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A Study on Autonomous Operation System of Caisson Shovels in High Air Pressure and Narrow Underground Space

(Demonstration of Trajectory Tracking Control)

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Abstract

In this paper, we develop an unmanned construction system using autonomous caisson shovels with a characteristic joint configuration. The caisson shovel is a link manipulator with five degrees of freedom (DOFs) and travels on a rail track of a working chamber ceiling in a caisson box. Here, to measure the joint variables, we first installed three laser sensors for traveling on the rail track, dumping, and extending the boom unit, an encoder for yawing the boom unit, and a pair of ultrasonic flow sensors for pitching the bucket. We then reproduced the trajectory of the caisson shovel during a soil mountain removal task by a skilled human operator using a proportional-derivative (PD) control and assessed the reproducibility and the motion characteristics of the system. The experimental results revealed that although the ultrasonic flow sensor had hysteresis and additionally the caisson shovel was subject to large inertia and friction, the tracking accuracy of this system was sufficient for simple operation.

Keywords: unmanned construction, pneumatic caisson method, caisson shovel, trajectory tracking

1 Introduction

A pneumatic caisson method (PCM) [1], [2] is a pneumatic process for constructing bridge foundations, underground retention basins, etc. The caisson shovel, which is mounted on a rail track of a working chamber ceiling, excavates the ground and immerses the steel reinforced concrete caisson box vertically into the underground (**Figure 1**). The inside of the working chamber is sealed and keeps high air pressure depending on the underground depth to avoid the intrusion of the groundwater. From this reason, since the excavation surface is not submerged, construction is possible even in water. The maximum depth and pressure are approximately 70m and 0.7MPa, respectively. The caisson shovel, a link manipulator with five degrees of freedom (DOFs), is assembled and disassembled through the material shaft connected to the working chamber and is teleoperated from an operation room above the ground through the images of the cameras mounted on the ceiling and the shovel. Although the teleoperated caisson shovel has solved many problems for safety, several issues and problems remain. (1) There are insufficient shovel operators. In a large construction area such as 70m*70m, for example, 30 caisson shovels would require 30 human operators. (2) There are also insufficient skilled operators. Learning the required skill is very time consuming. (3) Even routine simple tasks such as soil mountain removal must be performed by skilled operators. (4) Since the 2D camera image for teleoperation limits the field of view and loses distance information, the excavation efficiency deteriorates and accidental collisions may occur.

From these reasons, an unmanned construction system is required and has been desired and eagerly studied. Yamamoto *et al.* [3] proposed an automatic control and motion planning system using 3D ground shape map information for a 12t-class excavator. This system achieved the automatic target trajectory tracking. Kang *et al.* [4] automatically controlled the 3D trajectory of a 21t-class excavator with hydraulic cylinders. Ha *et al.* [5] demonstrated the trajectory tracking by impedance control for a small (mass: 1.5t, width: 1000mm, depth: 3495mm, height: 2240mm) excavator. Although these systems realized good performance for the trajectory tracking, unfortunately they cannot be used with a PCM because of the following constraint conditions. (C1) A large excavator cannot be used, because the equipment must pass through the material shaft with inner diameter of 1.08m to be assembled and disassembled in the narrow sealed working chamber. (C2) Machines that use combustion engines cannot be used in the sealed and pressurized working chamber. These constraints hamper the realization of an unmanned construction system for PCM.

From this point of view, we develop an automatic excavation system using a caisson shovel operating in high air pressure and narrow underground space. Here, we first implement the sensors into the caisson shovel with five DOFs to measure three rotary joint angles and two prismatic joint lengths and then reproduce the trajectory of soil mountain removal by a skilled human operator using a proportional-derivative (PD) control for hydraulic cylinders. Finally, we assess the trajectory tracking performance and the motion characteristics.

The remainder of this paper is organized as follows. In Section 2, we describe the architecture of the caisson shovel and the implemented sensors. In Section 3, we conduct the kinematics of the link manipulator, mathematically. In Section 4, we demonstrate the tracking trajectory by a skilled human operator and assess the performance and motion characteristics. In Section 5, we conclude the paper and outline future works.

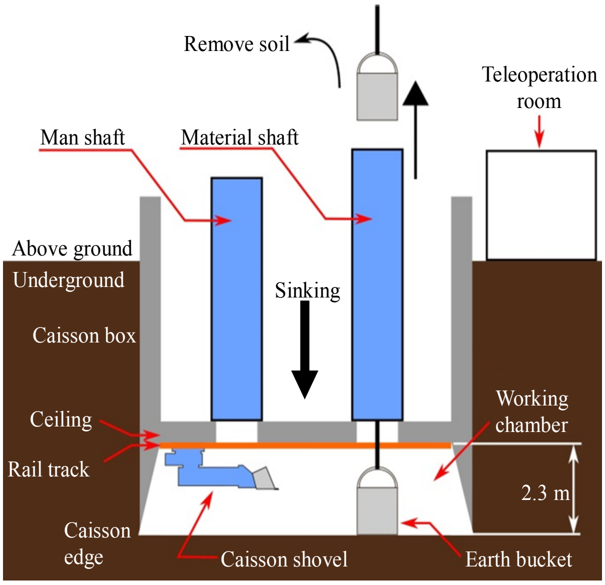

Fig. 1 Pneumatic caisson facilities

2 Caisson shovel

2.1 Joint configuration

Figure 2 shows a caisson shovel in an unpressurized test working chamber. The caisson shovel is disassembled into four units: carriage, boom, counter weight, and bucket units. These units are carried in the working chamber through the material shaft with inner diameter of 1.08m, assembled, and after construction completion, carried out again through the material shaft. The caisson shovel is a heavy machine with a weight of 4t and is modeled as a link manipulator with characteristic five DOFs: carriage traveling on the rail track (d_0), yaw rotation of the boom unit (θ_1), pitch rotation (dumping) of the boom unit (θ_2), expansion and contraction of the boom unit (d_3), and pitch rotation of the bucket unit (θ_4), as described in Section 3. **Table 1** lists the movable range for each DOF. Although a common backhoe [6] is driven using hydraulic cylinders by a combustion engine and consists only of rotary joints, the caisson shovel is driven using hydraulic cylinders through an external electric power supply and has two prismatic joints and three rotary joints. Moreover, while the former moves on the ground surface and supports the reaction force using the ground, the latter travels on a rail track and supports the reaction force using the rigid rail track on the ceiling. In addition, the carriage unit is fixed on the rail track by a locking mechanism during excavation (d_0 is constant).

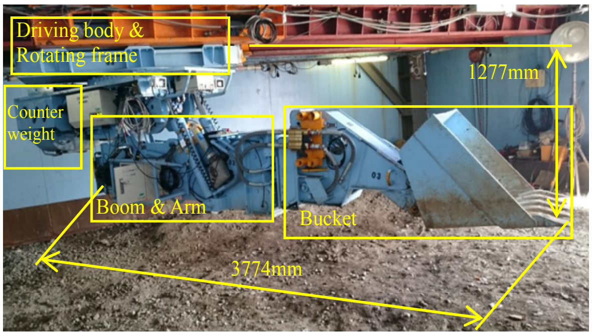

Fig. 2 Caisson shovel overview

Table 1 Movable range

Carriage traveling	$0\text{mm} \leq d_0 \leq 70000\text{mm}$
Boom yawing	$-180\text{ deg} \leq \theta_1 \leq 180\text{ deg}$
Boom pitching	$-27\text{ deg} \leq \theta_2 \leq 12\text{ deg}$
Boom expansion	$0\text{mm} \leq d_3 \leq 1390\text{mm}$
Bucket pitching	$-97\text{ deg} \leq \theta_4 \leq 41\text{ deg}$

2.2 Sensor implementation

Figure 3 shows sensors implemented to measure the joint variables. The kinematics, e.g., the relationship between the joint variables and the position-orientation of the caisson shovel, is uniquely determined. A laser rangefinder (A: DL50-N1123), rotary encoder (B: TRD-J1000RZ), laser range finder (C: LR-TB5000), laser range finder (D: LR-TB5000), and a pair (forward and backward) of ultrasonic flowmeters (E: FD-Q10C) are used to measure the position of the carriage on the rail track (d_0), the boom yaw angle (θ_1), the boom pitch angle (θ_2) from the displacement of the cylinder, the boom expansion and contraction (d_3), and the bucket pitch rotation (θ_4), respectively. Since an individual ultrasonic flowmeter is used to measure the unidirectional flow quantity, the bucket pitch angle is calculated by integrating the sensor value and multiplying the pipe diameter of the hydraulic cylinder. In this study, we chose such an indirect sensor capable of being mounted on the boom unit far from the bucket unit. Because, although the rotary encoder is useful and accurate, the bucket, i.e., the joint axis onto which the encoder is mounted, is sometimes submerged under muddy water.

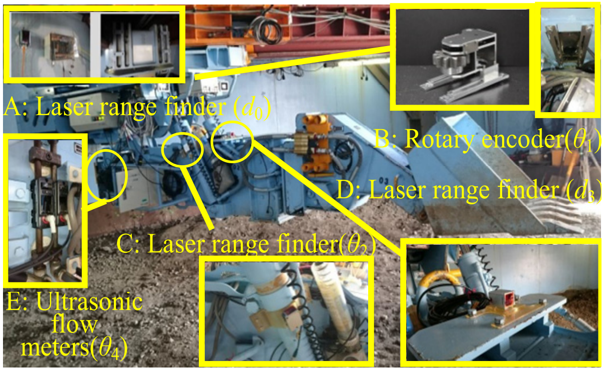

Fig. 3 Implemented sensors

2.2.1 Investigation of bucket pitch rotation accuracy

The pilot experiments revealed that the accuracies for the joint variables, d_0, θ_1, θ_2, and d_3, were sufficient for excavation operations, because these errors were less than 2mm, 2deg, 2deg, and 2mm, respectively. However, since the bucket pitch angle is indirectly calculated based on the forward and backward flow quantities through the hydraulic cylinder, we investigated the accuracy experimentally, as follows. We first rotated the bucket from the lowest angle (-97deg) to the highest angle (41eg), then rotated inversely to the lowest angle, and repeated this procedure five times. **Figure 4** shows the time history of the forward (blue) and backward (red) flow quantities integrated every 0.1s (right axis) and the bucket pitch angle (purple) calculated from the sensor values. The light blue and yellow green 1ines are the geometric upper and lower limit angles corresponding to above lowest and highest angles, respectively. The average flow quantities at the end of the ascending (41deg) and descending (-97deg) motions were 1.71L (standard deviation: std. 0.007L) and 0.048L (std. 0.016L), respectively. The calculated bucket pitch angles were 50.9deg (std. 1.13deg) and -86.9deg (std. 2.47deg), respectively. Based on these results, we found that since the standard deviation was low, the reproducibility was high. However, since the bucket pitch angle was overestimated during the ascending motion and underestimated during the descending motion, hysteresis existed. This is assumed to be due to the effect of gravity. The ascending motion requires a larger torque than the descending motion to counter gravity. Clarification of this mechanism is a subject for future investigation. Here, we compensated these values by multiplying the ascending and descending coefficients, i.e., proportionality constants: 0.012 and 0.012. **Figure 5** shows the time history of the compensated forward and backward flow quantities integrated every 0.1s and the bucket pitch angle calculated from the compensated sensor values. Naturally, the compensated values at the end of the ascending and descending motions corresponded with the theoretical values of 41deg and -97deg. The intermediate value will need to be investigated.

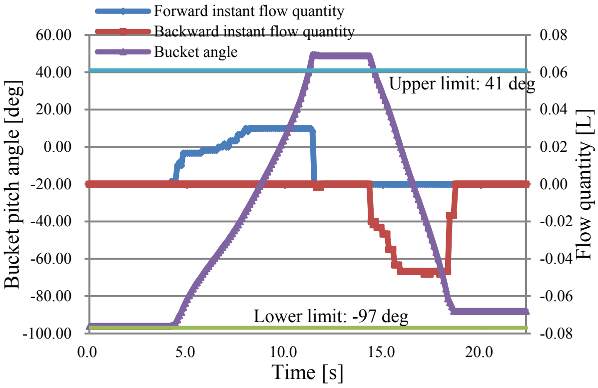

Fig. 4 Time history of flow quantity and calculated bucket pitch angle

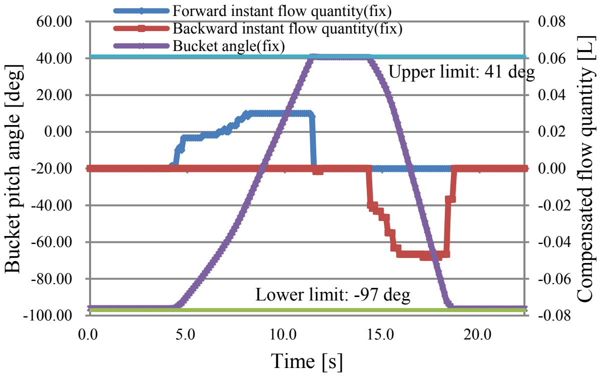

Fig. 5 Time history of compensated flow quantity and calculated bucket pitch angle

3 Caisson shovel model

3.1 Mathematical model and kinematics

Figure 6 shows the mathematical link model for the caisson shovel and the coordinate systems. This is the initial configuration when $d_0=\theta_1=\theta_2=d_3=\theta_4=0$. Here, Σ_R is the frame of reference set to the working chamber ceiling and Σ_E is the coordinate system for the bucket claw. **Table 2** shows the link parameters [7] from Σ_1 to Σ_E. Here, $a_{i\text{-}1}$, $\alpha_{i\text{-}1}$, d_i, and θ_i mean the translation and rotation around X axis and the translation and rotation around Z axis, respectively. The homogeneous transformation matrix is obtained from the link parameters and the relationship between Σ_R and Σ_0, as follows:

$$
{}^{R}T_{E}=\begin{bmatrix} C_1C_{2+4} & -S_1 & -C_1S_{2+4} & p_x \\ S_1C_{2+4} & C_1 & -S_1S_{2+4} & p_y \\ S_{2+4} & 0 & C_{2+4} & p_z \\ 0 & 0 & 0 & 1 \end{bmatrix}
$$

$$
\begin{aligned}
&\text{where} \\
&p_x = C_1(l_6S_{2+4}+l_5C_{2+4}-l_3C_2+(d_3+l_4)S_2-l_2)+d_0 \\
&p_y = S_1(l_6S_{2+4}+l_5C_{2+4}-l_3C_2+(d_3+l_4)S_2-l_2) \\
&p_z = -l_6C_{2+4}+l_5S_{2+4}-l_3S_2-(d_3+l_4)C_2-l_1
\end{aligned} \tag{1}
$$

Here, $S_i \equiv \sin\theta_i$ and $C_i \equiv \cos\theta_i$. From this, the relationship between the position and orientation of the shovel claw (bucket tip position), ***r***, is

$$
\boldsymbol{r}=\begin{bmatrix} x_E \\ y_E \\ z_E \\ \Phi \\ \Theta \\ \Psi \end{bmatrix}=\begin{bmatrix} p_x \\ p_y \\ p_z \\ \theta_1 \\ \theta_2+\theta_4 \\ 0 \end{bmatrix} \tag{2}
$$

where Φ , Θ , and Ψ are the yaw, pitch, and roll angles, respectively. Hence, this mechanism cannot change the roll angle. The position and orientation except for the role angle are uniquely determined by five DOF variables. The link lengths are as follows: $l_1=829$, $l_2=170$, $l_3=415$, $l_4=2631$, $l_5=813$, and $l_6=259$.

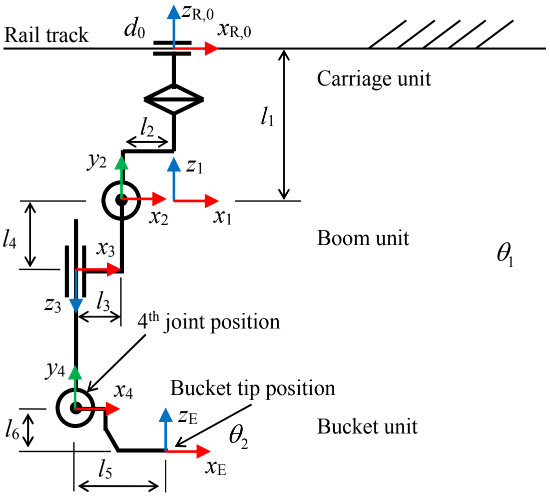

Fig. 6 Mathematical link model for caisson shovel

Table 2 Link parameters

i	a_{i-1}	α_{i-1}	d_i	θ_i
1	0	0	$-l_1$	θ_1
2	$-d_2$	90°	0	θ_2
3	$-l_3$	90°	d_3+l_4	0
4	0	-90°	0	θ_4
E	l_5	-90°	$-l_6$	0

4 Trajectory tracking performance

We investigate the trajectory tracking performance by reproducing the trajectory during soil mountain removal by a skilled human operator. Here, the caisson shovel reproduces the trajectory using three DOFs: boom pitching (θ_2), boom expansion and contraction (d_3), and bucket pitch rotation (θ_4) on the sagittal (x-z) plane by the PD control. The sampling time for the feedback control is 1s. The output of the hydraulic cylinder, i.e., the openness of the proportional solenoid valve, was set to 90% for the boom pitching, expansion, and contraction and to 80% for the bucket pitching based on pilot experiments.

Figure 7 shows the excavation trajectories for the bucket axis and claw by a skilled human operator using the PD control. The horizontal line at -2300mm indicates the distance from the ceiling of the working chamber to the ground surface. The trajectory tracking by the PD control overshot the target position when the caisson shovel started to move, because the inertia of the caisson shovel was very large. Moreover, the error for the bucket claw was larger than that for the bucket axis because of the error in the ultrasonic flow sensor described in the previous section. Since the static friction for the heavy machine was very large and differs with the dynamic friction, the control value for the target became nonlinear and complex. In this case, the boom unit started expanding from the output of 50% and contracting from the output of 50%. That is, the force by the output of 50% means the maximum static friction.

Figure 8 shows a photograph of soil mountain removal by the PD control. Although the accuracy of this system is sufficient for the simple soil mountain removal task, other complex operations, such as excavation planned by multiple caisson shovels, require optimized spatiotemporal control to avoid collisions. The characteristics that individual hydraulic outputs affect mutually and their torques are changed must be also considered. The PD control considering not only the nonlinearity of the caisson shovel with a large inertia and friction but also these issues is very important.

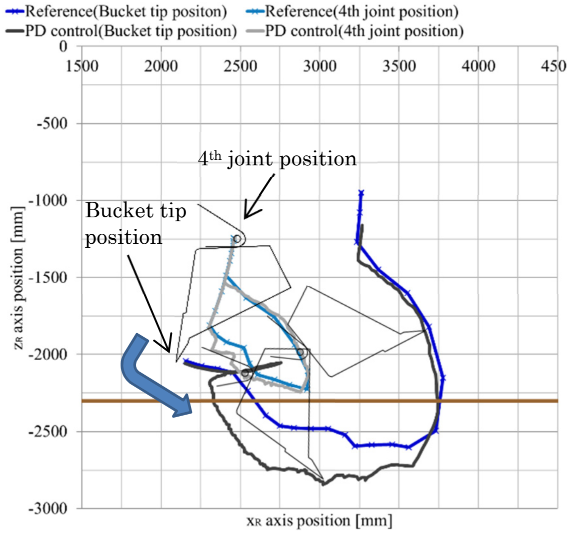

Fig. 7 Excavation trajectories for a human operator and PD controller

5 Conclusions

In this study, we developed an automatic excavation system using a caisson shovel operating in high air pressure and narrow underground space. Here, we implemented sensors to a caisson shovel with five DOFs and reproduced the trajectory for a soil mountain removal task by a skilled human operator using a PD control for hydraulic cylinders. The experimental results indicated that the ultrasonic flowmeter had hysteresis caused by gravity. This was compensated by the proportionality constants for the ascending and descending. Although the accuracy of our system was sufficient for simple operation, trajectory tracking by the PD control tended to overshoot, because the inertia and friction of the caisson shovel are very large.

The PD control considering the nonlinearity and the characteristics of the caisson shovel is a subject for future work. Moreover, we intend to analyze the kinematic characteristics based on the manipulability and manipulating force and to perform cooperative excavation using multiple caisson shovels.

Fig. 8 Soil mountain removal by the PD control

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References

[1] http://www.orsc.co.jp/english/tec/newm_v2/ncon02.html.

[2] Kodaki, K., Nakano, M., and Maeda, S., “Development of the automatic system for pneumatic caisson”, Automation in Construction, Vol. 6, (1997), pp. 241-255.

[3] Yamamoto, H., Moteki, M., Hui, S., Ootuki, K., Yanagisawa, Y., Sakaida, Y., Nozue, A., Yamaguchi, T., and Shin’ichi, Y., “Development of the Autonomous Hydraulic Excavator Prototype Using 3-D Information for Motion Planning and Control”, IEEE/SICE International Symposium on System Integration, (2010), pp. 49-54.

[4] Kang, S., Park, J., Kim, S., Lee, B., Kim, Y., Kim, P., and Kim, H., “Path Tracking for Hydraulic Excavator Utilizing Proportional-derivative and Linear Quadratic Control”, IEEE Conf. on Control Application, (2014), pp. 808-813.

[5] Q.P. Ha., Q.H. Nguyen., D.C. Rye., H.F. Durrant-Whyte., “Impedance control of a hydraulically actuated robotic excavator”, Automation in Construction, Vol. 9, (2000), pp. 421-435.

[6] Yamamoto, H., Uesaka, K., Ishimatsu, Y., Yamaguchi, T., Aritomi, K., and Tanaka, Y., “Introduction to the General Technology Development Project: Research and Development of Advanced Execution Technology by Remote Control Robot and Information Technology”, ISARC, 2006.

[7] J. Denavit and R.S. Hartenberg, "A Kinematic Notation for Lower-Pair Mechanisms Based on Matrices", ASME Journal of Applied Mechanics, Vol. 77, (1955), pp. 215-221.

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