Abstract. Recently, the increase of burden to operators and lack of skilled operators are the issue in the work of the hydraulic excavator. These problems are expected to be improved by autonomous control. In this paper, we present experimental results of hydraulic excavators using model predictive control (MPC) which incorporates servo mechanism. MPC optimizes digging operations by the optimal control input which is calculated by predicting the future states and satisfying the constraints. However, it is difficult for MPC to cope with the reaction force from soil when a hydraulic excavator performs excavation. Servo mechanism suppresses the influence of the constant disturbance using the error integration. However, the bucket tip deviates from a specified shape by the sudden change of the disturbance. We can expect that the tracking performance is improved by combining MPC and servo mechanism. Path-tracking controls of the bucket tip are performed using the optimal control input. We apply the proposed method to the Komatsu-made micro hydraulic excavator PC01 by experiments. We show the effectiveness of the proposed method through the experiment of digging soil by comparing servo mechanism and pure MPC with the proposed method.

1. Introduction
A hydraulic excavator executes digging operation for construction and road works etc. The digging operation must perform an accurate excavation against the specified shape. For example, there is a possibility that the hydraulic excavator accidentally hurts a water pipe which is in a ground when it digs deeper than the specified shape. The accurate excavation is important. However, a skilled operator is necessary for an accurate operational technique, because the digging operation needs the simultaneous movement of the boom, arm and bucket by a complex operation. Additionally, a burden to the operator is increased, because a work of poor working conditions is increased. However, the skilled operator who performs the accurate operation is decreasing in recent years. Then, a study of an autonomous action for the hydraulic excavator is being performed as the way to solve these problems [1][2][3]. An inexperienced operator can execute the digging operation in the same way as the skilled operator by the automation. Thus, the automation can alleviate the burden to the operator. In addition, there are many studies about the hydraulic excavator in a wide variety. For instance, they are the remote control [4][5], the trajectory generation [6] and the energy saving [7][8] etc.

We consider the path-tracking control which assumes the digging operation which is the main motion of the hydraulic excavator as the study of the automation action. The action plan is necessary in order to perform the digging operation [9][10]. Additionally, it is necessary for us to consider the action way
when the digging operation of the hydraulic excavator is performed. The skilled operator executes the tracking control by the efficient way of the action [11]. Thus, we can execute the efficient way of the automation action by analyzing how the skilled operator operates [10]. However, the tracking control fails when contacting to the unknown object which is difficult to detect. Thus, the autonomous action of the hydraulic excavator is necessary for a robust tracking control against various disturbance. Ha and Rye [12] realized the tracking control using sliding mode control (SMC) and demonstrated that the chattering of the control input was suppressed by using fuzzy control. Additionally, Choi [13] performed the chattering suppression by the time-varying of the sliding surface. However, it is difficult for SMC to perform the accurate tracking control due to the sudden input change which occurs by contacting the unknown object. Servo mechanism uses the error integration for feedback control to cope with the steady-state error caused by the digging resistance (disturbance) [14]. However, when the bucket tip is stuck due to the disturbance, the error integration grows rapidly and may result in the excessive control input.

We previously proposed the trajectory tracking control using the model predictive control (MPC) as the method of the optimization which considered the constraints to suppress the deviation from the specified shape. We verified the effectiveness by the simulation and experiment [15][16]. MPC is the control method that obtains the control input by the optimization calculation which predicts the state until finite-time future and can consider the constraint. Thus, MPC can perform the tracking control which considers the movable range of the controlled object and the maximum output of the actuator. The tracking performance of MPC can be perturbed by the unknown disturbance, because MPC predicts the future motion based on the model. To overcome this difficulty, combining MPC and servo mechanism have been proposed in our study [17]. In [17], the verification of the proposed method has been performed by using simulations which assumes the unknown disturbance. As the result, we have confirmed that it is possible to perform the trajectory tracking control which suppresses the influence of the unknown disturbance and predicts the future state, by combining MPC and servo mechanism. Still we have not performed the confirmation that the method is effective to the digging operation of the hydraulic excavator in the experiment.

In this paper, we show the effectiveness of the proposed method by comparing three methods using the experiment which digs the soil. We perform the tracking control against the specified shape by the simultaneous operation of the boom, arm and bucket.

2. Model of hydraulic excavator

2.1. Experimental equipment

The experimental equipment used in this study is the Komatsu-made micro hydraulic excavator PC01 depicted in Fig. 1. We construct the feedback control system as shown in Fig. 1 by attaching to the hydraulic excavator the potentiometer, the servo valve and the servo amplifier. The potentiometer measures the cylinder displacement, the servo valve adjusts the hydraulic oil flow and the servo amplifier amplifies the input signal. The schematic diagram of the control system is depicted in Fig. 2. The flow for operating the hydraulic excavator is as follows. We amplify the input signal obtained by the optimization calculation and perform the motion of the boom, arm and bucket cylinder by adjusting the hydraulic oil flow using the servo valve. Then, we measure the cylinder displacement by the potentiometer which is attached to each cylinder of the hydraulic excavator and perform the control by feedback.

2.2. Model of a cylinder

In this study, we consider the digging operation by modeling the controlled object depicted in Fig. 1. As shown in Fig. 3, the controlled object is the closed-loop system including P control. Since it is not easy to develop a detailed model of the hydraulic excavator, we perform the model identification of each cylinder from the relationship between the input signal and the output signal using the data obtained by the experiment. In this study, the model is constructed as a second-order lag system.
Figure 1. Komatsu-made micro hydraulic excavator PC01.

Figure 2. Constitution of experimental device.

Figure 3. Closed-loop control system.

Table 1. Parameters of the hydraulic cylinders.

|     | boom   | arm    | bucket |
|-----|--------|--------|--------|
| $a_1$ | 51.918 | 127.349| 133.129|
| $a_2$ | 11.564 | 17.809 | 17.892 |
| $b$   | 51.336 | 128.094| 133.418|

The model of each cylinder is as follows:

\[
\begin{align*}
\dot{x}_i(t) &= \begin{bmatrix} 0 & 1 \\ -a_{1,i} & -a_{2,i} \end{bmatrix} x_i(t) + \begin{bmatrix} 0 \\ b_i \end{bmatrix} u_i(t), \\
y_i(t) &= \begin{bmatrix} 1 & 0 \end{bmatrix} x_i(t),
\end{align*}
\]

where $u_i$ is the control input, $x_i := [\xi_i \ \dot{\xi}_i]^T$ is the state vector. $\xi_i$ and $\dot{\xi}_i$ are the cylinder displacement and velocity, respectively. In this paper, we express each cylinder as $i = \text{boom, arm, bucket}$. Parameters of each cylinder model are listed in Table 1.

2.3. Inverse kinematics

In this study, we set the digging shape of the target and consider the tracking control of the bucket tip to this shape. However, the control uses the cylinder displacement as the state variable of the model. Thus, the control cannot be performed directly from the shape of the target which is indicated by the X-Y coordinates. We give the target values of the coordinate and the attitude angle of the bucket tip, $(x, y, \theta)$. From these values, we calculate the cylinder displacements of the target using inverse kinematics. Figure 4 depicts the configuration of the boom, arm and bucket with the definitions of the
angle and the length, which leads kinematic relation as follows:

\[ x = L_1 \sin \theta_1 + L_2 \sin(\theta_1 + \theta_2) + L_3 \sin(\theta_1 + \theta_2 + \theta_3), \]  
(3)

\[ y = L_1 \cos \theta_1 + L_2 \cos(\theta_1 + \theta_2) + L_3 \cos(\theta_1 + \theta_2 + \theta_3), \]  
(4)

\[ \theta = \theta_1 + \theta_2 + \theta_3. \]  
(5)

We calculate \( \theta_1, \theta_2 \) and \( \theta_3 \) from the relationship of the equations (3), (4) and (5). Next, we calculate geometrically each cylinder displacement \( x_i \) by using cosine theorem [17]. We control each cylinder displacement using these values as the target values.

**Figure 4.** Definition of angles and lengths.

3. Servo mechanism[14]

Servo mechanism is the control method to suppress the steady-state error due to the constant disturbance by the feedback of error integration. Servo controller can be designed for the augmented plant combining the state equation (1) with the error integration as follows:

\[
\dot{x}_i(t) = \begin{bmatrix} 0 & 1 & 0 \\ -a_{1,i} & -a_{2,i} & 0 \\ -1 & 0 & 0 \end{bmatrix} x_i(t) + \begin{bmatrix} 0 \\ b_i \\ 0 \end{bmatrix} u_i(t) + \begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix} u_{r,i}(t),
\]  
(6)

\[
u_i(t) = -f_i x_i(t),
\]  
(7)

where the feedback gain \( f_i \) which is used for determining the input is calculated by optimal regulator theory.

4. Model predictive control

4.1. Outline

Model predictive control (MPC) predicts the state until finite-time future and is a kind of optimal control method to calculate the control input which minimizes the index function. Additionally, MPC can calculate the control input which satisfies the constraints. MPC had problem of the computational cost to execute the optimization calculation on the real time, but it has been actively studied and improved by the recent development of computer and algorithms [18]. In this study, we use CVXGEN of Mattingley et al [19] as the solver in order to process the computation at high speed. CVXGEN can solve the quadratic programming problem and can consider the linear constraint. In this paper, the optimal input is decided in order to perform tracking control of the bucket tip using MPC.

The equation (1) is the continuous state equation. Then, we discretize the equation (1) with the sampling interval \( \Delta t \) to apply MPC as follows:

\[
x_i[k+1] = \begin{bmatrix} 1 \\ -a_{1,i}\Delta t & 1 - a_{2,i}\Delta t \end{bmatrix} x_i[k] + \begin{bmatrix} 0 \\ b_i\Delta t \end{bmatrix} u_i[k].
\]  
(8)
4.2. Index function
The index function of MPC $J_{M,i}$ is defined as follows:

$$J_{M,i} = \psi_{M,i}(x_i[T]) + \sum_{k=0}^{T} \eta_{M,i}(x_i[k], u_i[k]),$$

where $T$ is the horizon, $\psi_{M,i}$ is the terminal cost and $\eta_{M,i}$ is the stage cost. $\psi_{M,i}$ and $\eta_{M,i}$ are shown as follows:

$$\psi_{M,i}(x_i[T]) = e_i[T]^T Q_{M,i} \psi_i[T],$$
$$\eta_{M,i}(x_i[k], u_i[k]) = e_i[k]^T Q_{M,i} e_i[k] + P_{M,i}(u_i[k] - u_{ri}[k])^2,$$

where $e_i = x_i - x_{ri}$ is the difference between the state vector $x_i$ and the target state vector $x_{ri}$, $u_{ri}$ is the target displacement of each cylinder. $Q_{M,i}$ and $Q_{M,i}$ are the weighting matrices to evaluate the error of the state vector. $P_{M,i}$ is the weighting matrix to evaluate the error of the input. In this time, the weighting matrices are positive semidefinite matrices.

4.3. Constraint of movable range
We consider the parallel straight line to the target shape as the constraint for the movable range of the bucket tip. Thus, the bucket tip does not move below the parallel straight line, because the constraint of the inequality expression (12) is given ($L, M, N$ are the coefficients).

$$Lx + My + N \geq 0.$$ (12)

In this study, each cylinder uses the cylinder displacement $\xi_j$ as the state variable. The equations (3) and (4) become the non-linear equations by showing about the cylinder displacement $\xi_j$, as follows:

$$x = h_x(\xi_{boom}, \xi_{arm}, \xi_{bucket}), \quad y = h_y(\xi_{boom}, \xi_{arm}, \xi_{bucket}).$$ (13)

However, CVXGEN which is the computation tool of MPC needs to use linear constraints. Thus, we linearize equations (13) using Taylor expansion of the equation (14) and obtains equations (15) and (16).

$$\gamma = \frac{\partial h_y}{\partial \xi_{boom}} (\xi_{boom} - \bar{\xi}_{boom}) + \frac{\partial h_y}{\partial \xi_{arm}} (\xi_{arm} - \bar{\xi}_{arm}) + \frac{\partial h_y}{\partial \xi_{bucket}} (\xi_{bucket} - \bar{\xi}_{bucket}) + h_y(\bar{\xi}_{boom}, \bar{\xi}_{arm}, \bar{\xi}_{bucket}),$$

$$x \approx \eta_{x1}\bar{\xi}_{boom} + \eta_{x2}\bar{\xi}_{arm} + \eta_{x3}\bar{\xi}_{bucket} + \eta_{x4},$$
$$y \approx \eta_{y1}\bar{\xi}_{boom} + \eta_{y2}\bar{\xi}_{arm} + \eta_{y3}\bar{\xi}_{bucket} + \eta_{y4}.$$ (15) (16)

We insert the linearized equations into inequality equation (12). The inequality expression of constraint is obtained using coefficients $\kappa_1, \cdots, \kappa_4$ as follows:

$$\kappa_1 \bar{\xi}_{boom} + \kappa_2 \bar{\xi}_{arm} + \kappa_3 \bar{\xi}_{bucket} + \kappa_4 \leq 0.$$ (17)

We get the parallel straight line at the vertical direction downward against the target shape of the straight line. Therefore, we set the maximum movable range of the bucket tip as the constraint.
5. Proposed method
5.1. Outline
The main purpose of hydraulic excavator is the digging operation. The resistance (disturbance) from the soil occurs when the hydraulic excavator performs the digging operation. MPC cannot cope with the influence of the unknown disturbance, because MPC is the model-based control. We perform the optimal control which suppresses the influence of the unknown disturbance and predicts the future state, by combining MPC and servo mechanism.

5.2. Model predictive control with servo mechanism (MPCS)
Because the state equation of servo mechanism used in MPCS is shown by the continuous system, we discretize the equation (6) with the sampling interval $\Delta t$ to apply MPC as follows:

$$\bar{x}_i[k+1] = \begin{bmatrix} 1 & \Delta t & 0 \\ -a_{1i}\Delta t & 1 - a_{2i}\Delta t & 0 \\ -\Delta t & 0 & 1 \end{bmatrix} \bar{x}_i[k] + \begin{bmatrix} 0 \\ 0 \\ b_i\Delta t \end{bmatrix} u_i[k] + \begin{bmatrix} 0 \\ 0 \\ \Delta t \end{bmatrix} u_{r,i}[k]. \quad (18)$$

The index function of MPCS $J_{MS,i}$ is defined as follows:

$$J_{MS,i} = \psi_{MS,i}(\bar{x}_i[T]) + \sum_{k=0}^{T} \eta_{MS,i}(\bar{x}_i[k], u_i[k]), \quad (19)$$

where $\psi_{MS,i}$ is the terminal cost and $\eta_{MS,i}$ is the stage cost. $\psi_{MS,i}$ and $\eta_{MS,i}$ are shown as follows:

$$\psi_{MS,i}(\bar{x}_i[T]) = \bar{e}_i[T]^T Q_{MS,i} \bar{e}_i[T], \quad (20)$$
$$\eta_{MS,i}(\bar{x}_i[k], u_i[k]) = \bar{e}_i[k]^T Q_{MS,i} \bar{e}_i[k] + P_{MS,i}(u_i[k] - u_{r,i}[k])^2, \quad (21)$$

where $\bar{e}_i = \bar{x}_i - \bar{x}_{r,i}$ is the difference between the state vector $\bar{x}_i$ and the target state vector $\bar{x}_{r,i}$. $Q_{MS,i}$ and $P_{MS,i}$ are the weighting matrices to evaluate the error of the state vector. $P_{MS,i}$ is the weighting matrix to evaluate the error of the input. In this time, the weighting matrices are positive semidefinite matrices.

The constraint of MPCS is given to the movable range of the bucket tip as with MPC.

6. Experiment
6.1. Experimental condition
Figure 5 shows the appearance of the experiment. We put pea gravels of 5 mm~15 mm into a container and dig the gravels by the hydraulic excavator. We show the flow of the control in Fig. 6. We calculate the $(x, y)$ coordinates of the bucket tip from the values of the current cylinder displacements using the forward kinematics. To achieve path-tracking control for the tip of bucket, we set the target of $x$ to be 5 mm ahead from the present tip position and set the target $y$ which corresponds to the target value of $x$. The target attitude angle of the bucket is $\theta = 2.827$ rad. The target cylinder displacements are obtained by the inverse kinematics from them, and the optimization calculation is performed by MPC. The obtained optimal control signal is amplified by the servo amplifier, and each cylinder is operated by adjusting the oil flow to the cylinder by the servo valve. In this time, each cylinder displacement is measured by the potentiometer, and the hydraulic excavator is controlled by feedback.

The digging shape is depicted in Fig. 7 where the constraint is set to be below the desired path by $d$ mm. Table 2 lists parameters of the experiment. The block of iron is put on the reference path like Fig. 5. In this experiment, the bucket is supposed to dislodge the block of iron. We intend to test the effectiveness of the proposed method by comparing tracking performances of servo mechanism, MPC and MPCS.
6.2. Experimental result

We demonstrated path-tracking control using servo mechanism, MPC and MPCS. In this experiment, path-tracking control starts after staying at the initial position for 2 s.

The movement locus of the bucket tip against the reference path is depicted in Fig. 8. The time variations of X coordinates are depicted in Fig. 9(a), Fig. 10(a) and Fig. 11(a). The time variations of Y coordinates are depicted in Fig. 9(b), Fig. 10(b) and Fig. 11(b). The control inputs of each cylinder are depicted in Fig. 9(c), Fig. 10(c) and Fig. 11(c). The generated forces of each cylinder are depicted in Fig. 9(d), Fig. 10(d) and Fig. 11(d). In this time, the direction to push the cylinder rod is defined as positive. The time variations of the error integrations in servo mechanism and MPCS are depicted in Fig. 12. The iteration counts of MPC and MPCS are depicted in Fig. 13.

From Fig. 8, servo mechanism can remove the influence of the unknown disturbance by error integration. However, the deviation of the path by the influence of the error integration is observed when the influence of the disturbance is eliminated. On the other hand, MPC cannot dislodge the block of iron, because MPC cannot remove the influence of the unknown disturbance. Then, the hydraulic excavator stops the movement in Fig. 8(b). Additionally, the reference path stops, because it is calculated using forward kinematics from the current state of the hydraulic excavator. MPCS can dislodge the block of iron, because MPCS performs the error integration the same as servo mechanism. Additionally, MPCS does not cause the sudden deviation when hydraulic excavator dislodges the block of iron, because MPCS predicts the state after the disturbance is removed.

From Fig. 9(a), Fig. 10(a) and Fig. 11(a), we confirm that they track the reference path. However, from Fig. 9(b), Fig. 10(b) and Fig. 11(b), we confirm that the path by each method deviates from the reference path by the influence of the disturbance. Additionally, it is confirmed that the error of MPC
Table 2. Experiments condition.

| Parameter               | Value                                      |
|-------------------------|--------------------------------------------|
| Initial tip position ($x_0$, $y_0$, $\theta$) | (1300 mm, -140 mm, 2.827 rad)             |
| Step width $\Delta t$  | 0.05 s                                     |
| Horizon $T$             | 5                                          |
| Reference path         | $y=x-1440$                                 |
| Constraint range $d$   | 15 mm                                      |
| Target distance        | 5 mm                                       |
| Servo mechanism        | $\vec{f}_{\text{boom}}$ = [0.652 0.051 3.162] |
|                        | $\vec{f}_{\text{arm}}$ = [0.422 0.022 3.162] |
|                        | $\vec{f}_{\text{bucket}}$ = [0.408 0.021 3.162] |
| MPC                     | $P_{M,i}$ = 1000                           |
|                        | $Q_{M,i}$ = diag(1000,100)                 |
|                        | $Q_{Mf,i}$ = diag(10,1)                    |
| MPCS                    | $P_{MS,i}$ = 500                           |
|                        | $Q_{MS,i}$ = diag(1,1,10000)               |
|                        | $Q_{MSf,i}$ = diag(5000,1,3000)            |

against the reference path remains. On the other hand, the bucket tip converges to the reference path for MPCS and servo mechanism, because they perform the error integration.

From Fig. 9(c), Fig. 10(c) and Fig. 11(c), it is confirmed that the change of the input in MPC occurs when the bucket tip contacts with the block of iron. On the other hand, it is confirmed that the change of the input in servo mechanism occurs in order to dislodge the block of iron. The input increases by accumulating the error integration as shown in Fig. 12. Then, the sudden change occurs after the block of iron is removed due to the accumulation of the error integration. The sudden change of the input does not occur in MPCS, because it predicts the future state and adds the input which suppresses the influence of the disturbance by the effect of the integration.

In Fig. 9(d) and Fig. 11(d), the generated force of the boom cylinder changes to the reverse direction after the block of iron is removed. We confirm that MPC can get the solution by the optimization calculation, because the iteration count is less than 25 counts which is maximum count. In Fig. 13(b), the iteration count increases, because the path deviates from the reference and reaches to the constraint after the block of iron is removed.

Each method is tested three times by experiment. In this time, maximum path errors of servo mechanism and MPCS are depicted in Fig. 14. Despite three times experiments, the result of MPC is not depicted in Fig. 14, because it cannot dislodge the block of iron. In Fig. 14, the path error of MPCS against the error of servo mechanism is about 39.4 %. Additionally, we confirm that MPCS can track within the constraint of the movable range. In addition, we calculate the average of the path errors in three times experiments. Servo mechanism and MPCS have the path error of less than 2 mm from the average. From this, the repeatability is confirmed.
Figure 8. Movement locus of bucket tip.

Figure 9. Servo mechanism.
Figure 10. MPC.

(a) Time variation of X coordinate.

(b) Time variation of Y coordinate.

(c) Control input of each cylinder.

(d) Generated force of each cylinder.

Figure 11. MPCS.

(c) Control input of each cylinder.

(d) Generated force of each cylinder.
(a) Servo mechanism.

Figure 12. Error integration of each cylinder.

(b) MPCS.

Figure 13. Iteration count of MPC and MPCS.

Figure 14. Maximum path error of servo mechanism and MPCS when the block of the iron is removed.
7. Conclusion

In this study, we performed the experiment of path-tracking control using servo mechanism, MPC and MPCS. We gave the constraint which considered the movable range of the bucket for MPC and MPCS. We confirmed that servo mechanism changed the input to suppress the influence of the disturbance. However, we also confirmed that the sudden motion of the hydraulic excavator occurred after the disturbance removal. Because MPC did not increase the input, the hydraulic excavator could not get the block off and stopped the motion. MPCS changed the input to suppress the influence of the disturbance by combining MPC and servo mechanism. Additionally, the sudden motion did not occur after the disturbance removal, which happened in the control of servo mechanism. We demonstrated effectiveness of the proposed method by comparing three control methods by the experiment.

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