EXPERIMENTAL STUDY OF TELE-OPERATION DEVICES FOR THE REMOTE HANDLING SYSTEM IN A PYROPROCESSING FACILITY

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ABSTRACT

Tele-operation manipulators applied in this paper are systems for the remote handling and management of pyroprocessing related facilities in an Argon cell of the KAERI (Korea Atomic Energy Research Institute). Generally, these kinds of systems are composed of a master-slave system and its peripherals installed along the wall of the cell, with the master transmitting the user's own motion to the gripper directly. This study introduced various considerations and modifications to improve the remote handling performance. The analysis of an operator's ability using his/her own upper arm motion range while manipulating the MSM, and considerations of its manipulation margin and the related tool modifications are also included. Finally, the test results of several remote handling tasks are presented, and an adequate operation strategy for the tele-operation system of hot-cell type facilities is proposed.

KEYWORDS

Tele-operation System, Pyroprocessing, Remote Handling System, Master-Slave System

INTRODUCTION

A remote handling manipulator is widely applied to operate and manage the equipment installed in a hot-cell facility. This kind of manipulator is generally composed of a master and slave system which has the same structure with each other to simplify the mechanical structure while achieving the operability of the user. Until now, many kinds of remote manipulators related to the remote handling tasks in a cell have been developed, and the tele-operation system using a manipulator is known as a reliable technology to reduce the user's radiation exposure (Rennich, 2006 and Pittman, 1999). In particular the technology is accepted as, not only a solution in the nuclear industry for completing tasks such as dismantling of outworn equipment and managing of the nuclear reactor core, but also for extreme cases (H.S. Lee, 2009). Most manipulators have to handle an object using his/her own muscle power including manipulation force transferred from the manipulator's own body. In particular, it is necessary to possess higher strength and skillset then even for bare hand tasks. (Yu, 2012) Therefore, it is necessary that the task load and ergonomic analysis for task environment correspond to industrial cases. This study evaluated the remote handling performance of a developed tele-operation system installed at the developed facility, "PRIDE" (PyRoprocess Integrated inactive DEmonstration facility, Figure 1), and proposed that the conceptual approach to promote the performance of a current system. The remote manipulator systems examined in this paper are a well-known master-slave system (MSM) and a BDSM (Bridge Transported Servo Manipulator) system developed by KAERI in Korea. (Lee, 2011 and Yu, 2012)

SYSTEM CONFIGURATION

The systems considered are wall-hanging type master-slave systems which are operated though a tendon driven system, and a servo-type manipulator operated via a wired remote master device. This paper discusses the operator's load and accessibility of the processing equipment using the remote handling system. Additionally, experimental evaluations for the remote handling task are proposed using modified tools by unit task analysis. BDSM is a servo control based manipulator system which is structured by two arms of 7 degrees of freedom for each extremity, and a telescopic type transportation system combined with two arms underneath. The MSM has two 6 DOF arms and is operated directly through a master device located outside of the cell. The master-slave system is combined with the wall-tube directly, which has the same structure and allows users to operate the system intuitively. Generally, MSM and BDSM can be operated through a window and additional remote vision system, respectively (Figure 1 and 2). MSM allow not only the execution of forces equivalent to those an unaided operator can achieve, but also forces up to a much higher level. This system is suitable for complicated tasks, and generally this one is installed in pairs. They allow the performance of complicated work throughout the whole volume of large cells and not only near the operation walls, by means of the mobility. As a result of their load capacities, they can be used also in place of light and medium load-capacity manipulator like BDSM as shown in Figure 1 and 2. (BDSM has the load capacity of around 20kgf for each arm.)

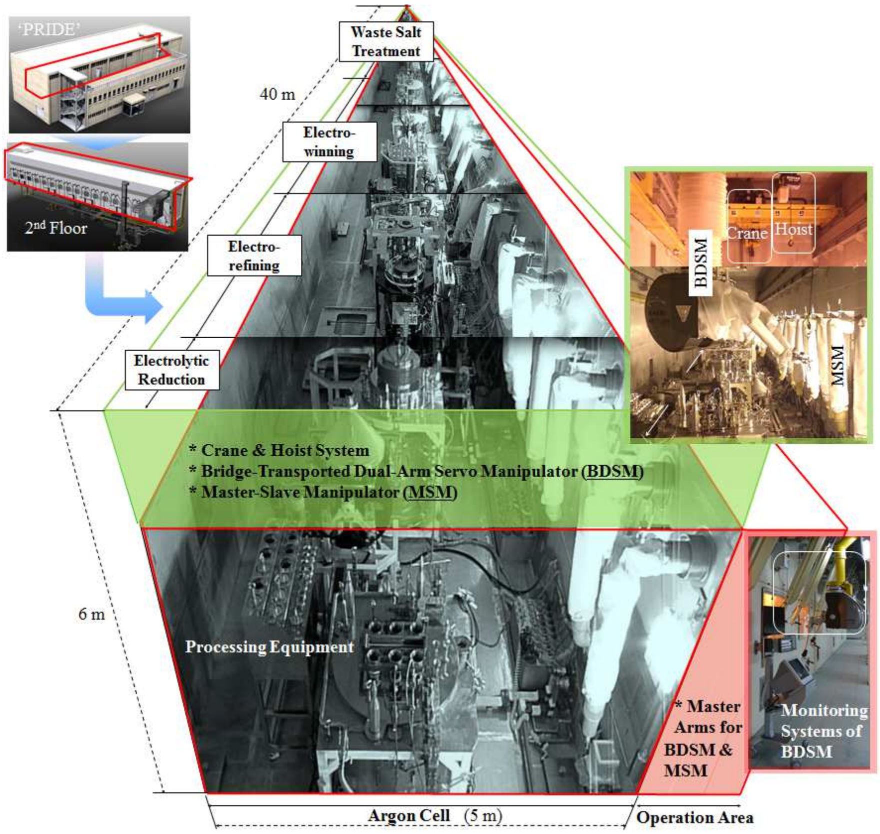

Figure 1 – Operation (Outer Side) and Process (Inner Side) Area of Pyroprocessing Facility

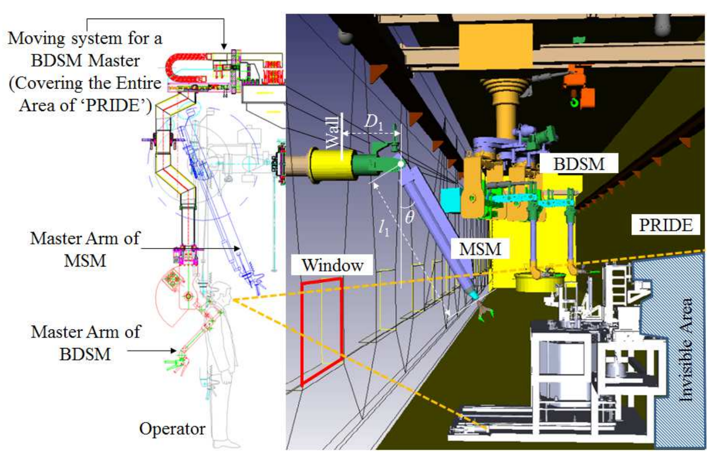

Figure 2 – Configuration of the Master-Slave Manipulator System (MSM) and Bride-Transported Dual Servo Manipulator (BDSM)

EXPERIMENTAL SETUP FOR THE TELE-OPERATION MANIPULATORS

In this section, to define the physical boundaries of remote handling task using remote handling manipulator based on the musculoskeletal load characteristics of operator's arm motion and intuitiveness. Then, it is proposed that the proper condition of arrangement of processing facilities handled by remote manipulator and remote handling skill which are applied in the experimental verification of remote handling task of facility repair task.

Considerations for the Equipment Arrangement (1) – The Manipulability of a Human Arm

Major portion of human physical activity in remote handling task takes place in manual manipulator handling activities using MSM. There is some remote handling of material for any pyroprocessing facility. Most remote handling tasks are required to handle parts, subassemblies, containers, and products on their job even cooperated with crane or hoist. In terms of work load, this study focused on the change of performance of the operator's arm along with their posture in the working area. Behaviors such as pushing, pulling and pulling up and down can be matched with proper types of tasks. As shown in Figure 4, if the angle of the elbow becomes stretched horizontally, it is disadvantageous to handle the tools for inserting/pulling vertically. If the arm is folded within 90 degrees near the torso, horizontal pushing and pulling tasks are harder to perform as it concentrates the heavy force along the horizontal axis. (Pulat, 1992) These characteristics have to be considered when locate the facilities and those associated modules which have to be handled remotely.

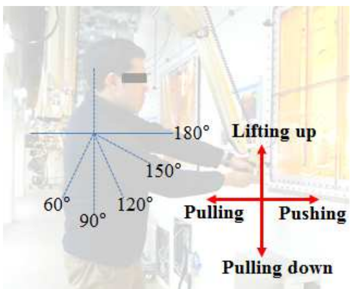

Figure 3 – Considered Four Directions of Exerted Force for a Manipulator

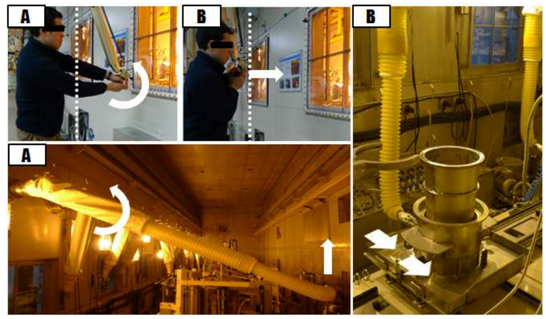

Figure 4 – Cases of Excessive Motion: Manipulation of Fully Stretched and Extremely Folded MSM

Based on the Pulat’s analysis, the positions of the objects have to be determined with a consideration of the proper motion to perform the task. (Figure 3 and 4) It is evident form this figure that push and pull capabilities are strongest in the sagittal plane of human at medium height.

Considerations for the Equipment Arrangement (2) – The Manipulation Margin of MSM

When the equipment is installed inside of the cell remotely, the accessibility of the manipulator system has to be considered. From this point of view, the study presents the manipulation margin for the specified remote handling task.

·Assumption 1: To assemble/disassemble the plug from a receptacle using MSM, it is necessary to reserve sufficient space.

·Assumption 2: A manipulation margin is mainly considered when the arm is fully stretched, and if the arm is folded completely, the value of margin becomes zero (Figure 5).

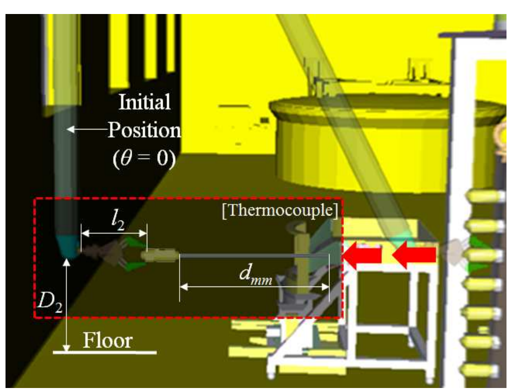

Figure 5 – Basic Parameters for a Consideration of Manipulation Margin of MSM to handle the front side of the Target Equipment

This is obviously simple consideration but important one to decide the specified location of target facility in PRIDE cell handled by remote manipulator. Most of all, the location of each facility affect to the location of adjoined other facilities operated simultaneously. As shown in Figure 5, the distance and height of the equipment from the window and ground can be expressed using the parameters of the manipulator as in the following equations, respectively.

$$h = (l_1 - l_1 cos\theta) + D_2 \quad (1)$$

$$w = l_1 \sin\theta + l_2 + d_{mm} \quad (2)$$

Using Equation 3, transformed from Equation 2, and conventional trigonometric equations, Equation 4 can be achieved.

$$\frac{w - l_2 - d_{mm}}{l_1} = \sin\theta \quad (3)$$

$$\sqrt{1 - \left(\frac{w - l_2 - d_{mm}}{l_1}\right)^2} = \cos\theta \quad (0 \le \theta \le 90°) \quad (4)$$

Substitute Equation 4 into Equation 1,

$$h = \left(l_1 - l_1\sqrt{1 - \left(\frac{w - l_2 - d_{mm}}{l_1}\right)^2}\right) + D_2 \quad (5)$$

The real dimension of PRIDE ($l_1 = 1378.8, l_2 = 183.5, D_1 = 654, D_2 = 1648$) and $D_{mm} = 500$ can be substituted in to Equation 5 and if h=1700, w can be achieved as follows.

$$w = 642.43mm$$

The overhang distance of MSM, D1=654 is added with w and finally, separation distance W can be deduced as follows.

$$W = w + D_1 = 642.43 + 654 = 1296.43$$
$$\cong 1300mm$$

Therefore, the considered equipment has to secure a distance of 1300 mm from the wall to perform the insertion and pulling out of the thermocouple, which has a length of 500 mm.

Manipulation Strategy of BDSM

The BDSM is designed to perform a task in the rear and upper side of the equipment against the window, where the MSM cannot reach. Therefore, the intuitiveness of the operation cannot be ensured, while the BDSM and operator face each other across the window because the operated arm of the BDSM is flipped against the master arm in the operator's view. Through a survey of many BDSM operators, this situation is extremely disadvantageous while performing a remote handling task.

With the mirrored-hands placement, the left hand of BDSM is at the right response location and right hand is at the left location. In such situations, responses are still faster when there is a direct correspondence between the BDSM and master locations, even though the opposing hand is used to make the response. However, the mirrored hands of BDSM have to be manipulated freely in that location, operator might be confused. Figure 6 show the utilization of an eye-in-hand camera to identify the target hole for the insertion of an electrode handled by the arm of the BDSM.

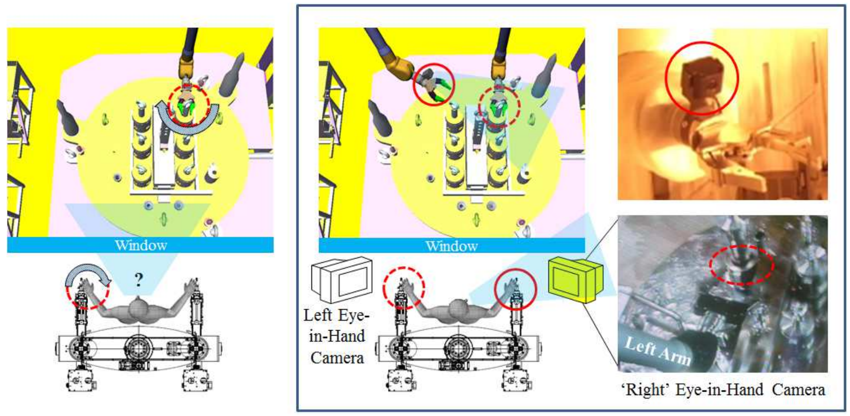

Figure 6 – Considered Operation Strategy for the Manipulation of BDSM using the Eye-in-Hand Camera of Grippers

EXPERIMENTAL SETUP FOR THE REMOTE HANDLING DEVICES

In the PRIDE cell, generally each type of manipulator is installed in the facility with a crane and hoist system. The hook module of a crane is frequently used to lift parts or entire systems out for repair or replacement. As shown in the left side of Figure 7, to manipulate the general hook of the manipulator, the operators have to perform an extreme pose with a manipulator while approaching the end of the hook to the target I-bolt because the hook is rotated entirely while holding the tail of the hook. Moreover, an unhooking task is harder than a hooking one because the snap of the hook has to be maintained in an unlocked position while separating the hook from the I-bolt using the gripper of the MSM remotely.

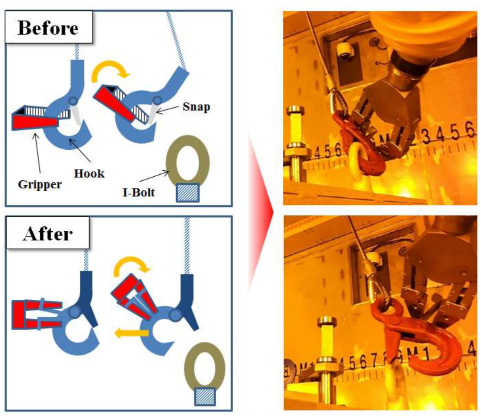

Figure 7 – Modified Design of the Hook

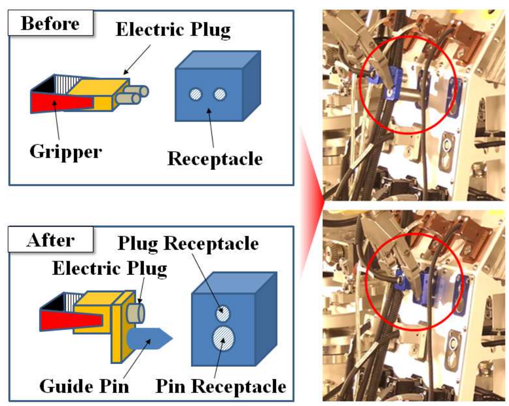

Figure 8 – Modified Design of the Plugging System

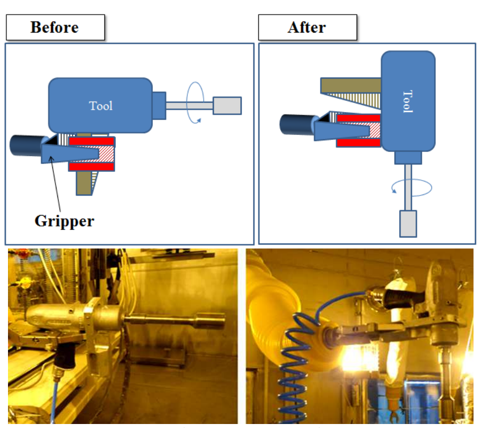

Figure 9 – Modified Design of the Tool System

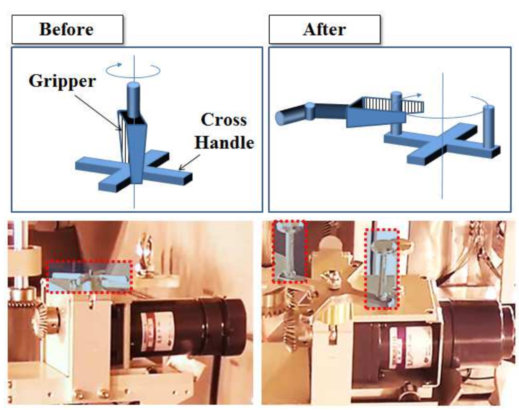

Figure 10 – Modified Design of the Cross Handle

A modified hook, however, is opened easily just by squeezing the grips connected with the stationary and the moving parts of standard clevis self-locking hook, respectively. Right side of Figure 7 shows the performance verification of the proposed hook module for practical equipment. A plugging task is another significant issue for remote handling of the processing equipment in the PRIDE facility. The formal plug module, however, is hard to handle and grip remotely because of its tiny size and, moreover, it is hard to recognize the hole of the receptacle matching the plug with a proper approach angle for the manipulator while holding the plug for insertion. To solve this problem, as shown in Figure 8, the plug is changed with a push-pull connector and a wedge-type guide pin is attached to the side of it. In Figure 9, after modification of a tool gripper, the tool gripped pose of the manipulator is fixed to maintain the normal position of the wrist while approaching the bolt vertically (the bolts mostly tighten along the vertical direction to the ground because the modules are ejected using the crane after releasing the bolts and the one belonging to the base frame works as a guide against the female module). Figure 10 shows the change of cross hand to allow for easy handling using remote manipulators. A rotating motion along the z-axis of the handle is one of the most difficult and inefficient motions for fastening and releasing the handle directly.

VERIFICATION OF REMOTE HANDLING PERFORMANCE

This section deals with an evaluation of the remote handling performance including maintenance tasks of the PRIDE facility. The most relevant quantifiable measures of performance for the applied manipulators are based on task completion time. Measure considered in this study is unit task time (time for elemental task components) which represents the time and accuracy of movement, instead of the performance measures of operator fatigues and ratio of task success which are difficult to quantify. Quantifying the performance measures of unit task time requires the task or a range of tasks be specified. The time required for units such as move, grasp, hook, and release is measured and plotted in Figure 13. The equipment of the PRIDE facility, which performs electro-reduction, electro-refining, electro-winning and salt waste treatment has commonly adapted motorized driving modules for their own moving parts. These parts are composed of motor, transmissions, and frames for support. Type 1 is connected along the horizontal direction along the guide slot, type 2 is connected along the vertical direction using gear jaw coupling and guide bar, type 3 is connected along the vertical direction using tapered gear jaw coupling and guide bar, type 4 is connected along the vertical direction using tapered gear jaw coupling and guide slot, respectively. (Figure 11)

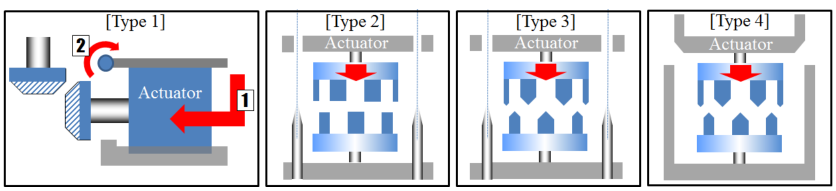

Figure 11 – Considered Type of Actuator Modules for the Remote Handling Task

Figure 12 and 13 shows the remote handling test results of four types of transmission modules of a motor driven system applied in the several kinds of processing facilities. For this test, an operator who has a middle-class operation skill is selected, and it is also assumed that his/her manipulation efficiency can be improved through the repetitive trial of inexperienced remote handling tasks. In the case of motor module type 1, reassembling the module requires a specified approach trajectory involving the vertical and horizontal directions. Therefore, the frequent intervention of the manipulator system is required while assembling the module into the target position remotely. Furthermore, the assembly position is far from the window, and the operator mostly had to use the eye-in-hand camera of the BDSM, and this condition leads to more time spent than for the similar task performed with the MSM near the window. The Motor Module type 2 can be handled easily for the bolt release, but hooking requires an unexpected working time because they did not use the modified hook dedicated to motion convenience of MSM (as shown in Figure 7). The task for the handling of motor module type 3 requires an extremely shorted time compared to type 1 because the module can be inserted into the target position using only a crane system. However, it was found that the arrangement of cables belonging to the motor module has to be improved to perform the assembly of the module easily. Type 4 spent the task time with cable arrangement and plugging. Based on the test result, it is found that the approaching direction of module and convenience of remote handling tools such as hook and connector are more important than mechanical treatment of gear jaw coupling.

Generally, positioning within a given tolerance in one dimension leaves the five remaining dimensions free, hence one degree of constraint. Fore examples, Inserting cylindrical electrode in a circular hole leaves the remaining four dimensions free, hence two degrees of constraint. A rectangular peg placed in a rectangular hole requires that three positions and two orientations be constrained, leaving only one degree of freedom. The tolerance in each degree of constraint can be used to specify the difficulty of the final positioning for insertions. The self-guiding feature of insertions with chamfers, for example, is required to compensate for manipulator characteristics such as backlash of each joint, rigidity or compliance of the remote unit and friction of remote unit between its counterparts.

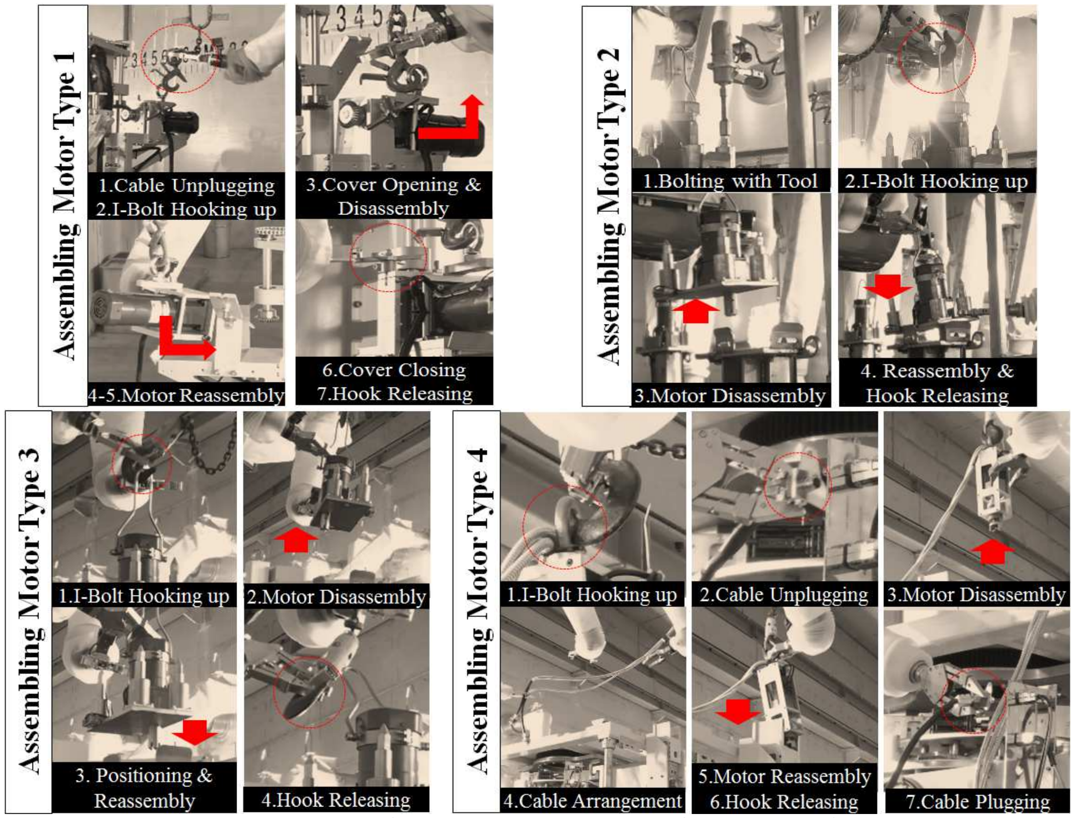

Figure 12 – Unit task of Module Replacement Task for each type of Module

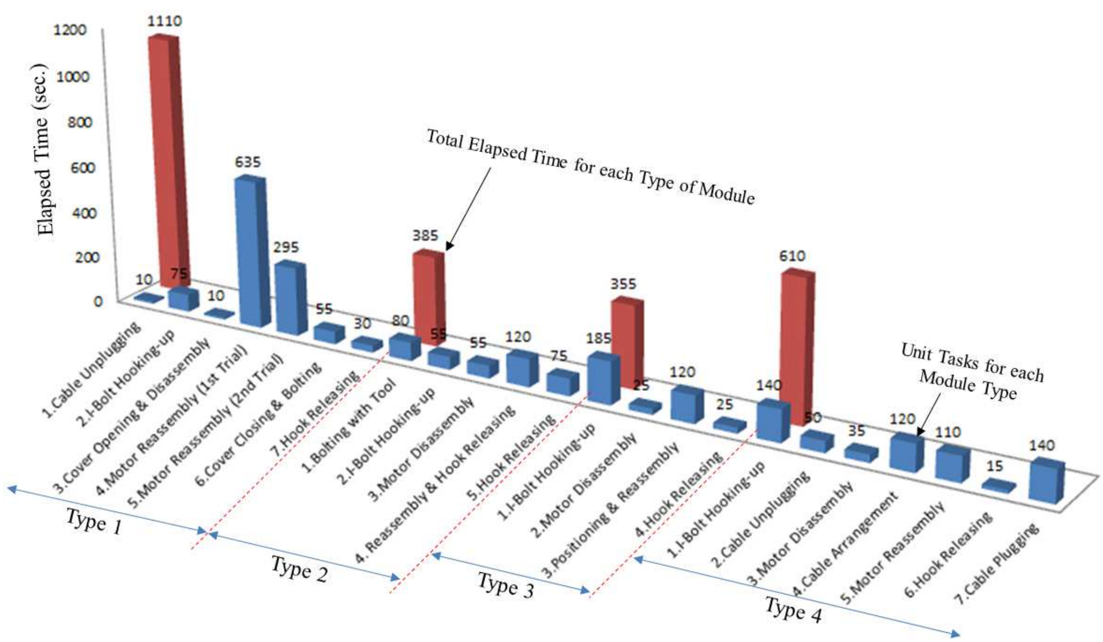

Figure 13 – Elapsed Time for Each Case of Remote Handling Task

CONCLUSION AND CONSIDERATIONS

This study analyzed remote handling tasks which were performed in the restricted cell facility of PRIDE. Generally, use of a remote manipulator system is a more complex and harder task than the normal hand-using task and to stabilize the performance of remote handling devices, repetitive test and evaluation of entire system are required. The following comments are about the additional results deduced from the practical test of the remote handling system considered.

1. MSM can be manipulated intuitively because of its hanging orientation near a window. But the main task performed by the manipulator is restricted to a low-payload job, such as picking, clicking, tooling, and hooking by using the crane and hoist system while lifting the weighted materials. In this study, two kinds of remote handling manipulator are applied and distributed the role of each manipulator based on the characteristics of remote handling tasks.
2. To avoid the extreme pose while performing a remote handling task, positioning of equipment and the assembling type of parts have to be modified. Additionally, the handling manner of tools for remote manipulator has to be designed by considering not only the basic normal hand-using task but also a lightened and shock-absorbed tooling system.
3. If the position of the remote handling system is hard to match with the master device, peripheral cameras can be utilized to acquire the intuitive visibility.
4. The handling trajectory of the assembly module tries to match with the vertical direction to utilize the crane and hoist system.

As a future work, user-friendly design for servo-type manipulator system (BDSM) cooperated with MSM will be considered. Current system is operated using multiple control devices of a master for slave arm and control device for the bridge transported system combined with slave arm, and controller for a 500kgf hoist system and monitoring cameras respectively. Even the controllers for each type of device are integrated into all-in-one hand-held device, it has to be handled with the master system simultaneously when performing the practical remote handling task. In the future work, a hands-free type controller device is proposed based on the ergonomic analysis for the operator of remote handling system including a heads-up display adapted on top of the master device instead of a knee-high mount of current position as shown in Figure 14.

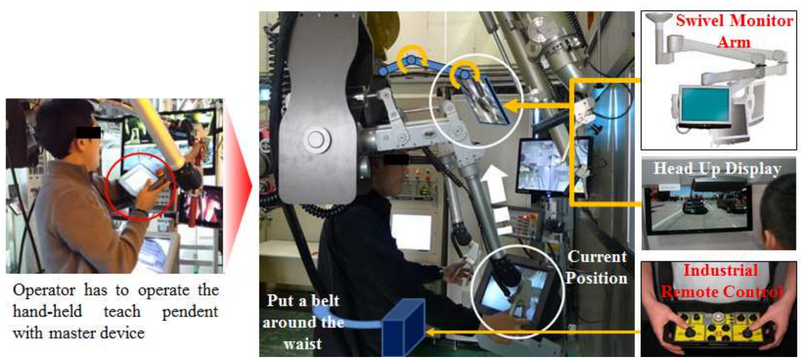

Figure 14 – Proposal of the Integration of the Control Monitoring Devices with the Master System

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