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Design of a Database-Driven Excavation Assist Controller Based on the Velocity of the Center-of-Mass for a Hydraulic Excavator

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ABSTRACT In recent years, the working population in the construction industry has been declining. However, the number of construction works projects is increasing because of the increase in development and infrastructure maintenance. Therefore, it is necessary to meet this increasing demand with limited resources. Productivity at construction sites is significantly improved through the extensive use of hydraulic excavators. However, productivity is affected by the skill of excavator operator. In addition, it is difficult and time-consuming to learn the operation of the machines required to achieve an efficient level of work. Therefore, novice operators need support to achieve high productivity. In this study, the behavior of the combined center-of-mass of the excavator attachment as an index that expresses the difference in operating characteristics of operators for hydraulic excavators is focused. In addition, a control system that assists the operation in excavation work based on the velocity of the combined center-of-mass of the attachment is proposed. Furthermore, the database-driven control is applied to correspond to the nonlinear characteristics of a hydraulic excavator. The proposed method is implemented on a hydraulic excavator and its effectiveness is verified.

INDEX TERMS Assist control, center-of-mass, database-driven, excavation, hydraulic excavator.

I. INTRODUCTION

The construction industry has been highly active in recent years, and the number of construction projects is considerable owing to the development of new and repair of existing infrastructure. However, because of the significantly declining birthrates coupled with an aging population since the 1990s, the working-age population has been declining [1], [2]. In particular, the turnover of generations with skilled workers is considerable, and has contributed to the decrease in productivity at construction sites. To address this issue, the Ministry of Land, Infrastructure, Transport and Tourism (Japan) is promoting "i-Construction," a measure to increase productivity per worker by actively utilizing information and communication technology(ICT) and streamlining work [3], [4]. This initiative aims to introduce advanced technology to automate and simplify work requiring specialized expertise and human resources and turn a profession marked by the "3Ks" ("kitsui," "kiken," and "kitanai" meaning "demanding," "dangerous," and "dirty," respectively) into an appealing industry revolving around the "new 3Ks" ("kyuyo," "kyuka," and "kibo" meaning "pay," "vacation," and "prospects," respectively) [5]. The automation of construction machines and semiautomation of work have been widely studied worldwide [6]–[9]. However, these technologies can be applied mainly to large-scale construction sites, and many sites still rely on human judgment and operation. The reason for this is expensive equipment, and there are many nonstationary tasks that are difficult to automate. Hydraulic excavators, which significantly contribute to productivity, are becoming increasingly ICT-enabled; however, most of them are conventional machines and have similar problems. Therefore, measures to increase productivity are necessary, even where conventional machines are used. Previous studies have proposed control of the movement trajectory of excavator attachments [10]–[12], and cooperative control in specific

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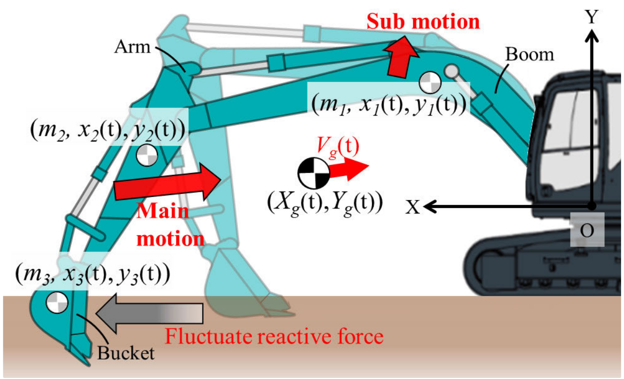

FIGURE 1. Attachment motions and combined CoM motion at the excavation work.

tasks [13]. As a result, anyone can perform the desired operation; however, it is necessary to set the target trajectory and coordinates determined by the operator in advance according to the work situation at the site. In addition, hydraulic excavators are generally controlled such that the horsepower does not exceed a set value and exhibits nonlinearity [14]. If the excavation load is large, it may not be possible to achieve the desired trajectory. Therefore, if operating characteristics are ideally controlled, instead of forced movement control, such as trajectory control, it is possible to assist the operator while maintaining the degree of freedom of the operation. Based on the aforedescribed background, an approach wherein the attachment system is represented by the combined center-of-mass (CoM) was proposed by the authors [15]. Regarding the CoM, many controls that improve robot movements and focus on zero-moment-point (ZMP) to suppress machine falls and improve safety have been proposed [16]–[19]. However, these do not affect human operations to improve productivity. On the other hand, a previous study by the authors clarified that CoM is a useful index to improve the motion of a hydraulic excavator (see Appendix and Ref. [15]).

In this study, a control system that assists a novice operator, based on the velocity of the combined CoM of the attachment, in the operation of excavation work is constructed. In addition, as the system characteristics of hydraulic excavators are nonlinear, a database-driven excavation controller that sequentially updates the controller parameters according to the operating point to achieve the desired excavation operation is proposed [20]. The database is learned offline using the fictitious reference iterative tuning (FRIT) method [21], [22]. The effectiveness of the proposed method was verified using a hydraulic excavator.

II. EXCAVATION CONTROL

A. CONTROL OBJECT

The attachment configuration of the hydraulic excavator is shown in Fig.1. The CoM of each element is combined with respect to the origin point O, which is the rotation axis of the boom, and the combined CoM coordinate is calculated using

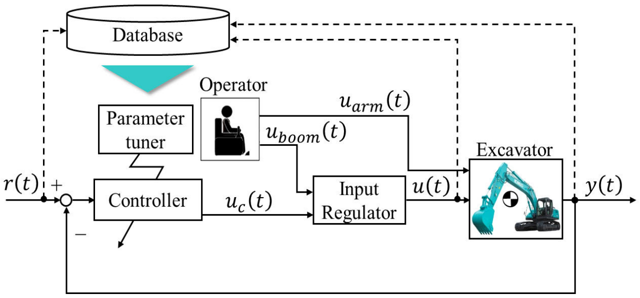

FIGURE 2. Block diagram of excavation assist control based on the CoM velocity using database-driven for a hydraulic excavator.

the following equation:

$$\left(X_g(t), Y_g(t)\right) = \left(\frac{\sum_{i=1}^{3} m_i x_i(t)}{m_1 + m_2 + m_3}, \frac{\sum_{i=1}^{3} m_i y_i(t)}{m_1 + m_2 + m_3}\right) \quad (1)$$

where, m_i is the mass of each attachment, $x_i(t)$ and $y_i(t)$ are the CoM coordinates of each attachment, and $i = 1, 2,$ and 3 indicate the boom, arm, and bucket, respectively. These parameters are known from the specifications of the hydraulic excavator, and the CoM coordinates at each time can be measured or calculated from the angle of the attachment or the length of the hydraulic cylinder. In addition, because the sediment weight in the bucket is expressed as the movement of the attachment, the sediment weight is ignored in the combined CoM calculation. Using the coordinates of the combined CoM obtained by (1), the combined CoM velocity $V_g(t)$ is obtained as follows:

$$V_g(t) = \sqrt{\frac{dX_g(t)^2}{dt} + \frac{dY_g(t)^2}{dt}} \quad (2)$$

Complex work is performed by combining multiple motions. For example, excavation work consists of the motions of the boom, arm, and bucket. In particular, boom and arm motions can be considered as the main motion and submotion, respectively. In this case, each velocity can be balanced using $V_g(t)$ as an index. In the case of the excavation work, when the arm-pull velocity decreases owing to the high excavation load, the boom-up operation is input to compensate for $V_g(t)$. Here, a boom-up is an operation that reduces the excavation load and contributes to the recovery of the arm-pull velocity. Novice operators find it difficult to handle the high response of a hydraulic excavator, and there is often excess operation when a high working velocity is required. Therefore, a control system shown in Fig.2 was constructed. Here, $u_{arm}(t)$ and $u_{boom}(t)$ are arm and boom inputs, respectively, by operators, and $u_c(t)$ is the boom input calculated by a controller. Here, $y(t)$ is attachment combined CoM velocity $V_g(t)$, and $r(t)$ is the reference velocity. To limit excess operation, the amount of boom-up operation $u(t)$ is calculated using the following equation:

$$u(t) = \min(u_{boom}(t), u_c(t)) \quad (3)$$

Thus, even novice operators who are not skilled at boom-up operations, which is an adjustment operation, can realize smooth excavation work while maintaining the velocity. In addition, it was experimentally determined that $V_g(t)$ has a steady state in cases of skilled operation; thus, this steady velocity is set as a reference value $r(t)$. In addition, this study features a control system in which the controller parameters are updated using a database to correspond to the nonlinearity of a hydraulic excavator. The details of the database-driven control are described in the following section.

B. CONTROLLER DESIGN

Noise and oscillations are likely to occur in the signal values of hydraulic excavators used for control because of the impact and hydraulic pulsations during their operations. Hence, when a controller has a derivative term, the oscillation is amplified, and the desired operation is difficult to achieve. Therefore, the following PI controller is used:

$$\Delta u_c(t) = K_p(t)\Delta e(t) + K_i(t)e(t) \tag{4}$$

$$e(t) := r(t) - y(t) \tag{5}$$

Here, $e(t)$ is the control error defined as the difference between the reference value $r(t)$ and the system output $y(t)$; $K_p(t)$ and $K_i(t)$ are the proportional and integral gains, respectively; and Δ represents a differencing operator defined as $\Delta := 1 - z^{-1}$.

C. DATABASE-DRIVEN CONTROL

This section details the database-driven control. The controller parameters $K_p(t)$ and $K_i(t)$ are adjusted based on the database-driven approach [20]. This adjustment method consists of the following three steps: 1) initial database construction, 2) offline database learning based on the FRIT method, and 3) implementing a learned database, and calculating $K_p(t)$ and $K_i(t)$ online. The adjustment method for the controller parameters is as follows;

1) CONSTRUCTION OF INITIAL DATABASE

The database-driven control was applied to the excavation control to correspond to the nonlinear system of a hydraulic excavator. Fig.3 shows a block diagram of the construction and offline learning of a database. First, an initial database was constructed to apply database-driven control. Using a PI controller with fixed parameters, the initial operational data $r(t)$, $u_0(t)$, and $y_0(t)$ were acquired, and the data at each time t were stored sequentially as follows:

$$\boldsymbol{\Phi}(t) = [\bar{\phi}(t), \boldsymbol{K}(t)], \qquad t = 1, 2, \ldots, N \tag{6}$$

Here, N is the total number of datasets, and $\bar{\phi}(t)$ and $\boldsymbol{K}(t)$ are defined as follows:

$$\bar{\phi}(t) := [r(t+1), r(t), y_0(t), \ldots, y_0(t-n_y+1), u_0(t-1), \ldots, u_0(t-n_u+1)] \tag{7}$$

$$\boldsymbol{K}(t) = [K_p(t), K_i(t)] \tag{8}$$

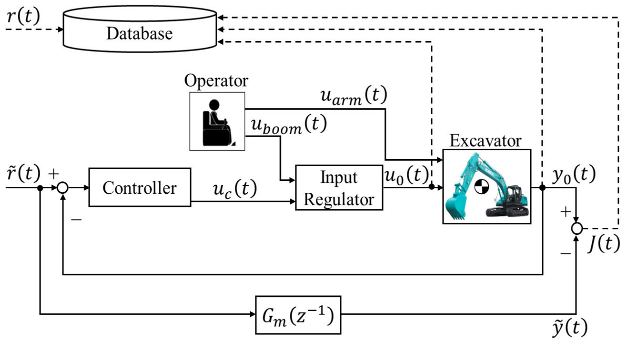

FIGURE 3. **Block diagram of offline learning a database using the FRIT method.**

where, n_u and n_y denote the degrees of $u(t)$ and $y(t)$, respectively.

2) COST FUNCTION

The initial database was learned offline using the FRIT method to achieve the desired dynamic characteristics [21]. The FRIT method is a technique for data-driven control, in which the control parameters are directly calculated from a set of operational data $(u_0(t), y_0(t))$. The method is suitable for application to the controller design of hydraulic excavators, in which the system modeling is difficult. Assuming the amount of boom-up operation during excavation as the input $u_0(t)$ and the attachment combined CoM velocity as the output $y_0(t)$, the fictitious reference input $\tilde{r}(t)$ is calculated from these data and (4) as follows:

$$\tilde{r}(t) = y_0(t) + \frac{1}{K_p(t)+K_i(t)}\Delta u_0(t) + \frac{K_p(t)}{K_p(t)+K_i(t)}(\tilde{r}(t-1) - y_0(t-1)) \tag{9}$$

Furthermore, the reference model $G_m(z^{-1})$, expressed as the desired characteristics, is designed as [23]:

$$G_m(z^{-1}) := \frac{z^{-(d+1)}P(1)}{P(z^{-1})} \tag{10}$$

$$P(z^{-1}) = 1 + p_1 z^{-1} + p_2 z^{-2}. \tag{11}$$

Here, $P(z^{-1})$ is a design polynomial defined as [23]

$$\left.\begin{aligned} p_1 &= -2\exp\left(\frac{-\rho}{2\mu}\right)\cos\left(\frac{\sqrt{4\mu-1}}{2\mu}\rho\right) \\ p_2 &= \exp\left(-\frac{\rho}{\mu}\right) \\ \rho &:= \frac{T_s}{\sigma} \\ \mu &:= 0.25(1-\delta) + 0.51\delta. \end{aligned}\right\} \tag{12}$$

where T_s is the sampling time, and σ and δ are the parameters for the response of the control system and attenuation characteristics, respectively, which are determined at the designer's discretion. Setting δ to $0 \leqq \delta \leqq 2$ is desirable, with $\delta = 0$ indicating a response equivalent to the Butterworth model and $\delta = 1$ indicating a response equivalent to a Binomial model. The fictitious reference input $\tilde{r}(t)$ is input into a designed reference model $G_m(z^{-1})$, and the reference model output $\tilde{y}(t)$ is obtained. $\tilde{y}(t)$ is calculated as follows, based on (9) and (10):

$$\tilde{y}(t) = -p_1\tilde{y}(t-1) - p_2\tilde{y}(t-2) + P(1)\tilde{r}(t-d-1) \tag{13}$$

Here, d is the dead time, and is known. In the FRIT method, cost function J is defined by the following equation:

$$J(t+1) := \frac{1}{2}(y_0(t+1) - \tilde{y}(t+1))^2 \tag{14}$$

At each time, a measure is adopted in which the control parameters are repeatedly updated around the operating point to obtain the desired control performance in a nonlinear system. Therefore, as shown in (14), the cost function is performed every time based on the square of the control error.

3) CALCULATION OF CONTROL PARAMETERS

The method of deriving the control parameters required for the calculation of the fictitious reference input $\tilde{r}(t)$ is shown. The distance d_s between the query $\bar{\phi}(t)$ at time t and each data set $\bar{\phi}(j)$ in the database is calculated by the following equation, and the data sets are sorted in ascending order of the distance;

$$d_s(\bar{\phi}(t), \bar{\phi}(j)) = \sum_{l=1}^{n_y+n_u+1} \left| \frac{\bar{\phi}_l(t) - \bar{\phi}_l(j)}{\max \bar{\phi}_l(m) - \min \bar{\phi}_l(m)} \right| \qquad j = 1, \ldots, N \tag{15}$$

Here, $\bar{\phi}_l(j)$ shown in (15) represents the l-th element in the j-th information vector of the database, and $\bar{\phi}_l(t)$ represents the l-th element of the query. In addition, $\max \bar{\phi}_l(m)$ and $\min \bar{\phi}_l(m)$ represent the maximum and minimum values of all the l-th elements in the database. Furthermore, among the sorted datasets, the datasets whose distance d_s obtained using (15) are smaller than the preset value are acquired as neighborhood datasets. From these neighborhood data, the control parameter $\boldsymbol{K}(t)$ at time t is calculated based on the following linear weighted average:

$$\boldsymbol{K}(t) = \sum_{i=1}^{n} w_i \boldsymbol{K}(i), \qquad \sum_{i=1}^{n} w_i = 1 \tag{16}$$

Here, w_i is a weighting coefficient, which is calculated and normalized by the following equation according to the magnitude of the distance d_s calculated based on (15):

$$w_i = \frac{\exp(-d_s(i))}{\sum_{i=1}^{n} \exp(-d_s(i))} \tag{17}$$

4) DATABASE LEARNING

The controller parameters, stored in the initial database, were assumed to be $\boldsymbol{K}^{old}(t)$ and updated with the following equation using the steepest descent method:

$$\boldsymbol{K}^{new}(t) = \boldsymbol{K}^{old}(t) - \boldsymbol{\eta}\frac{\partial J(t+1)}{\partial \boldsymbol{K}(t)} \tag{18}$$

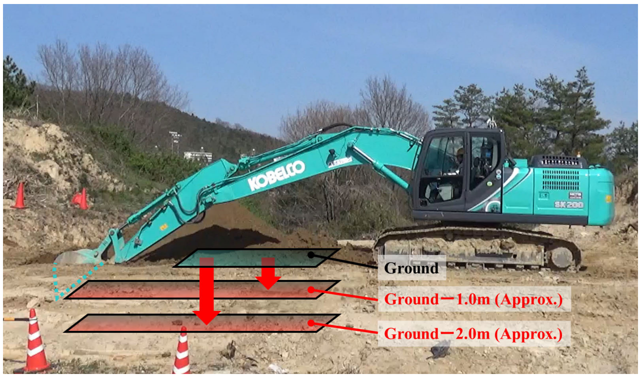

FIGURE 4. Initial posture.

$$\boldsymbol{\eta} := [\eta_p, \eta_i] \tag{19}$$

where, $\boldsymbol{\eta}$ is the learning coefficient vector. The gradient of each control parameter was calculated as follows:

$$\left.\begin{aligned} \frac{\partial J(t+1)}{\partial K_p(t)} &= \frac{\partial J(t+1)}{\partial \tilde{y}(t+1)} \frac{\partial \tilde{y}(t+1)}{\partial \tilde{r}(t)} \frac{\partial \tilde{r}(t)}{\partial K_p(t)} \\ \frac{\partial J(t+1)}{\partial K_i(t)} &= \frac{\partial J(t+1)}{\partial \tilde{y}(t+1)} \frac{\partial \tilde{y}(t+1)}{\partial \tilde{r}(t)} \frac{\partial \tilde{r}(t)}{\partial K_i(t)} \end{aligned}\right\} \tag{20}$$

Further details on the aforementioned partial differential equation can be found elsewhere [22]. The updated control parameters are calculated as $\boldsymbol{K}^{new}(t)$ and replaced with the control parameters of the neighborhood data in the database. Repeating steps 2) to 4) until the cost function J is sufficiently small at each time t, a database corresponding to the nonlinear system and realizing the desired dynamics can be obtained. By calculating the control gains using the learned database, gains that are an interpolation of the gain in the database are obtained.

III. VERIFICATION

A. EXPERIMENTAL CONDITION

The proposed method was applied to a hydraulic excavator and verified under the following conditions:

Initial posture)
The arm cylinder was fully retracted. The bucket tip was placed on the arm extension and ground. (see Fig.4).

Motions)
Excavation until the arm is vertical.

Operation)
Instantaneously input the maximum amount of both arm-pull and boom-up operations.

If the amount of operation $u_{boom}(t)$ is maximum at all times, the amount of operation $u_c(t)$ calculated by the controller is constantly selected by (3). Consequently, only the effectiveness of the boom-up operation assist in excavation work can be verified by the proposed method, without the influence of human operations.

By the way, the stability of this control system is briefly discussed below. The model to be controlled is unknown and its properties cannot be correctly described in the

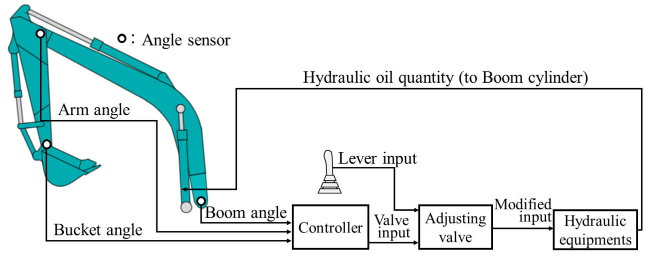

FIGURE 5. Schematic figure of hardware architecture for control system.

database-driven control applied in this study. Therefore, it is difficult to strictly prove the stability of the proposed control system. Although this issue remains, it has been confirmed that no unstable work occurred at all in actual operation. If the issue of the stability is occurred, it enables to ensure the stability by adjusting the parameter σ related to the responsiveness of the reference model $G_m(z^{-1})$ based on the results of the previous experiment.

In addition, a mechanism to adjust the operation amount is required to verify the proposed method. However, in the case of common hydraulic excavators using hydraulic pressure in the operation system, the operation amount cannot be controlled using only the equipment implemented in a hydraulic excavator. Therefore, a hydraulic excavator used for the experiment was modified by attaching hydraulic pressure adjusting valves that could be electrically controlled. The modified hydraulic excavator was based on SK200-10 (20t-class, standard model) [24] manufactured by KOBELCO Construction Machinery Co., Ltd. Fig.5 shows a schematic of the hardware architecture, and the boom input is modified by the adjusting valve. The detailed specifications of the valves and modifications deviated from the main purpose of this study and were thus omitted.

B. CONTROL RESULT

1) RESULT OF DIGGING CONTROL USING THE FRIT METHOD

Figs.6 and 7 show the results of the excavation work by a novice and by a skilled operator for comparison with the proposed method. Fig.6 illustrates the boom-up operation as an adjustment operation and that the $V_g(t)$ fluctuates. When an operator is regarded as a controller, the operation of the novice operator is mainly proportional action [25]. Therefore, it is considered that the result shown in Fig.6 does not correspond to the dynamic characteristics of the machine, and the lever operation becomes unstable. As a result, the $V_g(t)$, which indicates the movement of the attachment, is not constant but inefficient owing to the fluctuation movement. In contrast, it is confirmed that the skilled operator realized smooth lever operation and stable output, as shown in Fig.7. In the proposed method, the movement of the novice operator is improved, and the excavation is as smooth as that achieved by the skilled operator.

Figs.8 and 9 show the results of the excavation control based on the $V_g(t)$. The applied controller gains were adjusted using the FRIT method as follows:

$$K_p = 0.024, K_i = 0.014 \tag{21}$$

In addition, the FRIT method was applied considering the system as linear. These operations were performed by a novice operator. Here, the lever operations of the control input were normalized with the maximum operation amount, which was considered as 100%. The attachment combined CoM velocity of the system output was normalized with the reference velocity $r(t)$ as 100%. The experimental results from Figs.8 through 11 were processed similarly. Fig.8 shows that the response characteristics following the designed reference model output $y_r(t)$ were realized using the FRIT method. However, a slight overshoot is observed. Furthermore, Fig.9 shows the result excavated in a deeper range than in Fig.8. The overshoot in Fig.9 is larger than that shown in Fig.8. This is thought to be caused by fluctuations in the excavation reaction force, and the system characteristics change owing to the nonlinearity of the hydraulic excavator. In addition, repeated excavations led to the attachment initial posture gradually transitioning downward, and the effect of the reaction force direction and gravity changes. These are also nonlinearity factors. Therefore, although it is possible to locally obtain performance close to the desired output, linear controller is difficult to achieve with sufficient control performance according to each operation condition. An improvement of the excavation operation was attempted by using the proposed

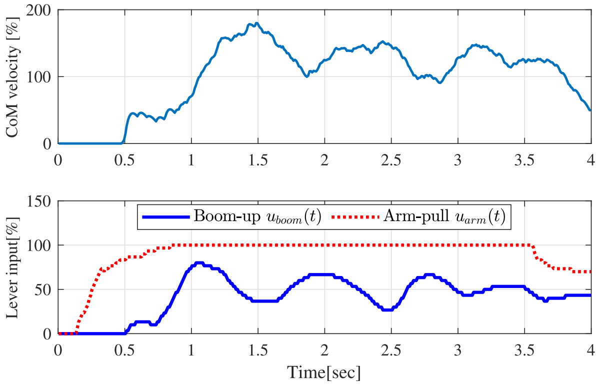

FIGURE 6. An example of manual operation by a novice operator.

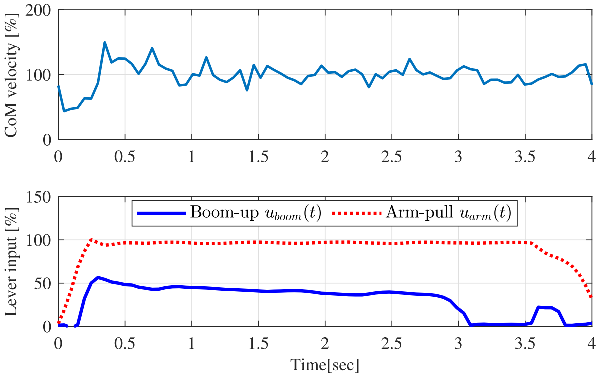

FIGURE 7. An example of manual operation by a skilled operator.

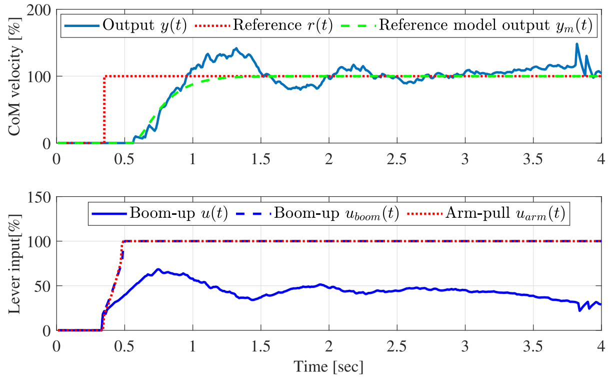

FIGURE 8. Experiment result of excavation at 1m depth using fixed PI controller tuned by the FRIT method.

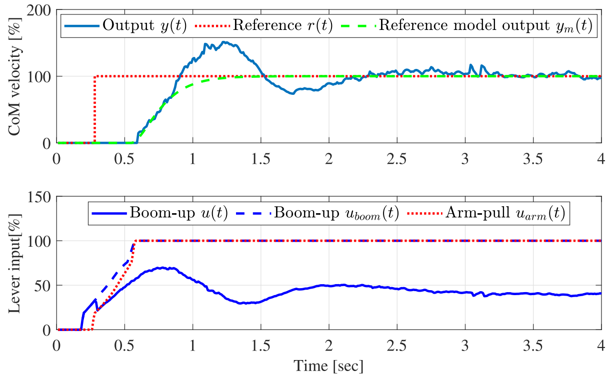

FIGURE 9. Experiment result of excavation at 2m depth using fixed PI controller tuned by the FRIT method.

TABLE 1. An example of database learning condition.

Sampling time [sec]	$T_s = 0.01$
Orders of the information vector	$n_y = 3$ $n_u = 2$
Number of data	$N = 1600$
Learning rates	$\eta_p, \eta_i = 0.00001$
Rise-time	$\sigma = 0.25$
Parameter related to damping property	$\delta = 0$
Number of learning	20

database-driven control to correspond with nonlinearity. In addition to the data in Figs.8 and 9, the input/output data $(u_0(t), y_0(t))$ obtained from several patterns of similar excavation operations were used to construct the database. Database learning was performed under the conditions listed in Table 1.

2) RESULT OF PROPOSED METHOD USING THE DD-FRIT

Figs.10 and 11 show the results of the input/output and controller parameters when the excavation is performed using the proposed method. The operator was the same novice operator who operated the experiments whose results are shown in Figs.8 and 9. Fig.10 shows that the controller parameters, $K_p(t)$ and $K_i(t)$, were sequentially adjusted to realize the appropriate boom-up operation $u_c(t)$, according to the operation points during excavation work. In addition, the attachment combined CoM velocity followed the reference model output $y_m(t)$ using the database-driven control. Compared to Fig.8, in which the control was performed with fixed controller parameters, the output fluctuations were

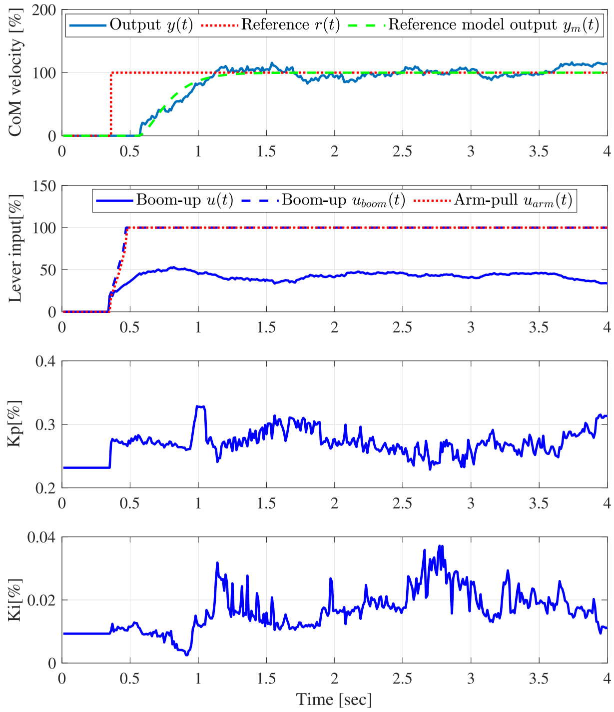

FIGURE 10. Experiment result of excavation at 1m depth using database-driven PI controller.

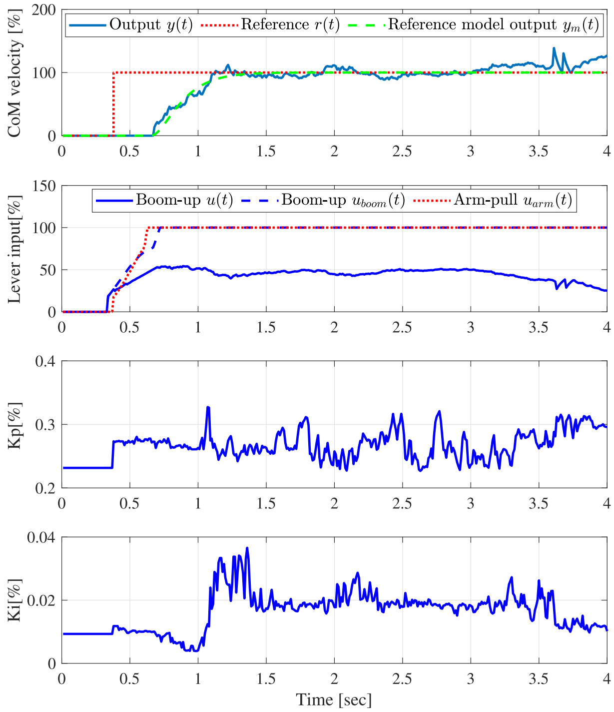

FIGURE 11. Experiment result of excavation at 2m depth using database-driven PI controller.

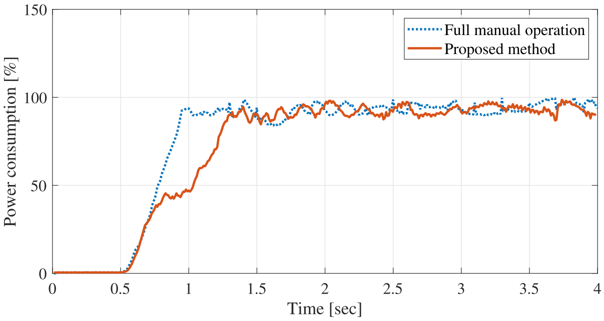

FIGURE 12. Comparison of power consumption of manual operation and proposed method during excavation work.

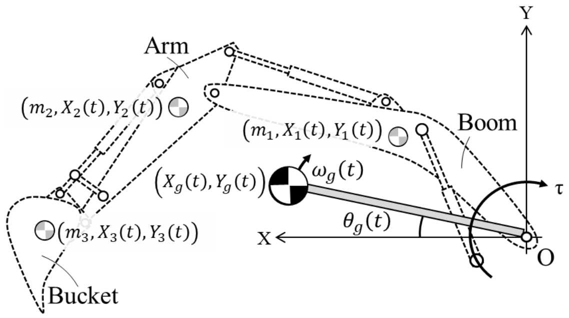

FIGURE 13. Attachment model expressed by the CoM.

clearly improved. In Fig.8, a maximum of 40% fluctuation due to overshoot occurred; however, in Fig.10, it was a maximum of 10%, and the control performance was improved. As shown in Fig.11, it is clear that the excavation velocity based on the combined CoM is steady and improved compared to Fig.9, even under conditions of greater excavation depth. Furthermore, Fig.12 shows the results of comparing the power consumption during the excavation. Here, the consumed power was normalized with the maximum consumed power during excavation, which was considered as 100%. As a result, it is confirmed that the consumed power in the section from 0.7 to 1.3 s of manual operation excavation by a novice operator is high. In contrast, it can be seen that the power consumption is reduced by approximately 5% by applying the proposed method. This is because the operation was assisted so that the attachment did not excessively bite into the soil. Based on the above results, the effectiveness of the desired excavation operation with operation assistance, even under nonlinear excavation conditions by applying the proposed method was confirmed, even for novice operators. Because the control performance depends on the adjustable parameters (included in Table 1) in database learning, it is necessary to consider these settings in future studies.

IV. CONCLUSION

In this study, an excavation assist controller based on the attachment combined CoM velocity for a hydraulic excavator is proposed. A database-driven approach was applied to the excavation control to improve the control performance of the nonlinear system. The proposed method was verified using a hydraulic excavator. The results demonstrate that a smooth excavation operation can be achieved even for novice operators.

In the future, studies will be conducted under conditions in which the manual operation $u_{boom}(t)$ fluctuates. Furthermore, the patterns of excavation data to be learned will be increased to improve the control performance and expand the applicable operations.

APPENDIX. CoM INDEX

For an index of skill difference and workability, there is an approach that evaluates the variation in the bucket tip trajectory during excavation work. However, as the trajectory changes every time, it is difficult to evaluate only the variation of the trajectory as an index. In addition, the index does not consider dynamics. Therefore, instead of the tip trajectory, the combined CoM of the attachment as the movement of the entire attachment is used.

Fig. 13 shows the attachment structure of the hydraulic excavator. The coordinates of the combined CoM of the attachment were calculated, and the movement of the combined CoM was expressed in a polar coordinate system. Because the problem is complicated when targeting multiple attachments, the boom-up / deceleration operation of the hydraulic excavator is targeted. The motion equation is expressed by the following equations:

$$\tau(t-L) = J_r \frac{d^2\omega(t)}{dt^2} + I\frac{d\omega(t)}{dt} + D_c\omega(t) \tag{22}$$

$$\omega_g(t) = \dot{\theta}_g(t) \tag{23}$$

$$\theta_g(t) = \tan^{-1}\frac{Y_g(t)}{X_g(t)} \tag{24}$$

Here, J_r, I, and D_c express the jerk, inertia, and damping coefficient, respectively. A transfer function $G(s)$ is a system that expresses the angular velocity $\omega_g(t)$ as an output and the rotational torque $\tau(t)$ as an input.

$$G(s) = \frac{1}{J_r s^2 + Is + D_c} e^{-Ls} \tag{25}$$

Here, the canonical form of the second-order plus dead-time system is as follows:

$$G(s) = \frac{K{\omega_n}^2}{s^2 + 2\zeta\omega_n s + {\omega_n}^2} e^{-Ls} \tag{26}$$

Therefore, compared to (25) and (26), the system attenuation coefficient ζ and natural angular frequency ω_n are obtained as follows:

$$\zeta = \frac{I}{2\sqrt{J_r D_c}} \tag{27}$$

$$\omega_n = \sqrt{\frac{D_c}{J_r}} \tag{28}$$

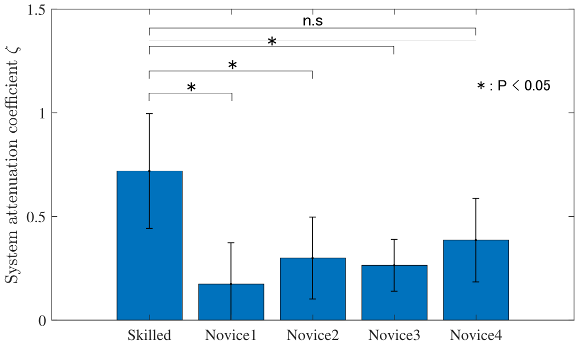

FIGURE 14. Estimated results of system parameter ζ.

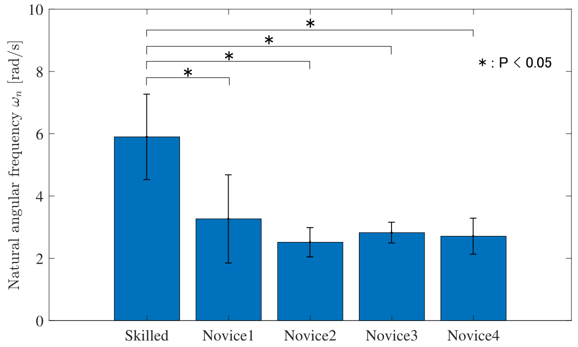

FIGURE 15. Estimated results of system parameter ω_n.

In the following condition, the difference in operation characteristics between skilled operator and novice operators is evaluated based on these system parameters.

Attachment posture)

Arm and bucket cylinder: Maximum contraction
Bucket: Grounded

Operation)

Boom-up deceleration operation from maximum velocity

Task)

Stop as fast and smooth as possible

This condition is difficult to stop because the actuator velocity and inertia are large. Because differences are likely to occur depending on the skill of the operator, an evaluation is performed in the deceleration section. In addition, the acceleration section is defined as the maximum operation, and it is not evaluated because there is no difference dependent on skill. The estimated results of ζ and ω_n are shown in Figs. 14 and 15, respectively. There was a clear difference in both ζ and ω_n between the skilled and novice operators, and a significant difference was observed in the t-test with a significance level of 5%. The ζ of the skilled operator is more than twice as large as that of the novice operator, indicating that the damping property when following the target is high. In addition, the ω_n of the skilled operator is approximately twice as large as that of novice operators, and it can be said that highly responsive operations can be realized. The aforedescribed results indicate that if the movement of the attachment is treated as the movement of the combined CoM, the characteristics of the operation are expressed in the system parameters. Therefore, it was suggested that in a system expressed by the combined CoM of attachment, if the work of novice operators is appropriately supported based on the CoM behavior, the work of the skilled operator can be realized.

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