# 핫셀내 원격유지보수 작업을 위한 천정이동 서보 매니퓰레이터 시스템의 개발 및 성능테스트

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

**Jae-hyun Jin, Byung-suk Park, Byung-seung Ko, Jis-up Yoon and Ki-Jung Jung**
Korea Atomic Energy Research Institute, 150 Duck-Jin Dong, Yusung-Ku, Daejeon

**진재현,박병석,고병승,윤지섭,정기정**
한국원자력연구소, 대전광역시 유성구 덕진동 150번지

**Abstract**

A prototype of the Bridge Transported Servo Manipulator (BTSM) system 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. In this paper, the system is introduced and several performance test results are presented. The results have been used to design an upgraded system that will be used during demonstrations of the advanced spent fuel conditioning process.

**Key word** : Teleoperation, Servo manipulator, Remote maintenance, Performance tests.

## 1. 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 spent nuclear fuels in a hot cell must be done remotely because high level radiation from spent nuclear fuels 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 the spent nuclear fuels, and the process is operated in an intense radiation field[1]. So operation and maintenance of the process equipment must be performed remotely.

Actually, remote operations and maintenances are done by the wall mounted mechanical master-slave manipulators (MSM). But 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 as an alternative device to the MSMs.

In this paper, we introduce the developed servo manipulator system and the result of performance tests. We have done several performance tests to verify and confirm that the developed servo manipulator is reliable and easily operable. 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 maintenance jobs in a hot cell.

## 2. 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.

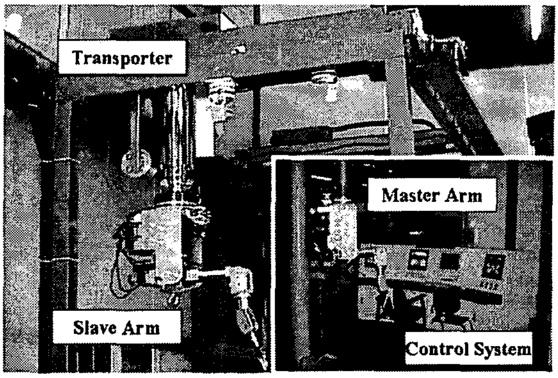


Fig. 1. The BTSM system in a mockup cell.

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

### 2.2. 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 axes definitions.

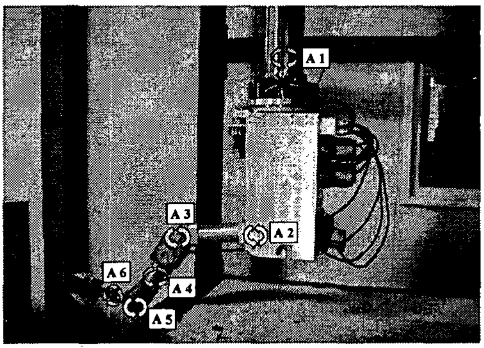


Fig. 2. The slave arm and its axes definitions.

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. Due to these mechanisms, all the servo motors can be installed on the backplate of the slave arm. A wire transmission mechanism is shown in Fig. 3. This mechanism has pros and cons. Even though there are couplings between the axes and modularized design is not easy[3], weight and friction are greatly reduced.

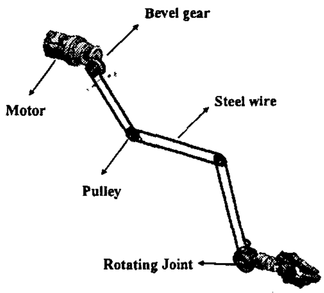



Fig. 3. The wire driving mechanism.

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 force with an object.

2.3. 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 a central device for controlling the BTSM system, and it is installed by the side of the master arm. The GUI program displays the status of the system, updates several control parameters, and controls the transporter and the slave arm (Fig. 4).

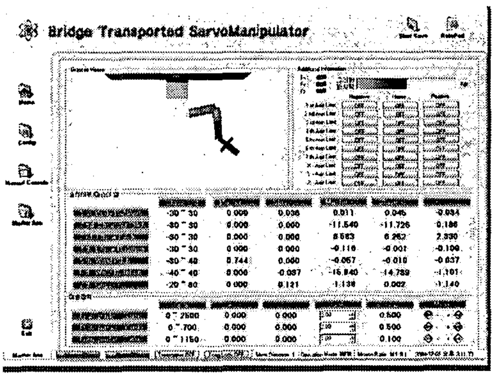



Fig. 4. The operating program of the BTSM system.

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 at the following section. The AD board reads the joints' absolute positional information from the potentiometers.

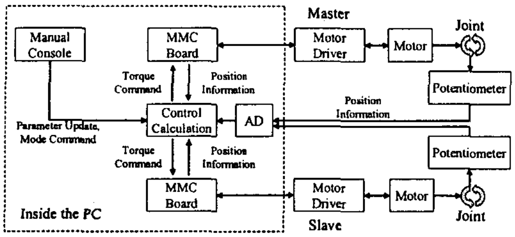



Fig. 5. The architecture of the control system.

## 3. Performance Issues and Tests

### 3.1. General specification

Performance issues to be tested have been chosen from several references and categorized into four groups: general specification, reliability, operability, and useful functions. General specification includes the mechanical and control characteristics.

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

Table 1. Axis definition and joints' range

| 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 |

(UA = upper arm, LA = lower arm)

B. 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 is defined as

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

$L$ 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. $N$ has to be small. $T_{JF}$ of the wire mechanism is smaller than the gear mechanism's friction torque. Fig. 6 shows that 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 good[4]. So we have to consider another methods to reduce friction.

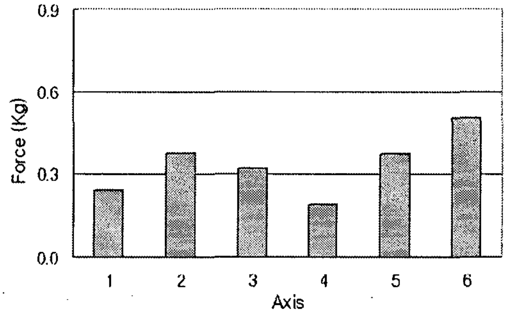



Fig. 6. Force threshold of the master arm.

C. Control characteristics

The general specification of the control system is as.

- 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
- Control algorithm: PID control 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 by using the master arm. Two modes have the same control logic as shown in Fig. 7.

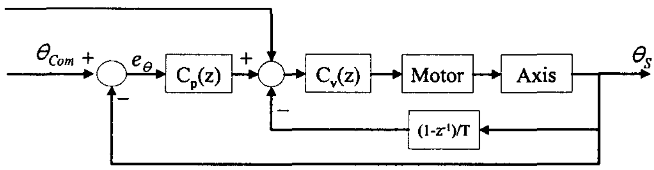



Fig. 7. The control block diagram.

The open loop transfer function of Fig. 7 is as.

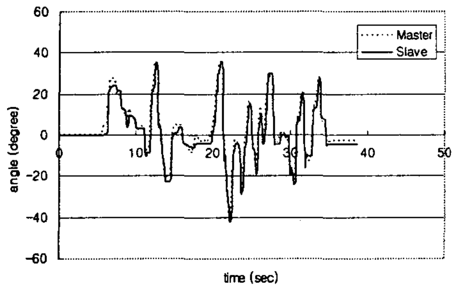
$$G_o(z) = \left(K_P + K_I\frac{z+1}{z-1} + K_D\frac{z-1}{z}\right)\frac{a}{z-b}\frac{z+1}{z-1} = \frac{a(z+1)}{z(z-1)^2(z-b)}\left(c_1z^2 + c_2z + c_3\right). \quad (2)$$

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 at the following section.

D. Positional tracking test

Positional tracking is a basic requirement for the 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. 8 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[5].



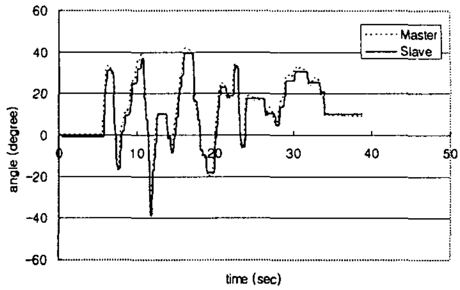




Fig. 8. Rotating angles of the master and slave's axes.

3.2. 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.

A. Integrity of the operating program

Even though the control algorithm for the slave and master is simple, several events related with the modes and operations may occur in a complicated manner. Because of this, if there are logical errors, the system may malfunction.

A discrete event simulation tool has been used to eliminate such logical errors. Events of pressing any function buttons are randomly generated and the behaviors of the system are monitored. Fig. 9 is the simplest model of the system. Logical errors have been eliminated by this simulation and actual tests.

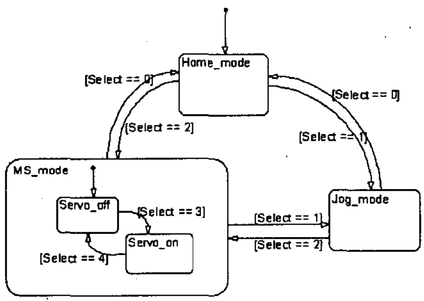



Fig. 9. Stateflow diagram of the system modes.

B. Limit cycle

Friction is a bothersome factor hindering 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 [6]. Here, the second option has been chosen because of simplicity and practicality.

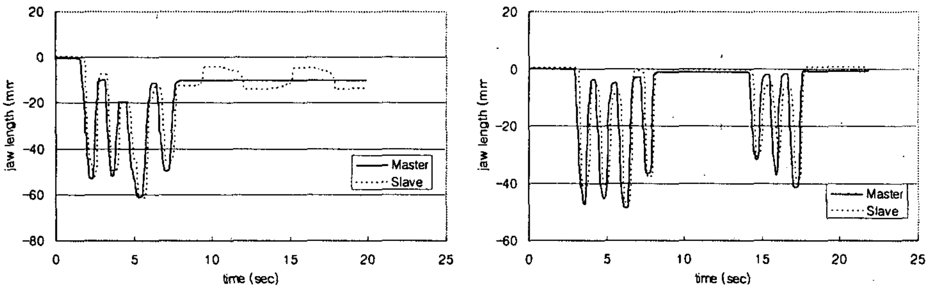



Fig. 10. The limit cycle and the improved response.

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.

C. Coupling between axes

It has been mentioned that there are couplings between axes because of the wire transmission mechanism. The axes may be decoupled by a kinematic compensation [7]. The authors have presented the kinematic compensation method and its result at the reference [8].

3.3. Operability

The operability is a set of factors related with easy operation. We have done remote maintenance tests with a mock-up of process equipment as shown in Fig. 11. The mock-up has one lifting bail, three captive bolts, six non-captive bolts, and two connectors. Based on the remote maintenance tests, we have derived some items to be modified.

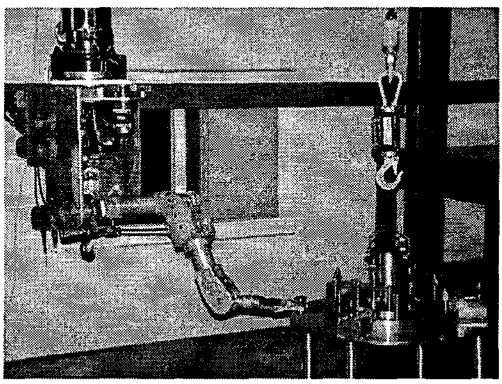


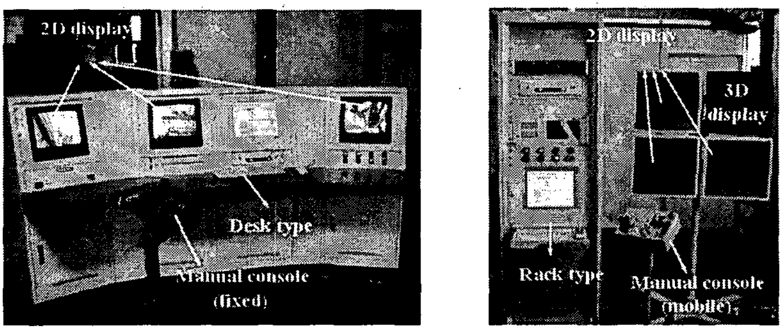
Fig. 11. The mockup and maintenance test.

A. Interfaces for the operator

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

For the transporter, a joystick is used as a control stick. The operator controls the three motions (X, Y, Z) of the transporter with this joystick.

The most important thing is the visual information of the slave and equipment. The monitors are installed to provide the visual information. 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).




(a) Prototype (b) Modified

Fig. 12. Displays for monitoring remote jobs.

B. 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 bilateral control. The master's and slave's signals become command signals to each other. This algorithm has proved to be simple and practical[9, 10].

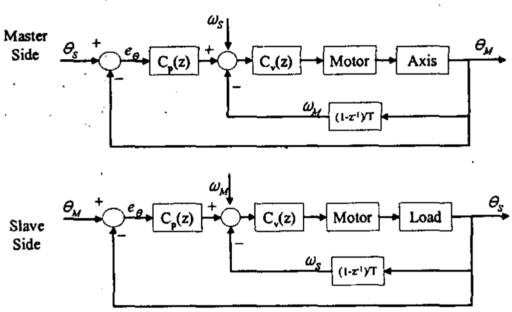



Fig. 13. Operation program of the BTSM system

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

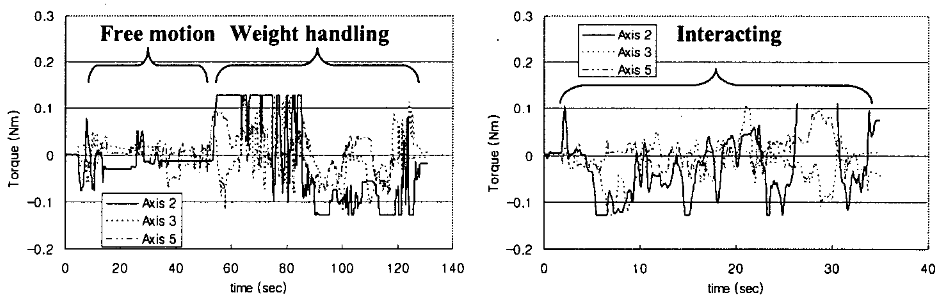



Fig. 14. Force reflection tests - reflected forces to the master.

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. The last one means to filter off low frequency signals of the positional errors. It is named as the relieved force reflection and discussed at the following section.

C. Relieved force reflection

Cut off low frequency positional error to reduce fatigue and increase sensitivity

$$e_r = \frac{1}{\tau s + 1} e. \tag{3}$$

This has a property cut off the low frequency positional errors. It means that only changes may be transmitted to the master as reflected forces.

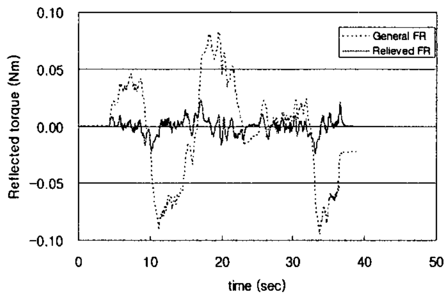



Fig. 15. Relieved force reflected to the operator.

3.4. Useful functions

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

A. 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 Fig. 16. The camera's attitude is controlled based on the position of the transporter and the configuration of the slave arm.

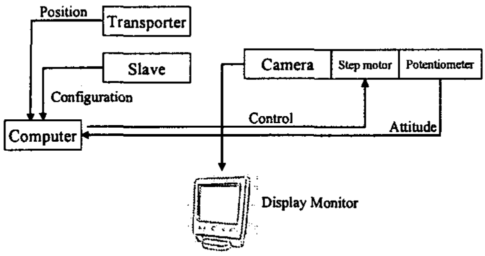



Fig. 16. The diagram of a camera tracking system.

B. Fault tolerant control

Fault tolerance is a system's property enduring unanticipated faults of components. Since the radiation from the spent fuels causes faults of electric components, fault tolerant designs have to be considered. For fault tolerance, radiation tolerant components have been used[10]. 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[9].

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

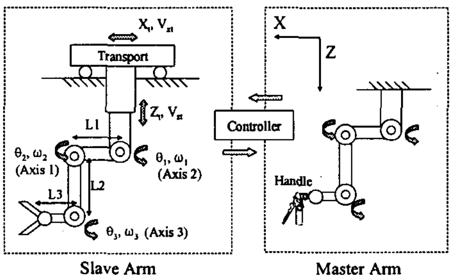



Fig. 17. Model of the transport, the slave, and the master.

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

$$e_p = J_s \Delta Q_s . \tag{4}$$

where

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

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

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

This reconfiguration problem has been formulated as an optimization problem as

$$\text{minimize } \frac{1}{2}\left(e_p - J_s^f \Delta Q_s^f\right)^T \left(e_p - J_s^f \Delta Q_s^f\right), \tag{5}$$

$$\text{subject to } \Delta Q_{s,\min}^f \leqq \Delta Q_s^f \leqq \Delta Q_{s,\max}^f.$$

where $J_s^f$ and $\Delta Q_s^f$ are the jacobbian 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[9].

## 4. Conclusion

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. 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: force threshold, positional tracking, force reflection. Maintenance tests are being currently performed. Test results show that the prototype satisfies the requirements and its performance is satisfactory.

An upgraded servo manipulator system (the second prototype) is under development. Some of the test results of the first prototype have been used for designing the second one. It has been determined that the second will be used during the demonstration of the ACP. We expect The BTSM system to be one of the most useful devices.

**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, et al., "Development of hot cell facilities for demonstration of ACP," Proceedings of the 4th Korea-China Joint Workshop on Nuclear Waste Management, Seoul, pp.191-204, 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, Seoul, pp.205-219, 2003.
3. 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, 1987.
4. P. Fischer, R. Daniel, and K. Siva, "Specification and design of input device for teleoperation," Proceedings of IEEE International Conference on Robotics and Automation, pp.540-545, 1990.
5. 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, Georgia, USA, pp.623-631, 1997.
6. G. Ellis, Control System Design Guide, Academic Press, pp.234-238, 2000.
7. R. Murray, Z. Li, S. Sastry, A Mathematical Introduction to Robotic Manipulation, CRC Press, pp.293-300, 1994.
8. B. Park, et al., "Transmission characteristics on wire driven links of a bridge transported servo manipulator for the ACP equipment maintenance," Journal of the Korean Radioactive Waste Society, vol.2, pp.189-199, 2004.
9. J. Jin, et al., "Reconfiguration of redundant joints for fault tolerance of a servo manipulator," Journal of Control, Automation, and Systems Engineering, vol.10, no.10, pp.899-906, 2004.
10. J. Jin, et al., "Fault tolerance design for servo manipulator system operating in a hot cell," Proceedings of International Conference on Control, Automation, and Systems, 2002.
11. Y. Park, et al., "Enhanced teleoperation for D&D," Proceedings of IEEE International Conference on Robotics and Automation, pp.3702-3707, 2004.