Reaching Difficulty Model of Swinging Operations of a Hydraulic Excavator Considering the First-Order Delay

K. Matsumura[a], M. Ito[b], C. Raima[b], S. Saiki[c], Y. Yamazaki[c], and Y. Kurita[b]

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

Abstract –

Hydraulic excavators are used for various purposes, such as excavation, dismantling, and leveling. The accurate positioning of the excavator is particularly important in loading operations, such as positioning a bucket immediately above a target. The positioning of a bucket via the swinging operation can also be regarded as a kind of pointing operation. There are the dynamic characteristics of hydraulic excavators. However, a pointing motion model that considers dynamic characteristics, such as delay, has not been proposed. In this study, the swinging operation of a hydraulic excavator was simulated and experiments were performed to clarify the relation between the dynamic characteristics of hydraulic excavators and their work efficiency. The dynamic characteristics of the swinging operation of the hydraulic excavator were assumed as a first-order system with dead time. Based on this result, a new difficulty model considering dead time and the time constant was proposed, and it was compared with the original Fitts' model based on the coefficient of determination. It was confirmed that the proposed model represented difficulty more accurately compared to the original Fitts' model.

Keywords –

Hydraulic excavator; Pointing; User Interface

1 Introduction

Hydraulic excavators (Figure 1), which are a type of construction machinery, are used for various purposes, such as excavation, dismantling, and leveling, because of many degrees of mechanical freedom and a variety of attachments. In recent years, teleoperated hydraulic excavators have been used at multiple disaster sites. These excavators are highly versatile. However, there are design problems based on ergonomics, such as the lack of feedback information and low visibility, and these problems reduce the work efficiency of excavators [1].

The operation of a hydraulic excavator in general civil engineering works is broadly divided into three operations, i.e., swinging, running, and excavation. Operators control hydraulic excavators using joysticks that are located close to their hands. When the swinging operation is carried out, according to the International Organization for Standardization, the swinging direction and swinging speed of a hydraulic excavator are determined by moving the left lever to the right or left. The accurate positioning of the excavator is particularly important in loading operations, such as positioning a bucket immediately above a target. Conventionally, the pointing operation involves pointing and selecting a target using a mouse or touchpad on a graphical user interface. However, the positioning of a bucket via the swinging operation can also be regarded as a kind of pointing operation. Hayashi and Tamura [2] experimentally investigated the pointing operation using a bucket to verify the effectiveness of the vibration of a joystick in a teleoperated hydraulic excavator system.

In our previous study [3], we developed a difficulty model that extends Fitts' law for the relationship between the range of view and work efficiency. The field of view affects the work efficiency of a hydraulic excavator when it performs the swinging operation. There is a boom on the right side of the driver's seat of the hydraulic excavator, and the field of view on the right side is narrower than that on the left side. Particularly in the case

Figure 1. Hydraulic excavator components

of teleoperation, the field of view is limited by the display range of the monitor. In addition, the dynamic characteristics of hydraulic excavators, such as dead time and inertia, cannot be neglected. The purpose of this study was to investigate the relationship between the dynamic characteristics and work efficiency of a hydraulic excavator. However, as it is difficult to change the dynamic characteristics of an actual hydraulic excavator, the swinging operation of a hydraulic excavator was simulated and experiments were performed. The dynamic characteristics of the swinging operation were assumed as a first-order system with dead time, and the time until turning to the target angle was measured for different dead times and time constants. Additionally, a difficulty model for estimating task time was proposed. By using this model, we can evaluate and increase the rotate work efficiency of the excavator.

2 Previous Studies on Pointing Motion Models

Numerous studies have attempted to model the difficulty of pointing motion. One of the existing models is Fitts' law, which models the relationship between the index of difficulty, ID, and the pointing time, MT, of a pointing task. According to Fitts' law, MT increases as the distance from the starting position to a target increases and the target size decreases. MacKenzie [4] improved Fitts' model and expressed the ID as follows:

$$ID = \log_2\left(\frac{D}{W} + 1\right) \quad (1)$$

where D is the pointing distance and W is the pointing size. MT tends to increase linearly with ID. This relationship can be expressed using experimentally obtained constants a and b, as follows:

$$MT = a + bID \quad (2)$$

Fitts' law was originally proposed as a simple motor response model with one dimension. MacKenzie [5] extended this model to consider two-dimensional pointing operations. Subsequently, Murata and Hirose [6] extended it to consider three-dimensional pointing operations. Various studies have extended Fitts' law to consider factors other than distance and size. Jax et al. [7] proposed the following equation to predict pointing time when pointing motion was performed on a curved line, OI, assuming that an obstacle existed:

$$MT = a + bID + cOI \quad (3)$$

where a, b, and c are experimentally obtained constants. Accot and Zhai [8] proposed an index of difficulty for the steering operation required by a vehicle passing an elongated path, such that the vehicle does not extend beyond the path's width.

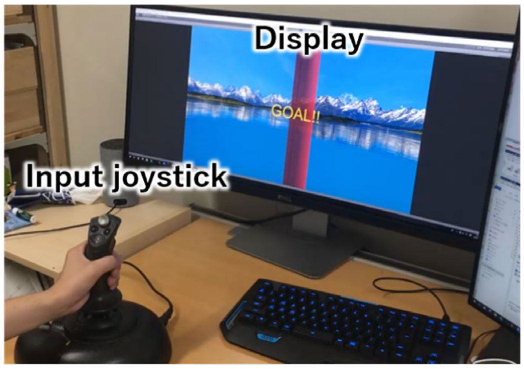

Figure 2. Swinging operation simulator

$$ID = \frac{D}{W} \quad (4)$$

MacKenzie and Buxton [9] proposed the following equation for extending Fitts' law to two dimensions. The equation incorporated the target width W and the target height H.

$$ID = \log_2\left(\frac{D}{\min(W, H)} + 1\right) \quad (5)$$

Bi et al. [10] conducted a pointing test using a smartphone-sized display and proposed a more accurate difficulty model for small displays. It is possible to evaluate the operability of pointing devices and environments using appropriately designed pointing difficulty models.

In our previous study [3], we attempted to model pointing motion considering the effect of the field of view. We created a simulation environment for swinging pointing operations and examined the relationship between the range of the field of view and pointing difficulty. Based on the results, the following equation, which incorporated the size, V, of the field of view, was proposed:

$$ID = \log_2\left(\frac{D}{W} \cdot \frac{D}{V} + 1\right) \quad (6)$$

To the best of our knowledge, a pointing motion model that considers dynamic characteristics, such as delay, has not been proposed. In this study, the swinging pointing operation with delay was simulated and the relationship between the delay parameter and pointing difficulty was investigated.

3 Approximation of Dynamic Characteristics of Hydraulic Excavator

A hydraulic excavator is operated using joysticks, and the angular velocity of the operated object changes according to the angle of the joysticks. The input from

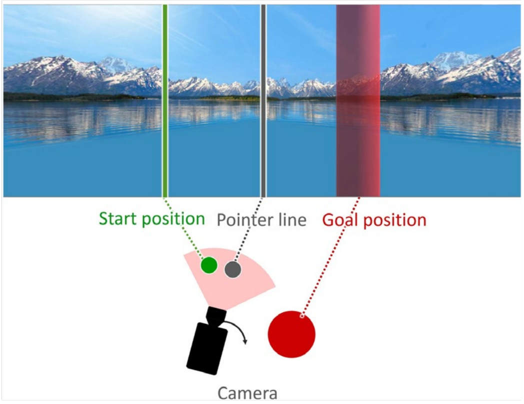

Figure 3. Display image of Simulator

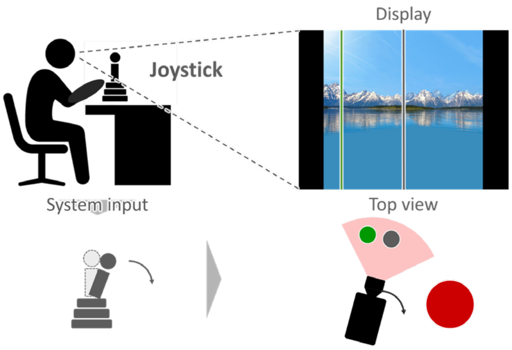

Figure 4. Task of simulation experiment

the joysticks causes attachments to move and swing through a hydraulic circuit and a hydraulic cylinder. Therefore, there is response delay. In this study, the dynamic characteristics, $G(s)$, of the swinging operation of the hydraulic excavator were assumed as a first-order system with dead time, as follows:

$$G(s) = \frac{K}{1+Ts}e^{-Ls} \tag{7}$$

where K is system gain, T is the time constant, and L is dead time. Dead time is the time elapsed from application of the input to the observation of the output, and the time constant is the constant about the rise time. We constructed a difficulty model that incorporated these parameters.

4 Experiments Using Swinging Pointing Simulator

4.1 Simulator Configuration

We created a system to simulate the swinging operation of hydraulic excavators to clarify the effect of dynamic characteristics. The system is shown in Figure 2; it consisted of a personal computer, a monitor, and an input joystick. The experimental system was created using Unity, which is a three-dimensional game engine. The start point, pointer line, and target area were displayed on the monitor, as shown in Figure 3. When the joystick was tilted, the camera in the Unity environment rotated according to the tilt direction and the angle of the joystick.

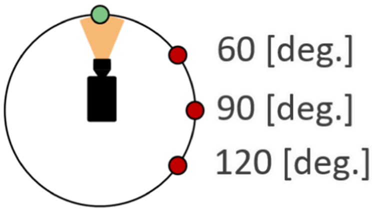

Figure 5. Target position

Table 1. Parameters of transfer function in simulation experiment

	Dead time (s)		Time constant (s)	
Condition	L_{acc}	L_{dec}	T_{acc}	T_{dec}
1	0	0	0	0
2	0.16	0.08	0.6	0.35
3	0.16	0.08	1.2	0.69
4	0.32	0.16	0.6	0.35
5	0.32	0.16	1.2	0.69
6	0.32	0.16	2.4	1.40
7	0.64	0.32	1.2	0.69
8	0.64	0.32	2.40	1.40

4.2 Experimental Protocol and Conditions

Experiments were performed with four participants (Sub. A to D). We recruited the participants from the students at Hiroshima University. Informed consent based on the Declaration of Helsinki was obtained from all participants prior to the experiments. The participants performed a swinging pointing task by viewing the image projected by the camera in the Unity environment (Figure 4). First, the camera pointed to the start point, which is indicated by the green line. The camera turned according to the operation of the joystick by the participants. The pointer line, which is indicated by the black line, existed at the center of the camera. The task was finished when the pointer was stopped in the target area, which is indicated in red. Prior to the task, the participants were informed that the target area exists in the right direction and that they must finish the task as quickly as possible. When one task was completed, it was displayed on the monitor that the task has been completed, and the next task was started after 1 (s).

The distance to the target, D, was defined as 60° ,

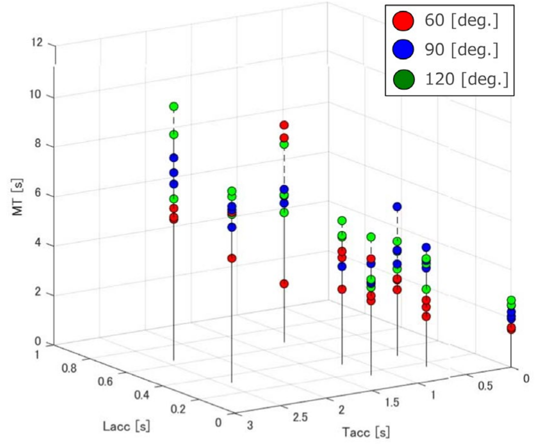

Figure 6. Experiment result (Sub. A)

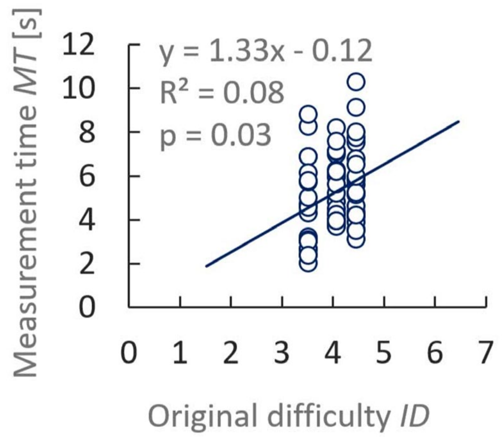

Figure 7. Correlation between index of difficulty ID and pointing time MT for original model

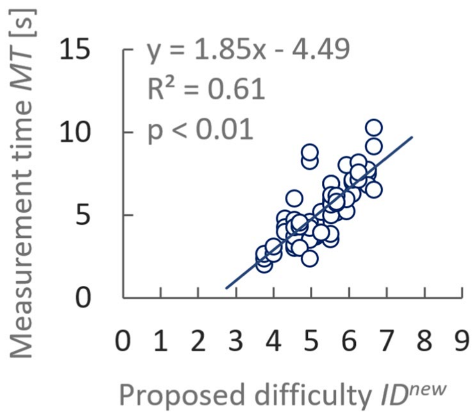

Figure 8. Correlation between index of difficulty ID^{new} and pointing time MT for proposed model

90°, and 120° (Figure 5). The values of the time constant, T, and dead time L are shown in Table 1. In the swinging of the hydraulic excavator, these parameters are different for acceleration and deceleration. The time constant and dead time were T_{acc} and L_{acc} for acceleration and T_{dec} and L_{dec} for deceleration, respectively. The target size, W, was 0.5 (m) and the range of the field of view was constant.

There were 24 experimental conditions, which were obtained based on the combination of three conditions of the distance to the target, D, and eight conditions of the dynamic characteristics. The order of the conditions was random for each participant. Each participant performed the task three times under each condition, and pointing time was measured. Participants practiced three times when conditions changed. The average pointing time calculated using the three measurements was considered as the pointing time under a particular condition.

4.3 Results

The experimental results for Sub. A are shown in Figure 6. This figure shows the pointing time, MT (s), under the target distance conditions of 60°, 90°, and 120° for the dead time, L_{acc} (s), and time constant, T_{acc} (s). It can be seen that the pointing time tends to increase as the distance to the target, D, increases, as in the original Fitts' law. Furthermore, it was confirmed that the pointing time increased with the time constant and dead time.

5 Modeling of Swinging Pointing Operations

5.1 Proposed Model

A new difficulty model is proposed based on the above results. The difficulty model incorporates dead time and the time constant for Fitts' model considering that pointing time increases with dead time and the time constant and difficulty increases with pointing time. The equation for the model is as follows:

$$ID^{new} = \log_2\left\{\frac{D}{W}(L_{acc} + L_{dec} + T_{acc} + T_{dec}) + 1\right\} \quad (8)$$

In this work, the coefficient of determination is used as an evaluation index, and the proposed model is compared with the original Fitts' model.

5.2 Evaluation of Proposed Model

Figures 7 and 8 show the relationship between the index of difficulty (horizontal axis) and pointing time (vertical axis) for Sub. A. The regression line and the coefficient of determination are shown. Figures 7 and 8 show are for the original and proposed models, respectively. The coefficient of determination for the

Table 2. Coefficient of determination (all subjects)

	Sub.A	Sub.B	Sub.C	Sub.D	Mean
for ID	0.076	0.078	0.073	0.063	0.073
for ID^{new}	0.61	0.45	0.34	0.35	0.44

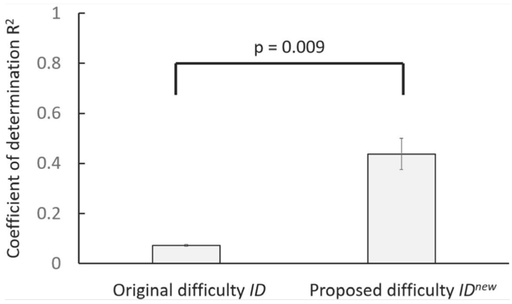

Figure 9. Comparison of coefficient of determination between original and proposed models

proposed model is R^2=0.61, which is higher than the coefficient of determination for the original model (R^2=0.08). Table 2 and Figure 9 show the coefficients of determination for all subjects and their mean values. The coefficient of determination for the proposed model is higher than that for the original model for all subjects. In addition, the average values of the coefficient of determination for the original and proposed models are compared using Student's t-test, and a statistically significant difference is observed (p=0.009).

6 Discussion and Conclusions

In this study, the swinging operation of a hydraulic excavator was simulated and experiments were performed to clarify the relation between the dynamic characteristics of hydraulic excavators and their work efficiency. The dynamic characteristics of the swinging operation were approximated as a first-order system with dead time, and the time until swinging to the target area was measured for different dead times and time constants. It was confirmed that pointing time increased with dead time and the time constant. Based on this result, a new difficulty model considering dead time and the time constant was proposed, and it was compared with the original Fitts' model based on the coefficient of determination. It was confirmed that the proposed model represented difficulty more accurately compared to the original Fitts' model. The original Fitts' model may not be applicable to the swinging operation of a hydraulic excavator because it does not consider response delay. The proposed model can be used to evaluate the performance of hydraulic excavators, and it is expected to improve their work efficiency. However, the size of the field of view is not considered in this study. It is necessary to develop and evaluate a model that considers the size of the field of view. In addition, the suitability of the proposed model must be confirmed in actual environments where hydraulic excavators are used.

References

[1] J. Akyeampong, S. Udoka, G. Caruso, and M. Bordegoni. Evaluation of hydraulic excavator human-machine interface concepts using NASA TLX. *International Journal of Industrial Ergonomics*, 44(3): 374–382, 2014. doi:10.1016/j.ergon.2013.12.002.

[2] K. Hayashi and T. Tamura. Teleoperation performance using excavator with tactile feedback. In *International Conference on Mechatronics and Automation*, pages 2759–2764, Changchun, China, 2009.

[3] K. Matsumura, M. Ito, S. Saiki, Y. Yamazaki, and Y. Kurita. Influence of restrictions on range of view from cockpit in operation of hydraulic excavator. *IEEE Access*, 8:90520–90527, 2020. doi:10.1109/ACCESS.2020.2994202.

[4] I. S. MacKenzie. Fitts' law as a research and design tool in human-computer interaction. *Human-Computer Interaction*, 7(1):91–139, 1992. doi:10.1207/s15327051hci0701_3.

[5] I. S. MacKenzie. A note on the information-theoretic basis for Fitts' law. *Journal of Motor Behavior*, 21(3):323–330, 1989. doi:10.1080/00222895.1989.10735486.

[6] A. Murata and H. Iwase. Extending Fitts' law to a three-dimensional pointing task. *Human Movement Science*, 20(6):791–805, 2001. doi:10.1016/S0167-9457(01)00058-6.

[7] S. A. Jax, D. A. Rosenbaum, and J. Vaughan. Extending Fitts' law to manual obstacle avoidance. *Experimental Brain Research*, 180(4):775–779, 2007. doi:10.1007/s00221-007-0996-y.

[8] J. Accot and S. Zhai. Beyond Fitts' law: Models for trajectory-based HCI tasks. In *Proceedings of ACM Human Factors in Computing Systems*, pages 295–302, Atlanta GA, USA, 1997. doi:10.1145/258549.258760.

[9] I. S. MacKenzie and W. Buxton. Extending Fitts' law to two-dimensional tasks. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, pages 219–226, Monterey CA, USA, 1992. doi:10.1145/142750.142794.

[10] X. Bi, Y. Li, and S. Zhai. FFitts law: Modeling finger touch with Fitts' law. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, pages 1363–1372, Paris, France, 2013. doi:10.1145/2470654.2466180.