Proposal of Workspace Mapping Method for Conversion-less Unmanned Excavation System to Improve Operative Performance

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ABSTRACT

The highest incidence of disaster at a construction site is about 33.1% and this disaster occurs when an excavator is operated in dangerous site that can have rollover, confinement, and fall. The development of unmanned excavator is realized briskly for the safety of the operator from these dangers. The system to operate an excavator from a remote can be divided into conversion and mounted type. We have implemented this research about a system that has advantages of conversion and mounted type. This system enables excavators to be unmanned and remotely controlled without any renovation, remodeling, change, or transformation by applying attachable and separable mechanism and modules and this proposed system has advantages of conversion and mounted type. The system had a problem of poor operation performance due to the workspace inconsistency between remote controller and lever control robot, which produced lower speed. To improve this problem, the workspace mapping between remote controller and the robot to operate the lever of an excavator is proposed to improve the workability of excavator that is operated from a remote in this paper.

Keywords – unmanned excavation system, workspace mapping, remote controller, lever control robot

1 Introduction

Excavators are one of the most heavily used construction industry machines that generally have high accident rate [1, 2]. Moreover, even though excavators are used in high-accident area abundant with overturn, strangulation, fall, etc. as well as in dangerous working environment such as building demolition, garbage removal, etc. the devices and plans that can guarantee the safety of workers are not sufficient. Thus, it is critical to develop a system that can guarantee the safety of workers through remote controlling of excavator. There are a number of domestic and foreign studies with research and development on this topic. Examples include 'underwater backhoe BC-3' that enables excavator works underwater, 'RoboQ' by Fujita in Japan, and 'HRP-1' by Advanced Industrial Science and Technology in Japan. In Korea, Seoul National University and Hanyang University have been conducting research and development in this field with diverse methods[3, 4, 5, 6].

The excavator unattended systems that were developed so far can be divided into the one that electrically controls by transforming excavator's hydraulic mechanical system into electro-hydraulic system and another that controls by installing a robot that handles the excavator's lever and pedal onto the excavator. We define the former as a 'convertible type' and the latter as an 'installation-type'.

Figure 1. Underwater backhoe BC-3

The convertible type Remote Control excavator as shown in BC-3 in Figure 1 has an advantage of high controllability because of direct control excavator system, but it a system transformation is necessary which requires time and cost. Moreover, the installation at the field is also impossible in this case. Meanwhile, the installation-type tele-operated excavator robots as shown in Robo-Q and HRP-1 in Figure 2, 3installs a robot that can operate the excavator's lever and pedal on the excavator, which solves the problems that convertible type has. However, it has shortcomings such as low controllability due to indirect control of excavator using operation robot, long installation time, and low portability[5, 6, 9].

Figure 2. RoboQ (Fujita, JPN)

Figure 3. HRP Series (Jaist, JPN)

The installation-type excavator operation robot developed at Hanyang University decreases the installation time which is a shortcoming of the previously mentioned installation-type, while enhancing portability by simplifying the operation robot[6]. In the case of the remote control system for excavator that was previously developed at Hanyang University, there was an inconsistency between the workspace generated when installing robot on lever and the workspace of the remote controller, and sluggish performance of the remote control excavator was observed. To improve this problem, the workspace mapping between remote controller and the robot to operate the lever of an excavator is proposed to improve the workability of excavator that is operated from a remote in this paper.

2 Lever Control Robot

2.1 Hardware Description

Figure 4 shows the overall system composition that includes main controller, lever control robot of degree of freedom 2, and pedal operation robot of degree of freedom 1. Controlling signal is transmitted from the remote controller which is manipulated by a worker, and the transmitted signal controls the lever and pedal operation robot through the connected main controller. The system above has a unilateral type of remote controller, which only supports a control from the controller to the robot, without any feedback about the robot's surrounding environment.

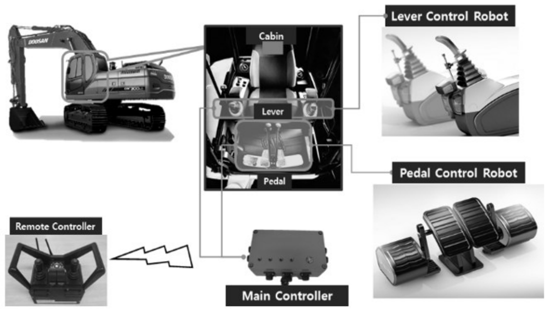


Figure 4. Configuration of system

The lever control robot is attached to the excavator's control stand using an adaptor and it was connected to the lever through prismatic joint as shown in Figure 5.

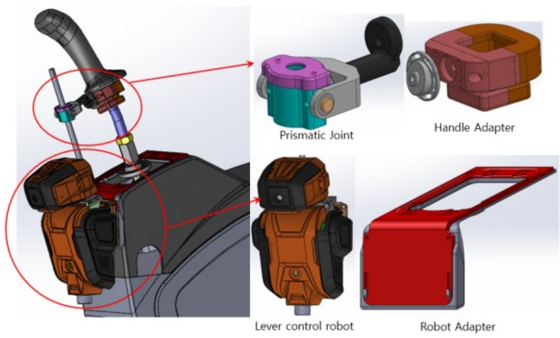
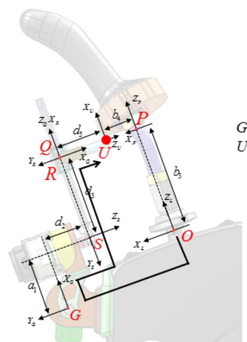


Figure 5. Lever control robot on the control stand

2.2 Workspace Analysis



$^{G}_{U}T$:

	α_{i-1}	a_{i-1}	d_i	θ_i
G	0	0	0	θ_1
S	$\frac{\pi}{2}$	a_1	d_2	$\theta_2+\frac{\pi}{2}$
Q	$\frac{\pi}{2}$	0	$d+d_3$	$\frac{\pi}{2}$
R	$\frac{\pi}{2}$	0	0	$\theta_4+\frac{\pi}{2}$
U	$\frac{\pi}{2}$	0	d_5	θ_5

Figure 6. The frames through lever control robot and DH table

The lever control robot is installed on an adaptor that is attached and fixed at the body of lever inside the excavator called control stand. This is for the purpose of enabling attaching and detaching of the remote control robot without renovating the interior of the excavator.

The lever and lever control robot share base frame O as is shown in the right side of Figure 6, along with End Effector U. Using the fact that these two frames are the same, we could find out that the transformation matrix from lever control robot and the one from excavator lever are identical.

$$ {}^{O}_{G}T \cdot {}^{G}_{S}T \cdot {}^{S}_{Q}T \cdot {}^{Q}_{R}T \cdot {}^{R}_{U}T = {}^{O}_{P}T \cdot {}^{P}_{U}T \quad (1)$$

First, let us examine the left part of Equation1, a transformation matrix that involves lever control robot.

$$ {}^{O}_{G}T = \{R(X, -\pi/2) \cdot R(Z, -\pi/2),\ {}^{O}P_{CORG}\} \quad (2)$$

Equation 2 shows the base frame from O to G of Figure 6.

Next, the right hand of Equation 1 which is a transformation matrix that passes lever is demonstrated in Figure 6 and is equal to Equation 3 below.

$$ {}^{O}_{U}T = T(Z, b_3) \cdot R(Y, -\pi/2) \cdot T(Z, -b_4) \quad (3)$$

Equation 4 is obtained by inputting rotation angle α and β in x-axis and y-axis of the lever in base frame O.

$$ {}^{O}_{U}T = R(X,\alpha) \cdot R(Y,\beta) \cdot \begin{bmatrix} 0 & 0 & -1 & b_4 \\ 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & b_3 \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} r_{11} & r_{12} & r_{13} & p_x \\ r_{21} & r_{22} & r_{23} & p_y \\ r_{31} & r_{32} & r_{33} & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (4)$$

$$ \theta_1 = Atan2(AD - BC, AC + BD) \quad (5)$$

$$ \theta_2 = Atan2(S_2, C_2) \quad (6)$$

Equation 5 and 6 are a relationship equation where the angle value θ_1 and θ_2 of motors of lever control robot are printed after input of rotation angle α and β in the lever as in Figure 7.Workspace can be obtained by using the motor's angle value according to the inputted lever degree, which is shown in Figure 8.

As is shown in Figure 8, the workspace created when lever control robot is installed has a nonlinear form and the range of operation of Motor 2 according to the angle value of Motor 1 changes. In case of lever control robot that has a form of RRPRR(R: Revolute, P : Prismatic), Motor 2 is accumulated on the axis of rotation of Motor 1 as in Figure 7, and hence, the axis of rotation of Motor 2 moves following the rotation of Motor 1.

Figure 9 shows that prismatic joint connected to Motor 2 moves following the movement of Motor 1 and the range of movement of Motor 2 according to the Motor 1's location changes.

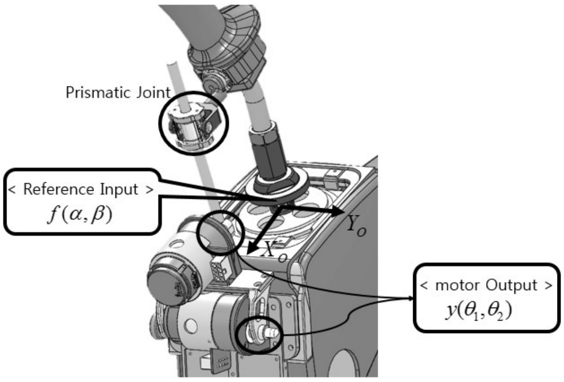


Figure 7. Relations between the input and output

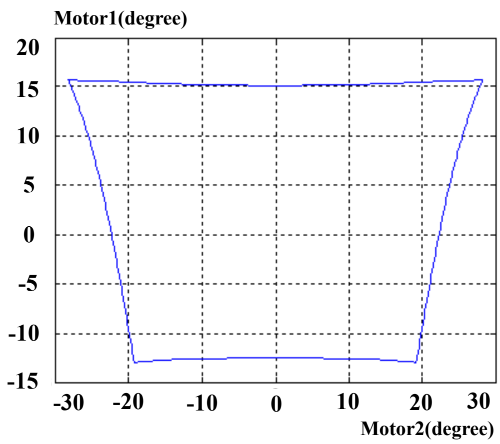


Figure 8. Drawn workspace

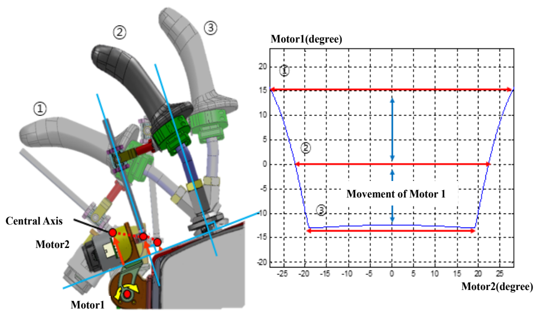


Figure 9. Relations between motion of lever control robot and shape of workspace

3 Workspace Mapping Method

3.1 Robot Installation Error

Prior to beginning mapping, we describe the method of installing lever control robot on excavator lever. In order to secure the detachable feature which was one of the concepts of the previously developed robot at Hanyang University, the robot was installed after installing adaptor on the excavator so that the robot can be assembled and dissembled afterwards. Frequent detachment results in differing location of installation at each attachment, and this causes workspace transformation as in Figure 10. Moreover, there is one additional factor that causes workspace transformation, i.e., the location difference of lever as is described in Figure 11. The shape of the lever installation changes at the initial assembly of the excavator or following the worker's preference, and hence the adaptor's location under the lever handle can transform. As the location of the lever adaptor changes, the parallel goes awry between the axis of lever and lever control robot, and interference between Motor 1 and Motor 2 is consequently created, resulting in workspace transformation as is shown in left of Figure 12.

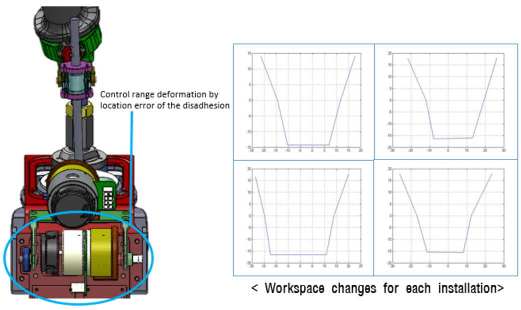


Figure 10. Workspace changes for each installation

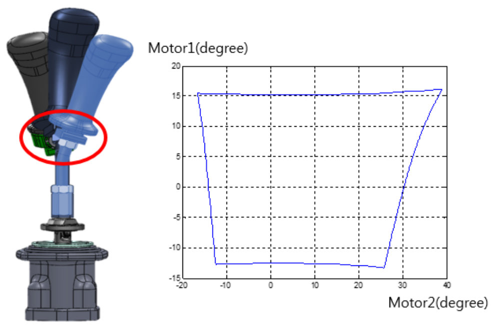


Figure 11. Workspace distortion by lever location

In order to prevent such transformation of the workspace, the interference between Motor 1 and Motor 2 was minimized by aligning axis of the lever and lever control robot as in Figure 12 and the mapping proceeded under the ideal workspace obtained in Chapter 2

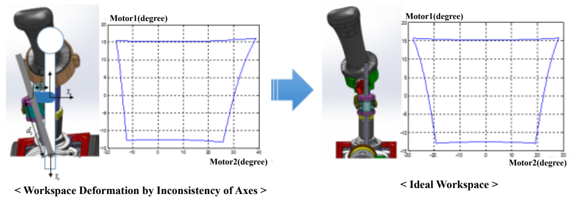


Figure 12. Parallel setting between axes

3.2 Mapping between motion of the lever control robot and remote controller

This chapter conducts scaling and workspace synchronization using data of six points in the workspace. A method that linearizes the nonlinear section created in the workspace by using two neighboring points was used.

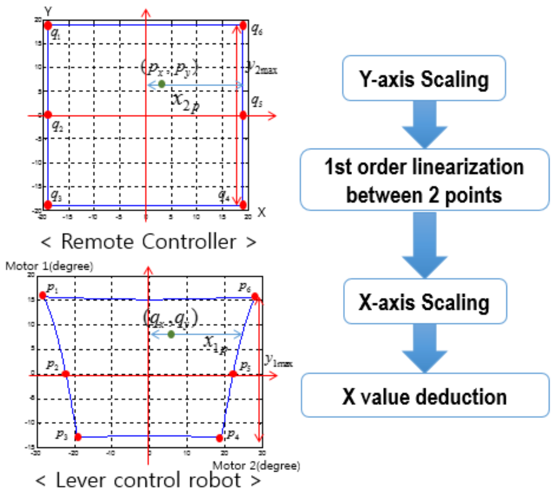


Figure 13. 6 Points mapping method and sequence

Figure 13 presents six points in workspace, with an illustration for the linearization. The nonlinear workspace was linearized through a first-order linearization between two neighboring points. Here, an unusable space in the workspace is created, but it is trivial and does not affect the efficiency of the excavator performance. After fitting the size of y-axis, the nonlinear section created in the workspace of the lever control robot was linearized using two neighboring points in each section. Afterwards, x-axis was scaled using a single random point, and corresponding workspace value of the lever control robot was computed. The equations below describe the process

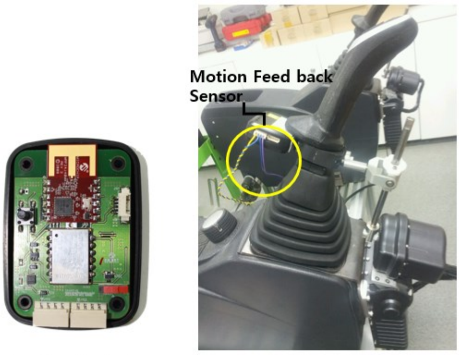
$$\alpha = y_2max / y_1max \quad (10)$$
$$y = a(x - x_{p1}) + y_{p1} \quad (11)$$
$$a = (y_{p1} - y_{p2})/(x_{p1} - x_{p2}) \quad (12)$$
$$\beta = x_{p2}/x_{p1} \quad (13)$$
$$q_x = \beta \cdot p_x, (q_y = \alpha \cdot p_y) \quad (14)$$

Equation 10 shows the scaling of y-axis, and Equation 11and 12 show the first-order linearization of the two points. Equation 13shows the scaling of x-axis, Finally, Equation 14 demonstrates the derivation of x value. The mapping process of the workspace was done following a series of works described above.

4 Experiments and Evaluation

4.1 Mapping Evaluation through Measuring the Lever Angle

Here, we compare the workspace arrival rate before and after the mapping by measuring the slope of the excavator's lever. As shown in Figure 14(b), experiment was conducted on test bed, where the motion feedback sensor developed in our lap was used. As is described in Figure 14(a), all of the roll and pitch angles of the sensor can be measured. The module interfaces with the exterior using either CAN or 2.4GHz wireless after obtaining each sensor's raw data, roll and pitch angle. The sensor's resolution can be measured at 0.01 interval, and the bandwidth was set at 40Hz.



< (a) Motion Feedback Sensor > < (b) Test Bed >

Figure 14. Motion feedback sensor and test bed

As is shown in the photograph in Figure 14(b), IMU sensor was installed under the lever handle to measure the outline of the workspace where lever moves.

The experiment followed the process described in Figure 15. First, the maximum workspace was measured by directly moving the lever with hand, and then workspace arrival rate was measured using slope data obtained from the motion feedback sensor before and after the mapping

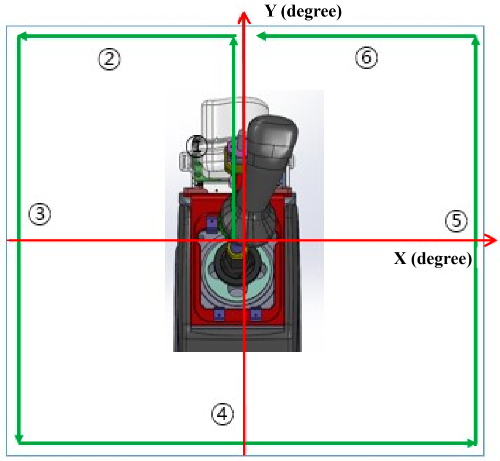


Figure 15. The sequence of the workspace measuring

Experiment results showed that as much as 70~80% of the original workspace arrives after the mapping while only 50% arrives before mapping. As shown in Figure 16, mapping allows more workspace to arrive.

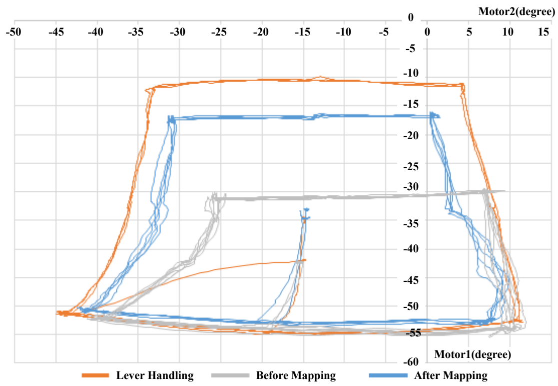


Figure 16. Experiment result

4.2 Mapping Verification through Evaluating the Excavator Performance

Figure 17. Sensors attached on the excavator

We install the lever control robot on the actual excavator and compare the excavator performance before and after the mapping. In the experiment, linear sensor(DWS-30) was installed on each of excavator's boom, arm, and bucket cylinder as shown in Figure 17.

Figure 18. Relations between levers and excavator motion

Input values using the remote controller are summarized in Figure 18. The joystick of the remote controller followed the excavator's interface. The y-axis of right-side lever moves boom and x-axis moves bucket. Meanwhile, the y-axis of left-side lever moves arm and x-axis moves excavator's body swing. Since the remote controller followed lever's interface, only x, y-axis of the right-side joystick and y-axis of the left-side joystick were measured.

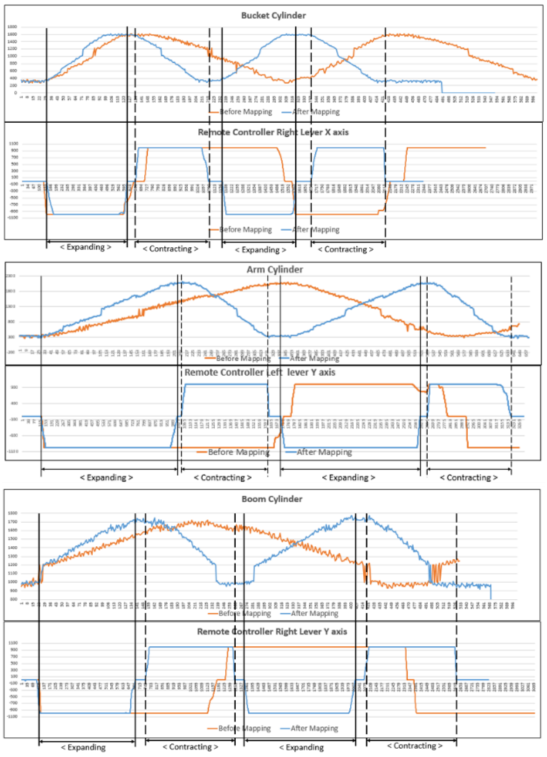


Figure 19. Experiment result of the each cylinders and the signal of the remote controller

The experiment first measured the movement of each of boom, arm, and bucket, and then evaluated the rate of arrival to the goal before and after the mapping. In each case, expansion and contraction were performed for twice and the measurement was done before and after the mapping following the remote controller's signal.

Afterwards, evaluation in case of actual excavating work was done in order to measure the excavating work efficiency. A total of three times of excavating work were executed before and after the mapping whose outcome was subsequently compared.

Experiment results on the movement of each of the boom, arm, and bucket are described in Figure 19. Same value was inputted from the remote controller, and the time it takes to arrive after starting at the same point halved after the mapping compared to the case before the mapping.

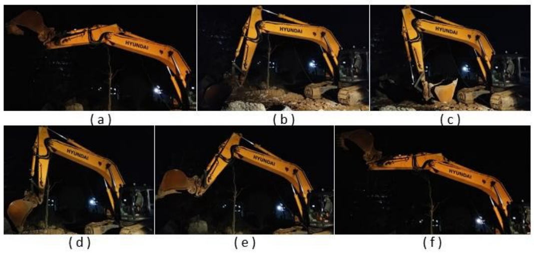


Figure 20. Experiment order of digging work

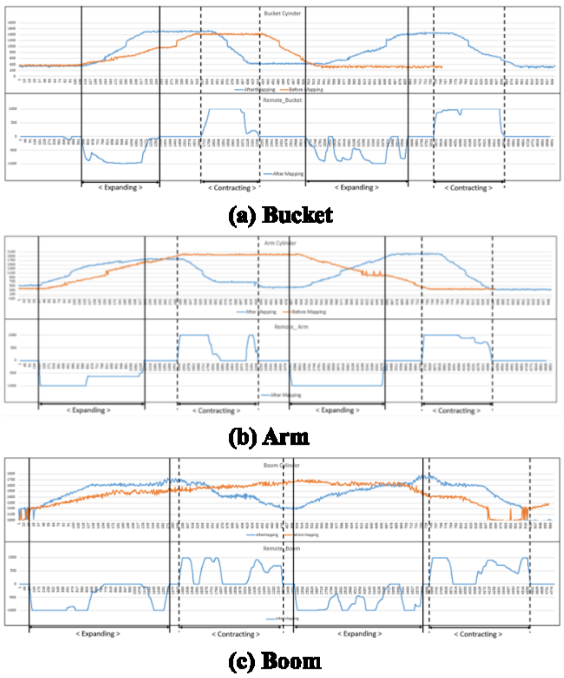


Figure 21. Experimental results of the digging work

The next experiment is the verification of work efficiency between before and after mapping during real digging work.

Experimental procedures, as shown in Figure 20(a), first to a state in with the bucket and arm which is contracted at a maximum, and boom made the bucket and arm are to be heard in the air. And ran the action to the excavation work, as shown in the order in the following figure.

Experiment result is shown in Figure 21. Figure 21(a) shows about bucket, (b) shows arm, and (c) shows boom. As seen in the graph of experiment result can be confirmed that after mapping is 2-times faster than before mapping.

This directly connects to the work performance of the excavator, implying that it accomplishes a performance level that satisfies the worker.

5 Conclusion

This paper summarizes the commercialization plan for the remote/unmanned excavator.

This study examines the mapping method that reinforces performance efficiency of the remote excavating system with a purpose of enhancing remote excavating work performance. Due to environmental limitations of the embedded system, this study focuses on a mapping method that uses data collected from only six points in the working environment, and it investigates the mapping between workspace obtained from kinematical interpretation and remote controller's workspace. As for the verification of the mapping, lever angle of the control stand installed on test bed was measured to examine the workspace arrival rate, and the contraction and expansion speed of boom, arm, and bucket cylinder of the excavator were measured to be compared before and after the mapping. The performance efficiency when applied to actual commercial excavator was also evaluated. The experiment results showed that the work efficiency after the mapping cut the working hour for more than half, compared to the case before the mapping, providing satisfactory work efficiency for the worker.

This can directly applied to the actual excavating work, and it can produce an efficiency that is equivalent to the case where actual worker runs an excavator by sitting on it, while decreasing the fatigue of the operator. Moreover, remotely operating excavator guarantees worker's safety in dangerous environment, and the accident rate of fatal disaster can also be diminished.

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