J. of the Korean Radioactive Waste Society
Vol.3(3), P. 257-268, Sept. 2005.

[Technical Paper]

Development and Performance Tests of the Bridge-Transported Servo Manipulator System for Remote Maintenance Jobs in a Hotcell

핫셀내 원격유지보수 작업을 위한 천정이동 서보 매니퓰레이터 시스템의 개발 및 성능테스트

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(Received July 15, 2005 / Approved July 29, 2005)

Abstract

In this paper, a prototype of the Bridge-Transported Servo Manipulator (BTSM) system is introduced, which has been developed to do operation and maintenance jobs remotely in a hot cell. The system consists of a telescopic transporter, a slave arm, a master arm, and a control system. Several tests such as a positional tracking, a weight handling, reliability, and operability have been performed and test results are presented. Based on the test results, an upgraded system which will be used during demonstrations of the advanced spent fuel conditioning process (ACP) has been designed.

Key words : Teleoperation, Servo manipulator, Remote maintenance, Performances tests, ACP.

요 약

본 논문에서는 핫셀에서의 원격 운전 및 유지보수 작업을 위해 개발한 천정이동 서보 조작기 시스템에 대해 소개한다. 조작기 시스템은 텔레스코픽형 이송장치, 슬레이브, 마스터, 그리고 제어시스템으로 구성되어 있다. 개발한 시스템에 대해 위치 추종, 하중 취급, 신뢰성, 및 조작성에 대한 테스트를 수행하였으며 이에 대한 테스트 결과를 제시한다. 이러한 테스트 결과를 바탕으

로 개선된 시스템이 설계되었으며 이 개선된 시스템이 차세대 공정의 실증에 적용될 예정이다.

중심단어 : 원격작업, 서보 조작기, 원격 유지보수, 성능 테스트, 차세대 공정

Ⅰ. Introduction

Even though remote operations and maintenances in the nuclear field are common and ordinary, those are difficult, laborious and time-consuming. The operation and maintenance of process equipment for radioactive materials in a hot cell must be done remotely because high level radiation from radioactive materials is extremely dangerous to people. The ACP (Advanced spent fuel Conditioning Process), which is being developed by KAERI, is a pre-disposal treatment process for spent nuclear fuels, and the process is operated in a strong radiation field [1]. So operation and maintenance of the process equipment must be performed remotely.

Actually, remote jobs are done by the wall-mounted mechanical master-slave manipulators (MSM). However, remote jobs are in need of the cooperation with another manipulators because of the limited workspace. The MSMs are fixed and their handling capabilities are limited to 8 kg per one arm. Furthermore, some graphical simulations showed that the MSMs' workspace was decreased for practical reasons such as joint limits, approach directions and collisions with the process equipment of the ACP [2]. For these reasons, a servo manipulator system was determined to be developed for the cooperation with the MSMs.

In this paper, the developed servo manipulator system and the results of performance tests are presented. The system is moved by a transporter like an overhead crane, so it is named the bridge-transported servo manipulator (BTSM) system. The whole configuration of the developed system is described, and then the performance issues are discussed with the test results. The results show that the developed system has a good performance and it is proper to the remote jobs in a hot cell.

An upgraded system (BTSM-2) based on this prototype has been designed, fabricated, and installed in the ACP hot cell recently [3]. After being tuned and tested, this upgraded system will be used during the demonstration of the ACP.

Ⅱ. The Configuration of the BTSM System

The BTSM system consists of a transporter, a slave arm, a master arm, and a main control system. Fig. 1 shows the system installed in a mockup cell.

1. Transporter

The transporter looks and moves like a crane, and it has a telescopic tube set that connects with the slave arm. It can move the slave arm to anywhere inside the hot cell. The telescopic tube set has one fixed and three sliding tubes, and its stroke

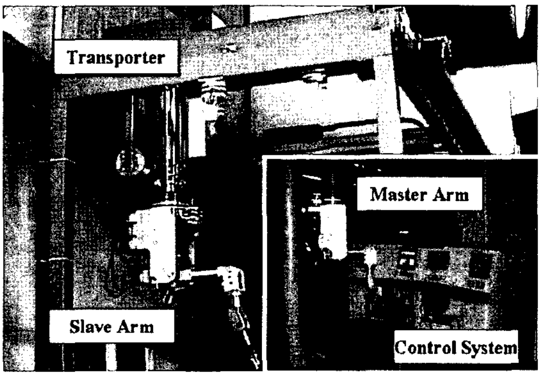


Fig. 1. The BTSM system in a mockup cell.

is about 1.1 m. Motions are controlled by servo motors installed inside the trolley box.

2. Slave and master arms

The slave arm is a single arm and it has 6 joints and one gripper to grasp an object. It has been designed to handle 15 kg objects in any configuration. Fig. 2 shows the slave arm and its axis definitions.

There are two torque transmission mechanisms as shown in Fig. 3. Axes 1, 2, and 3 adopt gear transmission mechanisms. These axes are connected to servo motors by gears. Axes 4, 5, 6, and the gripper adopt steel wire transmission mechanisms. A motor can be distant from its corresponding axis. Due to this mechanism, all the servo motors can be installed on the backplate of the slave arm. The wire transmission mechanism has pros and cons. Even though there are couplings between the axes and modularized design is not easy [4], weight and friction are greatly reduced.

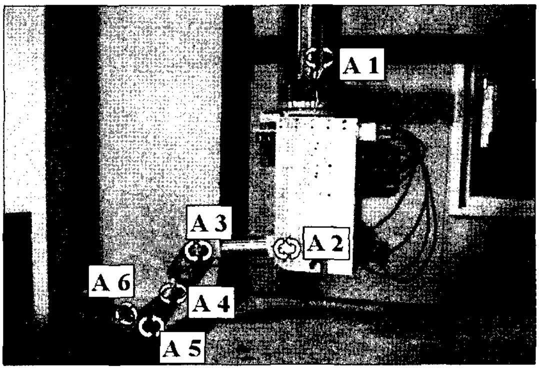


Fig. 2. The slave arm and its axes definitions.

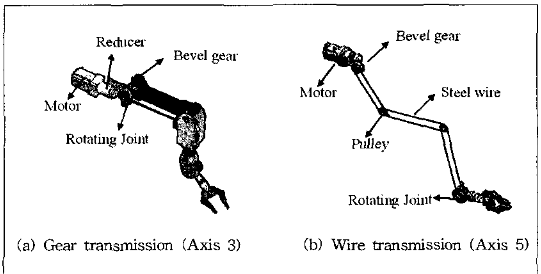


Fig. 3. The examples of torque transmission mechanisms.

The master arm is a replica of the slave. They have the same configurations. So, it is easy to design a control algorithm since it does not need to solve the inverse kinematics. The master arm has a force reflecting function that enables an operator to feel interacting forces with an object.

3. Main control system

The control system includes a control computer, three motion control boards, motor drivers, a manual control console, etc. The manual console is described at the following section. The GUI program displays the status of the system, updates several control parameters, and controls the transporter and the slave arm (Fig. 4).

The architecture of the control system is shown in Fig. 5. The master arm' s configuration is the command to the slave arm, and vice versa. The master arm' s configuration is controlled to mimic the interacting forces. This force reflection scheme will be introduced in the following section. The AD board reads the joints' absolute positional information from the potentiometers.

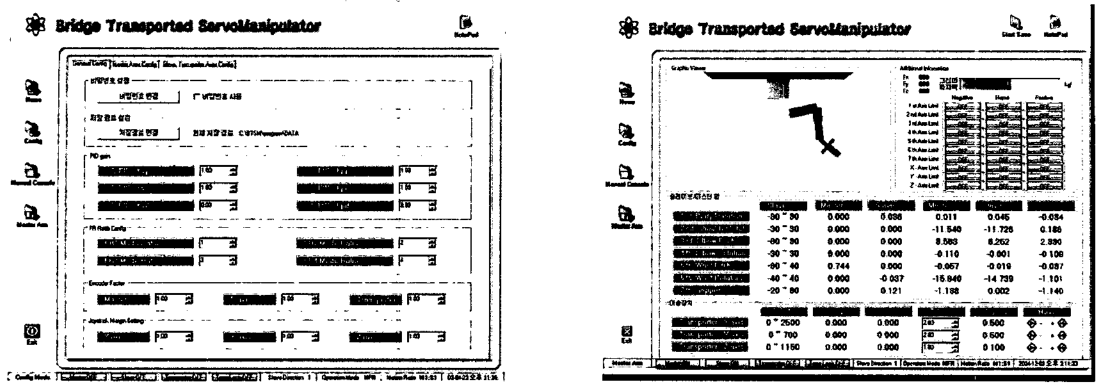
4. Manual console

The manual console in Fig. 6 is a supplementary input device. It is a small console installed by the master arm. The operator can control the slave arm' s axes separately using this console. There is a joystick to control the transporter and several switches to select parameters such as force reflection ratio and motion amplification ratio, and buttons to control cameras.

Ⅲ. Performance Issues and Tests

1. General specification

Performance issues to be tested have been



(a) Page for parameter setting (b) Page for status monitoring

Fig. 4. The operating program of the BTSM system.

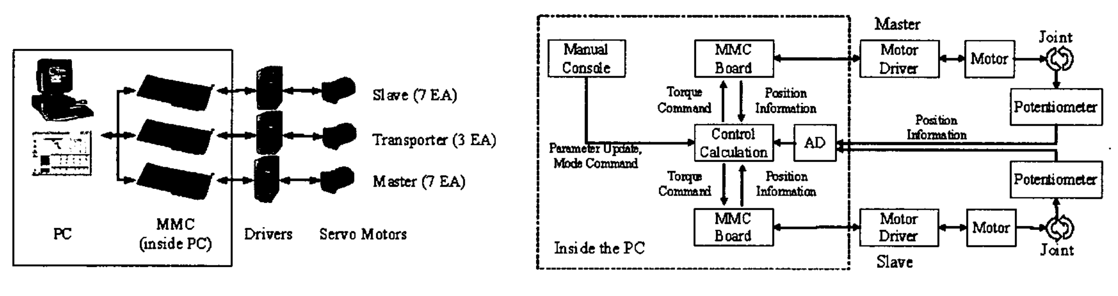


Fig. 5. The architecture of the control system.

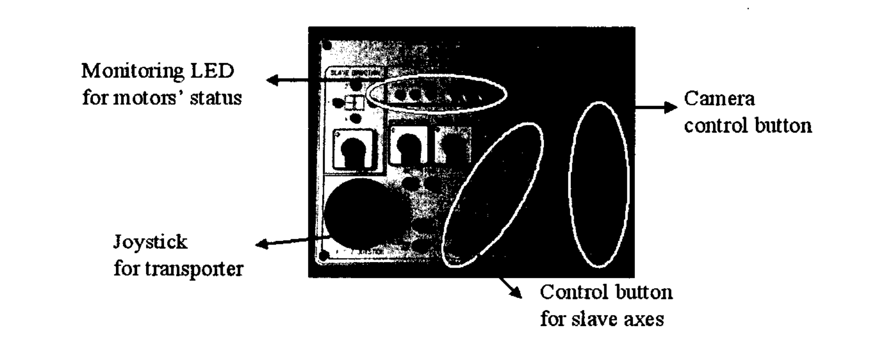


Fig. 6. The manual console.

chosen from several references and categorized into four groups: general specification, reliability, operability, and useful functions. General specification includes the mechanical and control characteristics.

① Joints motion and related specification

Table 1 shows each joint's range and driving motor's specification. Since Axes 2 and 3 require large torques, the reducing ratios are greater than any other axes. The upper arm's length is 350 mm

Table 1. Axis definitions and joints' range (UA = upper arm, LA = lower arm).

Axis	1	2	3	4	5	6	7
Name	Body rotation	UA tilt	LA tilt	LA rotation	Wrist tilt	Wrist rotation	Gripper
Motion	Yaw	Pitch	Pitch	Yaw	Pitch	Roll	Grip
Range(deg)	-180∼180	-45∼45	-45∼45	-180∼180	-135∼50	-180∼180	65 mm
Power(W)	200	200	200	200	200	200	200
Reduction ratio	32	80	64	20	37	31	3

and the lower arm's length is 350 mm. The length between the wrist and the center of the gripper is 250 mm.

② Force threshold measurement

Force threshold is the minimum force to rotate an axis backward. It is mainly related with friction and weight balance. It is desirable to be small. If the weight is balanced, the force threshold (F_{th}) is defined as the minimum force to move an axis and its moment has to overcome a frictional torque as

$$F_{th} \times L \geq T_{JF} + NT_{MF}, \qquad \text{..............(1)}$$

where L is the arm length, N is the reduction ratio, and T_{JF} and T_{MF} are the friction torques of the joint and the motor respectively. N has to be small. T_{JF} of the wire mechanism is smaller than the gear mechanism's friction torque. Fig. 7 shows the master's force thresholds. Threshold values are satisfactory because those are within target values which are 0.5 kg (5 % of the continuous force). However, it is said that 1 % of the continuous force is desirable [5]. So it is desirable to consider another methods to reduce friction further.

③ Control characteristics

The general specification of the control system is as follows:

- Control PC; Pentium 4, 2 GHz
- Motion control board; Samsung's 8 channel MMC, 3 EA
- Operating program; Windows 2000 based, developed by Boland C++
- Control update frequency; 50 Hz and
- Control algorithm; PID control $\left(K_P + K_I\frac{z+1}{z-1} + K_D\frac{z-1}{z}\right)$ for independent joints.

There are two control modes: manual and master. For the manual mode, the operator controls the slave arm with command buttons on the manual console. For the master mode, the operator controls the slave arm by the master arm. Two modes have the same control logic as shown in Fig. 8.

The open loop transfer function of Fig. 8 is

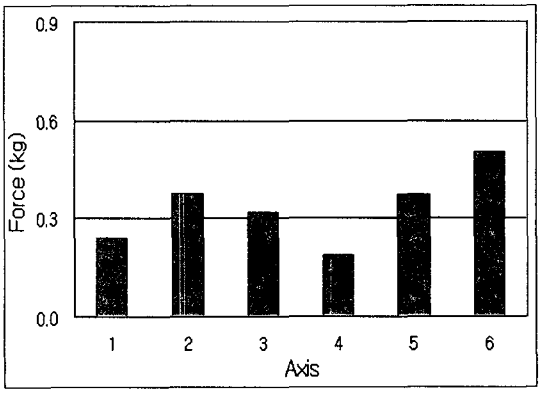


Fig. 7. Force threshold of the master arm.

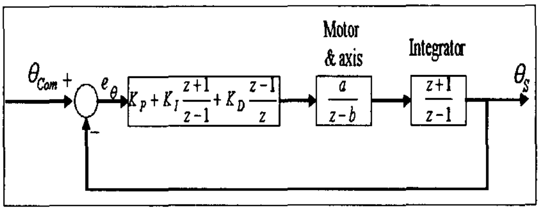


Fig. 8. The control block diagram.

expressed by the formula

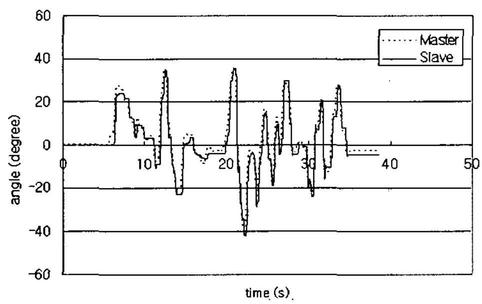
$$G_o(z) = \left(K_P + K_I\frac{z+1}{z-1} + K_D\frac{z-1}{z}\right)\frac{a}{z-b}\frac{z+1}{z-1}$$

$$= \frac{a(z+1)}{z(z-1)^2(z-b)}\left(c_1z^2 + c_2z + c_3\right). \quad \cdots\cdots\cdots(2)$$

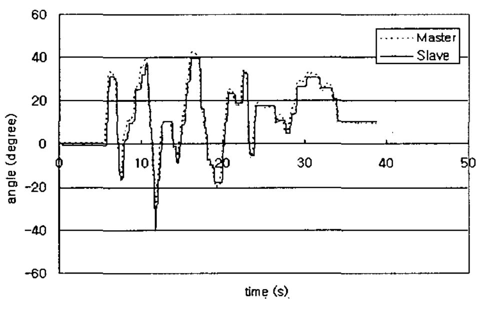
Since this is a type 2 system, the steady state error in response to the ramp input is zero theoretically. However, the integrator windup and a limit cycle due to friction problems are present in practice. These are explained in the following section.

④ Positional tracking test

Positional tracking is a basic requirement for servo manipulator systems. The slave has to move as the master moves. Since the configurations and arm lengths of the slave and the master are the same, the rotating angles of axes have been compared. Fig. 9 shows the time response of the selected axes' rotation (Axes 4 and 6). Tracking is generally satisfactory. Even though there are small errors, those are not significant in teleoperation [6].



(a) Axis 4



(b) Axis 6

Fig. 9. Rotating angles of the master and slave's axes.

⑤ Weight handling

The slave arm has been designed to handle 15 kg objects. However, the powers of Axes 2 and 3 were not sufficient. And the style of tightening a wire at the wrist was not capable of 15 kg. The wire was separated from its pulley when the slave arm handled a 12 kg object. When designing the upgraded system, these have been improved: the powers of Axes 2 and 3 have been doubled and the style of tightening a wire has been changed to prevent a wire from separating.

2. Reliability

The word of reliability has been chosen to express a qualitative property that the system does not have any malfunctions due to logical errors and discrepancy between the slave and the master. A quantitative property used in the reliability engineering is not pursued here.

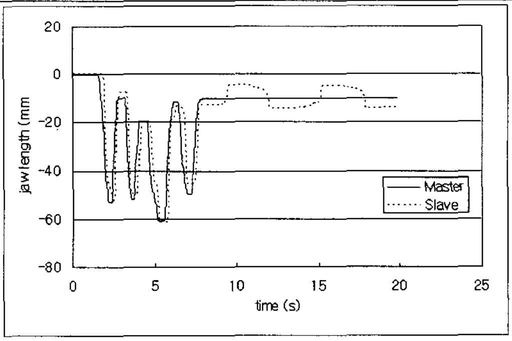
① Limit cycle

Friction is a bothersome factor hindering good positional tracking. It may cause a limit cycle if it combines with the integrating control. A limit cycle is mainly due to the sticking friction. Two options are available to avoid this problem: compensating friction exactly and introducing a dead band [7]. Here, the second option has been chosen because of the simplicity and practicality. Fig. 10 shows the limit cycle due to the sticking friction and the improved response by a dead band.

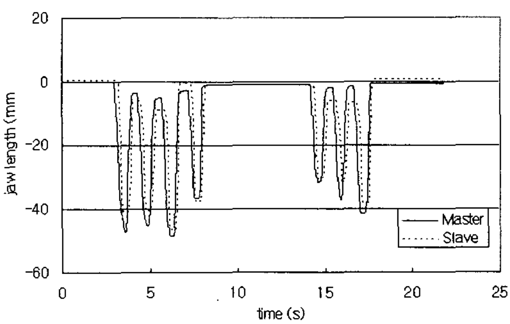
The integrating part of the control algorithm is useful to reduce the effect of disturbances, but it may cause other problems such as a limit cycle and the windup. So, if some performance deterioration due to disturbances is tolerable, it may be a remedy to exclude the integrating part [8].

② Discrepancy between the gripper and the handle

Because of axes couplings and the opposite behaviors of opening and closing, the prototype has a discrepancy between the gripper and the handle. The authors tried to reduce the discrepancy by a kinematic compensation method [9], but this method was not a proper solution. Modified designs and tests have shown that the discrepancy can be eliminated. For the upgraded system, the opposite behaviors have been corrected and the discrepancy has been eliminated except tracking errors. Due to this correction, a kinematic compensation is not necessary.



(a) A limit cycle due to friction



(b) Improved response by a dead band

Fig. 10. The limit cycle and the improved response.

3. Operability

The operability is a set of factors related with easy operation. We have done remote maintenance tests with a mock-up of the process equipment as shown in Fig. 11. The mock-up has one lifting bail, three captive bolts, six non-captive bolts, and two connectors. Fig. 11 shows a series of simple remote jobs with a crane to disassemble and move a part of the mock-up. Many of remote maintenance jobs may consist of such unit jobs. The test showed that the prototype servo manipulator could do unit jobs easily.

①Interfaces for the operator

The interfacing devices for the operator are the master arm, the manual console and 4 monitors. The manual console manages and controls the status and motions of the slave arm, the transporter, and the cameras.

A joystick on the manual console is used to control the transporter. The operator controls the three motions (X, Y, Z) of the transporter with this joystick. So the operator can control 10 DOF simultaneously. These redundancies are very useful to do remote jobs.

The most important thing is the visual information of the slave and equipment. The monitors are installed to provide the visual information. The operator looks at remote jobs through only the monitors. However, those are not centralized but separated. The tests have shown that such an arrangement was not good and the operator could not monitor working situations exactly. So the arrangement has to be modified. The monitors will be centralized and the left and right view of the slave' s end-effector must be shown together always (Fig. 12). Especially, a special lens which converts 2D images to 3D images is installed at one of cameras. The 3D display in Fig. 12 presents 3D images and this will greatly help the

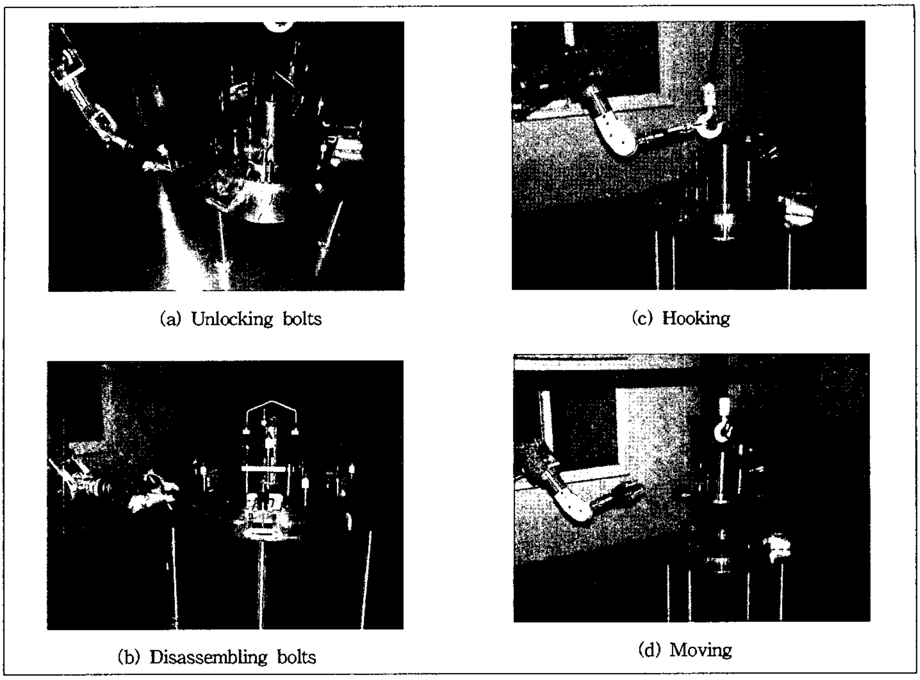

(a) Unlocking bolts (c) Hooking
(b) Disassembling bolts (d) Moving

Fig. 11. The mockup equipment and a maintenance test.

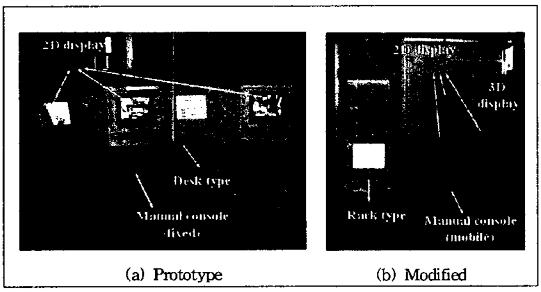
operator look at and do remote jobs.

② Force reflection

Force reflection is to transmit interacting forces between the slave and an object to an operator. Since it is not easy for an operator to do jobs with the visual feeling only, force reflection has been used as an auxiliary feeling (kinesthetic feeling) for most servo manipulators. There are several algorithms for force reflection: position-to-position, force-to-force, and force-to-position. For practical reasons, we have adopted the position-to-position algorithm. The reflected force is based on positional errors between the slave and the master (Fig. 13).

Fig. 13 is a block diagram for the bilateral control. This is a generalized algorithm of Fig. 8. The master' s and slave' s signals become command signals to each other. This algorithm has proved to be simple and practical [4, 10].

Fig. 14 shows reflected forces (Axes 2, 3, and 5) during a free motion, a weight handling motion (6



(a) Prototype (b) Modified

Fig. 12. Displays for monitoring remote jobs.

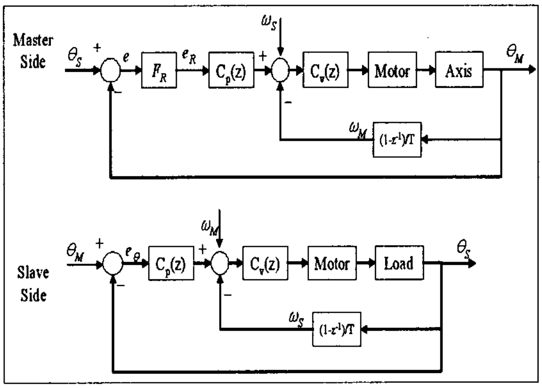
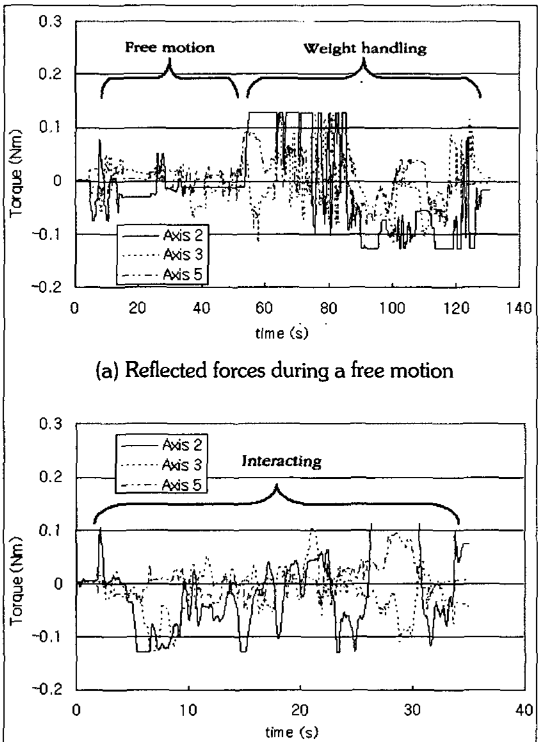


Fig. 13. Control block diagram of the BTSM system.

kg at the gripper of the slave), and an interacting motion. Since a weight hinders the slave from fast tracking, positional errors are greater than those during free motions. Also interactions with objects may induce large positional errors.

Since this method is based on the position error, forces may be reflected to the master or the operator always receives reflected forces during operations *even though there' s no interaction with an object.* It may fatigue an operator. Three approaches have been used to relieve the work load: balancing the weight, adjusting the ratio of force reflection, and cutting off slowly changing the positional errors.

There is a switch selecting the ratio of force reflection (F_R in Fig. 13). Three ratio values can be selected. These values also can be adjusted in the operating program. Experienced operators are inclined to select lower ratio values. The last one means to filter off low frequency signals of the positional errors. It is named as the relieved force reflection and discussed in the following section.



(a) Reflected forces during a free motion

(b) Reflected forces during an interaction and weight handling

Fig. 14. Force reflection tests : reflected forces to the master.

③ Relieved force reflection

For a conventional reflection algorithm, the force reflection ratio is a constant value. The ratio is replaced with a high pass filter as follows;

$$F_R(z) = K_R\frac{z-1}{z-a},\ 0 < a < 1. \quad \cdots\cdots\cdots(3)$$

Then, if a constant unit force is reflected or a constant unit positional error occurs equivalently, the reflected positional becomes

$$\lim_{t\to\infty} e_R(t) = \lim_{z\to 1}\left\{(z-1)F_R(z)\frac{z}{z-1}\right\} = 0. \quad \cdots(4)$$

The low frequency positional errors are cut off. Fig. 15 shows the conventional-reflected forces and relieved reflected forces with a=0.98. Low frequency reflections have been cut off. It means that changes in reflected forces may be easily felt.

4. Useful functions

Useful functions for remote operations are additional functions to ease an operation indirectly.

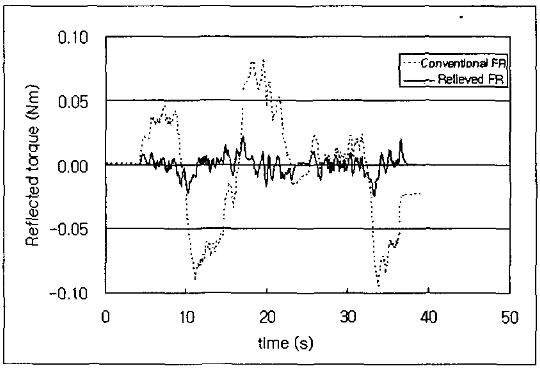


Fig. 15. Conventional and relieved reflected forces.

Some examples are autonomous camera tracking, fault tolerance, telerobotic motions [11], and weight compensation. The developed system has no telerobotic function. The weight compensation is done manually.

① Camera tracking

It has been mentioned that the visual information is the most important for remote jobs. For the prototype system, an operator can monitor remote jobs by 4 cameras. However, an operator has to adjust the cameras' attitude manually to obtain visual information around the slave's end effector. It is inconvenient and bothersome.

The system will be modified to have a camera tracking function as in Fig. 16. The camera's attitude is controlled based on the position of the transporter and the configuration of the slave arm.

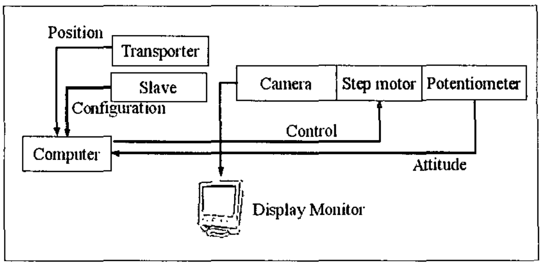


Fig. 16. The diagram of a camera tracking system.

② Fault tolerant control

Fault tolerance is a system's property enduring unanticipated faults of components. Since the radiation from spent fuels causes faults of electric components, fault tolerant designs have to be considered. For fault tolerance, radiation tolerant components have been used [12]. These include connectors and cables. The servo motors are not radiation tolerant, but their modules are designed to be easily maintained. Also, a reconfiguration algorithm has been developed to accommodate a single motor's failure. This algorithm aims to recover the end effector's motion despite of a single motor's failure [13].

Fig. 17 represents the dynamic model of the servo manipulator in planar motions.

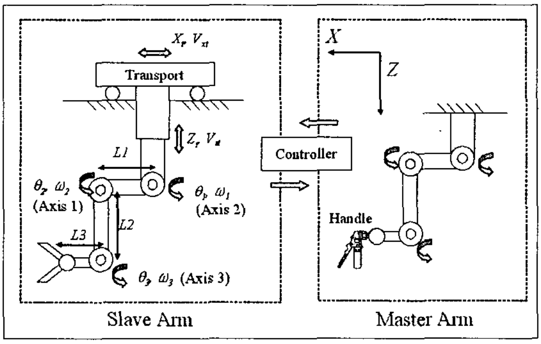


Fig. 17. Model of the transport, the slave, and the master.

The positional difference between the slave's end effector and the master's handle is represented the equation

$$e_p = J_s \Delta Q_s, \quad \cdots\cdots(5)$$

where

$$e_p = \begin{bmatrix} x \\ z \\ \theta \end{bmatrix}_M - \begin{bmatrix} x \\ z \\ \theta \end{bmatrix}_S, \quad \Delta Q_s = [\Delta x_t \ \Delta z_t \ \Delta\theta_1 \ \Delta\theta_2 \ \Delta\theta_3]_s^T$$

$$J_S = \begin{bmatrix} 1 & 0 & -L_1 s_1 - L_2 c_{12} - L_3 s_{123} & -L_2 c_{12} - L_3 s_{123} & -L_3 s_{123} \\ 0 & 1 & L_1 c_1 - L_2 s_{12} + L_3 c_{123} & -L_2 s_{12} + L_3 c_{123} & L_3 c_{123} \\ 0 & 0 & 1 & 1 & 1 \end{bmatrix},$$

$$s_{ijk} = \sin(\theta_i + \theta_j + \theta_k), \ c_{ijk} = \cos(\theta_i + \theta_j + \theta_k).$$

This reconfiguration problem has been formulated in terms of an optimization problem as follows;

$$\text{minimize } \frac{1}{2}(e_p - J_s^f \Delta Q_s^f)^T (e_p - J_s^f \Delta Q_s^f), \quad \cdots(6)$$
$$\text{subject to } \Delta Q_{s,\min}^f \leq \Delta Q_s^f \leq \Delta Q_{s,\max}^f,$$

where J_S^f and ΔQ_S^f are the Jacobian matrix and the control vector whose failed axis has been excluded. This reconfiguration method has been solved by a modified pseudo inverse redistribution method, and it has been tested and verified [13].

Ⅳ. Conclusions

In this paper, a prototype of the bridge-transported servo manipulator (BTSM) system has been introduced. It is developed for the remote operation and maintenance of the ACP equipment. The BTSM system consists of a telescopic transporter, a slave arm, a master arm, and a control system. The transporter is a type of a crane and has a telescopic tube set moving the slave to any position. The slave and master have the same configurations. They are driven by servo motors.

Several performance tests have been done: a force threshold, a positional tracking, a force reflection and a simple remote maintenance test. Test results have shown that the prototype satisfied the requirements and its performance was satisfactory.

An upgraded servo manipulator system (the second prototype) is under tests. The upgraded system will be used during the demonstration of the ACP. It is expected that the BTSM system will be one of the most useful devices for the ACP demonstration.

Acknowledgement

The authors are grateful for the support provided by a grant from Atomic Energy R&D Program of Ministry of Science and Technology in Korea.

References

1. G. You, S. Park, W. Jung, J. Goo, and J. Cho, " Development of hot cell facilities for demonstration of ACP," Proceedings of the 4th Korea-China Joint Workshop on Nuclear Waste Management, pp.191-204, Seoul(2003).
2. J. Yoon, S. Kim, and T. Song, "Visualization and analysis of remote operation involved in advanced conditioning process," Proceedings of the 4th Korea-China Joint Workshop on Nuclear Waste Management, pp.205-219, Seoul(2003).
3. B. Park, J. Jin, J. Lee, S. Ko, and J. Yoon, "Manufacturing of servo manipulator for remote maintenance of the advanced spent fuel conditioning process: BTSM-2", Proceedings of the Korean Radioactive Waste Society Spring 2005, pp.414-415, Gwangju(2005).
4. J. Herndon, C. Kring, and J. Rowe, "Advanced remote handling for future applications: the advanced integrated maintenance system," Proceedings of Remote Systems and Robotics in Hostile Environments, pp.622-629, Pasco, Washington(1987).
5. P. Fischer, R. Daniel, and K. Siva, "Specification and design of input device for teleoperation," Proceedings of 1990 IEEE International Conference on Robotics and Automation, pp.540-545, Cincinnati, Ohio(1990).
6. R. Kress, J. Jansen, M. Noakes, and J. Herndon, "The evolution of teleoperated manipulators at ORNL," Proc. of the ANS 79th Topical Meeting on Robotics and Remote Systems, pp.623-631, Augusta, Georgia(1997).
7. G. Ellis, Control System Design Guide, pp.234-238, Academic Press, London(2000).
8. B. Armstrong-Helouvry, P. Dupont, and C. Canudas De Wit, "A survey of models, analysis tools and compensation methods for the control of machines with friction," Automatica, 30(7), pp.1083-1138(1994).
9. B. Park, J. Jin, T. Song, S. Kim, and J. Yoon, "Transmission characteristics on wire driven links of a bridge transported servo manipulator for the ACP equipment maintenance," Journal of the

Korean Radioactive Waste Society, 2(3), pp.189-199(2004).

10. D. Kuban, M. Noakes, and E. Bradley, "The advanced servomanipulator system: Development status and preliminary test results," Proceedings of Remote Systems and Robotics in Hostile Environments, pp.638-644, Pasco, Washington (1987).
11. Y. Park, H. Kang, T. Ewing, E. Faulring, E. Colgate, and M. Peshkin, " Enhanced teleoperation for D&D," Proceedings of 2004 IEEE International Conference on Robotics and Automation, pp.3702-3707, New Orleans, Louisiana(2004).
12. J. Jin, S. Ahn, B. Park, J. Yoon, and J. Jung, "Fault tolerance design for servo manipulator system operating in a hot cell," Proceedings of International Conference on Control, Automation, and Systems, pp.2467-2470, Gyeongju(2003).
13. J. Jin, B. Park, S. Ahn, and J. Yoon, "Reconfiguration of redundant joints for fault tolerance of a servo manipulator," Journal of Control, Automation, and Systems Engineering, 10(10), pp.899-906(2004).