Excavator Posture Estimation and Position Tracking System Based on Kinematics and Sensor Network to Control Mist-Spraying Robot

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ABSTRACT In the construction field, when an excavator dismantles a building using an attachment, a large amount of fine dust is generated, causing air pollution. In this study, a mist-spraying robot was proposed, aiming to effectively suppress the generation of fine dust in the construction field. The robot could spray mist while motion tracking the attachment of the excavator. The mist-spraying robot recognized and tracked the source of the fine dust by estimating the posture and position of the excavator. Forward kinematics was used to estimate the posture of the excavator, and the position was estimated using a real-time kinematic global positioning system (RTK-GPS). The fine dust source motion tracking control performance of the mist-spraying robot was verified by measuring the error when the excavator attachment moved horizontally, vertically, and helically. The mean distance between the spraying direction of the mist-spraying robot and the attachment of the excavator was within 0.4 m. Considering the range in which mist is ordinarily sprayed, this mist-spraying robot is expected to successfully track and suppress the generation of fine dust.

INDEX TERMS Kinematics, mist-spraying robot, sensor network, autonomous position tracking, excavator.

I. INTRODUCTION

In recent years, air pollution has become increasingly severe, particularly owing to fine dust. Among the various sources of fine dust, the fine dust generated when dismantling buildings accounts for the largest proportion of dust in the construction field [1], [2]. The fine dust in construction sites arises mainly when an excavator breaks a building using its attachment [3]. There are two main methods for suppressing the fine dust generated from the attachment, which is the endpoint of the excavator. In the first method, a person manually sprays water near the excavator as shown Fig. 1 (a). This method has the advantage that the person can efficiently suppress fine dust by spraying water while motion tracking the source of fine dust. However, since fine dust suppression work must be done around the excavator that dismantles the building, the worker is exposed to the risk of a collapse of the building that causes a fatal injury. The second method is to continuously spray mist over a large area using a machine [4], [5]. This method does not require a person, so there is no risk of human accident. However, the source of fine dust does not be traced and it only reciprocates left and right. As such, the spraying direction of the mist and the location of the source of fine dust usually do not match as in Fig. 1(b). Therefore, it consumes a large amount of water and energy inefficiently to suppress the fine dust. The third method is shown in the Fig. 1 (c), a research on installing a fine dust suppression device directly on an excavator was conducted [6].
FIGURE 1. Conventional methods of suppressing fine dust at building dismantling sites. (a) Workers spraying water are exposed to the risk of collapse accident (b) The source of fine dust and the direction of mist-spraying do not match (c) A view of remodeling an existing excavator and attaching a mist-sprayer.

This method has the advantage that the mist can be directly sprayed on the fine dust generating source and no person is required. However, there are a few disadvantages in that the existing excavator needs to be remodeled, large volume and weight parts such as water tanks and pumps must be attached, and it cannot be used as an independent device. The next study is about a visual neural network-based excavator posture estimation, as shown in Fig. 2. Its research purpose is not for suppressing the fine dust in construction sites, but for recognizing and estimating the posture of the excavator. The excavator’s image data are obtained by a camera sensor. After a neural network-based algorithm recognizes the excavator and its components such as the boom, arm and bucket, the overall posture is approximately estimated. The only sensor for recognition and estimation is camera[7]. However, since it performs enormous matrix calculation based on a deep neural network, a high performing CPU or GPU is required to execute rapid computing operation. In this study a novel method for attaching small-volume sensors to an excavator using a magnet as shown in the Fig. 3 was proposed. In addition, the suggested mist-spraying robot can calculate the source of fine dust (excavator’s end-point) using the excavator’s posture and position data acquired through the inertial measurement unit (IMU) sensor and real-time kinematic global positioning system (RTK-GPS) attached to the excavator. The mist-spraying robot sprays mist while motion tracking the source of fine dust, effectively suppressing the fine dust at the building dismantling site. Furthermore, through experiments, we validated the performance of the real-time autonomous excavator endpoint motion tracking control.

FIGURE 2. Visual neural network-based excavator posture estimation.

FIGURE 3. Fine dust generation point motion tracking control system.
system in the mist-spraying robot. This study has three main contributions as follows.

- An efficient and safe mist-spraying robot was developed to prevent construction workers from being exposed to fatal accidents during dismantling work.
- Using a sensor network and a fine dust motion tracking control algorithm, fine dust can be effectively suppressed without an unnecessary energy dissipation.
- Air pollution can be reduced by suppressing the spread of fine dust at the building dismantling sites.

II. CONFIGURATION OF FINE DUST SOURCE MOTION TRACKING CONTROL SYSTEM

A. MIST-SPRAYING ROBOT

In general, a mist-spraying robot should move a sprayer to spray mist toward a fine dust source, and produce mist to suppress the fine dust [8], [9]. Fig. 4 shows the constructed mist-spraying robot. We used a linear actuator and hydraulic motor to control the direction of the sprayer for motion tracking the fine dust generation source. The vertical spraying direction of the sprayer was determined by adjusting the length of the linear actuator. For the horizontal spraying, we used a hydraulic motor installed on the lower side of the sprayer [10]. When the hydraulic motor rotated, the worm gear and spur gear were connected to the motor rotation, thereby driving the horizontal rotation of the sprayer.

![Spraying and actuator system configuration of mist-spraying robot.](image)

The mist suppressed fine dust in the following sequence. The water stored in the water tank passed through a filter to remove foreign substances. The water, whose pressure was increased by the pump, then passed through the nozzle installed at the front side of the sprayer, generating mist. The generated mist was blown at the source of the fine dust using the fan inside the sprayer. The fine dust stuck to the mist and fell to the ground, thereby preventing the dust from flying. Table 1 presents a summary of the hardware used in the mist-spraying robot to track the endpoint of the excavator, which represented the position of the fine dust generation.

![Hardware configuration diagram of the excavator posture and position tracking system.](image)

### Table 1. Sensor, actuator, and controller hardware configuration.

| Component                    | Model          | Specification                          |
|------------------------------|----------------|----------------------------------------|
| Microcontroller Unit         | N1-9054        | CPU: 1.33 GHz Dual-Core                |
| Motor Driver                 | DCMD-200-A     | Power: 200 W                           |
|                              |                | Control Signal: Analog                 |
| Linear Actuator              | TA2P           | Load: 1000 N                           |
| RTK-GPS                      | REACH RS+      | Corrections: Network Transport of “Radio Technical Commission for Maritime Services” (RTCM) via Internet Protocol (NTRIP) |
| Inertial Measurement Unit (IMU Sensor) | EBIMU-9DOFV5 | Gyroscope, Acceleration sensor, Geomagnetic sensor |
| Telemetry                    | Holby Radio V3 | Power: 500 mW                          |
| Solenoid Valve               | KSOG0266C      | Frequency: 433 MHz                     |
| Motor Driver                 | H300-MPV       | Voltage: 48 VDC                        |
| Hydraulic Motor              | SMR-80         | Type: Gerotor                          |

Fig. 5 shows the hardware configuration of the mist-spraying robot. Data acquisition is performed sequentially from the top of the Fig. 5. RTK-GPS acquires position data for estimating the relative distance between the excavator and the mist-spraying robot. IMU sensor acquires angular data for estimating the posture of the excavator. Telemetry is an RF communication module that allows data from excavators to be transmitted remotely to the mist-spraying robot. The IMU and GPS data of the excavator are acquired by the controller through the telemetry module, and the IMU and GPS data of the mist-spraying robot are acquired by wire. Solenoid valve...
controls the flow of the hydraulic motor used to rotate the sprayer of the mist-spraying robot. H300-MPV is a motor driver that is in charge of the hydraulic motor. A microcontroller unit is installed on the mist-spraying robot to acquire sensor data from the robot and the excavator, and generates control signals. DCMD-200-A is a motor driver that controls the linear actuators. For vertical movement of the mist-spraying robot sprayer. The controller estimated the position of the endpoint of the excavator and generated control signals to aim at the estimated position. The control signals were sent to the motor driver, and as the motor operated, the mist-spraying robot tracked the endpoint of the excavator.

**B. SENSOR NETWORK FOR MOTION TRACKING FINE DUST SOURCE**

To estimate the relative position between the mist-spraying robot and excavator’s attachment (representing the position of the fine dust source), the distance was measured by installing a global navigation satellite system [11], [12] (GNSS)-applied RTK-GPS on the excavator and mist-spraying robot. However, ordinarily, if a GNSS is installed directly on an excavator’s attachment that directly/indirectly dismantles a building, the building debris may interfere with or damage it. Therefore, we installed the RTK-GPS at a relatively safe center part of the excavator, and the position of the attachment from the center part was estimated through a kinematic analysis [13]. The kinematic analysis required the angle data of the arm, boom, and body links of the excavator [14], [15], [16], [17]. We collected the angle data by constructing angle measurement modules, as shown in Fig. 6.

Three modules were attached to the arm, boom, and body of the excavator to collect the angle data. Module 1 was attached to the arm and contained an IMU sensor for measuring the angle, wireless radio frequency (RF) module for transmitting the measured data to the next module, and microcontroller unit for controlling it. Module 2, attached to the boom, used a wireless RF module with 1:1 communication to receive the data transmitted from Module 1 and sent them with the measured boom’s angle data to Module 3. Module 3 sent all of the angle data of the excavator to the mist-spraying robot via telemetry module [18]. The mist-spraying robot recognized the position of the excavator by comparing the position data sent from the excavator and that measured using the RTK-GPS attached to the robot, and estimated the posture of the excavator through the angle data. Subsequently, the mist was sprayed towards the coordinates of the estimated endpoint of the excavator to suppress the fine dust [19].

In general, the precision of the sensors has a significant impact on the endpoint estimation performance of a mist-spraying robot, because the sensor network measures the angle of the excavator through the IMU sensors, and the positions of the mist-spraying robot and excavator through the RTK-GPS. Therefore, experiments were conducted to validate the precision of the selected sensor. First, we conducted an experiment to obtain measurements at angles of 0°, 30°, 45°, and 60° through the IMU sensor for 10 min, respectively, and compared them to the true values to validate the IMU sensor’s performance. Fig. 7 shows the angles...
measured using the IMU sensor for each situation. The maximum and minimum angles measured in 10 min using the IMU sensor are indicated. In the experiment on the IMU sensor’s precision, the maximum error is 0.05° at a reference angle of 0°, 0.08° at 30°, 0.05° at 45°, and 0.2° at 60°. This precision is sufficient to estimate the posture of the excavator; the experimental results for the posture estimation using these angles are described in Section IV.

Second, to validate the performance of the RTK-GPS, we fixed one RTK-GPS, and installed the other RTK-GPS at distances of 5, 10, and 15 m, respectively, to collect the position data for 5 min. We then calculated the relative distance and compared it with the actual distance. The mean errors of the calculated relative distances are 0.06, 0.040, and 0.123 m at reference distances of 5 m, 10 m, and 15 m, respectively, indicating that the precision of the RTK-GPS is sufficient for the mist-spraying robot to estimate the excavator’s position [20]. In Section IV, we discuss the results from the estimation experiments.

III. MECHANISM OF MOTION TRACKING FINE DUST SOURCE

A. EXCAVATOR’S POSTURE ESTIMATION

The distance from the position of the RTK-GPS attached to the extractor to the position of the excavator’s end-effector can be estimated through a kinematic analysis [21], [22], [23]. As shown in Fig. 9, if coordinate systems are constructed for the excavator’s mechanical parts, the relationship between the origin $O_0$ of the $\{O\}$ coordinate system where the RTK-GPS is installed and the endpoint $O_3(x^*, y^*, z^*)$ of the excavator can be explained through (1), i.e., a homogeneous transformation matrix [24]. In (1), $i = 0, 1, 2, 3$, $a_i$ is the length of the link between the coordinate systems, $\theta_i$ is the rotation angle of the link, $\alpha_i$ is the angle between $z_i$ and $z_{i-1}$, $x_i$ is the rotation axis according to the right-hand rule, and $d_i$ is the distance between the $i$-th link and joint. If the neighboring homogeneous transformation matrices are all multiplied, it can be rewritten as a rotational transformation matrix $R^3_0$ and a position vector $d^3_0$, as shown in (2). The components of the position vector $d^3_0$ consist of $(x^*, y^*, z^*)$, which indicate the position of the endpoint of the excavator relative to the RTK-GPS. $(x^*, y^*, z^*)$ can be calculated by multiplying the rotation angles $(\theta_1, \theta_2, \theta_3)$ of the excavator’s arm, boom, and body and the distances $(a_1, a_2, a_3)$ between the coordinate systems, respectively, as shown in (3). The distances between the coordinate systems can be determined by measuring the excavator. The angle of the excavator’s arm, boom, and body can be measured using the sensor network presented in Section II. Accordingly, the posture of the excavator can be estimated in real time to determine the position of the endpoint of the excavator from the RTK-GPS.

FIGURE 9. Coordinate systems for forward kinematics form RTK-GPS to the excavator endpoint.

FIGURE 8. Real-time kinematic global positioning system (RTK-GPS) accuracy verification experiment. (a) Relative distance experiment results. (b) Relative distance along time axis.
installed on the excavator.

\[
T_{i-1}^i = \begin{bmatrix}
\cos\theta_i & -\sin\theta_i \cos\alpha_i & \sin\theta_i \sin\alpha_i & a_i \cos\theta_i \\
\sin\theta_i & \cos\theta_i \sin\alpha_i & -\cos\theta_i \sin\alpha_i & a_i \sin\theta_i \\
0 & \sin\alpha_i & \cos\alpha_i & d_i \\
0 & 0 & 0 & 1
\end{bmatrix}
\] (1)

\[
T_3^0 = T_1^0 T_2^0 = \begin{bmatrix}
R_3^0 & d_3^0 \\
0 & 1
\end{bmatrix}
\] (2)

\[
\begin{bmatrix}
x^* \\
y^* \\
z^*
\end{bmatrix} = \begin{bmatrix}
\cos\theta_1 \cos (\theta_2 + \theta_3) & \cos\theta_1 \cos\theta_2 & \cos\theta_1 \\
\sin\theta_1 \cos (\theta_2 + \theta_3) & \sin\theta_1 \cos\theta_2 & \sin\theta_1 \\
\sin (\theta_2 + \theta_3) & \sin\theta_2 & 0
\end{bmatrix}
\cdot \begin{bmatrix}
a_3 \\
a_2 \\
a_1
\end{bmatrix}
\] (3)

B. EXCAVATOR’S POSITION ESTIMATION

Regular GPS can have an error of more than 10 m owing to the effects of the ionosphere and troposphere. If the precision of the GPS is not accurate, the position of the excavator estimated by the mist-spraying robot will be different from the actual position. Consequently, the mist will be sprayed in a direction away from the fine dust source, decreasing the fine dust reduction effect. To precisely estimate the endpoint position of the excavator, we used the RTK-GPS, which performs better than a regular GPS, to estimate the relative distance. The RTK-GPS measured the coordinates containing the errors caused by the ionosphere by installing a fixed GPS at a position where the coordinates are already known. Subsequently, the actual coordinates and coordinates containing the errors were compared to generate “Radio Technical Commission for Maritime Services” (RTCM) calibration signals. These were sent to the GPS installed on the object for the position estimation, and the errors are corrected. In order to calculate the relative distance in this method required a total of three GPSs, because an additional base GPS needed to be installed to calculate the error. In this study, instead of directly installing a base GPS, we used a “Network Transport of RTCM via Internet Protocol” (NTRIP) system, which can receive RTCM signals using the Internet. The Internet-connected RTK-GPS of the mist-spraying robot and excavator used the RTCM data generated at certain positions where the accurate coordinates were known; thus, it had a precision of several centimeters [25]. The distance between the mist-spraying robot and excavator was calculated using the latitude and longitude obtained through the RTK-GPS. Here, because the latitude and longitude were expressed in the decimal system, they were converted into the degree, minute, and second format before calculating the relative distance. The coordinates of the excavator, with the mist-spraying robot as the origin, represented the difference in the latitude \((y_{GPS})\) and longitude \((x_{GPS})\) between the two GPS coordinates. Based on this, the mist-spraying robot could determine the direction and distance of the excavator’s position.

C. MOTION TRACKING CONTROL OF FINE DUST SOURCE

The mist-spraying robot calculates the angle at which the sprayer moves based on the posture of the excavator and the relative position between the two. Thus, we can calculate the vector \((4, 5, 6, z^*)\) from the mist-spraying robot to the excavator’s endpoint by adding the excavator’s position vector \((x_{GPS}, y_{GPS})\) as estimated through the RTK-GPS.
and the endpoint position vector \((x^*, y^*, z^*)\) as calculated through the excavator’s posture estimation. Using the calculated vector, we can calculate the horizontal control angle \(\alpha_{yaw}\) and vertical control angle \(\beta_{pitch}\) for the nozzle of the mist-spraying robot so as to face the endpoint of the excavator, as shown in Fig. 10.

\[
x_{\text{endpoint}} = x^* + x_{\text{GPS}} \\
y_{\text{endpoint}} = y^* + y_{\text{GPS}} \\
distance_{\text{endpoint}} = \sqrt{(x^* + x_{\text{GPS}})^2 + (y^* + y_{\text{GPS}})^2} \\
\alpha_{yaw} = \tan^{-1}\left(\frac{y^* + y_{\text{GPS}}}{x^* + x_{\text{GPS}}}\right) \\
\beta_{pitch} = \tan^{-1}\left(\frac{z^*}{\sqrt{(x^* + x_{\text{GPS}})^2 + (y^* + y_{\text{GPS}})^2}}\right)
\]

In this study, we calculated the horizontal control angle by dividing the distance in the latitudinal direction by that in the longitudinal direction and applied an arctangent, as shown in (7). The vertical control angle was calculated by dividing the height of the excavator’s endpoint by the distance between the mist-spraying robot and the endpoint of the excavator and applying the arctangent [26], as shown in (8).

The mist-spraying robot tracked the endpoint of the excavator in the order shown in Fig. 11. The data were collected through the IMU sensors and RTK-GPS to estimate the endpoint of the excavator [27]. The posture of the excavator was estimated through the IMU sensors, and the relative distance between the mist-spraying robot and excavator was calculated using RTK-GPS data. The estimated excavator posture and relative distance were used to calculate the endpoint position of the excavator. They were then used to calculate the horizontal and vertical control angles for the mist-spraying robot, so as to be oriented toward the endpoint of the excavator. The results were examined for the occurrence of horizontal and vertical errors; As shown in Fig. 12 a PID controller was used to control the robot using the horizontal and vertical target angles calculated with the sensor data of the excavator and the mist-spraying robot. The error between the reference angle from the endpoint estimate and the current angle calculated by the sensor network is given to the PID controller. Then, the control command that is generated by the controller drives the mist-spraying robot. If the errors were corrected, the mist-spraying direction was maintained, and if there was still an error, the endpoint of the excavator was recalculated. By repeating the above process in real time, the mist-spraying robot tracked the endpoint of the excavator.

IV. EXPERIMENTS ON FINE DUST SOURCE MOTION TRACKING CONTROL

For the mist-spraying robot to track the endpoint of the excavator, i.e., the source of fine dust, the excavator’s position and posture should be estimated first. The performance of the mist-spraying robot in estimating the position of the excavator was verified through an earlier performance test of the RTK-GPS. Subsequently, we validated the performance of the mist-spraying robot through an excavator posture estimation experiment and endpoint motion tracking control experiment, as described below.

A. EXCAVATOR POSTURE ESTIMATION EXPERIMENT

To effectively suppress fine dust, a mist-spraying robot must determine the exact position of the fine dust source by determining the excavator’s position and estimating the posture of the excavator. Through an experiment, we examined the mist-spraying robot’s excavator posture estimation performance, i.e., one of the elements for motion tracking the source of fine dust. The excavator posture estimation performance was validated by comparing the actual endpoint position of the excavator and an endpoint position of the excavator as estimated using kinematics. For the excavator’s endpoint position estimated through kinematics, we substituted the excavator’s link lengths and angle of each link as measured using the IMU sensors in (3) to perform the calculation. We conducted the experiment for two postures, and Fig. 13 shows the experimental results. The excavator’s body is indicated by a solid line, the boom by a dotted line, the arm by an alternating long and short dashed line, and the joints by circles. The measured endpoint of the excavator is cross-shaped, and the endpoint of the excavator calculated using kinematics is indicated by a triangle. In the experimental results for the two postures, the distances between the two endpoints are 0.075 m and 0.036 m, respectively, confirming that the excavator’s posture is accurately estimated.
B. EXCAVATOR ENDPOINT MOTION TRACKING CONTROL EXPERIMENT

We expected that the mist-spraying robot would track the endpoint of the excavator based on the excavator’s position and posture estimations, and validated this through an experiment. When moving in the horizontal, vertical, and helical directions, which are representative movements of the excavator attachment, it was checked the direction of the mist-spraying robot tracks the end point of the excavator. As shown in Fig. 14, the mist-spraying robot was positioned approximately 17 m from the excavator, and the experiment was conducted for the excavator endpoint motion tracking control.

The data of the IMU sensors and RTK-GPS were stored to estimate the posture of the excavator, and the direction in which the mist-spraying robot sprayed mist was calculated. Subsequently, we validated the performance by comparing the angle for facing the endpoint of the excavator and the actual aiming direction of the mist-spraying robot’s sprayer. The aiming direction of the sprayer can be expressed by the horizontal and vertical rotation angles. Fig. 15 shows the target angle at which the mist-spraying robot aims at the endpoint of the excavator, and the actual facing angle. The target angle is represented by a solid line, the actual angle by a dotted line, the vertical angle in gray, and the horizontal...
angle in black. Fig. 15 (a), (b), and (c) show the results when the endpoint of the excavator moves horizontally, vertically, and helically, respectively. Table 2 presents a summary of the experimental results.

When the endpoint of the excavator moves horizontally, the mean differences between the angles of the mist-spraying robot and actual horizontal and vertical angles are 1.1231° and 0.3540°, respectively. When the endpoint of the excavator moves vertically, the mean horizontal error is 0.6195°, and the mean vertical error is 0.3910°. When the endpoint of the excavator moves helically, the mean horizontal and vertical errors are 0.9976° and 0.4196°, respectively. The errors are larger when the mist-spraying robot moves horizontally relative to when it moves vertically. The errors are different because of the different precisions of the actuators: the linear actuator was used for the vertical movements of the mist-spraying robot, whereas the hydraulic motor was used for the horizontal movements.

The distance between the endpoint of the excavator and the line in which the mist is actually sprayed increases proportionally to the relative distance between the excavator and mist-spraying robot. The angle errors seem to be small enough; however, when the mist is sprayed, it may not reach the endpoint of the excavator. We calculated the shortest distance between the line on which the mist is sprayed and the excavator’s endpoint to check whether the mist could reach the source of the fine dust and suppress the dust.

When the endpoint of the excavator is a point \( P(x, y, z) \) and the mist sprayer’s direction vector is \( d(u, v, w) \), \( P \) can be projected in the \( d \) direction through (9), as follows:

\[
\text{proj}_d(P) = \left( \frac{d \cdot P}{d \cdot d} \right) d
\]

Because \( d \) is a vector with a size of 1, the result of the dot product of the denominator in (9) is 1, which can be written as shown in (10) as follows:

\[
\text{proj}_d(P) = (xu + yv + zw)[u, v, w]^T
\]

\( \text{proj}_d(P) \) is a vector with a size of \( xu + yv + zw \) and a direction of \( u, v, w \), and because it meets \( P \) vertically, it becomes the closest point to the endpoint of the excavator from the line that the mist sprayer faces. The distance between \( P \) and \( \text{proj}_d(P) \) can be calculated using the Euclidean distance, shown in (11) as follows:

\[
\text{Minimum Distance} = \|P - \text{proj}_d(P)\|
\]

Fig. 16 shows the minimum distance calculated using the above equation in three dimensions. The dotted line represents the direction of the mist sprayer, and the triangle represents the endpoint of the excavator. The circle represents \( \text{proj}_d(P) \), and the alternating long and short dashed lines represent the minimum distance. Fig. 16 (b) shows a magnification of Fig. 16 (a). Fig. 17 shows a three-dimensional representation of the excavator endpoint motion tracking control experiment conducted above. Fig. 17 (a) shows the path of the excavator endpoint, \( \text{proj}_d(P) \), and the point where the mist-spraying robot sprays when the endpoint of the excavator is moving while drawing circles horizontally. Fig. 17 (b) shows the results when moving up and down. Fig. 17 (c) shows the results when moving while drawing helically, \( \text{proj}_d(P) \) and the excavator endpoint path, as calculated using (9), (10), and (11), are also displayed. The star represents the position of the mist-spraying robot, the black line represents the path of the excavator endpoint, and the circle represents \( \text{proj}_d(P) \). The experiment was conducted with a distance of approximately 17 m between the mist-spraying robot and excavator. Because \( \text{proj}_d(P) \) appears around the path of the excavator endpoint, the mist-spraying robot appears to properly track the excavator’s endpoint. Nevertheless, to represent this quantitatively, we show the minimum distance calculated using (11) in Fig. 18. In particular, Fig. 18 (a) shows the minimum distance when the endpoint of the excavator moves horizontally. It can be observed that the minimum distance is larger than that in other experiments; this may be caused by the slow response of the system,

**TABLE 2. Mean error of excavator endpoint tacking experiment.**

| Mode     | Horizontal Mean Error | Vertical Mean Error |
|----------|-----------------------|---------------------|
| Horizontal | 1.1231°               | 0.3540°             |
| Vertical  | 0.6195°               | 0.3910°             |
| Helical   | 0.9976°               | 0.4196°             |

**FIGURE 16. Calculation of the minimum distance between the excavator endpoint and the mist-spraying direction in excavator endpoint motion tracking control experiment. (a) Excavator endpoint path and mist-spraying direction (b) Enlarged view of minimum distance.**
as the horizontal operation of the mist-spraying robot uses the hydraulic motor. Furthermore, the error is larger between 30 and 45 s than between 15 and 25 s. This is because the endpoint of the excavator rotated in a direction far from the mist-spraying robot, and then rotated toward the closer side. As the distance from the endpoint of the excavator to the mist-spraying robot decreases, the motion tracking speed increases, but the larger error occurs because the response speed of the hydraulic system is slow. Fig. 18 (b) shows the minimum distance when the endpoint of the excavator moves up and down. The minimum distance is smaller because the mist-spraying robot moves up and down using the linear actuator, which is more responsive than the hydraulic system. In the case of Fig. 18 (c), in which the excavator’s endpoint moves helically, the minimum distance is between that when moving horizontally and that when moving vertically.
because the mist-spraying robot has to operate both vertically and horizontally to track the endpoint of the excavator. Table 3 presents a summary of the experimental results.

### Table 3. Minimum distance of excavator endpoint motion tracking control experiment.

| Motion Tracking Type          | Mean Minimum Distance |
|------------------------------|-----------------------|
| Horizontal motion tracking   | 0.3724 m              |
| Vertical motion tracking     | 0.2431 m              |
| Helical motion tracking      | 0.2737 m              |

#### V. CONCLUSION

The fine dust generated when an excavator dismantles a building is usually suppressed by manually spraying water at the source. However, in this method, humans work near the excavator, and are exposed to the risk of accidents. Alternatively, mist-spraying equipment can be used to suppress fine dust, but it sprays mist by using large amounts of water and energy while reciprocating horizontally, because it cannot spray mist while motion tracking the source of the fine dust.

In this study, to solve the problem of accident risks when humans suppress fine dust and the inefficiency when mist-spraying equipment is used, we developed a mist-spraying robot for spraying mist while motion tracking the source of fine dust, and validated the performance in motion tracking control and efficiency. To validate the fine-dust suppression performance and efficiency, a mist-spraying robot was developed and experimentally tested to motion track the source of the fine dust generated at the attachment of the excavator when it dismantles a building. We measured the minimum distance between the spraying end point of the excavator and the actual excavator endpoint for two postures and confirmed that the estimation is very accurate.

In the experimental results for the excavator endpoint motion tracking control, the mean minimum distance between the excavator endpoint and the line of the direction facing the mist-spraying robot is 0.2431 m when the endpoint of the excavator moves vertically, 0.3724 m when it moves horizontally, and 0.2737 m when it moves helically, confirming that the mist-spraying robot can track the source of fine dust in real time. In the future, we plan to conduct a study on mist-spraying equipment for suppressing fine dust by reciprocating horizontally without the fine dust source motion tracking control function, and a mist-spraying robot for suppressing fine dust by motion tracking control the source of fine dust in real time, so as to validate the fine dust suppression performance and efficiency.

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