Path tracking of bucket edge using a hydraulic excavator with a built-in angular velocity controller

Daisuke Endo[1], Genki Yamauchi[1], Takeshi Hashimoto[1], Yoshiaki Tsutsumi[2], Shinjiro Yamamoto[2], Kenta Furuuchi[2] and Shinya Imura[2]

[1]National Research and Development Agency Public Works Research Institute,
Construction Technology Research Department Advanced Technology Research Team, Japan
[2]Hitachi Construction Machinery Co., Ltd.,
Research and Development Department Advanced Development Center, Japan

endou-d177cl@pwri.go.jp, yamauchi-g573bs@pwri.go.jp, t-hashimoto@pwri.go.jp,
y.tsutsumi.ii@hitachi-kenki.com, s.yamamoto.jp@hitachi-kenki.com, k.furuuchi.ur@hitachi-kenki.com,
s.imura.hk@hitachi-kenki.com

Abstract -

This study presents the development and evaluation of a hydraulic excavator equipped with a built-in angular velocity controller to improve the precision of excavation operations. By integrating a velocity control system that takes into account the characteristics of the hydraulic system, the proposed approach enhances the path-tracking accuracy of the bucket edge during digging tasks. Experimental results demonstrate that the angular velocity controller significantly reduces path errors compared to conventional lever-based control systems, achieving improvement in path accuracy. This advancement facilitates the automation of hydraulic excavators, and provides a reliable foundation for further developments in construction robotics.

Keywords -

Motion Control; Hydraulic System Dynamics; Excavation Path Tracking;

1 Introduction

In recent years, there has been a growing demand for the automation of construction machinery, driven by labor shortages in construction and industrial plants, particularly the declining availability of skilled workers. To address this issue, technologies enabling the autonomous operation of construction machinery, such as hydraulic excavators performing excavation tasks automatically, have been developed [1].

Previous automation technologies were typically built upon conventional machines designed for manual operation. These systems relied on human-optimized interfaces—lever manipulation, pedal operation, and steering inputs—and replaced human inputs with a controller mounted externally on the machine. Moreover, feedback elements, such as rotary angle sensors, optical cameras, LiDAR, and GNSS, were often added to the machinery to determine control inputs, which required additional hardware installations. However, this approach presents several challenges:

- Nonlinear elements optimized for human operation (e.g., play, sensitivity adjustments) make it difficult to enhance servo system responsiveness[2].
- The cost of modifying the hardware of the machinery is significant for users.
- Modeling and parameter identification necessary for controlling the hydraulic excavator system are technically complex for users[3].

To overcome these issues, it is desirable for hydraulic excavator manufacturers to incorporate controllers into the machinery itself, taking into account the system's characteristics and enabling users to provide input directly through interfaces. This integration facilitates automation by treating the excavator's components as a four-degree-of-freedom manipulator and developing a control framework similar to that of industrial robotic arms. This facilitates the ease of automation for hydraulic excavator. This approach is expected to enable highly precise control of the bucket's edge path. If such technology is realized, it could automate hydraulic excavator operations that require strict conformance to design specifications, such as shaping embankment slopes. Additionally, it would facilitate autonomous operations in environments with surrounding obstacles, allowing the excavator to avoid contact with them effectively.

Hitachi Construction Machinery has previously provided machine control functions, such as the automatic control of boom movements to ensure the bucket of a hydraulic excavator follows a target surface [4]. Additionally, the company developed the ZCORE® system platform, which allows for easy function expansion and customization based on automation needs [5]. By enabling hydraulic excavators to operate using common control messages proposed by the Public Works Research Institute [6], it is anticipated that construction operators will be able to command multiple hydraulic excavators from different manufacturers using a unified system, thereby promoting the widespread adoption of automation. In September 2022, Hitachi Construction Machinery (Hitachi CM) and the Public Works Research Institute (PWRI) launched a joint research project aimed at improving the productivity of mechanized earthwork using the OPERA autonomous construction technology open platform [6]. In this project, Hitachi Construction Machinery developed a hydraulic excavator equipped with a built-in angular velocity controller, taking into account the characteristics of the hydraulic system (Figure 1). This paper confirms the effectiveness of the developed system in advancing the automation of hydraulic excavators and is organized as follows.

In Chapter 2, the system architecture for controlling the path of the edge of the bucket is described. We present an example of a conventional approach where a servo system outputs lever operations from an external motion controller of the excavator. In contrast, an example of the proposed approach using the developed velocity controller, which outputs target joint angular velocity from an external motion controller, is also explained.

Chapter 3 provides a detailed explanation of the developed velocity controller. Chapter 4 reports on the experimental validation by performing excavation tasks using both the conventional and proposed methods, comparing the behavior of each actuator in the excavator. Finally, Chapter 5 concludes the findings of this study.

Figure 1. Developed excavator built-in velocity controller.

2 System configuration for bucket edge path control

This chapter describes the system configuration required to automate the bucket edge path control of a hydraulic excavator. The excavator used in this study is equipped with an electronically controlled hardware system capable of receiving pilot pressure commands corresponding to lever operations. Figure 2 illustrates the hardware system configuration.

2.1 Conventional method: Lever operation-based commands

In the conventional approach, the hydraulic excavator is controlled using lever operation commands as the operational input. The system architecture is shown in Figure 3-(a). A motion planner sequentially calculates the target joint angles required to achieve the desired bucket edge pose. These angles are then controlled by a Joint Position Controller, which outputs lever operation commands to the Joint Control Unit (JCU). The JCU sends the vehicle control data to the Motion Control Unit (MCU) as feedback data and generates target pilot pressure for the actuators.

2.2 Proposed method: Angular velocity-based commands

The proposed method replaces lever operation commands with angular velocity commands as the operational input. Figure 3-(b) illustrates this system configuration. The motion planner calculates the sequential target joint angles for achieving the desired bucket edge pose. These angles are converted into target angular velocities by the joint position controller and transmitted to the JCU. Within the JCU, a dedicated velocity control algorithm calculates the necessary target pilot pressure and sends commands to the solenoid valve controller, thereby driving the hydraulic system. The output of the Hydraulic Pressure Sensors in Figure 2 is used to measure the load applied to the actuator and improve the accuracy of angular velocity control. Details are described in Chapter 3.

The proposed method offers significant advantages over the conventional approach. By directly controlling the angular velocity of each joint, the system improves path tracking accuracy and responsiveness. Moreover, this method simplifies the control architecture by reducing dependency on external hardware, enabling easier integration into automated systems.

3 Joint velocity controller considering hydraulic system characteristics

This chapter details the joint velocity controller that considers the characteristics of the hydraulic system built

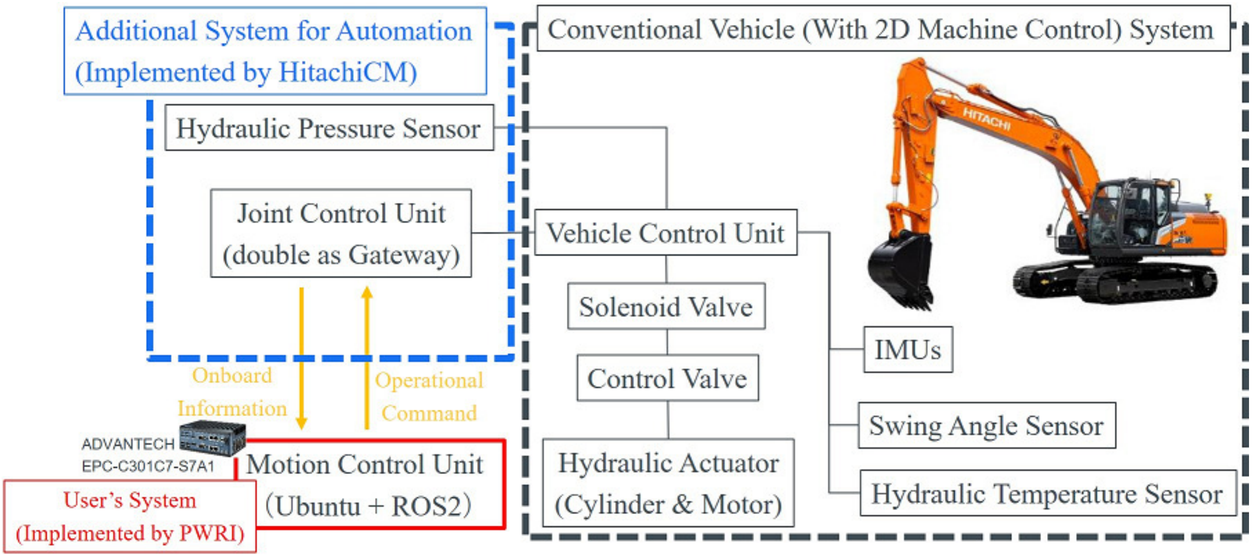

Figure 2. Hardware system configuration of the hydraulic excavator.

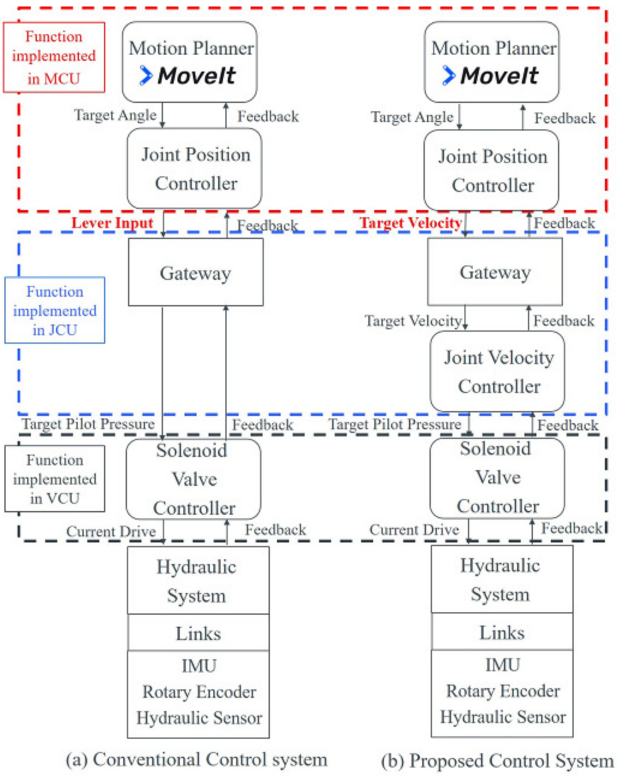

Figure 3. Schematic diagram of automated system for excavator.

into the excavator. As shown in Figure 4, this controller consists of three computational processes: (a) Link calculation, (b) Pump flow rate calculation, and (c) Valve opening calculation. Each of these processes is described in the following subsections.

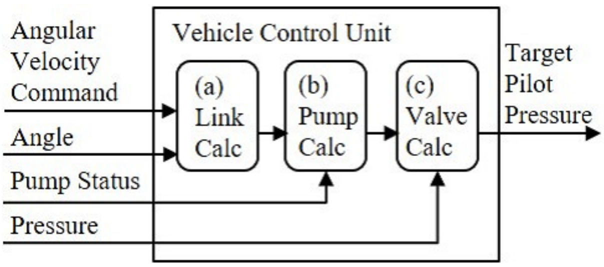

Figure 4. Schematic diagram of the Joint Velocity Controller.

3.1 Link calculation

As an example, the relationship between the boom angle and the boom cylinder length is explained. The kinematic relationship between the boom and the boom cylinder is shown in Figure 5. The relative angle $\angle BAC$ of the boom to the chassis and the boom cylinder length BC can be expressed by Equation (1).

$$\overline{BC}^2 = \overline{AB}^2 + \overline{AC}^2 - 2\overline{AB} \cdot \overline{AC} \cos \angle BAC \tag{1}$$

The relationship between the angular velocity ω of the boom and the boom cylinder speed can be derived by differentiating Equation (1) with respect to time, resulting in Equation (2).

$$\frac{d\overline{BC}}{dt} = \frac{\overline{AB} \cdot \overline{AC} \sin \angle BAC}{\overline{BC}} \omega \quad (2)$$

Assuming the hydraulic fluid is incompressible and the cylinder has a circular cross-section, the boom cylinder speed obtained in Equation (2) can be converted to the flow rate Q of the hydraulic fluid using the cylinder cross-sectional area A_{cyl}, as expressed in Equation (3).

$$Q = A_{\text{cyl}} \frac{d\overline{BC}}{dt} \quad (3)$$

In this manner, the angular velocity command can be converted to the flow rate Q of hydraulic fluid supplied to the actuator from the pump.

When an angular velocity command is input to the JCU, a process is implemented to calculate the optimal target pilot pressure required for operation at the target angular velocity, taking into account the pump output and the load on the actuator. Figure 6 shows a schematic diagram of the power transmission to the actuator. The changes in joint angles of each link can be converted into the volume of incompressible hydraulic fluid supplied from the pump to the actuator, which is a cylinder. Based on this, the flow rate of the actuator corresponding to the commanded angular velocity can be calculated.

$$Q = CA\sqrt{\frac{2\Delta P}{\rho}} \quad (4)$$

The flow rate Q_{in} from the pump to the actuator is generally expressed by the orifice equation (4), which relates the opening area A of the spool on the path to the pressure difference before and after it. Therefore, the spool opening area A required to achieve the target angular velocity can be calculated. In equation (4), C is the flow coefficient, ρ is the fluid density, and ΔP is the differential pressure across the spool opening ($P_P - P_{\text{in}}$). The relationship between the spool opening area A and the pilot pressure is determined by the opening characteristics of each spool.

3.2 Pump flow rate calculation

Hydraulic excavators are generally designed with hydraulic circuits that allow a single pump to operate multiple actuators. Therefore, when simultaneous operation commands are input to multiple joints, calculating the target pilot pressure for each command as if operating a single joint may result in the total flow exceeding the output capacity of a single pump. In such cases, differences in the load on each actuator may lead to an uneven distribution of flow, causing one side to receive more flow and making it impossible to achieve the target angular velocity. Particularly, if the ratio of the current value to the target value differs among joints, the bucket tip may deviate from the path planned by the Motion Controller. This issue can be critical in use cases where avoiding contact with obstacles around the hydraulic excavator is required.

On the other hand, even if there is a deviation between the current value and the target value for each joint, as long as the ratio of the current value to the target value remains consistent across all joints, the planned path can be maintained. This is considered desirable in use cases that involve avoiding surrounding obstacles. To address this, when angular velocity commands are simultaneously given to multiple joints, a control algorithm is implemented in the Joint Velocity Controller to determine the target pilot pressure. This algorithm ensures that the ratio of angular velocities is maintained such that the total flow does not exceed the pump's discharge capacity.

Figure 7 shows an example of a circuit where flow is distributed to multiple actuators from a single pump. When the pressure in the hydraulic line does not reach the bleed-off pressure, the bleed-off flow Q_T flowing into the tank in the figure can be considered as $Q_T = 0$. In this case, as shown in Equation (5), the pump flow Q_P is equal to the sum of the actuator flows $Q_{\text{in}1}$ and $Q_{\text{in}2}$.

$$Q_P = Q_{\text{in}1} + Q_{\text{in}2} \quad (5)$$

On the other hand, based on the linkage mechanism calculations described in Section 3.1, the required flows $Q_{\text{Req in}1}$ and $Q_{\text{Req in}2}$ for each actuator at the commanded angular velocity can be determined.

$$\text{If } Q_p < Q_{\text{Req in}1} + Q_{\text{Req in}2},$$

$$Q_{\text{in}1} = \frac{Q_{\text{Req in}1}}{Q_{\text{Req in}1} + Q_{\text{Req in}2}} Q_p, \quad (6)$$

$$Q_{\text{in}2} = \frac{Q_{\text{Req in}2}}{Q_{\text{Req in}1} + Q_{\text{Req in}2}} Q_p, \quad (7)$$

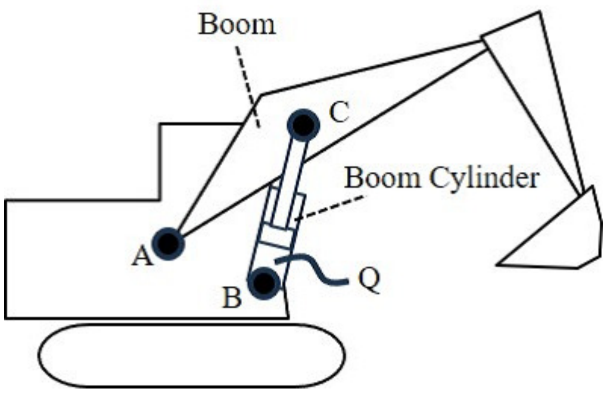

Figure 5. Kinematic relationship between the boom and the boom cylinder.

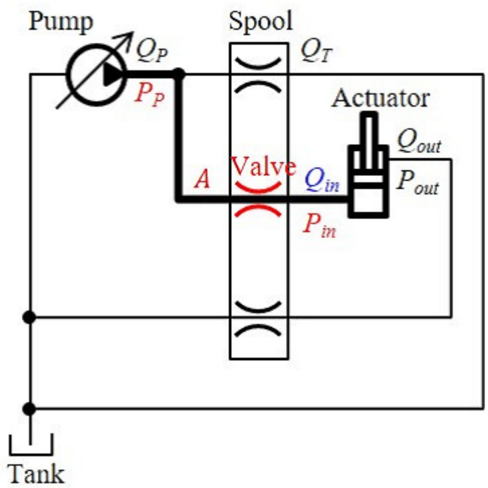

Figure 6. Hydraulic circuit diagram of power transmission from pump to actuator(Single pump to single cylinder).

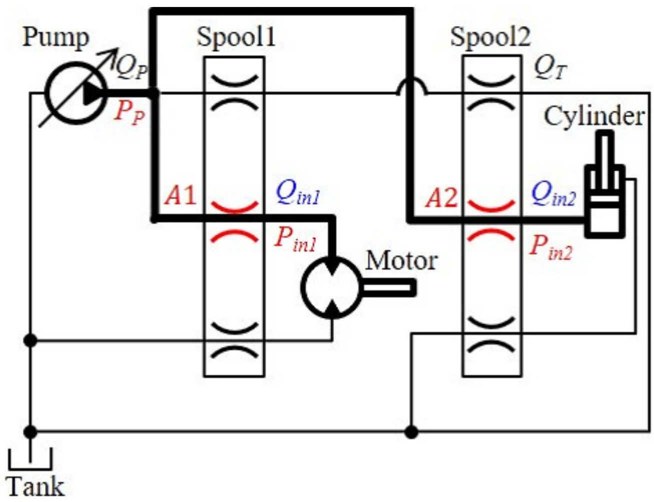

Figure 7. Hydraulic circuit diagram of power transmission from pump to actuator(Single pump to double cylinder).

As shown in Equation (6) and (7), if the sum of the required flows $Q_{\text{Req in1}}$ and $Q_{\text{Req in2}}$ exceeds the pump's discharge capacity Q_P, the target actuator flows Q_{in1} and Q_{in2} are adjusted by multiplying them by the ratio of the pump's discharge capacity to the required flow. By doing so, deviations of the bucket tip from the target path can be suppressed within the pump's discharge capacity.

$$Q_{\text{in1}} : Q_{\text{in2}} = Q_{\text{Req in1}} : Q_{\text{Req in2}}, \tag{8}$$

$$\omega_1 : \omega_2 = \omega_{\text{Req1}} : \omega_{\text{Req2}}, \tag{9}$$

$$Q_{\text{in1}} = CA1\sqrt{\frac{2(P_p - P_{\text{in1}})}{\rho}}, \tag{10}$$

$$Q_{\text{in2}} = CA2\sqrt{\frac{2(P_p - P_{\text{in2}})}{\rho}}, \tag{11}$$

$$A1 = \frac{1}{C}\frac{Q_{\text{Req in1}}Q_p}{Q_{\text{Req in1}} + Q_{\text{Req in2}}}\sqrt{\frac{\rho}{2(P_p - P_{\text{in1}})}}, \tag{12}$$

$$A2 = \frac{1}{C}\frac{Q_{\text{Req in2}}Q_p}{Q_{\text{Req in1}} + Q_{\text{Req in2}}}\sqrt{\frac{\rho}{2(P_p - P_{\text{in2}})}}. \tag{13}$$

3.3 Valve opening calculation

The flow rate Q_{in} flowing into the actuator from the pump is generally expressed by the orifice equation (Equation (4)) using the valve opening area A of the spool and the pressure difference ΔP before and after the valve. Therefore, the valve opening area A required to achieve the target angular velocity can be calculated. The relationship between the valve opening area A and the pilot pressure is uniquely determined by the valve characteristics.

4 Experimental verification of conventional and proposed methods

4.1 Experimental purpose

The objective of this experiment was to confirm the effectiveness of the velocity controller, which takes into account the characteristics of the hydraulic system of the excavator's working mechanism. The comparison was made with the conventional method outlined in Section 2.1, which uses simple proportional controllers (P controllers) on the external *Joint Position Controller* of the excavator. The conventional method does not consider hydraulic system characteristics and relies on lever inputs as commands.

4.2 Experimental procedure

The experiment involved excavating a flat surface using the hydraulic excavator. During this process, errors in the cutting-edge path and joint angle control (the difference between the commanded and actual values) were measured. The excavator was placed on a nearly level ground surface. To standardize the hardness of the ground, the excavation area was manually dug beforehand to loosen the soil, and the terrain was leveled to ensure that the plane of the excavation surface matched the ground plane of the excavator.

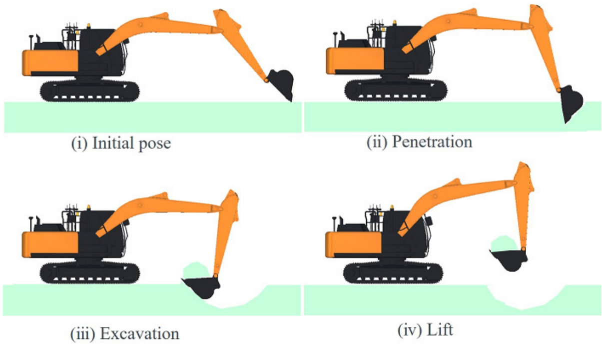

Figure 8. Display of test movements: (i) Initial pose, (ii) Penetration, (iii) Excavation, (iv) Lift.

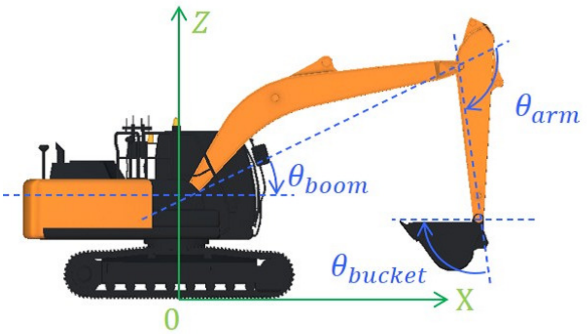

Figure 9. The definition of each coordinate.

The experimental motions were carried out sequentially as shown in Figure 8 from states (i) to (iv). The target joint angles for each state are summarized in Table 1. The definition of each joint angle and cartesian coordinates system are shown in Figure 9 .

During the transitions between these states, the commanded and actual joint angles (calculated using sensors such as IMUs) were recorded. The recorded joint angles were then used to calculate the cutting-edge path using forward kinematics. This allowed the path traversed during the experiment to be determined. Deformations caused by external forces acting on the excavator's links during motion were not considered.

Table 1. Target joint angles for each state (i)-(iv)

State	Boom	Arm	Bucket
(i) Initial Pose	-0.24 rad	1.19 rad	-0.07 rad
(ii) Penetration	-0.24 rad	1.57 rad	-0.07 rad
(iii) Excavation	-0.24 rad	1.92 rad	1.36 rad
(iv) Lift	-0.44 rad	1.92 rad	1.55 rad

4.3 Experimental conditions

Two experimental conditions were evaluated to compare the path followed by the cutting-edge:

1. **Condition 1: Conventional method (Without velocity control)**
   The method described in Section 2.1 was employed, where lever inputs were commanded to the excavator. The target angles for the cutting-edge were calculated sequentially using *MoveIt2*[7], and these values were input to the P controllers outside the excavator.

2. **Condition 2: Proposed method (With velocity control)**
   The method described in Section 2.2 was employed, where target joint angular velocities were directly commanded to the excavator. The target angular velocities required to achieve the desired cutting-edge pose were calculated and directly input to the excavator.

The various parameters related to the motion controller, MoveIt2, used in the experiment are summarized in Table 2. In this table, θ_{limit}^{upper} and θ_{limit}^{lower} represents upper or lower limit angles of the range of motion, $\dot{\theta}_{limit}$ represents angular velocity limit, and $\ddot{\theta}_{limit}$ represents angular acceleration limit, for each joint respectively. Additionally, variables K_P, K_I and K_D with the superscript "lev" and "vel" represent the P, I, and D gains of the joint position controller in conventional method or proposed method respectively. Essentially, in this experiment, the joint position controller is a pure proportional controller in both conditions. This is a measure to simplify the comparison between the conventional method and the proposed method.

The tolerance value for the control error of joint angles was set to 0.03 rad for all axes and tests. This means that the target poses from (i) to (iv) are switched only when the control errors of all joint axes fall within this allowable range. The control timeout was set to 30 seconds. This means that if 30 seconds have elapsed since the control target value stabilized, the bucket edge target position will be forcibly switched to the next target position, even if a control error exceeding the tolerance remains.

Table 2. Parameters related to the motion controller

Parameter	Boom	Arm	Bucket
θ_{limit}^{upper}	0.349 rad	2.687 rad	2.372 rad
θ_{limit}^{lower}	-1.137 rad	0.594 rad	-0.622 rad
$\dot{\theta}_{limit}$	0.3 rad/s	0.7 rad/s	1.0 rad/s
$\ddot{\theta}_{limit}$	0.2 rad/s^2	0.7 rad/s^2	1.0 rad/s^2
K_P^{lev}	1.7	1.4	0.6
K_I^{lev}	0.0	0.0	0.0
K_D^{lev}	0.0	0.0	0.0
K_P^{vel}	1.4	1.5	1.0
K_I^{vel}	0.0	0.0	0.0
K_D^{vel}	0.0	0.0	0.0

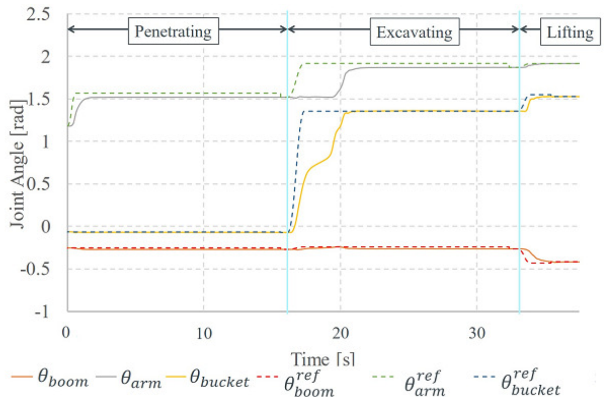

Figure 10. Angle profile in conventional control system.

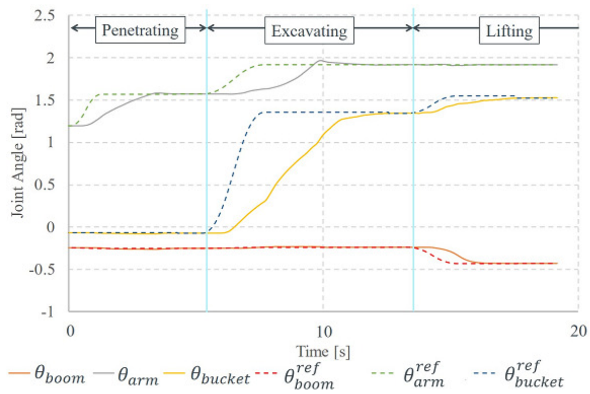

Figure 11. Angle profile in proposed control system.

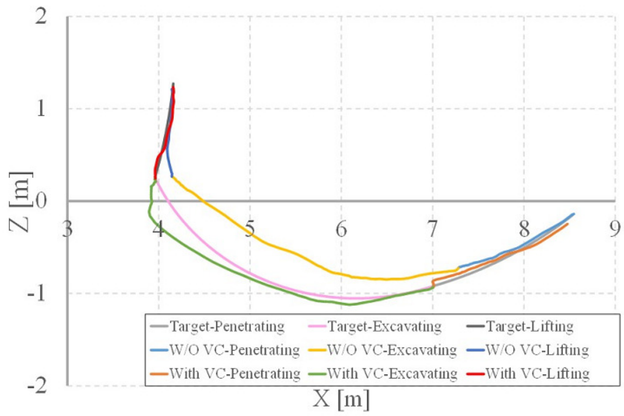

Figure 12. Cutting-edge path comparison: conventional vs. proposed methods.

4.4 Experimental results

Figure 10 and 11 present the angle profiles (commanded and actual) for the conventional and proposed methods, respectively. Figure 12 shows the path of the cutting-edge for both methods compared to the target path.

The horizontal axis (X) represents the forward direction from the excavator's crawler as projected onto the ground, while the vertical axis (Z) represents the upward direction. The line $Z = 0$ corresponds to the ground plane. The operational modes are labeled as *Penetration*, *Excavation*, and *Lift*, as indicated in Figure 8.

From Figure 12, it is evident that during *Penetration* and *Excavation*, the proposed method achieved trajectories closer to the target than the conventional method. During the *Lift* phase, both methods performed comparably, indicating that the proposed method maintained path accuracy even under reduced load conditions.

Next, Figure 13 shows the results of comparing the control errors of the bucket edge path between the conventional and the proposed method. The vertical axis represents the control error, which is the Root Mean Square (RMS) value of the bucket edge position. The calculation was performed across the entire bucket edge path. It can be observed that the proposed method reduces the error to 41% compared to the conventional method.

4.5 Discussion

As shown in Figure 12, the proposed method effectively maintained cutting-edge path closer to the target than the conventional method, particularly during the *Penetrating* and *Excavating* phase. Analysis of the control profiles in Figs. 10 and 11 indicates that the conventional method experienced delays, particularly for the arm joint, where *Excavating* phase started, for approximately 3 seconds after receiving the command. This discrepancy can be attributed to unbalanced oil flow in the conventional method, as lever inputs cannot ensure balanced motion across multiple joints. Furthermore, at the end of both the *Penetrating* and *Excavating* phases, the arm joint exhibited a steady-state deviation exceeding the tolerance range of 0.03 rad relative to the target value, which persisted for more than 10 seconds, resulting in a prolonged operating time.

Conversely, the proposed method mitigated this issue by utilizing angular velocity control via joint velocity controller, allowing the system to compensate for variations in resistance and disturbances encountered during excavation. This feature ensured adherence to the target path, which was unattainable with the conventional proportional control approach. In the conventional method, the lever operation amount is determined by proportional (P) control based on the angle. Consequently, when external loads act on each joint during excavation, the operation halts when the load balances with the force generated by the lever operation amount output by the P controller. For

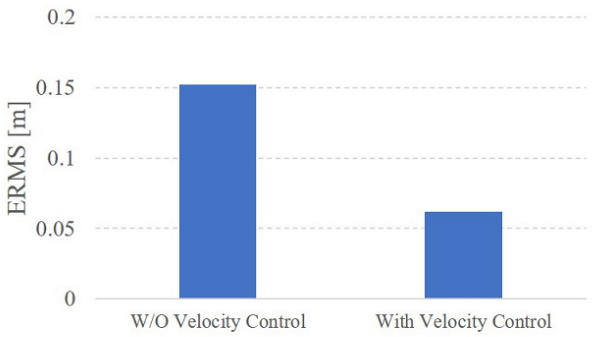

Figure 13. Error comparison: RMS cutting-edge error for conventional and proposed methods.

this reason, it is considered that the conventional method required about 30 seconds (equals to the control timeout) to reach the final target position in each operation mode.

5 Conclusion

To advance the automation of construction, we prototyped automated system for a hydraulic excavator with a velocity controller considering the characteristics of the hydraulic system. This velocity controller allows users to issue rotational velocity commands for each axis of the excavator's working device. Using this controller, the excavator performed ground excavation tasks, and the path control accuracy of the bucket cutting edge was compared between cases with and without the proposed controller.

The results confirmed that the path deviation of the cutting-edge was reduced to less than half when using the proposed velocity controller. This finding demonstrates that for automating hydraulic excavators, embedding controllers capable of realizing actuator angular velocities within the excavator and using angular velocity commands from the upper motion control system instead of lever-based commands is a a preferable approach. The proposed velocity control method is effective in achieving this goal.

Skilled human operators adeptly perform various tasks through lever operation. For example, during excavation, they adapt their operations based on the load conditions, distinguishing between hard and soft ground. This suggests that, even if control commands are given only as lever operation inputs, it may be possible to develop an autonomous system capable of executing tasks at a level comparable to humans, provided the upper-level control system is sufficiently sophisticated. However, implementing such an advanced upper-level system poses significant technical challenges for users. By contrast, if the angular velocity control utilizing hydraulic pressure information proposed in this study is pre-installed within the hydraulic excavator, the upper-level system can be simplified. In future work, we will not only aim to further enhance the robustness of angular velocity control but also explore optimal system configuration to improve user-friendliness in automation. This includes integrating a high-level controller within the excavator, allowing users to specify the desired path of the bucket's cutting edge.

References

[1] T. Bock and T. Linner. *Construction Robots*. Cambridge University Press, New York, NY, USA, 2016.

[2] T.C.S. Hsia. A new technique for robust control of servo systems. *IEEE Transactions on Industrial Electronics*, 36(1):1–7, 1989. doi:10.1109/41.20338.

[3] Chang PH. Lee, SJ. Modeling of a hydraulic excavator based on bond graph method and its parameter estimation. *Journal of Mechanical Science and Technology*, 26:195–204, 2012. doi:https://doi.org/10.1007/s12206-011-0938-2.

[4] Hitachi Construction Machinery. Ict construction solution. On-line: `https://www.hitachicm.com/global/en/solutions/solution-linkage/ict-construction/`, Accessed: 16/12/2024.

[5] Hitachi Construction Machinery. Hitachi review construction machinery products. On-line: `https://www.hitachihyoron.com/rev/archive/2021/r2021_03/16/index.html`, Accessed: 06/12/2024.

[6] G. Yamauchi, D. Endo, H. Suzuki, and T. Hashimoto. Proposal of an open platform for autonomous construction machinery development. In *Proceedings of ISARC 2023*, pages 186–191, Chennai, India, 2023.

[7] MoveIt Motion Planning Framework. Moveit motion planning framework. On-line: `https://moveit.ros.org`, Accessed: 06/12/2024.