order hybrid controller based on the joint torque feedback is adopted to reduce the influence of joint flexibility, brought by the harmonic drivers and torque sensor, on the control precision. A single-joint control experiment, designed to lift up a load at the tip of a link, about two meters in length, is used to test the ability of trajectory tracking in the gravity field.**

Index Terms- Space Robot, Modular Joint, Driver & Control.

I. Introduction

During recent years, space robots have attracted extensive attentions from the world, especially for those with the capability of moving large payload mass. In 2001, the Space Station Remote Manipulator System (SSRMS) from Canada was launched, installed and checked-out on the International Space Station (ISS)[1] successfully. The SSRMS (1336kg), about 14 meters in length, has seven degrees of freedom (DOFs) and can handle large (up to 100,000 kg) payloads, playing an important role in the construction of new infrastructure in space and maintenance of the ISS. The European Robotic Arm (ERA) with a weight of 630 kg, planned to be launched in 2011, is a symmetric seven degrees of freedom manipulator, about 11 meters in length, which can relocate to various positions (base points) on the Russian Segment. It can transport large objects (up to a 8000 kg) during the Russian Segment Assembly Phase, exchange Orbit Replaceable Units (ORUs), and inspect the Russian Segment during the Operational Phase of the station[2]. JEMRMS, consisting of a Main Arm (MA), a Small Fine Arm (SFA) and a console, is used to assist astronauts in doing experiments in exposed environment and to maintain the facility of Japanese Experiment Module. JEMRMS-MA, with a weight of 780 kg and a length of 10 m, is a manipulator of six DOFs, comprising two main arm booms, six identical joint mechanical/electronics units, an end effector at the tip and two cameras with pan/tilt units on elbow and wrist[3].

The current trend is towards the realization of large torque output with relatively small joint size by means of harmonic drivers. And torque sensor is becoming an indispensable component to improve the interaction ability with the environment. The joints of the ground engineering model for a long arm, large torque space remote manipulator presented in this paper are designed with harmonic drivers and torque sensors. The influence of joint flexibility, long arm and large payload mass on the control precision has been eliminated to a certain extent during the design process of joint driver and control system.

This paper presents an account of the development, to date, of the driver and control system, which will control the movement of the robotic flexible joints of the space remote manipulator system ground engineering model (SRMSGEM). The structure of the paper is as follows: In Section II an overview of the system structure and requirements of SRMSGEM is briefly given; Joint structure and sensor system are presented in Section III; Driver and control design of the joint are discussed in Section IV; The experimental design and results are reported in Section V; Finally, conclusions and the future work are addressed.

II. Robotic Structure & Requirements

At present, SRMSGEM is designed to have six DOFs with a length of about 10 meters (Fig. 1). The degrees of freedom, oriented orthogonally, are provided by identical rotational joints, *i.e.*, a waist joint, a shoulder joint, an elbow joint, a wrist pitch, a wrist yaw, and a wrist roll. One end of the robot is fixed to the base station, where arm-level controller (central controller) is installed. The other end of the robot is equipped with an end effector, used to dock with other orbit target objects. Two camera & lighting units (CLU) are installed on the elbow joint and the end effector of SRMSGEM, respectively. The one, placed on elbow joint, is used to provide global vision for operators. The other one is used to convey feedback of relative orientation and distance between the end effector and the grapple fixture of target docking object to the central controller of SRMSGEM so as to eliminate the effects of misalignments.

Based on the experience of the existing three main long-reach remote manipulator systems, SRMSGEM is designed with three control modes:

Free motion: In this mode, SRMSGEM runs in a "safe" space, without the restriction of surrounding objects. Joint's internal position sensors are used to position the SRMSGEM either in joint space or in Cartesian space, under one of the

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three following control conditions: autonomous operation, crew manual operation and teleoperation.

Proximity motion: In proximity motion, the camera and lighting unit at the tip of SRMSGEM, feeding back the relative distance between the end effector and the grapple fixture of target docking object to central controller, in order to guide robotic tip approaching the anticipant area.

Impedance motion: In impedance mode, SRMSGEM can dock with target object compliantly without producing destructive stress, or keep the position of robot tip stably without being influenced by disturbing moment, depending on different stiffness of robot arm set by the commands.

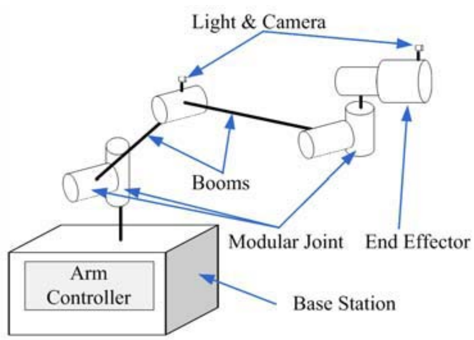

Fig. 1 The Construction of the SRMSGEM.

As to the joint drive system, the following requirements should be satisfied:

Velocity & Position control: The arm-level kinematic control algorithms generate six velocity or position commands, respectively, which will conveyed to the corresponding joint drive controllers. The ability of the arm tip to follow a desired trajectory is dependent in part on the joints tracking their respective commands.

Emergency braking: The arm must be "safed" by the application of each joint's failsafe brake mechanism in any dangerous case.

Torque control: When driving, or being back driven, the torque must be controllable and limited to levels that none of the joint components will be damaged. And position control mode and compliance control mode are able to be switched easily to meet different requirements.

Fail safety: No single failure occurs in any system component shall present any hazard to the base station crew or equipments. Second failure independent from the first one shall not present hazard to the base station crew or equipment, either.

On-orbit maintain: All the maintenance and repairing work of the joints can be done on-orbit, with software being updated by teleoperation.

III Joint Structure and Sensor System

A. Modular Joint

In the space, the zero gravity environment permits a robot to move relatively large masses with small joint torque. The modular concept not only makes the design and modification of the robot easy, but also shortens the development period, reduces the development cost and keeps the maintenance of the system easy. So the full modular concept is adopted over all the robot design. SRMSGEM is composed of 6 entirely identical modular joints. Fig. 2 shows the construction of the modular joint, including joint mechanics, electronics and sensors, which presents a highly integrated mechatronics system. Permanent magnet synchronous motor (PMSM) and harmonic drive gears are selected as the driver of the modular joint. In order to make the cables and plugs to pass through the joints easily, the harmonic drive gears are designed with big center holes. A permanent magnet safe brake is installed on the motor shaft, providing a timely and effective braking protection. All the electric components are installed inside the joint internal space. With the protection from the shielding effect of joint metal crust, the life-span will be prolonged and the reliability will also be enhanced.

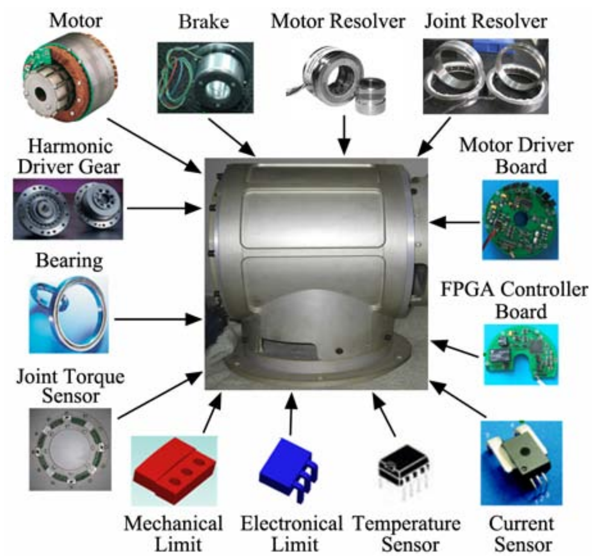

Fig. 2 Construction of the modular joint.

B. Joint sensor system

In order to enable some control schemes, such as speed control, position control and impedance control in condition of autonomous operation, crew manual operation and teleoperation, robot needs some force and position sensors. Hence, every joint is equipped with several sensors, including joint position sensors, motor position sensors, joint torque sensor and joint temperature sensors. Table I shows all the sensors integrated in the modular joint. In order to prevent the joint from destruction and measure the actually exerted torque to each joint, when the robot performs complex manipulations in space, torque sensor is used and placed between the output of harmonic drive gear and the link. The deformation of radial beams is measured by strain gauges. However, the harmonic drivers and joint torque sensor increase the flexibility of the joint, and reduce the control precision. Thus an absolute joint position sensor is needed, and we adopt the special designed multipolar and two-speed electrical resolvers with big central hole (Fig. 3). Also two Hall-effect limit switches have been equipped to prevent the joint from being damaged. In order to increase the system reliability, three digital Hall sensors and a resolver (Fig. 4), are selected as the motor position sensors, realizing the redundant design. And two current sensors based on Hall-effect are integrated in the motor driver board to feed back two-phase current of the three-phase PMSM. Moreover, some temperature sensors are integrated in each joint to check the temperature of interested places.

TABLE I SENSORS IN ONE MODULAR JOINT

No.	Sensor	Type	Quantity
1	Torque sensor	Strain gauge	1
2	Joint position sensor	Resolver	2
3	Limit position switch	Hall effect	2
4	Motor position sensor	Hall effect	3
5	Motor position sensor	Resolver	1
6	Current Sensor	Hall effect	2
7	Temperature sensor	Thermometer	5
8	Thermal switch	Bi-Metal thermostat	2

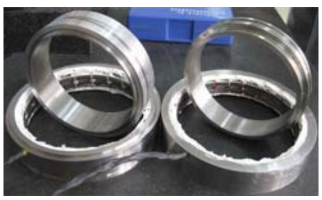

Fig. 3 Two-speed resolvers of joint.

Fig 4 Resolver of motor.

C. *Joint FPGA based hardware structure*

The hardware structure of joint, as shown in Fig. 5, is realized based on the Cyclone FPGA from the ALTERA Corporation. The FPGA integrates a 32 bit NIOS II processor, which can realize single-instruction 32×32 multiply and divide to produce a 32-bit result, and provide a development environment based on the GNU C/C++ tool chain and Eclipse Integrated Development Environment (IDE). As to the components defined by the user, such as SVPWM/RPWM Generation, CAN Communication Controller, Resolver interface and SPI interface are written by VHDL. NIOS II processor can make the access of the user defined components via Avalon bus realizable.

To decrease Electro Magnetic Interference (EMI), a filter and a soft-start circuit, together with an overcurrent detection circuit are utilized. The motor driver inverter module consists of drive chip and MOSFET switches. While the MOSFET, controlling the input voltage of the brake, is driven by the PWM signal, which is directly generated by the I/O pin of FPGA. Analogue signal from torque sensor and temperature sensors are amplified and converted into digital signals by ADC, and transmitted to FPGA through SPI.

D. *Resolver based position & speed sensing schemes*

Resolver based sensing schemes, composed of resolvers and monolithic tracking resolver to digital converters (RDCs), have been selected to feed back the motor shaft position and joint output position. The application of the sensing schemes ascribes to the low cost, wide tolerance to disturbance and easy installment and adjustment of the resolver, as compared with other shaft position transducers, such as rotational inductosyn and optical encoders[4].

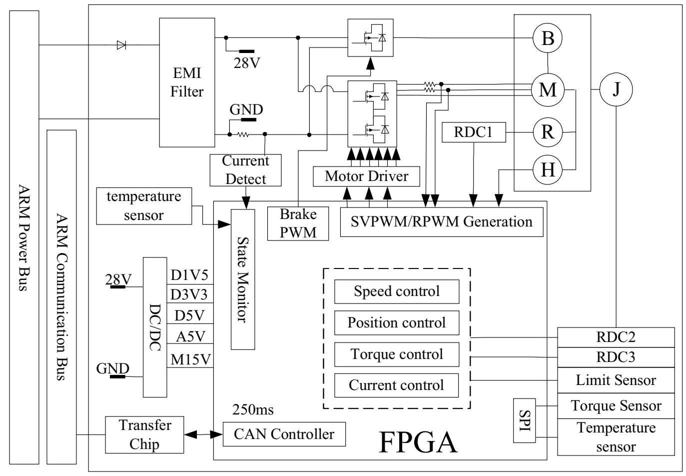

Fig. 5 Hardware structure of modular joint.

The present joint driver uses one resolver/RDC to measure the motor shaft position and a two-speed resolver/RDCs, including a “coarse” and a “fine”, to measure joint output position. FPGA can read three 16-bit digital signals from three corresponding RDC chips, respectively, *i.e.* a motor shaft position, a coarse joint output position and a fine joint output position. The combination of coarse and fine signals can effectively obtain joint angular position with 20-bit resolution. However, manufacturing tolerances of the resolver may cause evident measurement error. A ‘look-up’ table compensation method is used to increase the measurement accuracy, and the control accuracy will be increased accordingly under the limited manufacturing and installation conditions. The compensation result of joint output position is shown in Fig 6.

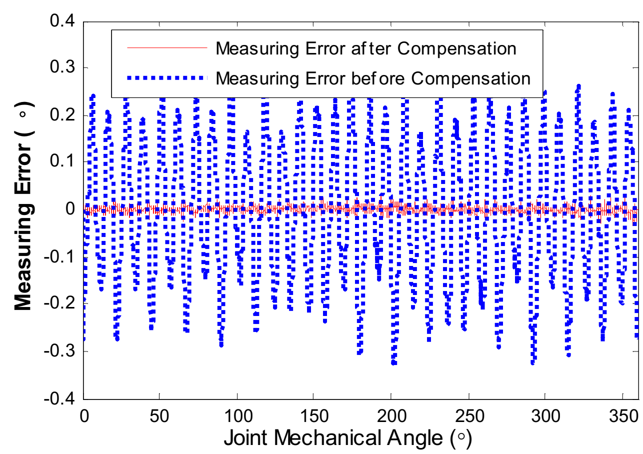

Fig. 6 The compensation result of joint output position.

Motor speed and joint speed can be gained from the differential computation of position signal. So the global joint state information, including motor position, motor speed, joint position, joint speed, joint torque and torque differentiation can be obtained. Besides participating in the joint control, joint position signal is transmitted to the robot controller for the Cartesian level control, through communication bus with a period of 250 ms.

JOINT DRIVER MODE AND CONTROLLER DESIGN

A. Joint driver mode

In order to reduce the vibration of the robot tip, joint output torque should be controlled effectively. The field oriented control (FOC) mode, which relies on the space vector pulse width modulation (SVPWM) control strategy, is usually one of the best candidates for controlling the output moments of PMSM efficiently. The PMSM magnetic flux and torque can be controlled separately by adopting the SVPWM strategy.

As shown in Fig. 7 and Fig. 8, the three-phase stator current, *i.e.* i_a, i_b, i_c, is transformed to the torque feedback current i_{sq} and the field flux feedback current i_{sd} in the synchronous rotor frame *d–q*, via Clarke and Park transition matrix. Two PI controllers are used to adjust the i_{sq} and i_{sd} to track their reference values, respectively, and produce the required voltage commands, *i.e.* u_{sq} and u_{sd}, which are transformed back to the two-phase stationary-frame *α-β* for controlling the SVPWM module. As to the surface mounted permanent magnet synchronous motor, field flux feedback current i_{dref} is usually set to zero. The torque reference current i_{qref}, presenting the desire output torque of the motor, is generated by joint controller. Hence, the output torque of permanent magnet synchronous motor can be controlled efficiently through taking the field oriented control mode[5].

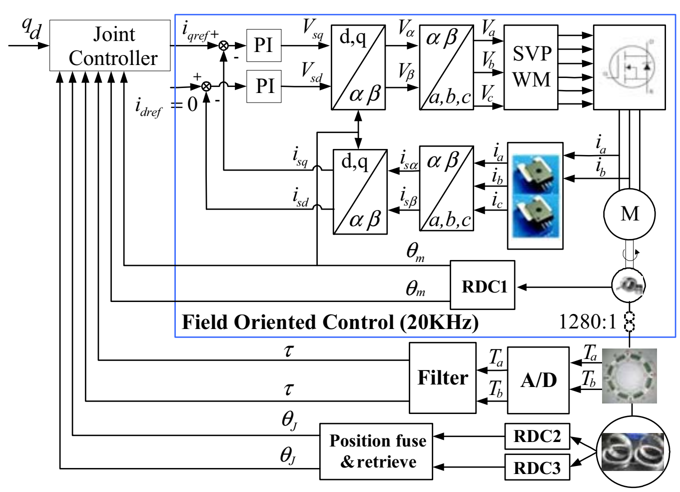

Fig. 7 The structure of joint drive mode based on vector control.

Three digital Hall sensors, providing absolute rotor position and commutation moment of PMSM, are retained to increase the reliability of system. Therefore, "square-wave" drive mode will be used as an alternative way, if a failure takes place on the motor resolver. And these two driver modes can be chosen arbitrarily by control command.

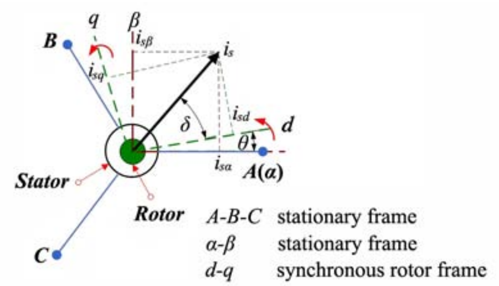

Fig. 8 Reference frames for vector control.

B. Joint controller design

Motivated by the fact that maximum joint rate is five degrees per second, the arm level control is designed based on independent joint control, where the dynamic interaction between the links is considered as disturbance. The arm controller sends commands to each joint controller by CAN communication bus per 250 ms.

Due to the presence of harmonic drive gears and torque sensor, joint can be simplified to a typical two-inertia system, including a spring element connecting motor and load inertia, and coulomb friction [6]. With joint torque feedback, the system bandwidth can be increased to a certain extent [7].So an architecture of joint controller used by Ni [8] is adopted to control the ground joint modular, as shown in Fig. 9. The joint controller takes motor position (θ_m), motor speed ($\dot{\theta}_m$), joint output torque (τ) and torque differentiation ($\dot{\tau}$) as state variables, and regards the joint position θ_a as the output of the controller. And PD type controllers are used separately to adjust joint position and joint output torque, thus a fourth-order state feedback controller is obtained.

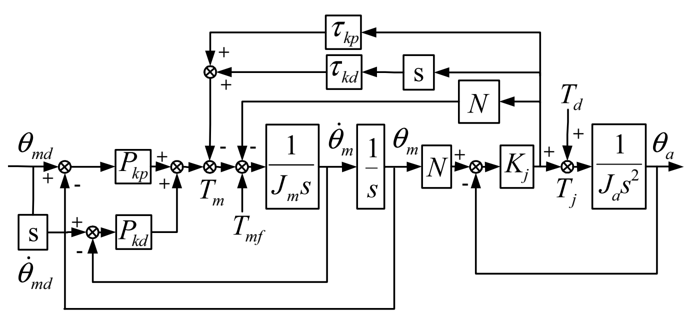

Fig. 9 The architecture of joint controller.

The whole architecture of joint controller is shown in Fig. 10. The central controller, which is taken place by PC now, is used to achieve motion planning and dynamic computation for the whole robot. The command of anticipant position, as well as the control parameters are sent to every joint through CAN communication bus per 250 ms. Both the motion planner for joint level and the hybrid controller for joint torque and position take 1 millisecond as their respective computation cycle. The joint controller is built upon the NIOS II processor of FPGA.

EXPERIMENTS

The distributed control scheme is designed to control the

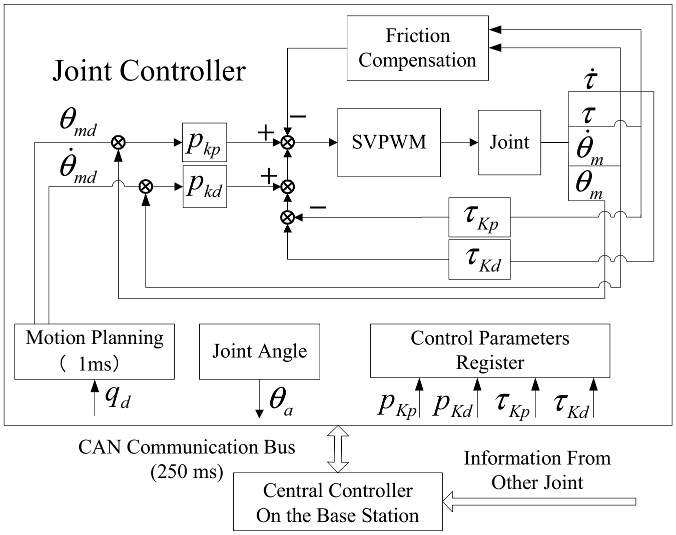

Fig. 10 The whole architecture of joint controller.

motion of robot, and every joint only communicates with the central controller through CAN communication bus per 250 ms. Therefore, each joint is independent but takes the same control structure mentioned above. So the experiment was designed to check the effect of joint controller structure on joint level.

Besides the second order Butterworth filter and second order Bessel filter designed in the torque sensor processing circuit, a software filter structure, used in Ref. [7], has also been adopted to reduce the biggish noise of torque information. The filtering algorithm can be expressed by

$$\mu\dot{\tau}_{fil} = -\tau_{fil} + \tau \tag{1}$$

where τ_{fil} is defined as the output of joint torque signal, $\dot{\tau}_{fil}$ refers to the differentiation of τ_{fil}. The parameter μ can be determined empirically through experiments. This filtering algorithm is favourable to engineering application, because the filtered torque signal and its differentiation can be obtained at the same time. Also the noise brought by the digital differentiation algorithms can be avoided [7].

Due to the designed joint output torque, more than 750 Nm, the single joint experiment is to lift up a load at the tip of a two-meter steel link in gravity field. The weights of load and link are 7.5 kg and 10 kg, respectively (Fig. 11). In the experiment, Coriolis force and centrifugal force are ignored, as a result of the low output speed of the joint ($< 5^{\circ}/s$). The effect of link flexibility has not been considered yet.

As shown in Fig 12 (solid line), a desired 180° trajectory, from the horizontal position of the link to the vertical direction and then back to the origin again, is designed. The real output trajectory of the joint (dashed line) is measured by the magnetic encode (RPN886) connected with joint output through elastic coupling, with a encode accuracy of ±1''. The position-tracking error (dot line) is presented in Fig.12. The experimental results indicate that the joint disturbed by the gravity force can also follow the desired trajectory perfectly.

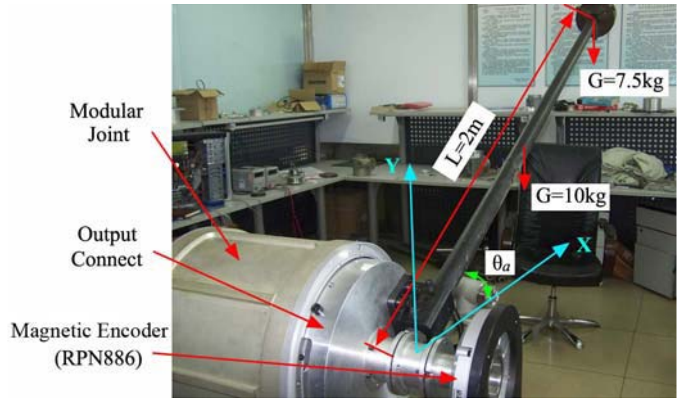

Fig. 11 Experimental equipment.

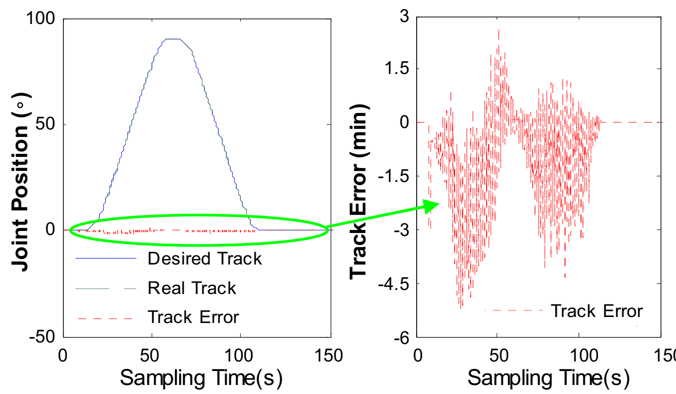

Fig. 12 Experimental results.

CONCLUSIONS

This paper addresses the recent progress of joint driver and controller designing of the ground engineering model for a long arm, large torque space remote manipulator system. The working modes and requirements of the robotic system have been investigated. The whole joint driver, sensor and control structure are also built, adopting the resolver based position and speed sensor structures of motor and joint. A fourth-order state feedback hybrid controller of joint is used to reduce the elastic influence brought by the harmonic drive gears and torque sensor. Experimental results indicate that the designed joint has a good ability of trajectory tracking, even interfered by the gravity field.

The Future work will be concentrated on the multiple-degree-of-freedom experiments. And the control architecture, considering the effects of link flexibility, will be designed accordingly.

ACKNOWLEDGEMENTS

This project is supported by the National High Technology Research and Development Program of China (grant no. 2006AA04Z228) and the “111” Project (B07018).

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