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ERGONOMIC ANALYSIS OF A TELEMANIPULATION TECHNIQUE FOR A PYROPROCESS DEMONSTRATION FACILITY

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In this study, remote handling strategies for a large-scale argon cell facility were considered. The suggested strategies were evaluated by several types of field test. The teleoperation tasks were performed using a developed remote handling system, which enabled traveling over entire cell area using a bridge transport system. Each arm of the system had six DOFs (degrees of freedom), and the bridge transport system had four DOFs. However, despite the dexterous manipulators and redundant monitoring system, many operators, including professionals, experienced difficulties in operating the remote handling system. This was because of the lack of a strategy for handling the installed camera system, and the difficulty in recognizing the gripper pose, which might fall outside the FOV (field of vision) of the system during teleoperation. Hence, in this paper, several considerations for the remote handling tasks performed in the target facility were discussed, and the tasks were analyzed based on ergonomic factors such as the workload. Toward the development of a successful operation strategy, several ergonomic issues, such as active/passive view of the remote handling system, eye/hand alignment, and FOV were considered. Furthermore, using the method for classifying remote handling tasks, several unit tasks were defined and evaluated.

KEYWORDS : Teleoperation, Telemanipulator, Remote Handling System, Ergonomic Analysis, Telepresence, Pyroprocessing

1. INTRODUCTION

Teleoperation is the performance of a task or action from a distance. Although, in this sense, teleoperation can be applied to any operation performed from a distance, the term is most commonly associated with robotics and mobile robots and indicates the operation of such machines from a place far from the location of the machine [1]. Several factors are involved in a teleoperated robotic system, including human-machine interaction, bilateral control strategy, signal transmission, and virtual reality and augmented reality (VR and AR). The areas in which such systems are applied are extremely diverse, and teleoperation promises to be useful in the efficient accomplishment of the pertinent tasks. Many types of remote manipulators have been developed with the purpose of executing the handling tasks in a cell, and teleoperation systems that use such manipulators are known to be reliable and to reduce hazardous exposure, for example, to radiation [2-3]. The technology is considered as a solution to some dangerous tasks in the nuclear industry, for example, the dismantling of outworn equipment and management of a nuclear reactor core [4].

In this study, a remote handling manipulator was used to operate and manage equipment installed in an argon cell facility for a pyroprocess demonstration. This type of manipulator is generally composed of a master-slave system with a simple mechanical structure that enhances operability. The particular remote manipulator systems examined in this study are a mechanical master-slave system (MSM) developed by HWM Ltd. in Germany, and a bridge-transported dual arm servo manipulator (BDSM) system developed by KAERI in Korea [5–6]. The developed remote handling system uses servo-driven actuators and travels over the entire cell area using a bridge transport system. However, despite the dexterous manipulators and redundant monitoring system, many operators, including professionals, experience difficulty operating this type of remote handling system. This is because of the lack of a strategy for handling the installed camera system, and the difficulty of recognizing the gripper pose, which may fall outside the field of vision (FOV) of the system during the performance of a remote handling task. In this study, we considered the following four strategic issues of teleoperation:

- Estimation of distance between manipulator and object.
- Alignment of the eye and hand coordinates.
- Alternation between visual servoing and force feedback strategy
- Necessity of 3D vision system for the remote handling task

To address the first and second issues, we apply an active view strategy using an eye-in-hand (EIH) camera. An EIH camera is widely used in remote handling systems. The main interest of this study was the suggestion of a practical strategy for the camera system involving the cooperative use of both arms based on ergonomic analysis. We developed various strategies for using the EIH camera from first, second, and third person points of view (FPV, SPV, and TPV), respectively. These are discussed with some detail in the following sections. In previous work, we proposed a modified remote handling tool and equipment to improve the efficiency of the operator based on ergonomic factors [7]. In this study, which is an extension of the previous study, we propose strategies for handling a manipulator. Furthermore, we evaluated the operation efficiency when the proposed remote handling device and manipulation strategies were applied to current pyroprocessing equipment, and examined how to find the effective workload for teleoperation explicitly.

2. SYSTEM CONFIGURATIONS

Fig. 1 and 2 illustrate the configurations of the processing equipment and teleoperation system of the considered pyroprocessing demonstration facility. A BDSM is a servo-control-based manipulator system that includes two arms with six degrees of freedom (DOFs) for each extremity and a telescopic-type transportation system with two arms underneath.

An MSM has two arms with six DOFs and is operated through a master device located outside the cell. The master and slave system are directly connected to each other through a wall tube, which allows users to operate the system intuitively. Generally, an MSM and a BDSM can be operated through window vision (WV) and additional remote vision, respectively. An MSM not only allows the application of forces equivalent to those that an unaided operator would apply, but also slightly larger forces by the motorized joints. Such systems are suitable for frequent and low-payload tasks performed near the inside wall, and are generally installed in pairs. Owing to its mobility, a BDSM enables the performance of complicated tasks throughout the entire volume of large cells, not only near the operation walls. Its load capacity also allows its use instead of other similar light- and medium-load manipulators, such as those shown in Fig. 2. Each arm of a BDSM has a load capacity of about 25 kgf.

3. TELEOPERATION STRATEGIES FOR REMOTE HANDLING TASKS IN THE "PRIDE" FACILITY

3.1 Distance Estimation through the Monitor

The connection between perception and action is weakened during teleoperation because the manipulator is controlled remotely by an operator without the perceptual information that one typically receives directly from the environment. It was concluded from a previous study that the subjects underestimated distances to objects in both real and virtual environments; however, the underestimation was significantly greater in virtual environments [11]. The reason for the increased underestimation in a virtual environment is the lack of cues. Fig. 3 shows the example of the different aspects of distance perception when using an EIH camera of the considered teleoperation system.

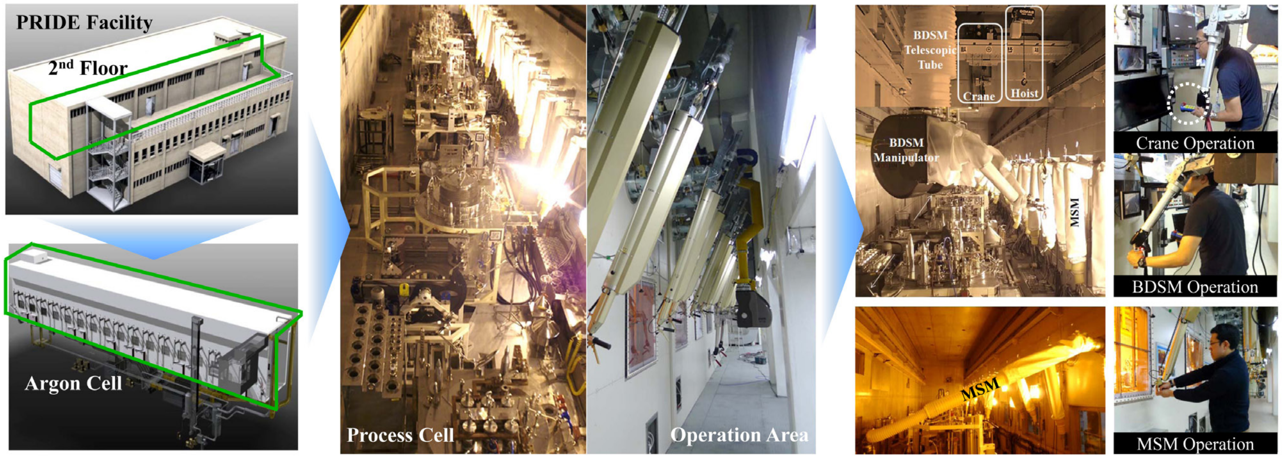


Fig. 1. Operation (Outer Side) and Process (Inner Side) Areas of the Pyroprocessing Facility known as "PRIDE (PyRoprocess Integrated Inactive Demonstration Facility)" [8-9]

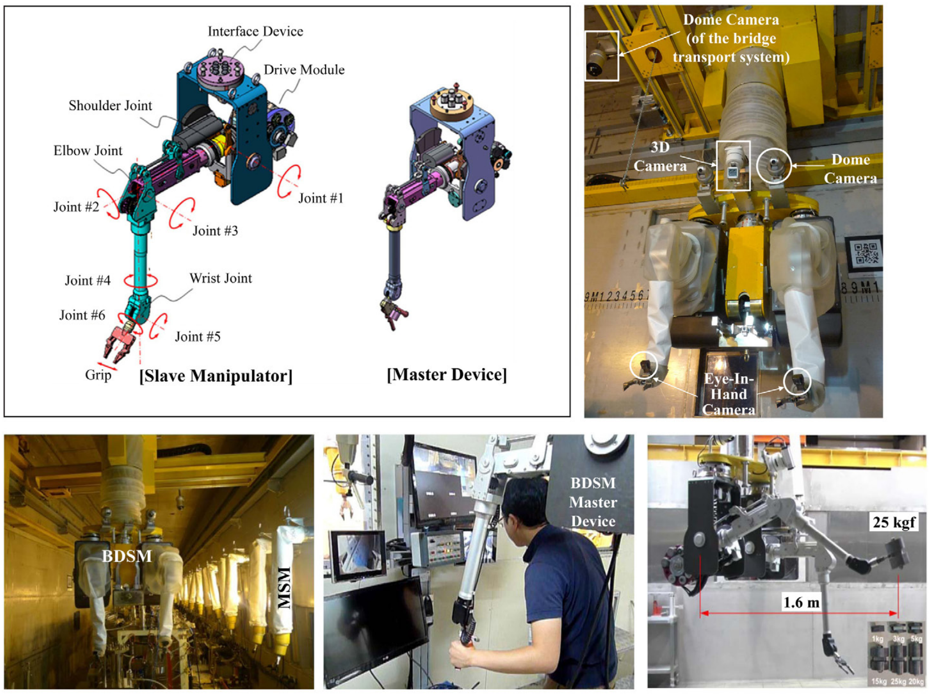


Fig. 2. Considered Camera Modules and Master-Slave System of BDSM [10]

In a real situation, motion parallax and a wider field of view (FOV), which are both obtained from additional textural information, enable more accurate depth perception. The problems of spatial perception during teleoperation occur for many of the same reasons as those encountered in virtual environments. The problems that arise during teleoperation are partially due to the reduced ability to appropriately scale objects, which is known as scale ambiguities [12]. The scale ambiguities are partly due to the fact that the video feed is a 2D representation of a 3D space, which compresses the depth of the environment. Placing the camera closer to the base worsens the quality of the compressed image [13]. Practical experience has shown that operators have difficulty in perceiving some aspects of a remotely operated manipulator and their environments [12, 14, 15]. Previous research has also shown that movement of the head facilitates depth perception [16]. Three experiments were used to develop a method for improving depth perception, wherein subjects watched remote targets using a moving camera. The camera was mounted on a teleoperated manipulator, which oscillated toward and away from white squares placed in a black space, thereby expanding and contracting the targets on a video monitor. The subjects watched the expansion and contraction and guessed the distance between the remote camera and the targets. Using different experimental conditions, the movements of the remote arm of the camera were coupled with those of the head of the subjects, and were controlled by a joystick to follow a set of preprogrammed oscillatory motions. Under each of these conditions, the subjects' judgments of the distance varied semantically with the actual target distances. A third experiment was conducted to demonstrate that the use of well-known objects and provision of feedback was an effective strategy for teleoperation training. This was also successfully applied to a condition in which unknown targets were used and distance feedback was not provided. The results indicated that the use of the radial outflow produced by active or passive front-to-back camera motions and training using familiar objects may be effective strategies for improving depth perception during teleoperation [17]. Fig. 4 illustrates the distance perception training for the use of a teleoperation manipulator and its EIH camera system. Iterative performance of the following several steps of gazing at a wall was used for operator training in this study.

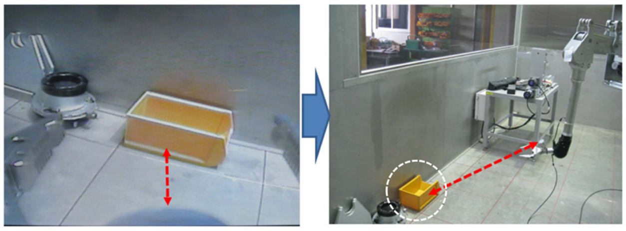


Fig. 3. Different Aspects of Distance Perception when using an EIH Camera to View an Object

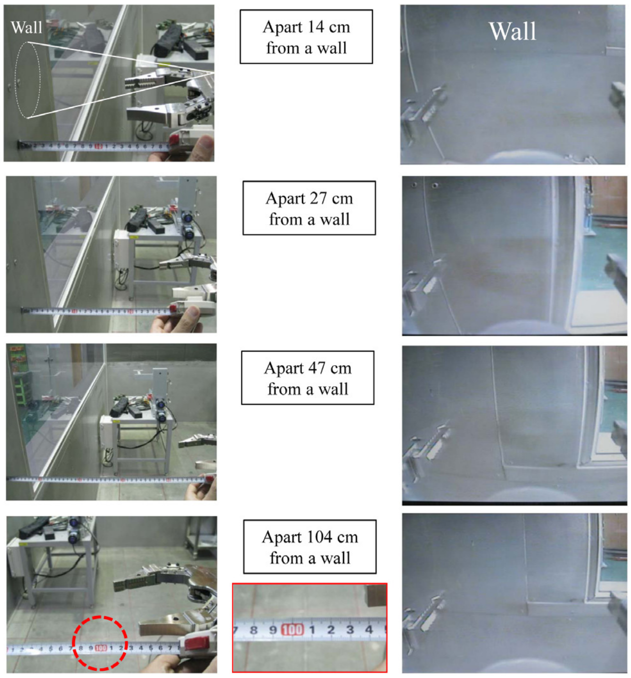


Fig. 4. Four Steps of Distance Perception through an EIH Camera

3.2 Application of Active View to an EIH Camera

The position of the gripper in a cell is largely determined by the perception of continuous texture gradients in the environment. Every visible surface is textured and the inherent coarseness results in the non-uniform reflection of light. The texture gradients depend on the point of view of the operator, with the texture appearing coarser when the surface is closer. A restricted field of view does not allow for continuous texture gradients[18]. According to a previous study, the optic flow patterns in the retinal picture in the human eye are an essential cue for spatial perception in daily life [19]. To obtain a spatial impression of the manipulator environment, the operator utilizes the flow patterns in the end-effector camera picture (i.e., the movements of the target and the other visible objects in the picture) in a similar way. In the display, the presence of textured spatial objects facilitates clearer motion perspective, and manipulation is a lot easier when one can see their hand(s). To manipulate the remote handling system, the operator does not need to wear any special devices, which ensures the operator has complete freedom, although some parts of the slave's arm may easily fall outside the field of vision of the system, which makes recognition of the arm pose through images a difficult task. Although additional visual information from additional passive view cameras would help the operator to realize how stable their remote grasp is, they can only confirm the effectiveness of a very simple grasp. A TPV strategy is thus necessary to facilitate the concentration of the operator on the performed task. The ability of active observation to see other parts of the body enhances orientation skills and the feeling of telepresence in vision systems.

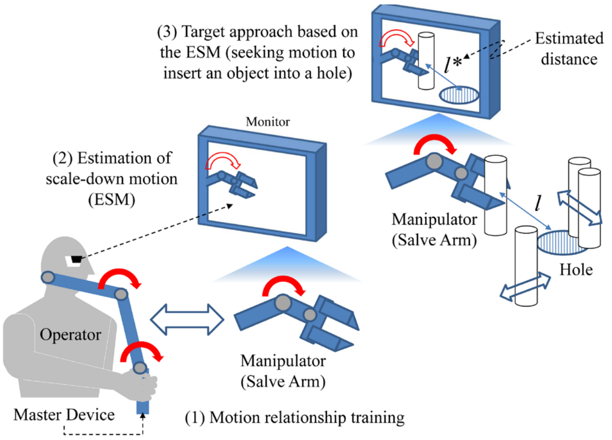


Fig. 5. Estimation of Manipulator Motion Displayed on a Different Scale

As shown in Fig. 5, the operator has to learn the ability of the estimation of the manipulator motion displayed on a different scale to prevent the misperceive of the actual distance between the manipulator and the object. Therefore, the operator needs to become familiar with the displayed motion of slave arm performed by the master as a different scale. Although additional sensors such as a laser sensor for detecting distance can be installed on the hand of the manipulator, additional cabling and installation space for that device are required. Based on the findings of a previous study, the display of additional information on the screen such as angular posture, remained distance might be useless, especially while performing a precision task using an EIH camera, because of the limited FOV of the operator [20].

Figs. 6–8 illustrate the successful operation of the remote handling system for tasks frequently performed in the PRIDE cell using only an EIH camera. In this study, the point of view of the EIH camera of the gripper used to hold an object is defined as the FPV; the point of view of the grippers facing the gripper holding the object is defined as the SPV; and the point of view of the gripper that is not involved with the other grippers but freely watches the site is the TPV. Fig. 9 describes the typical procedure for performing the task for handing over a tool using an EIH camera, and Fig. 10 describes the filter repair task. This filter system is located at a corner of the PRIDE cell and a large transfer lock blocks the window view of the operator. The operator can therefore approach the body of the BDSM near the target site using the window view, and the remaining repair tasks are performed using only an EIH camera.

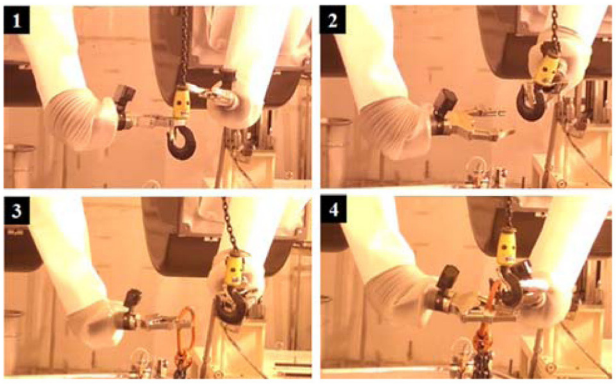


Fig. 6. Remote Handling Task using EIH Camera: Handing Over of Hoist Hook and Hooking Task: (1) Grasping the Hook (Right Gripper), (2) Handing Over the Hook to Another Gripper (using FPV and SPV), (3) Approach to the Hoist Sling (Left Gripper: Holding Position, Right Gripper: SPV), (4) Hooking to the Hoist Sling

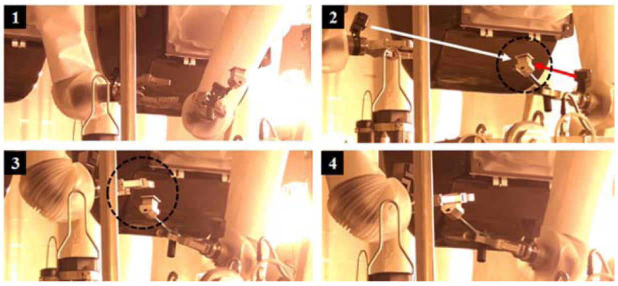


Fig. 7. Remote Handling Task using an EIH Camera: Handing Over a Fastening Tool: (1) Initial Position, (2) Aligning the Grippers (Left Gripper: FPV, Right Gripper: SPV), (3) Moving the Grippers to Grip a Wrench (Left Gripper: FPV, Right Gripper: SPV), (4) Grasping the Wrench

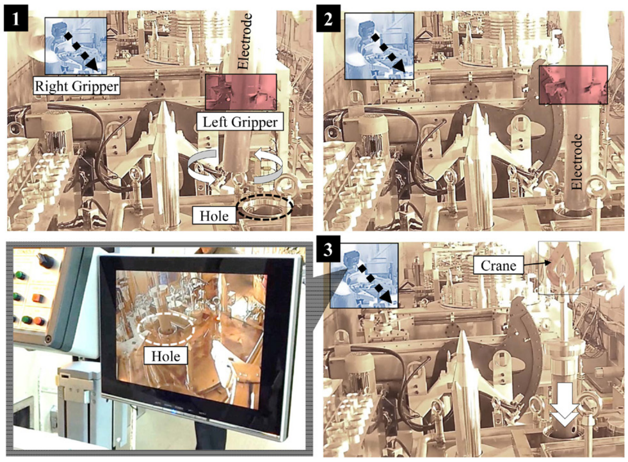


Fig. 8. Remote Handling Task using an EIH: Electrode Handling and Insertion Task: (1) Viewing the Target Position by the EIH Camera of the Right Gripper, while Holding an Electrode by the Left Gripper (the TPV of the Right EIH Camera Guides the Left Gripper), (2) Manipulating the Left Gripper and Engaging the Electrode with the Target Hole, (3) Releasing the Gripper and Inserting the Extruded Part into the Hole

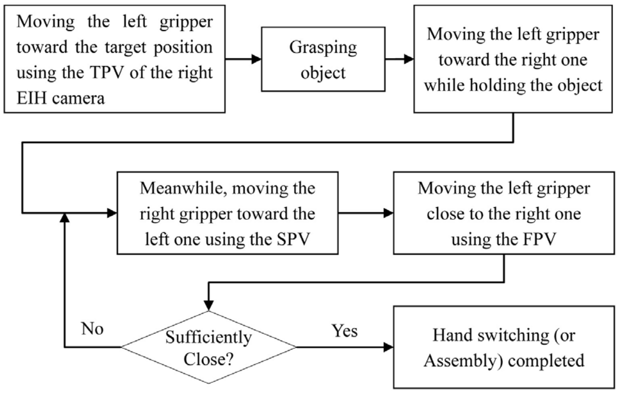
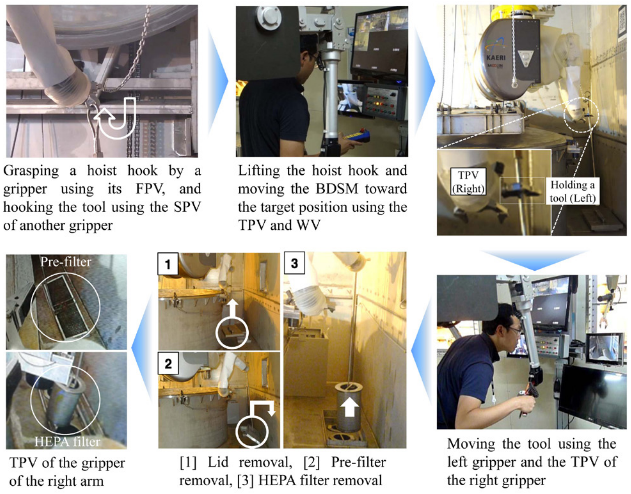


Fig. 9. Procedure for the Handing Over Task using an EIH Camera



Grasping a hoist hook by a gripper using its FPV, and hooking the tool using the SPV of another gripper

Lifting the hoist hook and moving the BDSM toward the target position using the TPV and WV

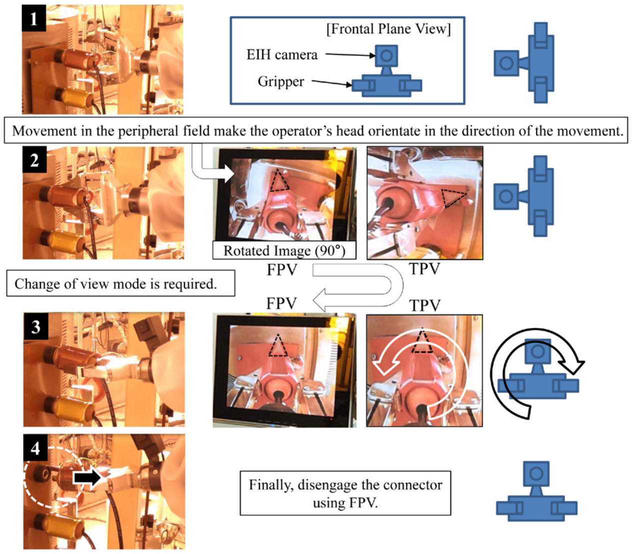
TPV of the gripper of the right arm

[1] Lid removal, [2] Pre-filter removal, [3] HEPA filter removal

Moving the tool using the left gripper and the TPV of the right gripper

Fig. 10. Filter Repair Task using an EIH Camera

Humans have both central and peripheral vision. A movement in the peripheral field prompts reorientation of the head in the direction of the movement. The central field is more sensitive for the detection of details and acuity, whereas the peripheral field is more sensitive to movement and potential danger. The latter also facilitates orientation and perception of self-motion [18, 21]. Fig. 11 illustrates a practical case of the foregoing. At the end of the positioning task, hardly any spatial cues are present in the camera picture of the end-effector. This resulted in decreased spatial awareness in the experiments because the subject had to intermittently turn their eyes to the display of the SPV or TPV to determine the remaining distance between the end-effector and the target. Furthermore, while inserting the object to the counterpart using the gripper, the operator has to watch the rotated display of the FPV of the twisting motion of the object. It has been observed by repetitive tests that, in this kind of situ-

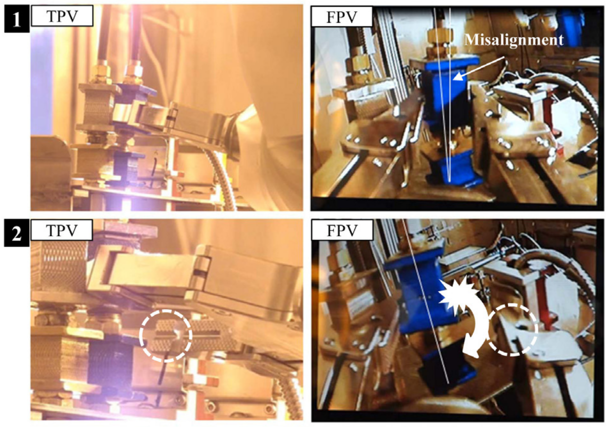


Movement in the peripheral field make the operator’s head orientate in the direction of the movement.

Change of view mode is required.

Finally, disengage the connector using FPV.

Fig. 11. Rotation of Peripheral Field of View in FPV



Connection is completed but the gripper loses the grip of a connector

Fig. 12. Hand/eye Coordination Experiment for Inserting Connector by the BDSM and its EIH Camera

ation, a movement in the peripheral field causes one to orientate the head in the direction of the movement. The operator therefore needs to first use the FPV to align the imaginary coordinates of the gripper and the object. If the gripper is initially approached, and then use the TPV to grasp the object, rotate the wrist of the gripper and disengage the object sequentially as shown in Fig. 11.

3.3 Alignment of the Eye and Hand Coordinates

Lack of tactile and touch information results in mismatch of proprioceptive feedback. The major drawback of current remote manipulation systems is that their teleoperation is slow and imprecise, despite the many years of manipulator development. This has been practically confirmed by a teleoperated manipulator system [22]. Despite significant improvement in the performance of the manipulator handling system and methodology, it was observed that most of the operation time was spent on alignment procedures, with the remaining time used to perform the actual handling operations. In addition, because the operation of the manipulator depends solely on the operator’s perception-action link, precise motions are achieved by the servo manipulator, and programmed control and motion strategy are extremely difficult to implement under the teleoperation condition. Another case study was used to suggest an online alignment strategy for the hand of the manipulators using a vision algorithm, which might enhance eye/hand alignment. The study was, however, limited to a facility with a simple shape [22].

Fig. 12 shows an example of misalignment of the coordinates of the hand of the manipulator and eye of the operator. Consideration of the angle of misalignment between the visual and vestibular reference frames is important because Under the remote handling situation, operators have to depend on the remote camera only, and small misalignment in the first step would make the larger problem in the last step such as jamming while inserting the connector into the counterpart, because the operator could acquire only narrow vision from monitor display and it is hard to take a view of entire situation of the handling object. The assumption is that the performance of a hand/eye coordination task is improved when the cameras, monitor, and hand are aligned with the visual and vestibular reference frames of the human operator [23]. Fig. 13 shows the reference frames of each component of the remote handling system. Based on an awareness of the hand, visual and display reference frames, the operator can precisely and remotely move the gripper even though the angle of the camera reference frame is inclined downward by 20°, as shown in the bottom-right corner of Fig. 13.

The collected data supported the hypothesis that the precision of a hand/eye coordination task is improved by placing the object in the field of stereo acuity and the reference frame of the body of the operator. This was quantitatively exhibited by the improved speed, positioning accuracy, and reduced incidence of errors. Qualitatively, all the subjects agreed that proper alignment of the reference frames and the use of stereo vision reduced the amount of training required, and also improved confidence while reducing physical and mental fatigue. These results show that significant performance improvement can be achieved in many teleoperation applications through the use of stereo vision, or at least by providing a full-size 2D image aligned with the axes of the hand controller [23]. However, there is also a drawback of the application of stereo vision to precise remote handling tasks if that vision system could serve the passive view only. This is discussed in the next section.

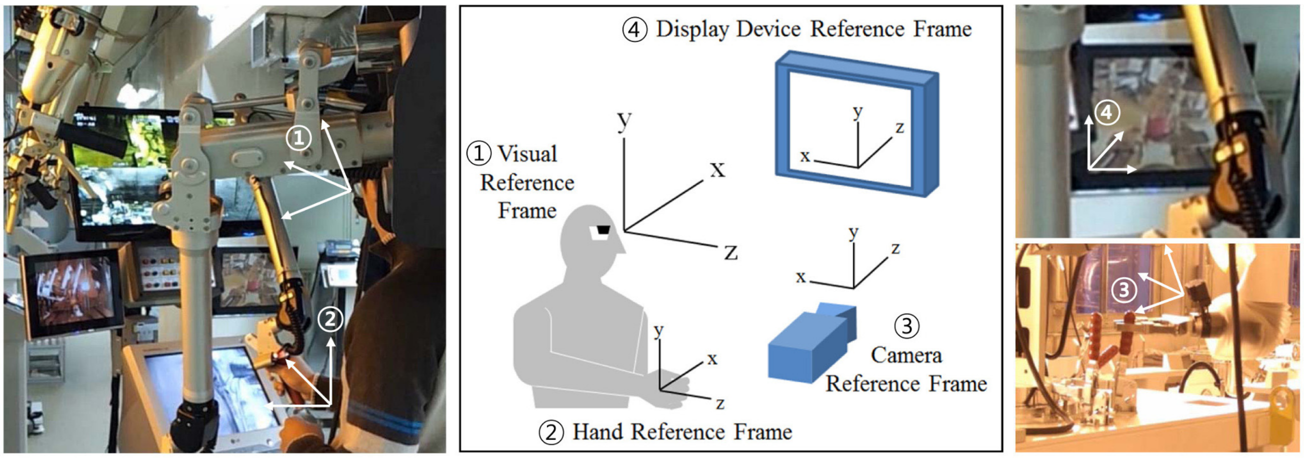


Fig. 13. Hand/eye Coordination for using the Remote Handling System

3.4 Necessity of Force Feedback and 3D Display

Force feedback is sometimes incorporated in assembly and material handling systems. It is, however, sometimes difficult to utilize because of the instabilities that arise when contact is made, and the uncertainty that characterizes the transmission of the signals of the force/torque sensors. This has limited its use, even in an industrial area. Other types of sensors may be used for assembly in conjunction with force sensors to overcome the problems associated with force feedback. Tactile sensor technology is well-developed and have been successfully applied in assembly systems. Tactile sensors are, however, also prone to many of the problems of force sensors because the feedback is localized and noise often makes it difficult to distinguish the information produced by the sensor [24]. In this context, the requirement for the force reflection effect can be minimized. Draper et al. found that force reflection did not always enhance the efficiency of performance of representative nuclear industry remote handling tasks, but only enhanced the effect of the moderating forces applied by master device to operators to reduce the number of errors committed [25, 26]. Similarly, Experience in the use of PRIDE results in force reflection becoming less critical, and it can be decreased or inactivated. Moreover, the peg-in-hole problem can be minimized by modification of the tolerance of the mechanical parts or by using a guide bar to place or assembly the part through exact alignment of the axis. Actually, These alternative tasks have been successfully performed in the PRIDE facility using only the EIH camera.

In this respect, the necessity of a 3D camera system can be reconsidered. Despite the improved spatial awareness of the operators, they commented that the usefulness of the 3D vision system for the end-effector positioning task of the BDSM was not clear. This tendency was more pronounced when the vision-target was viewed from a farther distance. Moreover, no exact additional information about the translation and rotation misfits in specific directions was provided. That is, the reason why the EIH camera is required for the precise work of the end-effector. Based on operator opinion, an active view produced by a low-definition camera seems to be more effective than a passive view produced by a high-resolution 3D camera. The proposed 3D system can be achieved using exclusive glasses. Fig. 14 shows the FPV of one eye of the glasses of the 3D vision system display. Although it is difficult to present the real 3D display in this paper, it is obvious that a full-HD 3D vision system gives a clear perspective view of the target system. However, the most significant problem of the system is the absence of an active view that the operator can freely manipulate. The 3D vision system of the BDSM has self-motion capabilities such as pan, tilt, and zoom, but the system still only affords passive view because the base frame of the camera is fixed on the BDSM, which hinders dexterous manipulation. For the same reason, the other cameras of the BDSM can-

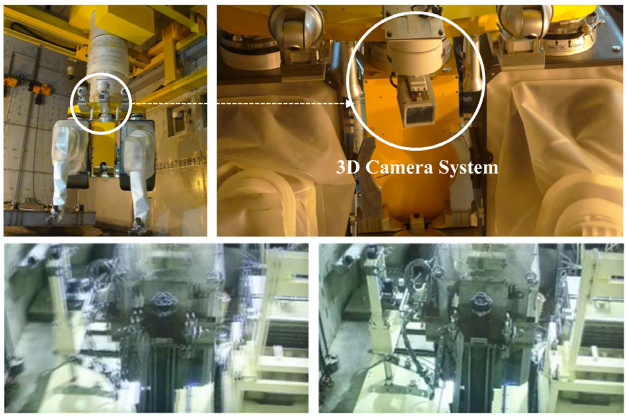


Fig. 14. 3D Vision System of the BDSM and the FPV before and after using the Glasses for the Display of the 3D Vision System

not be easily used frequently while performing a remote handling task using the manipulator. This is the reason why the BDSM requires an additional EIH camera on the distal grippers.

We concluded that it would be difficult to efficiently use any built-in camera system on the body of the manipulator for material handling tasks if the camera cannot provide an active view, even if it is of high resolution and has self-motion capabilities. This issue can be explained based on the operation characteristic of the BDSM. Common BDSM operators tend to watch one (or maximum of two) main display systems when performing a manipulator handling task. Although it can be expected that redundant vision would be generally beneficial to an operator, most operators can perform most aspects of a remote handling task using just one passive view (or window vision) and one or two active views (the BDSM system has a seven-camera system on its body). Furthermore, more important than the number of cameras is the perceptive movement of parts of the body of the operator, such as the arm and hand. It has indeed been observed that Softenon children have severe 3D perception problems, which is considered to be due to the unavailability of arm manipulation and absence of the hand as a reference frame for recognizing neighboring circumstances. It is important to note here that the learning process is significantly improved when more than one modality is used to display the visual information [27]. In this respect, manipulation training through the display could be helpful to the improvement of the above mentioned abilities, such as the estimation of manipulator motion displayed on a different scale and the alignment of the eye-hand coordinates.

4. WORKLOAD ANALYSIS OF PYROPROCESSING EQUIPMENT

Based on the abovementioned ergonomic considerations, we suggest seven unit tasks for the performance of a remote handling task in PRIDE, namely, bolting (BT), move/turn (MT), apply pressure/crank (APC), hook (HK), grasp/contact (GC), and insert/disengage (IS/DI) as shown in Table 1 and 2. The target systems are the equipment installed in PRIDE for the entire process, which ranges from electro-reduction to waste salt treatment. Both the specified process and configuration of all the equipment were obtained from [4]. The tasks considered in this study were those required for repairing all the equipment. Table 3 shows the determined workload scores for each unit task to evaluate the workload for candidate equipment. These criteria were applied to the unit tasks of the target equipment based on the required handling tasks. The workloads deduced from the multiplication of frequencies by the normalized workload scores of the individual equipment. Finally, experimental test for the practical processing equipment were performed and Table 4 is the tabulation of the acquired data for each equipment.

Table 1. Unit Task for Target Equipment

#.	Unit Task	Description	Frequently Used Manipulator
1	Bolting (using impact wrench)	Fasten (or release) the bolt on the equipment using an impact wrench.	MSM
2	Move/turn	Transport the end-effector some distance from the original position and rotate it about the primary axis of the forearm.	MSM
3	Apply pressure/crank	Apply force to overcome the resistance using negligible movement and follow a constrained circular path by pivoting the elbow of the manipulator.	MSM, BDSM
4	Hook/unhook	Hook (or unhook) the hook of a hoist to the target i-bolt, clevis, shackle, etc.	MSM, BDSM
5	Grasp/contact	Close and hold the end-effector to secure the object and ensure contact with the surface of the equipment, tool, switch, etc.	MSM
6	Insert, insert supporting/disengage, disengage supporting	Engage (or reverse insert) two objects in the end-effector within the tolerance	MSM, BDSM

Table 2. Unit Task used to Evaluate the Remote Handling of Pyroprocessing Equipment

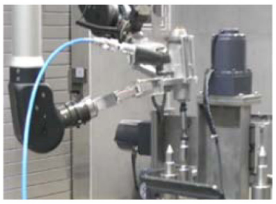
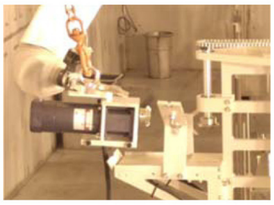
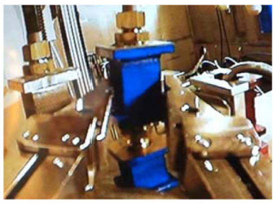
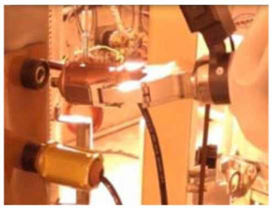
		
Bolting (using impact wrench, BT)	Move/turn (MT)	Apply pressure/crank (APC)
		
Hook/unhook (HK)	Grasp/contact (GC)	Insert/disengage (IS/DI)

Table 3. Typical Load Factors of the Designated Tasks for the Remote Handling of the Target Facilities

Unit Task (Required view) *: use if necessary	Scores of Workload Factors			Sum of Workload Scores
	Physical Load		Mental Load	
	High DOF Motion : 1	High Intensive Strength : 2	High Concentration : 3	
BT (TPV)	-	●	-	2
MT (TPV)	-	●	-	2
APC (FPV, TPV)	●	-	●	4
HK (FPV, SPV, TPV)	●	-	●	4
GC (FPV, TPV)	●	●	●	6
IS (TPV, FPV*)	-	-	●	3
DI (TPV, FPV*)	●	-	-	1

Table 4. Frequencies and Workloads of the Designated Tasks for the Target Facilities
(Workload = frequency × normalized value of the typical load factor, "-": Not applicable)

Facility / Unit Task	Frequency/Work Load							
	1	2	3	4	5	6	7	8
	ERD/CP	ERF	ST	SD	RAR/ LCC	CD	LCSD	WST
BT	7/0.636	-	11/1	-	-	-	-	2/0.182
MT	-	-	10/0.909	2/0.182	3/0.273	-	6/0.545	2/0.182
APC	3/0.545	1/0.182	9/1.636	1/0.182	1/0.182	-	5/0.909	-
HK	48/8.727	4/0.727	9/1.636	6/1.091	2/0.364	12/2.182	6/1.091	4/0.727
GC	17/4.636	10/2.727	-	-	24/6.545	-	2/0.545	-
IS	42/1.909	-	1/0.045	-	1/0.045	-	-	3/0.136
DI	22/3	1/0.136	1/0.136	-	7/0.954	1/0.136	-	2/0.273

- ERD: Electrolytic reducer, CP: Cathode processor, ERF: Electrorefiner, ST: Salt transport system, SD: Salt distillation equipment, RAR: Residual actinides recovery process equipment, LCC: Liquid cadmium cathode electro-winning equipment, CD: Cadmium distillation equipment , LCSD: Layer crystallization and solid LiCl detachment equipment, WST: Waste salt treatment equipment [4]

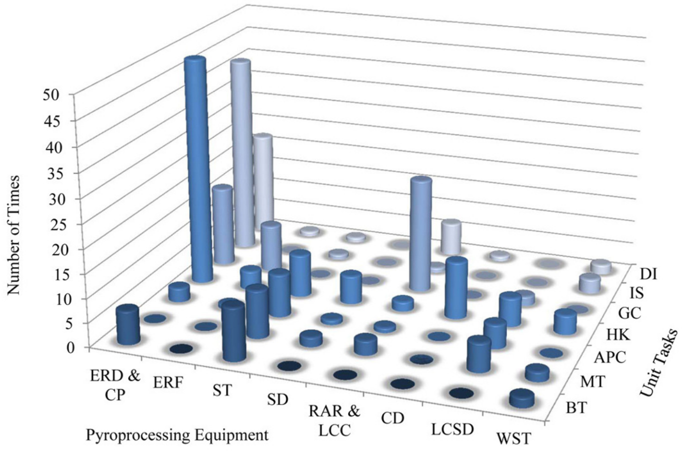


Fig. 15. Number of Times (Frequencies) of the Required Tasks are Carried out for Each Equipment during the One-cycle Operation

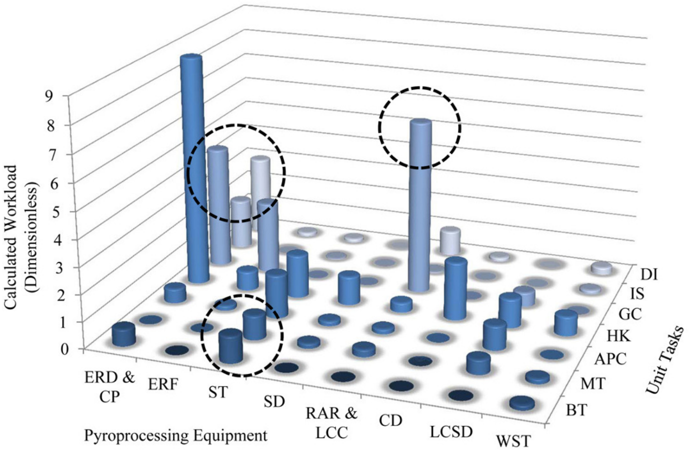


Fig. 16. Calculated Workloads of the Required Tasks for Each Equipment during the One-cycle Operation

Number of times of the required tasks plotted in Fig. 15. As shown in the figure, all the equipment have a specified combination of typical unit tasks based on the material handling characteristics of each equipment. Fig. 16 shows the data when the weight factors of the normalized workload score are applied. Compared to Fig. 15, there is a tendency for the value for each piece of equipment to change as dashed circles. The practical requirements for improving a system from an ergonomic perspective can be determined from these data.

5. DISCUSSIONS

In this section, we discuss and analyze cases of the current operating system. The entire operating system consists of a master and many other control devices, including those of the bridge transportation system, the 370-kgf hoisting system, and the monitoring systems. A monitoring system is comprised of devices for monitoring the EIH camera, a head-mounted 3D camera, shoulder-mounted cameras of the BDSM, and dome cameras mounted on the girder of the crane system as shown in Fig. 2. The crane control device is hand-held and must thus be simultaneously operated with the master device. By field testing, it was determined that a hands-free device was required because both hands of the operator were used to operate the master device. Although the hand-held control device can be operated by a cooperating operator, the two-way communication required for a specific task obstructs the efficiency and performance of the target task. Moreover, although a button-on-grip approach may be adopted, it would be difficult to achieve intuitiveness in the control of the button on the grip of the master device if the pose of the master changes with that of the slave. This is because it would be difficult to recognize the button that matches the direction of the movement. Additionally, to minimize distraction, a heads-up display can be installed on top of the master device instead of a display system mounted on the movable display stand at knee height. The ergonomic benefits of the suggested modified display and control devices shown in Fig. 17 will be evaluated in future work. This

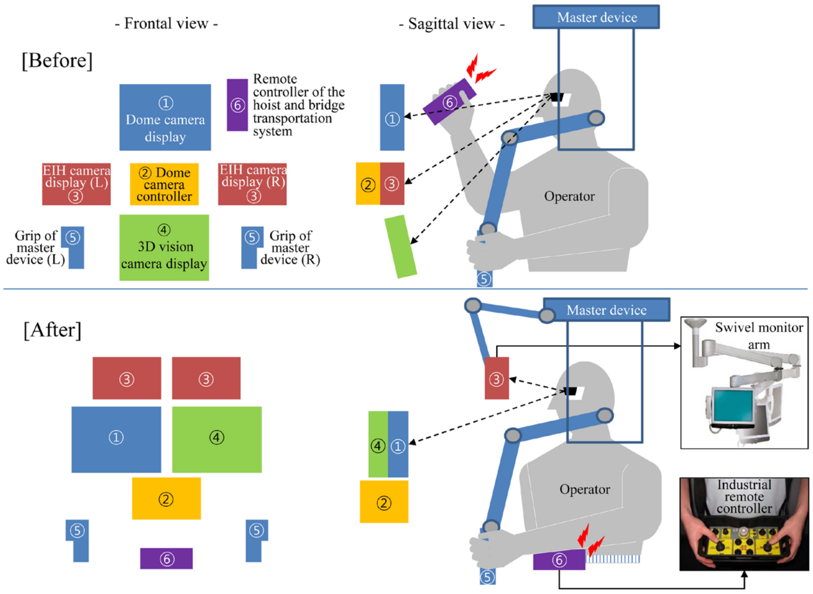


Fig. 17. Proposed Integration of the Control Monitoring Devices with the Master System

can be done by physical measurement of the workloads of the telemanipulation tasks. The workload analysis of the present study can be improved in terms of the quantification and classification of the workload for each unit task.

6. CONCLUSION

It is generally believed that the most important requirements for the efficient performance of a teleopera-tion task are a high-resolution display, 3D vision, and force reflection. However, through practical experiments, we determined that visual information on the gripper pose and surroundings was a more important factor. The performance of visual servoing using the EIH cameras of both hands of the manipulator was observed to be sufficient for every type of remote handling considered in this study.

The remote handling systems of the considered PRIDE facility comprise an MSM system and a BDSM system. Generally, most tasks of an MSM can be performed using a passive view through the window, with the exception of some specific tasks that require the combined use of the BDSM, which affords an active view by an EIH camera. In case of BDSM, contrarily, most tasks can be performed using the active view of EIH camera and WV is supplementary utilized. We thus identified the importance of visual servoing using the active view, which can be used alternately with the force feedback function. Force control and tactile-sensor-based systems can presently not be used to secure reliable performance, and considering the extremely complicated electric signal lines around the PRIDE facility, they may also generate unexpected errors and problems. Above all, the skilled operators did not prefer the force reflecting function because the moderating reaction from the master device preventing the excessive physical interactions between manipulator and environment obstructed the operators' skilled movements frequently.

The active view strategy is also effective for evaluating distance through the display device and working using both hands. Distance estimation and pose recognition are important issues when moving a telemanipulator. Humans focus on an object using both eyes, but it is difficult to estimate the distance of the object displayed on the screen owing to scale and perspective problems. The perception of texture gradients is equivalently important factor of immersive remote handling, but it is hard to perform in the restrictive display condition either. Therefore, observations of this study suggest that arm pose recognition using an active view of an EIH camera is essential factor for the effective remote handling task. For example, if one attempts to remotely insert a long item into a hole, a small initial misalignment could have significant consequences. The performance of such continuous tasks thus requires an active view of EIH that the operator can freely adjust to guide that object by the other side of the manipulator while recognizing its pose and to observe the entire situation of the object and surrounded obstacles. This active view strategy is not required in advanced camera performances such as the high resolution, or motion synchronization with the movement of an operator's head suggested by previous researchers. It can be achieved using an EIH camera instead, which is generally considered as a sub-camera for supporting a main high-resolution camera. Actually, the EIH camera applied in the BDSM, which has a resolution of only 0.3 mega pixels, can be used successfully for the purpose of remote handling task in various ways such as for FPV, SPV, and TPV, as explained in previous sections.

Finally, this paper presented the workload of unit tasks defined and evaluated in the developed PRIDE facility. The rating of the workload of each unit task is based on the empirical data from the questionnaires of the skilled operators and considerations about the above mentioned ergonomic issues. The workload analysis is performed for the practical equipment of PRIDE, and effective workload could be deduced while operating the telemanipulator in that facility by using the weight factors derived from the ratings of each unit task. This activity is meaningful to improve the installed equipment to meet with the performance of telemanipulator. As a mentioned in the previous chapter, the future work will include the improvement and evaluation of the display system for the remote handling equipment in the ergonomics and biomechanics aspect.

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