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An Implementation of a Teleoperation System for Robotic Beam Assembly in Construction

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Recently, a robot-based construction automation (RCA) project was finished in Korea, whose purpose was to employ a robotic system instead of human labor in steel beam assembly tasks. In that research, a robotic beam assembly (RBA) system was developed to execute a beam assembly task. A field application using the RBA system at an actual construction site was completed. Because a human operator had to board the cabin and manipulate the system in the air, causing possible safety problems, a teleoperation system was developed and is the subject of this paper. To evaluate the performance of the teleoperation system, a pointing task experiment based on Fitts' law was conducted to determine whether it obeyed speed-accuracy tradeoff rules. Results are discussed and an overview of the actual bolting test using the teleoperation system is presented here. Finally, conclusions are drawn about the feasibility of implementing an RBA system with teleoperation in actual building construction applications.

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1. Introduction

The construction industry has been known as one of the most labor-intensive industries and has earned the distinction of being a "3D" (dirty, dangerous, and difficult) industry. It has a high accidental death rate, which is caused by several risk factors, and a low productivity rate, which is affected by environmental elements, such as weather conditions, and by high labor costs and low working efficiency. Because, traditionally, it is one of the oldest industries, it has been difficult to introduce and implement advanced technologies within it.

To overcome these problems, several attempts have been made to implement robotic technology in the construction industry. This implementation can result in many benefits, which include not only the improvement of efficiency and productivity, but also more accurate and uniform construction quality. Various research projects to implement robotic technology in the construction industry have been initiated in many countries.[1-4] In Japan especially, diverse types of semi-automated construction equipment have been developed since the 1980s. Practical applications have been attempted, such as a horizontal concrete distributor, a concrete floor leveler, a concrete surface treatment robot, concrete floor surface finishing robots, a steel frame welding robot, and a water absorbing robot on concrete surfaces.[5,6]

The approach to employ robotic technology for construction automation adopted construction factory (CF) methods. CF is a factory-like structure that provides a suitable and safe environment for automated systems. It also protects the automated systems from external factors dust, wind, rain, and temperature.

Recently in Korea, a research project on an automated construction system that adopted CF technology was successfully finished. This project was named robot-based construction automation (RCA) and was developed as an automated system for steel beam assembly in building construction.[7-12] It addressed four research issues: (1) construction automation planning and integration for robot-based high-rise buildings; (2) the use of a CF structure and hydraulic lifting module; (3) robot-based steel beam assembly; and (4) radio frequency identification (RFID) and multi-degree of freedom (DOF) computer-aided design (CAD)-based intelligent construction material supply. A robotic beam assembly (RBA) system was developed. Using the RBA system, we executed a field application for an actual 7-story building structure and achieved successful results. The developed RBA system provided human laborers with a safe working environment and improved efficiency and productivity for building construction.

However, to operate the RBA system, a human operator still needed to board on its control station and manipulate it in the air, a possible safety problem. For this reason, in this research, we adopted teleoperation technology for the RBA system. By employing teleoperation technology, the operator does not need to board the RBA system, so improved safety can be guaranteed. To evaluate the developed teleoperation system, we performed intensive experiments based on Fitts' law. This law which is widely used for the validation of teleoperation systems suggests a mathematical model for tradeoff between speed and accuracy.[13-16] Using various input devices, including a joystick in this research, provides a theoretical framework for evaluating pointing tasks. Experiments were conducted to compare two kinds of control methods: (1) the original RBA system and (2) the teleoperation system. All experiments were executed under the same conditions. Two-point pointing experiments were performed using the two control systems. Various pointing environments were adopted, and each movement time was measured to analyze the speed-accuracy tradeoff with Fitts' law. In addition, we conducted actual bolting tasks using the teleoperation system and examined the feasibility of using the teleoperation system in an actual construction application.

This paper is organized as follows. In section 2, we introduce the configuration of the original RBA system. The role and specifications of each component of the developed RBA system are described. In section 3, the configuration of the teleoperation system for an RBA is described. Details of the teleoperation system and its specifications are included. In section 4, we evaluate the performance of the teleoperation system based on Fitts' law. It includes information about the actual bolting tasks completed with the teleoperation system. Conclusions drawn from this research are outlined in section 5.

2. Configuration of the Robotic Beam Assembly System

The RBA system was developed to automatically conduct steel beam bolting tasks at construction sites. This system consisted of two primary parts: (1) a robotic bolting device and (2) a robotic transport mechanism. The robotic bolting device conducted an actual beam assembly task. The robotic transport mechanism transported the robotic bolting device to target bolting positions. Because in traditional beam assembly processes, human laborers had to climb a steel beam structure to approach the bolting positions, accidents were possible. In addition, most construction sites, including those for steel beam assemblies, are affected by weather conditions and seasonal weather fluctuations. To overcome these disadvantages, a CF was constructed to protect the steel beam structure from adverse environmental influences. It contained various kinds of robotic equipment, including, for example, a rail system to help the robotic transport mechanism move completely around the building floor and a sliding door mechanism installed on the ceiling to protect the system from rain or snow. The RBA system for steel beam assembly was also installed in the CF.

2.1 Robotic Bolting Device

As mentioned in the previous section, the robotic bolting device had the role of bolting an actual steel beam assembly. Fig. 1 shows a real picture of the developed robotic bolting device. As shown in Fig. 1, the device was composed of a robotic manipulator, a bolt feeding device, bolt-tightening tools, and a cabin. The bolt feeding device consisted of an insertion and attachment tool and a gripping and shooting tool to insert bolts into bolt holes. There were two types of bolt-tightening tools: (1) a primary-bolting tool and (2) a complete-bolting tool. In the RBA system construction process, first, nuts were tightened slightly by using the primary bolting tool because it generated high speed but low torque. Then, the H-beams were aligned by human laborers. Finally, nut tightening was completed by using the complete bolting tool because it generated high torque but low speed. The robotic manipulator, which had a gantry-type mechanism, precisely transported the bolt feeding device and the bolting tools to the target bolting positions. Its workspace was $770 \times 500 \times 300$ mm. Details of the robotic bolting device have been reported elsewhere.

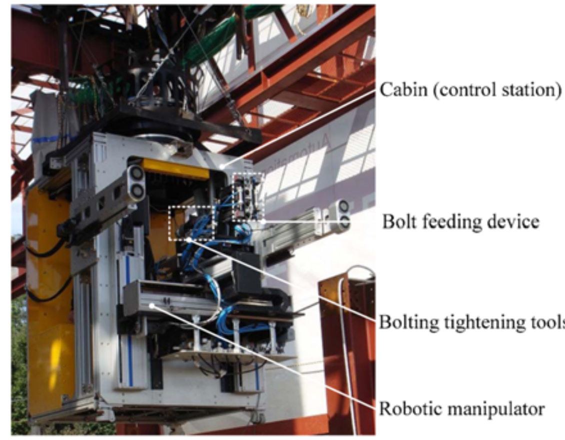


Fig. 1 Real picture of the developed robotic bolting device

2.2 Control System of the Robotic Bolting Device

The RBA system was operated by using TCP/IP communication between the motion controllers of each robotic system and the main controller. Fig. 2 shows the RBA communication system. As shown in Fig. 2, each robotic mechanism, the rail sliding mechanism, cross-wired lift, and robotic manipulator had an independent motion controller. Each motion controller transferred position/state information to the main controller, and the main controller transferred operational signals to each motion controller This information was displayed the to the operator on three monitors installed in the cabin. Monitor 1, which belonged to the main controller, displayed detailed information about the RBA system operation, including the bolting process, working method, and current position and state of each robotic system. Monitor 2, connected to the visual system, showed data from a laser sensor and a CCD camera attached to the end-effector. This information assisted the operator in maneuvering the robotic manipulator to transport the end-effectors to the target bolting positions precisely. Monitor 2 additionally displayed a top-view image, which provided the operator with surrounding environmental information for safety purposes. Both Monitor 2 and Monitor 3 are touch screen monitors. Using Monitor 2, the operator obtains visual information of the bolt hole position or end point position of the bolt, and selects a target by touching on the screen for visual servo control. And on Monitor 3, the operator gets auxiliary information for robotic manipulation, and uses the touch screen to input commands for some bolting process such as bolt-inserting. Monitor 3 was connected to the motion controller of the robotic manipulator (PLC) (QJ71E71/ Mitsubishi). It provided position data for the robotic

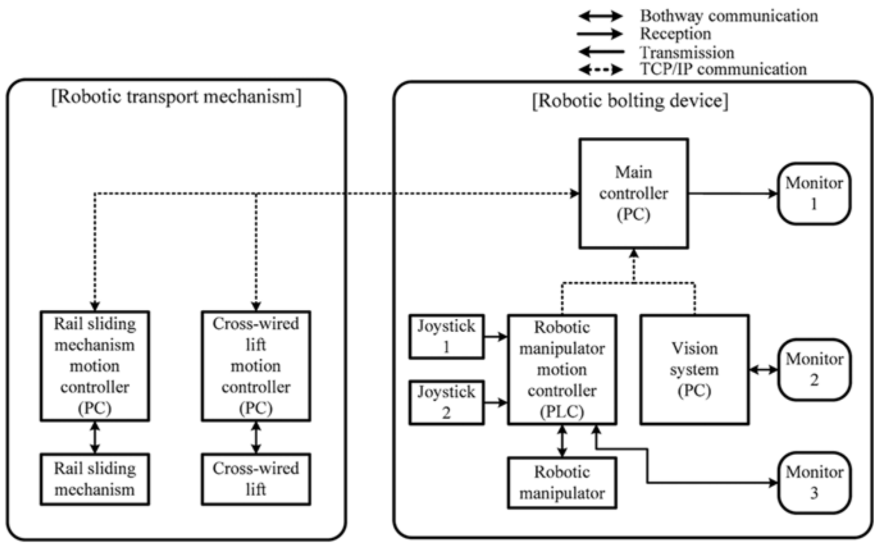


Fig. 2 The RBA communication system

manipulator. The operational signals for the motion control of each robotic system were generated by tilting two joysticks connected to the PLC and delivered to the main controller. The PLC administrated the motion control of the robotic manipulator and transferred the operational signals from the joysticks to the main controller. In addition, there were many control devices, such as switches and buttons, in the cabin to facilitate the convenient and quick operation of the RBA system. Fig. 3 shows the control devices in the cabin. The monitors, joysticks, switches, and buttons were intuitionally set to provide the operator with a convenient working environment.

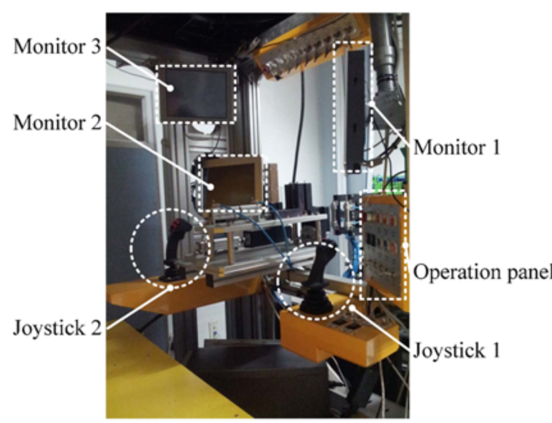


Fig. 3 The control devices in the cabin

3. Teleoperation System for the Robotic Beam Assembly

The beam assembly process using the RBA system was proven to be more efficient and safer than the traditional beam assembly. Because, however, a human operator must still enter the cabin of the RBA system, contingent accidents can occur, including the injury or death of the operator. To solve this safety issue, teleoperation of the RBA system is proposed in this paper. Fig. 4 shows a teleoperation communication system for the RBA system. As mentioned in section 2.2, the original RBA system was equipped with joysticks and monitoring systems in the cabin. However, in the teleoperation system, the joysticks, monitors, and controller connecting the visual system to the main controller were installed outside the cabin. By using this system, the operator can conduct the beam assembly task without having to enter the cabin. The teleoperation controller transferred the operational signals, which were scaled from the joysticks to the main controller in the cabin by using TCP/IP communication. Then, the main controller transferred the operation signals to each motion controller.

We built a control station for teleoperation outside the cabin with two joysticks, monitoring systems, and a controller for teleoperation. Fig. 5 shows the control station for teleoperation. Many physical control devices, such as keys, switches, and buttons were replaced with virtual buttons on the screen. The monitoring system was also improved so that the operator could recognize environmental information easily and obtain additional information from the visual system. Monitor 1 provided the operator with a view that would have been seen from the cabin. Monitor 2 provided top-view images around the cabin and assistive images for visual-based control.

Monitor 4 supported task information and virtual buttons for the actual bolting tasks. Fig. 6 shows the workspace of the robotic manipulator and the joystick motion. As shown in Fig. 6, when the joystick was tilted forward/backward or to the left/right, the robotic manipulator transported the end-effectors downward/upward or to the left/right in the Cartesian coordinate system. It allowed the operator to intuitively maneuver the robotic manipulator.

4. Evaluation of the Teleoperation System

Using the RBA system in the beam assembly process, we first translated the robotic bolting device to the target bolting position around the building by using the robotic transport mechanism. Then, the robotic manipulator attached to the cabin transported the bolting end-effector to the region of interest (ROI), which was approximately near the actual target bolt hole. Fig. 7 shows a screen capture of the visual system monitor. To transport the bolting end-effector to the ROI, the operator used the camera view shown in Fig. 7 and a joystick. The

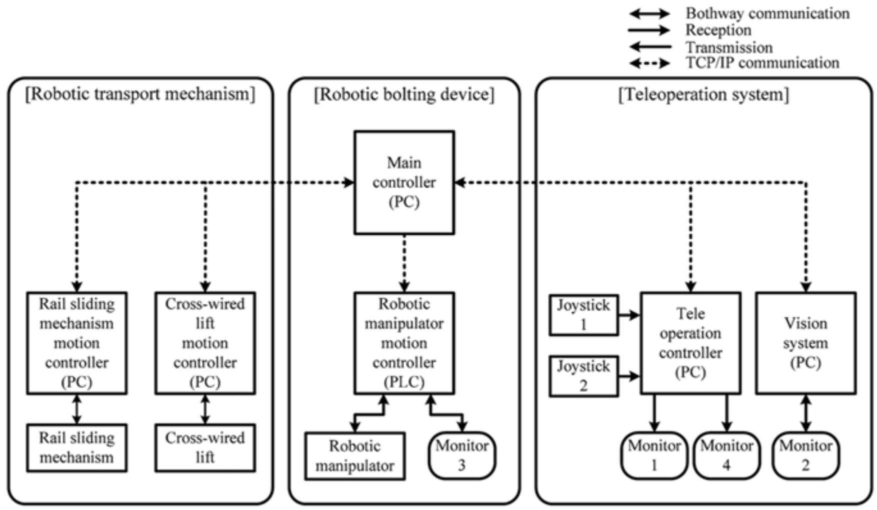


Fig. 4 Teleoperation communication system for the RBA system

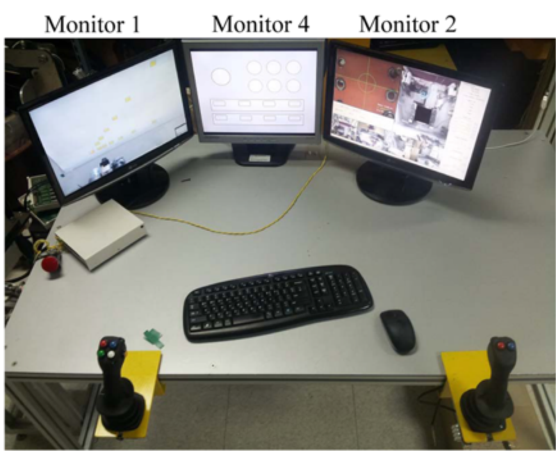


Fig. 5 The control station for teleoperation

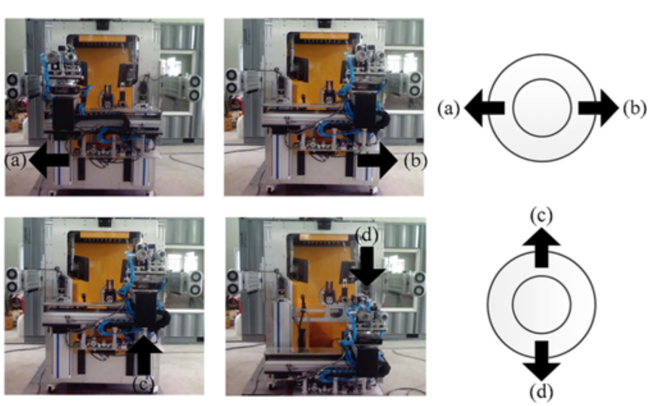


Fig. 6 Workspace of the robotic manipulator and the joystick motion

field of view was approximately $400 \times 300\text{-}500 \times 375\ \text{mm}^2$. After transporting the end-effector to the ROI, the bolting end-effector precisely reached the target bolt hole by automatically using the visual-based control. Therefore, for the teleoperation of the RBA system, we focused on the operator's task, which was to transport the end-effector to the ROI. In this study, the teleoperation of the RBA system was evaluated by the movement of the bolting end-effector to the ROI. To evaluate the teleoperation system of the RBA system, intensive experiments based on Fitts' law were performed. In the experiments,

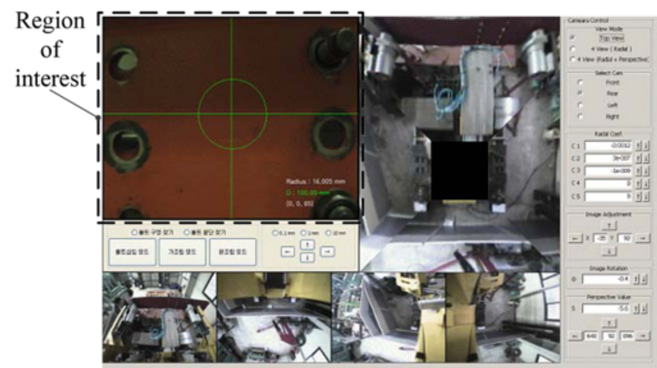


Fig. 7 Screen capture of the visual system monitor

we compared the time to move from a starting point to target points under various experimental conditions by using one joystick from the original RBA system in the cabin and another joystick from the operation system outside the cabin. We also conducted actual bolting tests with the teleoperation system.

4.1 Experiments based on Fitts' Law

Fitts' law is one of the most representative evaluation methods for human control performance based on a speed-accuracy tradeoff. By suggesting a mathematical model for a linear compensating relationship between the speed and the accuracy, we can use Fitts' law to quantify the performance of a teleoperation system. In the pointing task of this research, the relationship between movement time for speed and task difficulty for accuracy was modeled by Fitts' law.

Equation (1) represents an index of difficulty (*ID*) of Fitts' law,

$$ID = \log_2\left(\frac{A}{W}+1\right) \tag{1}$$

where A denotes the distance between the centers of each target and W denotes the width of the targets. Generally, ID tends to be large when W is small and A is large.

Equation (2) is one of the most popular modifications of Fitts' model,

$$MT = a + b\log_2\left(\frac{A}{W}+1\right) \tag{2}$$

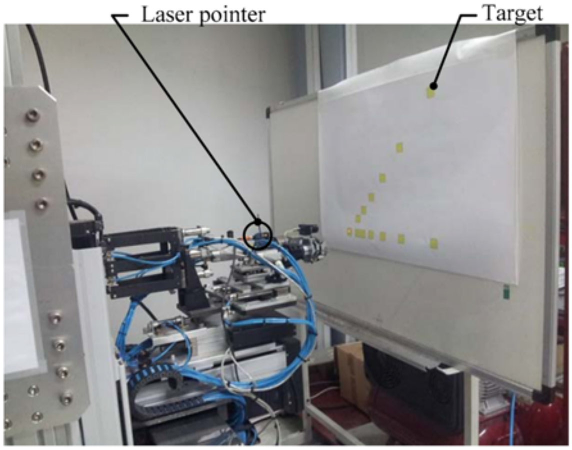


Fig. 8 Picture of the experimental environment for the pointing task

Table 1 Conditions of each ID

W = 30 mm					
A(mm)	30	54.9	90	139.7	210
ID	1	1.5	2	2.5	3

W = 50 mm				
A(mm)	50	91.4	150	232.8
ID	1	1.5	2	2.5

Table 2 Eight conditions with target conditions of the experiment

		W = 30 mm	W = 50 mm
Manual	Horizontal	Case 1	Case 5
	Diagonal	Case 2	Case 6
Teleoperation	Horizontal	Case 3	Case 7
	Diagonal	Case 4	Case 8

where *MT* denotes pointing completion time in the experiments, and *a* and *b* are the information transmission coefficients, which indicate the efficiency of the pointing system. In Fitts' law, *ID* and *MT* show a linear relationship, which indicates that as *ID* increases, the amount of information for performing movement increases.

Equation (3) derives an index of performance (*IP*).

$$IP = \frac{ID}{MT} \tag{3}$$

IP is calculated by dividing *ID* by *MT*. This index shows the capacity of the human motor system.[13-16]

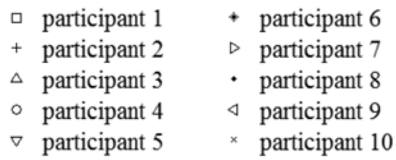
4.1.1 Experimental Method

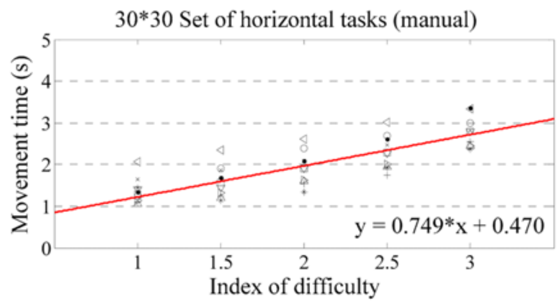
In the RBA system, after the operator transported the bolting end-effector to the ROI using the joystick, bolt insertion or bolt tightening was conducted by automatically using visual-based control. When the bolting end-effector reached the ROI, the operator could observe the target bolting position and begin the automatic visual-based control. Therefore, in this research, the target teleoperation task was to transport the bolting end-effector to the ROI. This task was almost the same as the pointing task in Fitts' experiment to move from one point to another in a plane.

In this research, two kinds of pointing experiments were conducted using the original RBA system in the cabin and the teleoperated RBA system outside the cabin. The purpose of these experiments was to analyze whether the teleoperation system performed similarly to the RBA system in the cabin. Fig. 8 shows a picture of the experimental environment for the pointing task. As shown Fig. 8, a laser pointer that was attached to the bolting end-effector revealed the position of that bolting end-effector. Squared targets were marked on the panel and indicated by the laser pointer. Their size, including width (*W*) and distance (*A*), was already known. Table 1 represents conditions of each ID. This experimental configuration was used to measure the pointing completion time. A camera on the cabin provided the operator in the teleoperation system with a view from the cabin. The experiment was conducted by inexperienced participants (their average age was 24.8 years, there were 8 males and 2 females, and all participants were right-handed). Each participant had a 10-min training. During the training, participants practiced operating the robotic manipulator by using the joystick to become acquainted with the system. Participants executed the pointing tasks under eight conditions. Table 2 lists the eight conditions with target conditions of the experiment. The pointing completion time from the initial position to each target was observed under the various experimental conditions. Success rates of the experiments were estimated according to the eight conditions to evaluate the difficulty of the operation. If the laser pointer did not reach the target or passed the target, the attempt was regarded as a failure.

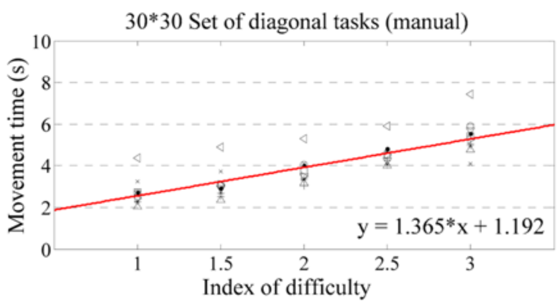
4.1.2 Experimental Results and Discussion

The experiments were performed to evaluate the performance of the teleoperation system in comparison to the original RBA system. Various experimental conditions to determine the *IDs* were set, and corresponding *MT*s were measured. The *IP*s of the two systems were compared. In the experiments, eight males and two females, whose majors were engineering, participated. All were right-handed. Fig. 9 compares the movement times of the two systems according to various *ID*s. Two target sizes (30×30 and 50×50 mm) and two motion tasks (horizontal and diagonal) were used to improve the reliability of the experiments. Each graph in Fig. 9 proves that both the teleoperation system and the original RBA system follow the Fitts' law because their *ID* and *MT* had linear relationships regardless of experimental conditions. Table 3 lists the parameters of the linearly fitted graphs of the eight cases, as shown in Fig. 9, where *b* indicates the proportional relationship between *ID* and *MT*. For all four experimental cases, the teleoperation system had a larger value of *b* than the original RBA system. This discrepancy indicated that the operation of the teleoperation system was more sensitive and a more elaborate operation was required to manage it. In addition, the average *MT* values of the teleoperation system were larger than those of the original RBA system. There are two reasons for this discrepancy in performance. The first is attributable to a communication delay. From a comparison of Figs. 3 and 5 for the original RBA system, it is apparent that the operational signal from the joystick in the cabin was directly connected to the PLC. However, in the teleoperation system, the joystick signal was transmitted to the main controller by the teleoperation controller and then delivered to PLC, thus explaining the delay. The second was attributable to the transmission method of the visual information. In the teleoperation system, the operator was indirectly provided the visual

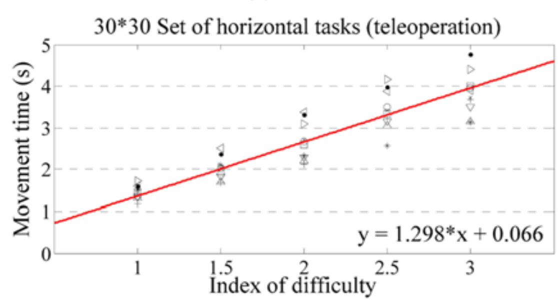




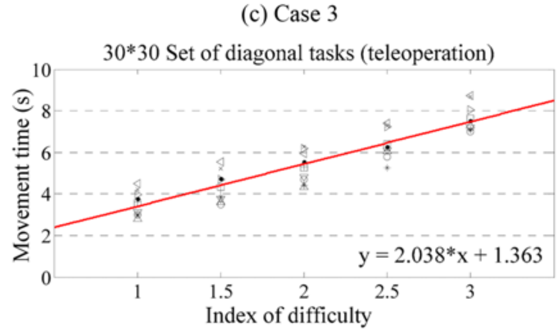
(a) Case 1



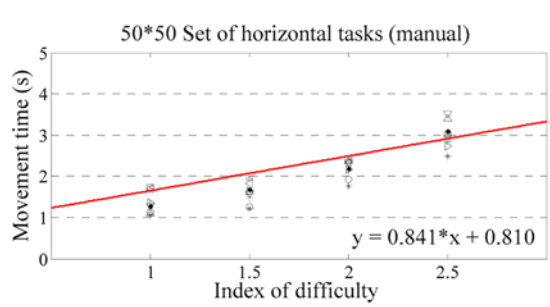
(b) Case 2



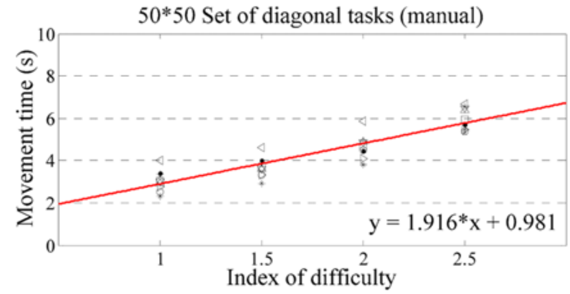
(c) Case 3



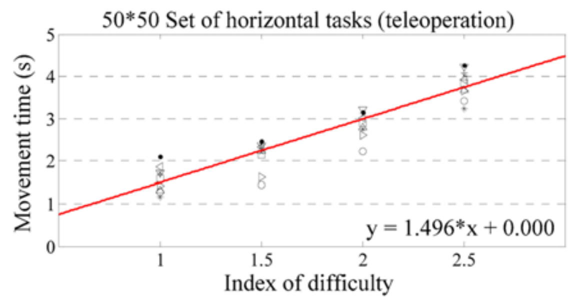
(d) Case 4



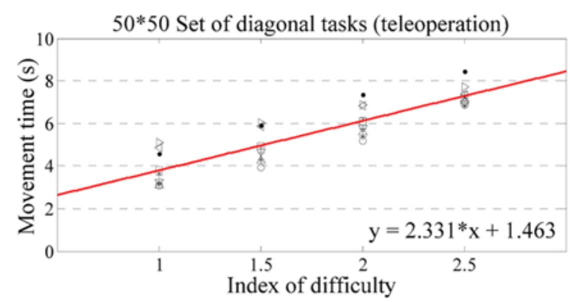
(e) Case 5



(f) Case 6



(g) Case 7



(h) Case 8

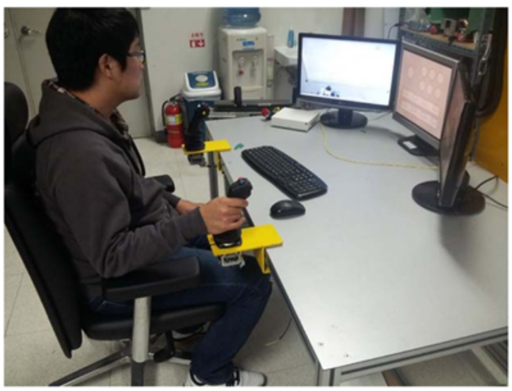
Fig. 9 Compares the movement times of the two systems according to various *ID*s

Table 3 Parameters of the linearly fitted graphs of the eight cases

	a	b
Case 1	0.749	0.465
Case 2	1.298	0.066
Case 3	1.365	1.192
Case 4	2.038	1.363
Case 5	0.841	0.810
Case 6	1.496	0.000
Case 7	1.916	0.981
Case 8	2.331	1.463

information from the camera installed in the control cabin. This is an inherent disadvantage of the teleoperation system. These constraints generated a delay that caused the difference in performance. Success rates of target sized 30*30 show 89% using the RBA system and 83% using the teleoperation system. In case of target sized 50*50, the rates are 97% inside the cabin and 92% when controlled remotely. Through the experimental results, we could notice that remote control system is not better but almost as stable as inside control system. Besides work time, when safety is taken into consideration, remote control system is efficient.

(a) The original RBA system



(b) The teleoperation system

Fig. 10 Actual bolting tests

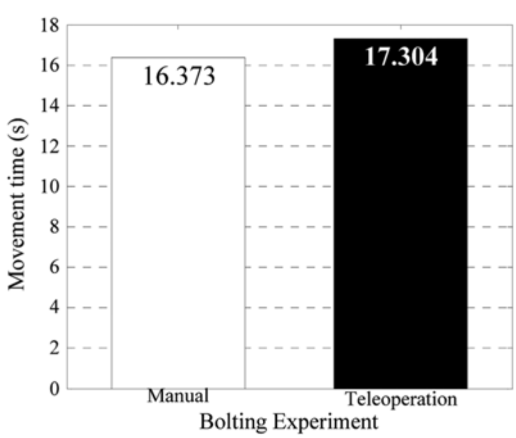


Fig. 11 The result of the average bolting completion time in the original RBA system and in the teleoperation system

4.2 Bolting Test

4.2.1 Experimental Method

Beam assembly tests with an actual H-beam were conducted with the teleoperation system and the original RBA system. In the experiments, the participants transported only the bolting end-effector to the ROI with the two systems. Then, the bolt holes were detected by visual-based control, and the remaining bolting process, including precise transportation and bolt insertion, was automatically performed.

Fig. 10 shows the actual bolting tests for (a) the original RBA system and (b) the teleoperation system. Each participant performed the test three times, and the time to move the bolting end-effector to the ROI using the joystick of each system was measured. The overall operation time of the bolting process, including the movement time, was observed.

4.2.2 Experimental Results and Discussion

Fig. 11 presents the result of the average bolting completion time in the original RBA system and in the teleoperation system. The difference between the bolting completion times of the two systems was 0.931s. As mentioned in section 4.1.2, the difference was caused by a communication delay and the limited visual information available for joystick manipulation. In other words, the delayed visual information was less informative than the actual operator's view from the cabin. However, the time difference of the two systems was relatively smaller than the total bolting time, so it can be considered negligible in an actual implementation. In addition, the operator is not required to board the RBA system. A safer working environment for the operator is guaranteed. For these reasons, the teleoperation system was confirmed to be not only feasible but also useful for robotic steel beam assembly.

5. Conclusions

In this study, we adopted teleoperation technology for an RBA system. Using the teleoperation system, we resolved the safety problem in the original RBA system in which the operator boarded the cabin in a potentially unsafe manner. The developed teleoperation system provided an operational environment that was similar to the operational environment in the cabin when using visual information and joysticks. Experiments were conducted to evaluate the performance of the teleoperation system in comparison to the original RBA system. A pointing task experiment showed that the teleoperation system had the same speed-accuracy tradeoff as the original RBA system. Beam assembly tests were performed by using two systems. The times to complete bolting with each system were measured and compared. The results showed that the developed teleoperation system had a comparable performance to the original RBA system. Although delays were measured, they would be negligible in an actual implementation.

With these experiments, we demonstrated that the developed teleoperation system is feasible and useful. In future work, we need to develop intuitionally joystick to improve operational performance. In addition, we need to adopt augmented reality and haptic technology to provide the operator an improved environment.

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