An Assistive Interface of a Teleoperation System of an Excavator by Overlapping the Predicted Position of the Arm

Y. Okawa[a], M. Ito[a], R. Sekizuka[b], S. Saiki[c], Y. Yamazaki[c] and Y. Kurita[a]

[a]Graduate School of Advanced Science and Engineering, Hiroshima University, Japan
[b]Graduate School of Engineering, Hiroshima University, Japan
[c]Kobelco Construction Machinery Co., Ltd., Japan
E-mail: yuzukiokawa@hiroshima-u.ac.jp, itoma@hiroshima-u.ac.jp,
ryotasekizuka@hiroshima-u.ac.jp, ykurita@hiroshima-u.ac.jp

Abstract -
A teleoperated hydraulic excavator is introduced to perform safe and quick restoration work in sites affected by disasters. However, the current efficiency of this system is approximately 40–60%, compared to boarding an actual hydraulic excavator, because of the communication delay. To reduce this delay, we developed a system that can display the predicted position of the excavator attachment to the operator. For predicting the movement of the hydraulic excavator relative to the lever input, it is necessary to consider the dynamic characteristics of the hydraulic excavator. In this study, the dynamic characteristics of the turning motion of the hydraulic excavator were assumed to be the first-order delay with a dead time system, followed by the construction of the turning motion simulator of the hydraulic excavator. Through an experiment in which the bucket tip was stopped toward the target position, the operational time was confirmed to be significantly shortened by displaying the predicted position.

Keywords -
Teleoperated hydraulic excavator; Swinging motion; Interface; Communication delay

1 Introduction

Hydraulic excavators often operate in dangerous locations, such as disaster sites. Recently, teleoperated hydraulic excavators have been introduced and have gradually become mainstream, through which several unmanned construction works have been carried out [1, 2, 3]. However, it is believed to have approximately 40–60% work efficiency compared to an actual machine boarding. Thus, the performance improvement of the teleoperated hydraulic excavator is necessary. Communication delays are one of the factors that reduce work efficiency. Michael et al. [4] investigated the effect of time delay on the surgical performance of teleoperated surgery and confirmed that the accuracy of moving the remote surgery robot decreased as the time delay increased. In the teleoperated system of a hydraulic excavator, Sugawara et al. [5] achieved high picture quality with low image delay and confirmed the operational efficiency improvement through simulation. However, for a teleoperated hydraulic excavator, which is supposed to be utilized in various work sites, secure and stable communication cannot always be guaranteed. Consequently, eliminating communication delay is challenging. Therefore, a technique that can improve work efficiency, even when communication delay exists, is necessary. Richter et al. [6] developed a system to predict a position without time delay to an operator in a teleoperated manipulation robot. When positioning was difficult, the ring was picked up by one arm and placed back after passing it to another arm. By evaluating the operating hours, with and without the proposed system, a significant difference was confirmed. Walker et al. [7] showed that the operation could be facilitated using a virtual aerial robot, which can provide information regarding where and how the robot finally reaches a position. However, to the best of our knowledge, the prediction superposition technique has not been applied to the teleoperated hydraulic excavators yet.

In this study, we propose a teleoperated system for hydraulic excavators that can overlap the predicted position of the arm with the operation input. We focus on the turning motion of the hydraulic excavator and verify the effectiveness of our proposed method through simulation. First, a simulator of a teleoperated hydraulic excavator was generated; then, the overlapping system for the arm predicted position was mounted for the turning operation. Finally, the difference in the work efficiency with and without the existence of the proposed system was experimentally verified.

2 Simlation of overlapping the predicted position of the arm

A simulator was developed to confirm the effectiveness by the overlapping predicted position and by displaying it in the turning operation of a teleoperated hydraulic excavator. A hydraulic excavator was installed in a three-dimensional virtual space using the Unity game engine. A joystick (Logitech Extreme 3D Pro) was used as an operator interface. It was possible to turn the simulated hydraulic excavator by tilting the joystick to the right and left like the operation lever of an actual machine. The transfer function G(s) of the teleoperated system was approximated by the first-order delay with the dead time system, as shown in Equation 1. Here, the input was the operation quantity, and the output was the turning angular velocity of the hydraulic excavator, where K, T, and L represent the system gain, time constant, and dead time, respectively.

$$G(s) = \frac{K}{1+Ts}e^{-Ls} \tag{1}$$

The communication delay caused by the teleoperated system of the hydraulic excavator is demonstrated in Figure 1. If the communication delay, L_1, is known, the relationship between the operation input and predicted position can be expressed by the following transfer function, $G_{pre}(s)$.

$$G_{pre}(s) = \frac{K}{1+Ts}e^{-(L-L_1)s} \tag{2}$$

Using the transfer function of Equation 2, the predicted angular velocity was derived from the master input, as shown in Figure 2, and displayed as translucent in Figure 3.

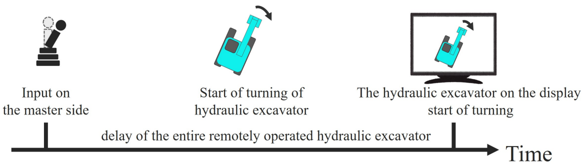

Figure 1. Delay occurred in teleoperated excavators

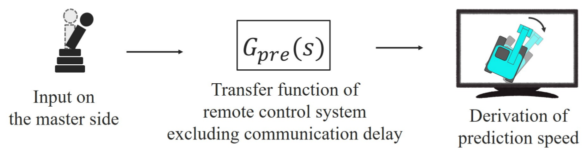

Figure 2. Derivation method of predicted turning speed

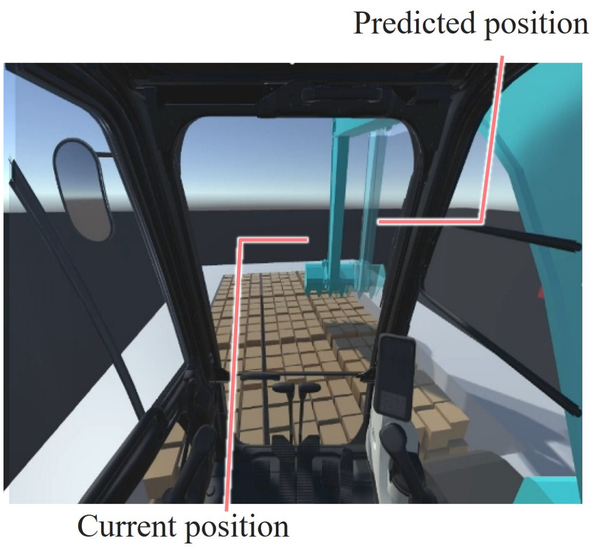

Figure 3. Presentation of predicted position of the attachment in the simulator

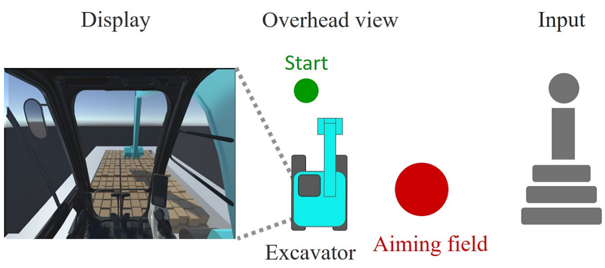

Figure 4. Initial state of the pointing task

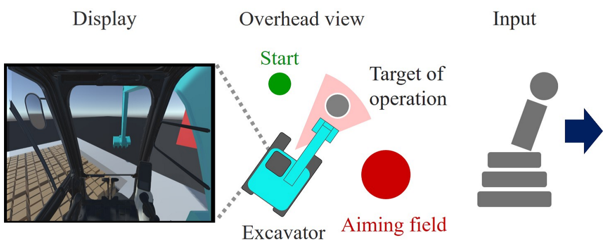

Figure 5. Turning operation state of the pointing task

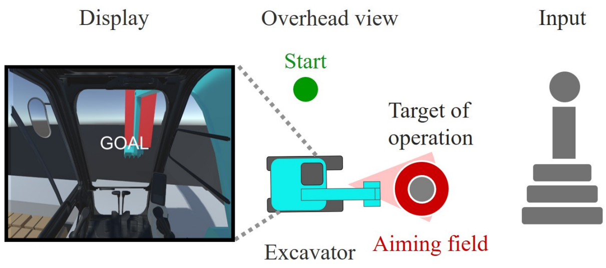

Figure 6. End state of the pointing task

3 Experiment

3.1 Procedure

Using the simulator, a pointing experiment was conducted, in which the bucket tip was turned to the red pole (target position) and stopped. The task started with the state shown in Figure 4 and the subject operated the joystick to turn the hydraulic excavator as shown in Figure 5. Once the target position was reached, the word "GOAL" was displayed on the screen as shown in Figure 6, indicating the completion of a task. The target positions were 30°, 60°, and 90° angles. These were used ten times each for thirty trials forming a task set, and the trial order was randomized. The measured items were the operation time of each task. The subjects performed the above set under the following three conditions.

1. Without dead time and without predicted position display (WOd+WOp)

2. With dead time and without predicted position display (Wd+WOp)

3. With dead time and with predicted position display (Wd+Wp)

Condition 1 assumes the case of operating an actual hydraulic excavator; condition 2 assumes the case of operating a teleoperated hydraulic excavator; condition 3 assumes the case of operating a teleoperated hydraulic excavator by overlapping the predicted position of the arm.

By comparing these three conditions, it was verified how close the working time approaches were in the boarding operation by overlapping the predicted position of the arm in the teleoperated system. Regarding L and T, we set them based on the assumption of an actual machine with a 13-ton excavator, as shown in Table 1, which presents all the relevant parameter values. The communication delay, L_1, was set to 0.26 (s). The subjects were ten healthy persons (Average age 22.7 ± 1.50 years). Before initiating the experiment, the subjects were instructed to finish the task as soon as possible and informed that the target position was on the right side. To eliminate the order effect, the execution order of the above three conditions were randomly made for each subject. Moreover, all subjects performed the test after sufficient practice and agreed to informed consent beforehand based on the Helsinki Declaration.

Table 1. Experiment parameters

	L(s)	T(s)
Acceleration	0.576	1.207
Deceleration	0.422	0.685

3.2 Result

The results of the simulation experiment were shown in Table 2 and Figure 7. For each condition and target position, the average operation time of each subject, as well as that of all subjects, were obtained. Applying the Fisher's LSD test ($\alpha = 0.05$ significant level) revealed that there existed significant differences between Wd + WOp and Wd + Wp at 30° and 90°. Furthermore, a significant difference between the conditions of WOd + WOp and Wd + WOp was confirmed at 30° and 90°. No significant difference was found between the WOd + WOp and Wd + Wp conditions. Detailed statistical results are given in Tables 3, 4, and 5.

Table 2. Result of the experiment

	WOd+WOp	Wd+WOp	Wd+Wp
30°	2.89 ± 0.51	3.93 ± 0.67	3.27 ± 0.67
60°	3.73 ± 0.41	4.17 ± 0.77	3.75 ± 0.59
90°	4.42 ± 0.49	5.69 ± 0.98	4.93 ± 0.63

Table 3. Result of the t-test (WOd+WOp, Wd+WOp)

	degree of freedom	p-value
30°	18	1.00×10^{-3}
60°	18	0.14
90°	18	1.00×10^{-3}

Table 4. Result of the t-test (Wd+WOp, Wd+Wp)

	degree of freedom	p-value
30°	18	3.0×10^{-2}
60°	18	0.15
90°	18	4.00×10^{-2}

Table 5. Result of the t-test WOd+WOp, Wd+Wp)

	degree of freedom	p-value
30°	18	0.20
60°	18	0.96
90°	18	0.16

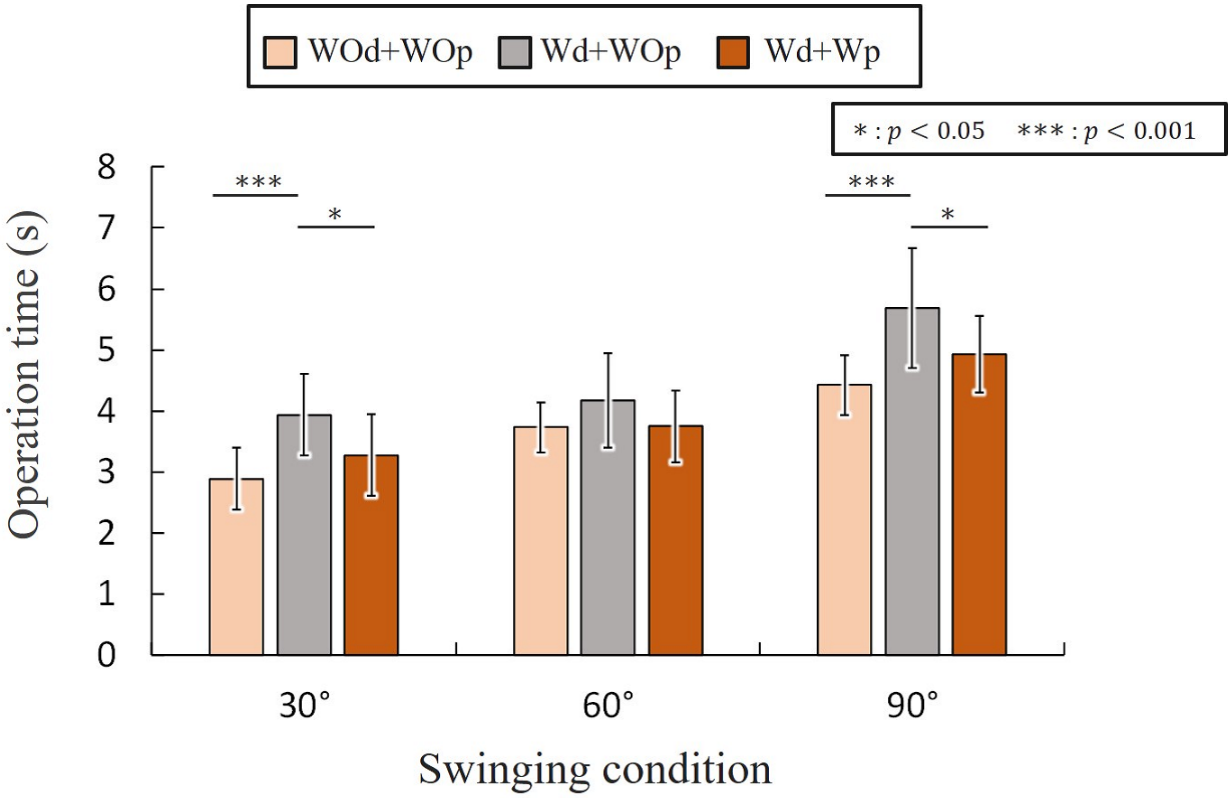

Figure 7. Result of the experiment

3.3 Discussion

This study verified the effectiveness of overlapping the predicted position of the arm in the turning operation using a simulator. The experimental results confirmed that the turning operation time was decreased at 30° and 90° by overlapping the predicted position on Wd + WOp. Moreover, the decreasing tendency of the operation time can be observed even at 60°, although the significance of this tendency could not be confirmed. As seen from Figure 7, it is confirmed that the operation time of Wd + Wp approached that of WOd + WOp. However, some subject commented after the trial that, "The predicted position was always overlapped, and I thought it was in the way.". We think that determining which position should be viewed and which should be operated was challenging when the predicted position overlapped with the current position. Therefore, the work efficiency is thought to be further improved by investigating the display technique of the prediction position, and that it may approach the turning work efficiency of WOd + WOp. Concretely, when the distance between the predicted position and the present position approaches, the predicted position will not be displayed.

4 Conclusion

In this study, the overlapping effects of the predicted position of the arm of the teleoperated hydraulic excavator was verified, during the turning operation, through simulation. The experimental results confirmed that the turning work efficiency, decreased by becoming tele-operational, approached the efficiency of the boarding operation by overlapping the predicted position of the arm. There is the problem of the predicted position on the screen blocking the current arm position. In the future, work efficiency could be further improved by examining the display technique. Furthermore, installing on the actual teleoperated system of the hydraulic excavator is a future investigation topic. With the moment of inertia changes caused by the inclination of the machine body and the weight of the loaded soil, it is necessary to improve the accuracy of the predicted arm position in the actual teleoperated system of the hydraulic excavator.

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