Development of a Retrofit Backhoe Teleoperation System using Cat Command

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Abstract— **Most existing retrofit remote-control systems for backhoes are large, hard-to-install, and expensive. Therefore, we propose an easy-to-install and inexpensive teleoperation system. The proposed system comprised remote-control and sensing systems. The remote-control system retrofits robot arm-based devices to "Cat Command", a compact embedded teleoperation system with a limited communication range, and controls these devices via a 5G commercial network to realize control from a remote office. Because this system does not require any additional modifications to the embedded control unit in the cockpit, the operator can continue working in the cockpit even if the backhoe is remotely controlled. The system enables the remote control of various devices from an extremely long distance by changing the joint parts between the robot arm and the embedded remote-control device. The sensing system estimates the posture and position of the backhoe by attaching original sensing devices to the backhoe. In addition, a 360° camera was installed in the cockpit to transmit work images from the construction site to a remote office in real time. The sensing device was smaller and lighter than conventional devices. We confirmed that the proposed system can be used to operate a construction site backhoe from a remote office, and that the system can be used to excavate soil using an actual backhoe.**

I. INTRODUCTION

Construction sites are hazardous environments, and some developed countries face problems such as fatal accidents and a declining workforce owing to falling birthrates and aging populations. Unmanned and automated construction work has gained attention as a solution, and the development of teleoperating systems for construction equipment has been promoted worldwide as part of this effort.

Teleoperation systems can be broadly classified into two types: embedded and retrofitted. Embedded systems are developed by construction-equipment manufacturers, and their internal specifications are often not disclosed, making it difficult for users to add functions. In addition, because most systems are designed to be visually monitored by the operator, it is difficult to remotely control construction equipment from a safe remote office away from the job site. To solve this problem, construction companies develop retrofitting systems. Previous studies proposed systems in which a robot is retrofitted to an operator's seat. However, most existing systems are large, hard-to-install, and expensive, posing a challenge for the automation of construction work.

This study proposed a retrofit teleoperation system that is compact, inexpensive, and easy-to-install. The proposed system comprises a remote-control system and a sensing system. Both systems were developed using a robot operating system (ROS) to reduce development costs and ensure scalability.

The remote-control system was designed to control an on-site backhoe from a remote office. In this system, robot arms and electric cylinders were retrofitted to an embedded remote controller for a backhoe of Cat Command, a compact embedded remote control system with a maximum communication distance limited to 400 m. The robot arms and electric cylinders were controlled from a safe office away from a site via a 5G commercial network. The system is more compact and cost-effective than existing systems because it retrofits an equipment to an embedded remote controller.

The sensing system was intended to transmit the posture and position information of a backhoe and the state of the construction site environment to a remote operator. To obtain the backhoe's posture and position information, we developed a sensing device with built-in accelerometer, gyroscope, and global navigation satellite system (GNSS) receiver functions. The sensing device was fixed to the cabin, boom, arm, and bucket to measure the joint angles. The sensing devices were fixed to the metal surface of the backhoe using a magnetic force, and each device transmitted the measured values via wireless communication, eliminating the need for additional backhoe machining or wiring. The backhoe surface did not require additional work. The sensing device used an inexpensive microcontroller and sensor, and a resin housing fabricated using a fused deposition modeling (FDM) 3D printer was used to protect the sensor module, making it inexpensive and easy to manufacture. Considering outdoor operations, the enclosure was structurally designed to have few gaps and was entirely covered with an acrylic coating to ensure waterproofing and dustproofing. A 360° camera was installed in the backhoe cockpit to provide real-time images of the work to a remote operator. The operator could control the backhoe using the remote-control system while viewing the estimated backhoe posture obtained by the sensing devices and images transmitted from the 360° camera, thereby enabling teleoperation.

This paper reports the results of an experiment conducted using an actual backhoe to confirm its effectiveness

The main contributions of this study are as follows.

1) **Development of an inexpensive, compact and easy-**

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to-install teleoperation system
The remote-control system used part of the embedded remote-control system to reduce the size of the retrofitted device to a 524.0 mm × 445.0 mm × 760.5 mm frame. The proposed remote-control system did not require any additional equipment to be fixed to the control device in the cockpit; thus, the operator could easily get into the cockpit to work even if the backhoe was remotely controlled. The sensing device weighed 71.6 % less than a conventional sensor box because its housing used resin coated with a waterproof material. The required size to effectively affix was reduced by 60.0 %. Furthermore, by incorporating a GNSS antenna, the backhoe's posture and position could be acquired using only a sensing device that could be easily attached to and removed from the backhoe's metal surface.

2) **Development of a versatile remote-control system using robot arms**
The remote-control system used 6-axis general-purpose robot arms to operate the equipment used to control the backhoe. Therefore, the robot arm could be remotely controlled from an office by changing the connection components between the robot arm and the embedded control device for various embedded control device that can be incorporated into the relay device described below.

II. RELATED WORKS

To date, several retrofit backhoe teleoperation systems have been proposed. Most retrofit remote-control systems have robots installed in cockpits, and remote control is achieved using robots [1], [2]. These systems are large, hard-to-install and expensive. A system can be operated by a manned operator even if a remote-control device is installed in the cockpit. However, the installation of the device deteriorates the operability of some embedded devices [3]. When a backhoe is operated from a remote office, it is necessary to understand the status of the construction site and backhoe to proceed with the work safely and smoothly. Therefore, a removable sensor box was developed to measure the backhoe behavior during loading operations [4]. This sensor box is easily detachable by a magnetic force and can acquire the angle of the installed point; however, a GNSS antenna must be installed separately on the backhoe.

Therefore, this study proposed a remote-control system that is compact and easy to use by retrofitting a robot arm-based device to an embedded remote-control system without adding any devices to the control unit in the cockpit. We proposed a sensing device with a built-in GNSS antenna that was smaller and lighter than a conventional sensor box.

III. RETROFIT TELEOPERATION SYSTEM FOR BACKHOE

We developed an inexpensive and easy-to-install retrofit backhoe teleoperation system for autonomous construction. The proposed system consisted of a remote-control system to control a backhoe from a remote office and a sensing system to transmit the backhoe's posture and images observed from the backhoe's cockpit to a remote operator (Fig 1). The backhoe was controlled by an operator using a remote-control system based on the information transmitted from the sensing system. The following sections describe these two systems in detail.

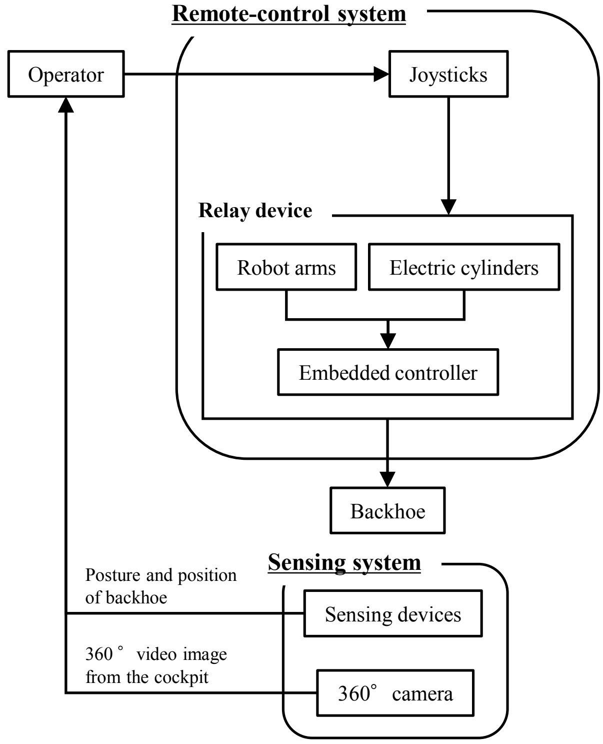

Fig. 1. Architecture of teleoperation system.

A. *REMOTE-CONTROL SYSTEM*

1) HARDWARE: We developed a remote-control system to control a backhoe onsite from a remote office. The aim of this study was to develop a system that is smaller and easier to install than conventional retrofit remote-control systems for backhoes. The architecture of the system is shown in Fig 2. The system consisted of a joystick that allowed a remote operator to input control commands to the backhoe and a device that reflected the joystick input to the backhoe's embedded controller on behalf of the operator (hereinafter referred to as "relay device"). The joystick and relay device were connected via a 5G commercial network, and inputs to the joystick were transmitted to the relay device in a construction site via an ROS topic. The relay device consisted of two 6-axis small general-purpose robot arms (myCobot 280 M5, Elephant Robotics) and two electric cylinders (EACM2WE10ARMK-G, Oriental Motor) retrofitted to the remote controller (hereinafter referred to as "embedded controller") of the embedded remote-control system (Cat Command, Caterpillar). The robot arm was connected to an analog stick to control the backhoe manipulator and cabin swivel angle through the original connection component (Fig.

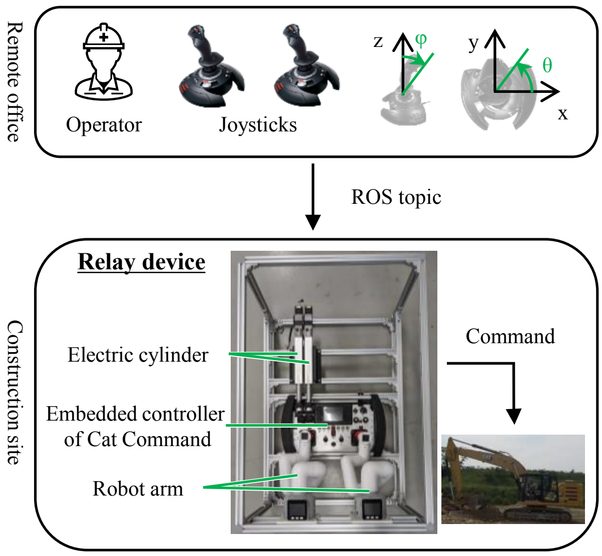

Fig. 2. Architecture of the remote-control system.

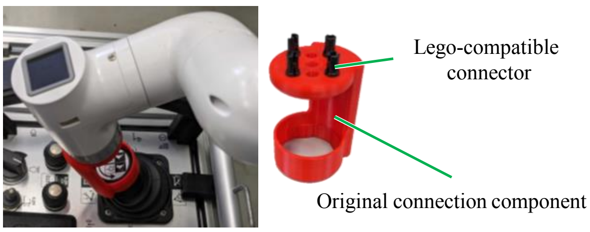

Fig. 3. Original connection component to easily connect a robot arm and analog stick on the embedded controller.

3). The connecting parts were fabricated using an FDM 3D printer and connected to the robot arm using Lego-compatible connectors. The robot arm was connected to the embedded controller by covering the analog sticks on the embedded controller using the connecting component. When the relay device was used, the relative positions of the end effector on the robot arm and the upper surface of the analog stick on the embedded controller were fixed. Therefore, the above connection components provided a firm connection between the robot arm and embedded controller while the relay device was in use; the robot arm and embedded controller could be easily connected and disconnected when the device was not in use. The connecting parts had notches to prevent interference with the embedded controller, and the robot arm could tilt the analog stick in any direction up to the physical limit of the embedded controller. The electric cylinder was connected to a lever to control the crawler of the backhoe. To prevent physical interference during the device operation, the slider-crank mechanism shown in Fig. 4 was designed. This mechanism allowed the crawler's control lever to be folded up to its physical limit on the embedded controller.

The robot arms and electric cylinders described above were controlled using joysticks. Specifically, when the joystick was tilted without pulling the joystick trigger, the robot arm corresponding to the joystick tilted the analog stick on the embedded controller according to the joystick tilt. However, when the joystick was tilted by pulling the joystick trigger, the corresponding electric cylinder tilted the lever on the embedded controller according to the joystick tilt.

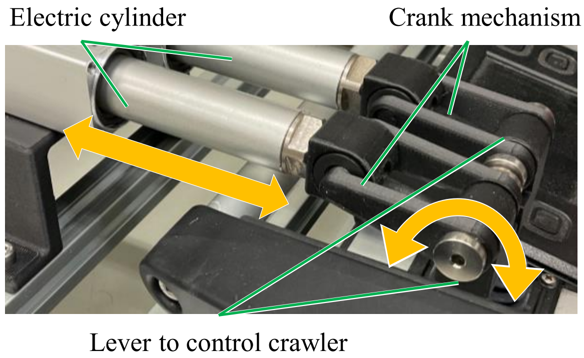

Fig. 4. Mechanism to move a lever to control the crawler.

Thus, the remote-control system enables remote control by retrofitting devices based on 6-axis general-purpose robot arms onto an embedded control device. Therefore, various embedded control device that can be incorporated into the relay device can be controlled remotely from an office by changing the connection components between the robot arm and the embedded control device.

2) SOFTWARE: This section describes the control software used for the robot arm in the relay system. To reduce motion delay, the system calculates and records the posture of the robot arm in response to inputs, and recalls the recorded posture each time an input is made. First, we considered the joystick input pattern. As shown in Fig. 2, the range of θ [deg.] was $0 \leq \theta < 360$ and that of ϕ [deg.] was considered to be $0 \leq \phi \leq 45$. Assuming that the joystick input was in 1° increments, the total number of arbitrary θ and ϕ pairs was 360×46. Subsequently, for each arbitrary pair of θ and ϕ, the corresponding robot-arm posture was calculated and recorded. The robot arm posture was calculated using the open motion-planning library (OMPL) implemented in MoveIt [5], a planning framework for manipulators compatible with the ROS. To evaluate the improvement in the latency of the implemented method, we compared the time between the case in which the target position of the end effector and the posture calculated and the case in which the method implemented ran. The time was measured by randomly generating 100 joystick inputs and measuring the time required to obtain the target posture value for the robot arm for each input. The average measured values are listed in Table I. The table shows that the time was reduced by precalculating the posture of the robot arm.

B. SENSING SYSTEM

We developed a sensing system that can transmit the posture of a backhoe and the viewpoint image from the cockpit of the backhoe to a remote operator. The system used

TABLE I

AVERAGE TIME FROM INPUT TO GET TARGET POSTURE OF ROBOT ARM.

	Sequential computation	Precalculation
Time [ms]	99.8	6.94×10^{-4}

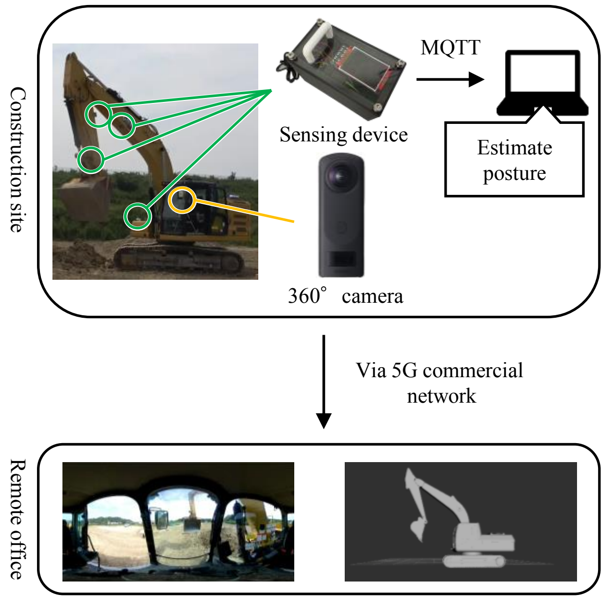

Fig. 5. Architecture of the sensing system.

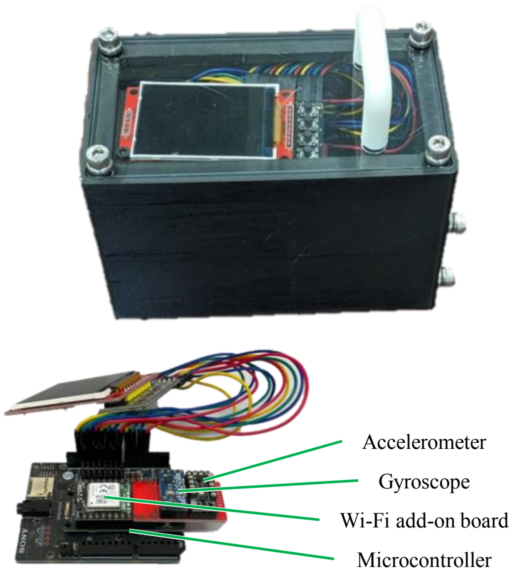

Fig. 6. Sensing device that has angle estimation and self-position estimation functions.

an inexpensive high-performance microcontroller (Spresense, SONY) and sensors to reduce costs while maintaining performance comparable to conventional systems. The architecture of the proposed sensing system is shown in Fig. 5. The system consisted of a sensing device for measuring the backhoe's posture and self-position and a 360° camera (Theta Z1, RICOH) for transmitting viewpoint images from the backhoe cockpit. Sensing devices were attached to the cabin, boom, arm, and bucket of the backhoe, and each joint angle was measured. Each sensing device sent the measured values to an external PC, which estimated the posture of the backhoe from the values of each joint angle. The estimated posture was transmitted to a remote office via a ROS topic. The work scene was transmitted from a 360° camera installed in the backhoe cockpit via a 5G commercial network. This allows the remote operator to receive the necessary information for the task.

Table II presents the characteristics of the sensing device. Fig. 6 shows the specifications of the sensing device, which was a sensor module with a microcontroller, gyroscope (BMI160, Bosch) add-on board, accelerometer (KX126, Kionix) add-on board, Wi-Fi add-on board (iS110B, IDY), and mobile battery (PowerCore 10000, Anker). The sensing device had angle-estimation and self-position-estimation functions. For the angle estimation function, the sensing device acquired the angle of the main body at 100 Hz by applying a Madgwick filter [6] to the values measured by the built-in gyroscope and accelerometer. The sensing device was attached to the cabin, boom, arm, and bucket of the backhoe to estimate its posture (Fig. 5). However, because the direct attachment of the sensing device to the bucket interferes with the soil, only the sensing device for the bucket was attached to a portion of the four-joint linkage mechanism that included the bucket.

For the self-position estimation function, Spresense was equipped with a GNSS receiver and an onboard chip antenna and used quasi-zenith satellite system (QZSS), which were compatible with the submeter-level augmentation service (SLAS). The sensing device implemented a self-position-estimation function using a GNSS receiver function and an onboard chip antenna. Because each sensing device had a self-position estimation function, the backhoe direction could be estimated from the position information of each sensing device.

The angle and location information acquired by the sensing device was sent to an external PC using a message-queuing telemetry transport (MQTT) protocol. Communication between the sensing device and PC was performed wirelessly. Each sensing device had a built-in mobile battery; therefore, wiring was not required when installing the sensing device.

The housing of the sensing device was fabricated using an FDM 3D printer. As the minute gaps created during 3D printing can cause water leakage, an acrylic coating was applied to the entire enclosure to make it waterproof. The cover of the enclosure was made of an acrylic plate, and the gap between the cover and enclosure could be sealed to improve airtightness. Waterproof washers were used in screw-fastened parts to improve airtightness. As described above, the design considered both waterproofing and dustproofing. Four neodymium magnets were embedded at the bottom of the sensing device enclosure, to make it

TABLE II

DATA FOR THE PROPOSED SENSING DEVICE.

Item	Unit	Value
Weight	g	659.4
Required size to affix	mm	140.0×80.0
Accelerometer tolerance	g	± 2
Accelerometer resolution	LSB/g	16384
Gyroscope tolerance	°/s	2000
Gyroscope resolution	LSB/°/s	16.4
Angle sampling frequency	Hz	100
Satellite system in use	-	GPS L1 C/A, QZSS L1 C/A, QZSS L1 S
GNSS-sensor sampling frequency	Hz	1

easily attach to the metal surface of the backhoe. The weight and required size to effectively affix of the sensing device were 71.6% and 60.0% smaller than those of a conventional sensor box [4]. This makes the retrofitting of the sensor to the backhoe more easy.

IV. EXPERIMENTS

A. ACCURACY OF ESTIMATED ANGLES

The accuracy of the angle estimation of the sensing device was determined as follows: First, Spresense, a gyroscope add-on board, and an accelerometer add-on board were fixed to a rod connected to a servomotor. The device was fabricated to stand upright and tilt by 45° every 2 s, and the acceleration and angular velocity were measured at 100 Hz. The estimated angles were calibrated using 10 s of upright state data. The true values were measured using an encoder (UN-1000, MUTOH).

The measured and estimated angles are shown in Fig. 7. The root mean square error (RMSE) of the estimated value was 1.48°. It was found that there was a discrepancy between the converged value of the estimated angle after the servomotor stopped and the measured value. This discrepancy is thought to be partially due to the low accuracy of the accelerometer, which estimates the tilt angle relative to the direction of gravity in static conditions. The accuracy of the angle estimation required for teleoperation and autopilot will be verified in the future.

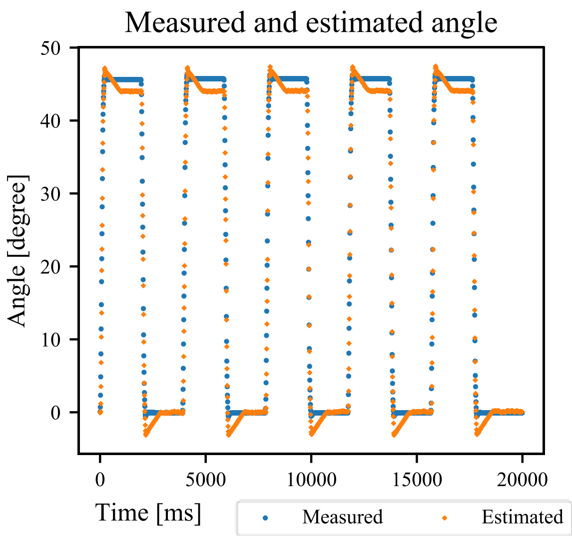

Fig. 7. Results for measured and estimated angle.

B. TELEOPERATION EXPERIMENT

In this experiment, with the cooperation of an experienced operator, we confirmed that the developed system could be used to excavate soil. The excavation procedure is as follows:

1) The backhoe was moved to a pile of earth.
2) A pile of earth was excavated.
3) While holding the excavated soil in the bucket, the backhoe moved to the position where the soil was to be released.
4) The soil was released.
5) The backhoe was moved to the starting position.

The backhoe used was a backhoe (CAT 320, Caterpillar) with a sensing device and 360° camera, as shown in Fig. 5. A remote operator teleoperated the backhoe from an office located 1.2 km away from the construction site, based on the information transmitted by the sensing system. The equipment at the remote office and construction site communicated via SINET6 [7] using 5G communication.

The scene of this experiment is shown in Fig. 8. The remote-control system transmitted inputs from the remote office to the backhoe. The sensing system estimated the latitude and longitude of the backhoe and the angles of the cabin, boom, arm, and bucket, and transmitted the estimated posture of the backhoe and viewpoint image from the cockpit to a remote operator. As shown in Fig. 9, the proposed system can be used to excavate soil.

However, there were situations where the backhoe was moved more than expected, due to delays in the remote-control system and transmitted video. The delay from input to the joystick until the backhoe started moving was 2.0 s. The delay of the transmitted video was 1.0 s. Because communication between the remote office and the construction site was conducted over a 5G commercial network, the delay could vary depending on the communication status of the entire network. A potential remedy is to reduce transmission volume by lowering the quality of the transmitted video. We also observed that Wi-Fi communication was interrupted when the distance between the Wi-Fi router and the devices

Fig. 8. Photograph and schematic of the teleoperation experiment using a backhoe operated by the proposed system. Operator (upper left), relay device (upper right), actual backhoe (lower left), and estimated posture of the backhoe (lower right).

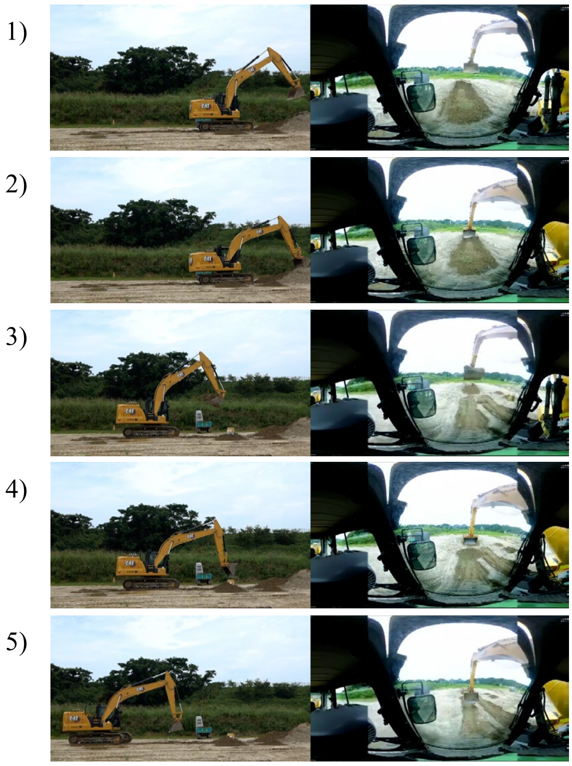

Fig. 9. Excavation procedure. Actual backhoe (left) and a viewpoint image from the cockpit of the backhoe (right).

was far apart or when obstacles were placed in between. One possible solution is to construct a mesh Wi-Fi network to maintain a constant communication path.

In the future, we will verify the accuracy of the latitude and longitude and verify whether the direction of the backhoe can be estimated from the location information of multiple sensing devices. In addition, the system will be able to display images from a 360° camera on a head-mounted display to enable maneuvering under conditions similar to those in a construction site. The proposed system will be linked to the ROS2-TMS-FOR-CONSTRUCTION [8] cyber-physical system for construction sites to realize autonomous backhoe operation.

V. CONCLUSIONS

We developed a retrofitted backhoe teleoperation system that is compact, relatively inexpensive, and easy-to-install using Cat Command. The proposed system comprised remote-control and sensing systems. The remote-control system used a portion of an embedded remote-control system to control remotely at a relatively low cost with less difficulty. The proposed system is highly versatile because it can be used with a variety of embedded remote-control systems by changing the joint components between the embedded remote-control system and the robot arm-based equipment to be retrofitted. For the sensing system, we developed a compact, inexpensive, and high-performance device with built-in microcontrollers and sensors. The sensing device can be easily attached to and removed from the metal surface of the backhoe, and can estimate the posture and position of the backhoe in real time. The estimated posture can be transmitted to a remote operator via a 5G commercial network together with the viewpoint image from the cockpit streamed by a 360° camera. We confirmed that the proposed system can be used to excavate soil using an actual backhoe, controlled from an office located 1.2 km away.

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