Development of Autonomous Robots for Construction

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Abstract –

We have developed two types of autonomous robots for construction works. One is an autonomous mobile robot composed of two industrial robotic arms for ceiling board construction work. It can attach plasterboard weighing approximately 14 kg to ceiling foundations with tapping screws. The other is also an autonomous mobile robot composed of two industrial robotic arms for raised floor construction work. It can install pedestals and panels to floor slabs. Moreover, we have developed assist robots which are autonomous mobile robots to supply materials for each construction work robot. In this paper, we describe overviews of these robots and case studies.

Keywords –

Autonomous mobile robot; Industrial robot; Ceiling board construction; Raised floor construction

1 Introduction

In recent years, the number of skilled workers in Japan has declined by approximately 1.4 million over the past 25 years [1]. About 35% of workers in the construction industry are 55 years old or older, and only about 12% are 29 years old or younger.

Currently, in the construction industry, many examples of efforts to improve productivity by using robotics and digital technology have been reported [2-5]. The introduction of robots to construction sites is expected to improve productivity, alleviate labor shortage, and improve the working environment. However, several issues exist to install robots at construction sites. At the construction sites, the robots need mobility. Self-localization and alignment may be issues because the surrounding environment changes daily. Le et al. [6] developed a mobile robot that automatically fixed cross laminated timber (CLT) panels with screws, and determined the construction position by matching BIM data with the surrounding environment acquired by LiDAR sensors. Satoh et al. [7] developed a mobile robot equipped with a manipulator to patrol agricultural fields. The robot worked in farmland, where the environment also changes daily, by using GNSS and 3D-LiDAR to determine self-position and the surrounding environment. Lauer et al. [8] developed a force control system for a construction machine equipped with a large manipulator to automatically position wood components when they were assembled on site. The system enabled positioning of large workpieces while allowing for divergence between the real construction site and the plan.

We have developed two types of robots to automate the ceiling board construction and the raised floor construction. In this paper, we report overviews and case studies of these autonomous robots. This paper is organized into 4 parts. We explain the overviews of the autonomous robots for ceiling board construction in Sec. 2, the overviews of the autonomous robots for raised floor construction in Sec. 3, and we give our conclusions in Sec. 4.

2 Autonomous robots for ceiling board construction

We have developed autonomous robots for ceiling board construction. Ceiling board construction is one of interior construction works and the process of fixing boards made of gypsum or other materials to steel or wooden foundations using tapping screws or staples. The

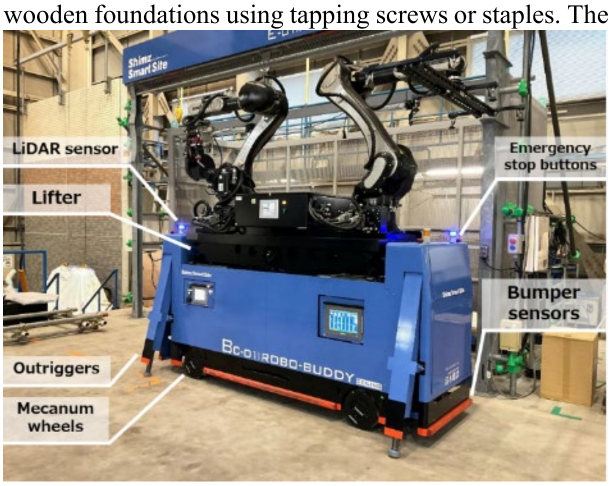

Figure 1. Ceiling construction robot.

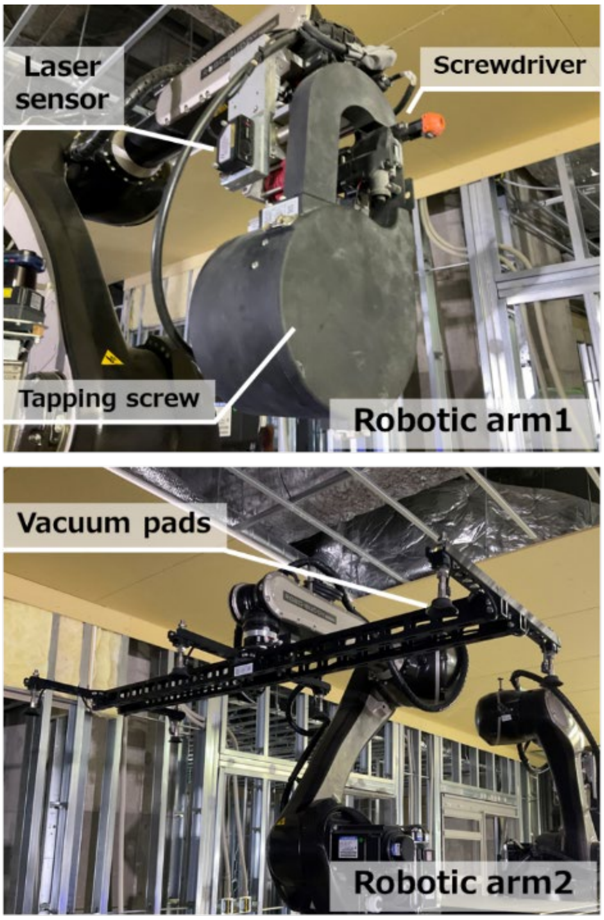

Figure 2. Robotic arms of ceiling construction robot.

Figure 3. Assist robot for ceiling construction robot.

ceiling board construction can conceal equipment materials (e.g., lightings, air conditionings, plumbing, codes) and improve thermal insulation, sound absorption, moisture proofing, and appearance. This is physically demanding work because it requires lifting and supporting a plasterboard and fixing it to the ceiling foundation in an upward posture. In addition, this work requires some temporary scaffolds and a lot of materials. The installation and dismantling of temporary scaffolds are time-consuming, and it involves high-place work.

2.1 Specification

Figures 1 and 2 show a ceiling construction robot and its robotic arms, and figure 3 shows an assist robot for ceiling board construction. The specifications of these robots are shown in Table 1. The robotic arm1 has the end-effector equipped with a screwdriver, a tapping screw case, and a laser sensor to measure the plasterboards and the ceiling foundations. The tapping screw case can load with up to 400 tapping screws. The robotic arm2 has the end-effector equipped six suction pads for grasping the plasterboard.

Table 1 Specification of ceiling construction robot and assist robot for ceiling construction.

	Ceiling construction robot	Assist robot for ceiling construction
Dimensions [mm] L × W × H	2,400 × 800 × 2,600	2,100 × 800 × 2,100
Weight [kg]	2,160	1,115
Power supply	Battery-powered (Lithium-ion recharge battery)	
Control interface	Tablet	
Communication	Mobile or Wi-Fi	
Materials	Plasterboard	

The ceiling construction robot has three PLCs (Programmable Logic Controller). The integration PLC has control functions to communicate with the cloud server, send and receive robot status and commands, process the data obtained from the laser distance sensor and LiDAR sensor, and calculate the speed command value for wheels. The mobility PLC controls the wheels, the lifter, and the outriggers. The robotic arm PLC shares with both robotic arm controllers. These PLCs are connected to the same network and allow the ceiling construction robot to execute the commands autonomously. The assist robot for ceiling board construction can load up to 60 plasterboards and pass to the ceiling construction robot. Both robots have a lifter so they can work at height of up to 4 m. They can recognize self-location with 2D-LiDAR (Light Detection And Ranging) [9] and move autonomously to destinations; as a result, they can move without markers or magnetic tapes.

At construction sites, materials are moved frequently and the surrounding environment changes as construction progresses. Therefore, it is necessary to assume the environment with dynamic obstacles such as workers and materials. To avoid these obstacles, the LiDAR sensor is mounted at the top of a mast which has a telescopic slider mechanism. It is retracted except when the robots move, so it does not interfere with the movement of the robotic arms. The controller can recognize self-location by comparing the map data created from the CAD drawing of the construction site and the point cloud data obtained by 2D-LiDAR. The wheels are mecanum wheels [10], which allow the robots to move in any direction. These robots are equipped with safety sensors (laser distance sensors, 2D-LiDARs, and bumper sensors) to ensure safety and allows them to slow down or stop if there is an obstacle, and they can stop all operations immediately in case of an imminent collision.

All our robots are managed by our cloud server. Our cloud server has a platform that integrates information such as robot status, site drawings, and robot travel routes. The cloud server can command the robots, monitor their status, and navigate the robots through their shortest paths. Since the robots are designed to operate in buildings under construction, we can control the robots without LAN infrastructure. By using a public mobile line, we enable the robots to communicate with the cloud server without any special preparation. And the robots can communicate with the cloud server directly to the VPN through the mobile line and ensure security.

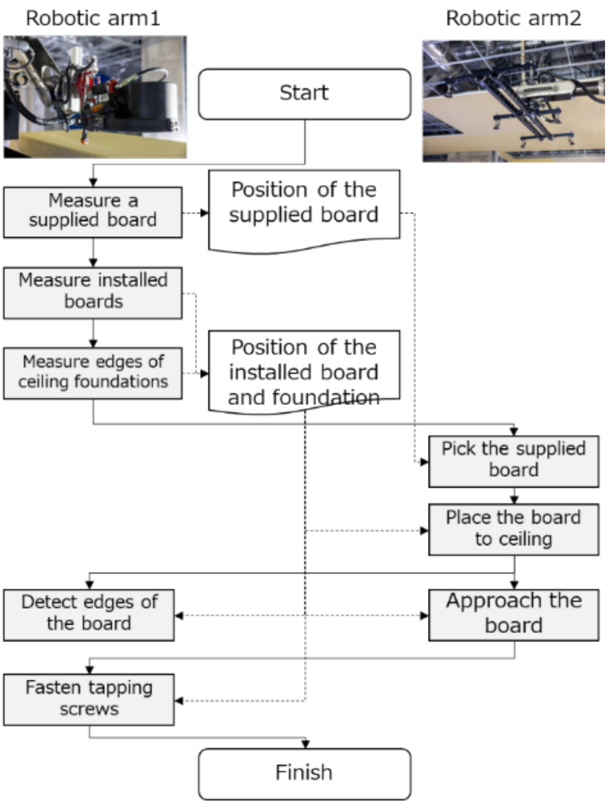

Figure 4. Flowchart of ceiling construction robot.

2.2 Construction procedure

Operators input tasks with a tablet. These tasks are sent to the cloud server via the mobile line connection and are converted into detailed commands on the basis of the maps and machine data. The detailed commands are sent to the integration PLC from the cloud server. The cloud server sequentially sends commands and the associated detailed information depending on the task. Then, the integration PLC sends move commands to the mobility PLC by referring to the self-location obtained by the 2D-LiDAR and the status. After arriving at the destination, the integration PLC sends work commands to the robotic arm PLC.

Figure 4 shows the flowchart of the sequence of robot construction and figure 5 shows the trajectories of robotic arm1. First, robotic arm1 measures the position of the plasterboard on the assist robot. Figure 5 (A) shows the sequence of measuring the position of the board supplied by the assist robot. Robotic arm1 measures the distance from its hand to the top of the stacked boards with a laser sensor at points Z_{A1} and Z_{A2}, then averages the obtained values to determine the distance of point C. Next, robotic arm1 detects the long side by moving its hand in the $-y_r$ direction on the robot's coordinate system O_r to obtain the edges X_{A1} and X_{A2} of the board. Similarly, the robotic arm1 detects the short side by moving its hand in the $-x_r$ direction to obtain the edges Y_{A1} and Y_{A2} of the board. The board coordinates system O can be obtained from the straight lines formed by connecting the edges.

Figure 5 (B) shows the sequence of measuring the position of the boards that have already been installed on the ceiling. Robotic arm1 detects the long side by moving its hand in the $-x_r$ direction on the O_r, to obtain the edges Y_{B1} and Y_{B2} of the board. Similarly, robotic arm1 detects the short side by moving its hand in the $-y_r$ direction to obtain two coordinates of the edges X_{B1} and X_{B2} of the board. Robotic arm1 measures the distance from its hand to the board at Z_{B1} to Z_{B4} in the sequence of detecting edges and averages the obtained values to determine the height of the ceiling. The long side line is calculated with X_{B1} and X_{B2}. The short side line is calculated with Y_{B1} and Y_{B2}. Then, the corner of the board and the relative coordinate system O' are calculated as the intersection of these two straight lines.

Figure 5 (C) shows the sequence of the measuring positions of the ceiling foundations. Robotic arm1 detects the edges of the metal foundations by moving in $-y'$ and $+y'$ directions on O'. The robot calculates straight lines for each foundation using the obtained P'_{n1} and P'_{n2}, and coordinates to fasten the tapping screws. These obtained coordinates are shared with both robotic arm controllers through the robotic arm PLC.

After the measurement of the board, robotic arm2

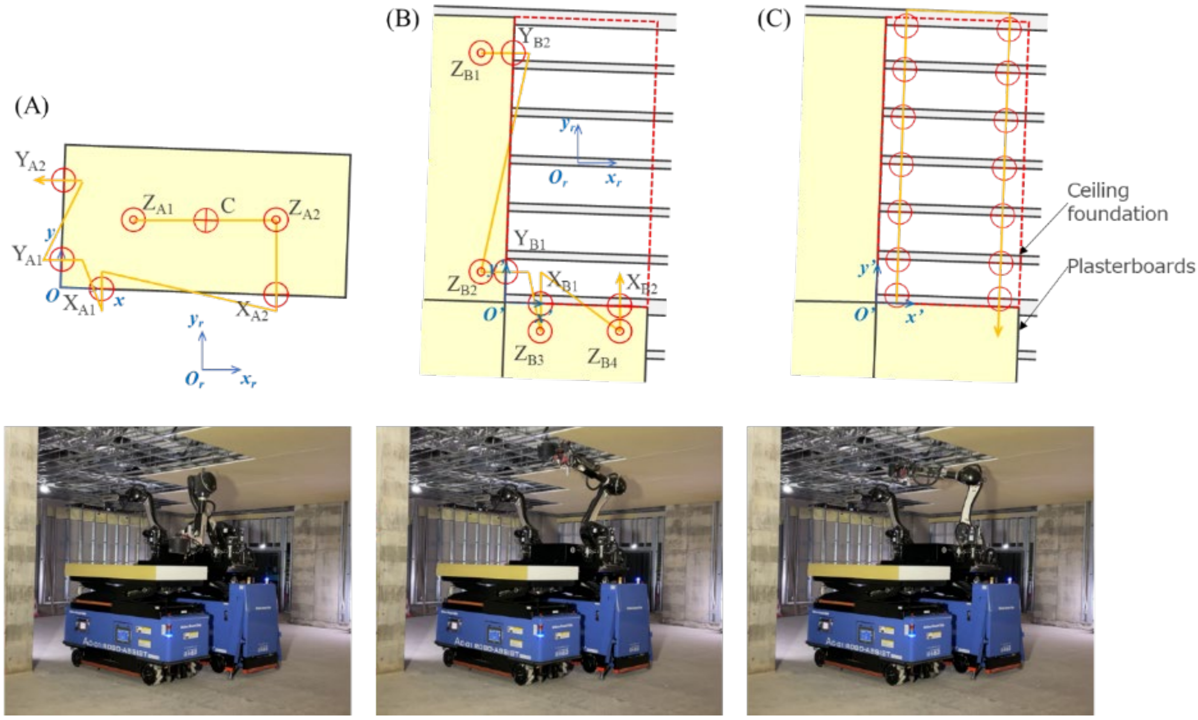

Figure 5. Trajectories of ceiling construction robot. (A) Process of measuring a board supplied by assist robot. Red circles indicate measurement points, and the yellow line represents the trajectory of the robot hand. (B) Process of measuring boards that have been installed on the ceiling and (C) Process of measuring the positions of the ceiling foundations.

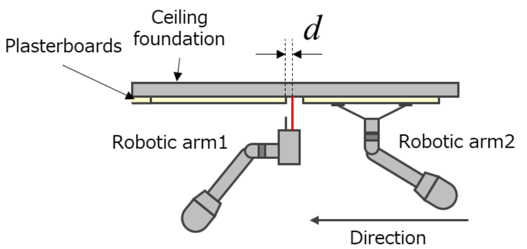

Figure 6. Board positioning process.

picks up the board on the basis of the measured position, turns it over and places it on the ceiling foundations. At this time, robotic arm2 presses the board against the adjacent one to prevent gaps in the −*x*’ and −*y*’ directions. Figure 6 shows a board positioning process. First, the robot sets observation coordinates at *d* away from the edge of the installed ceiling boards. Robotic arm1 moves to the observation point and starts observation with its laser sensor. Robotic arm2 continues to move in the pushing direction. If robotic arm1 detects the board, robotic arm2 moves in the pushing direction by *d* to adjust the board without gaps. The robots execute these processes for the long and short sides. This is an effective method for accurately positioning large objects using only simple measurements.

After adjusting the board, robotic arm1 fixes the board with tapping screws. After it completely fixes the board, the robotic arm PLC sends a completion signal to the cloud server through the integration PLC. By repeating this flow and move commands, the robots can continuously install the ceiling boards.

2.3 Case study

We applied the ceiling board construction robot and the assist robot to a construction site in Japan. We constructed 74 boards (123 m^2). Generally, a pair of workers install ceiling boards. The workers install one plasterboard in about 6 minutes, including setting up and taking down the scaffold. If the workers install 100 m^2 (60 plasterboards), it takes 6 hours a day. On the other hand, the robots install one plasterboard in about 8 minutes. If the robots install 100 m^2, it takes 8 hours a day. As long as the operator can charge the battery and supply materials, the robots can work day and night, and replace more work. The robots can be operated by a single operator and does not require special skills, thus reducing costs. In addition, the robot work does not require temporary scaffolding, eliminating the need to set up and remove scaffolding and reducing the need for work at heights. This allows the robots to replace simple, repetitive, and hard labor, and workers can focus on tasks such as plasterboard processing and precision tasks that require accuracy. In this way, cooperative work between workers and robots can free the workers from hard labor and contribute to improved work efficiency.

3 Autonomous robots for raised floor construction

We have developed a floor construction robot to automate the raised floor construction work. It is a work to store wiring and piping by providing space on the floor slab. Raised floors offer easy access to wiring, and concealing cables prevent damage to cabling and tripping and falling hazards. Supports, generally called pedestals, are installed to adjust the height, and panels are laid on top of them. This work requires a considerable physical burden, for example, on the waist, because workers must constantly lean forward to perform the task.

3.1 Specification

Figures 7 and 8 show the floor construction robot and its robotic arms, and figure 9 shows the assist robot for the floor construction robot. The specifications of these robots are shown in Table 2. Similar to the ceiling construction robot, the floor construction robot is an autonomous mobile robot composed two robotic arms. The robotic arm1 has an end effector equipped with a camera, a laser distance sensor, a rotating laser receiver, and a gripper, which can locate floor line markings, pick up pedestals, dip into adhesive to the pedestals, and adjust the pedestal height by turning the screw. The robotic arm2 also has an end effector with a camera, a laser distance sensor, and vacuum pads, which can pick up panels. The assist robot for floor construction robot has feeders for loading pedestals and panels. It can carry up to 36 panels and up to 88 pedestals. The upper part of the pedestal feeder has a feed mechanism to place the pedestals where the robot can pick them up so that they

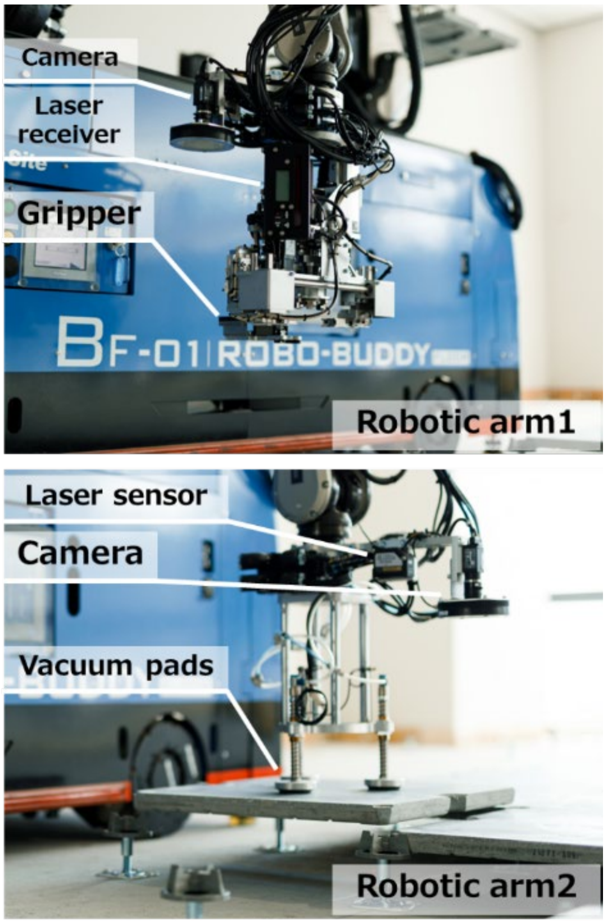

Figure 8. Robotic arms of floor construction robot.

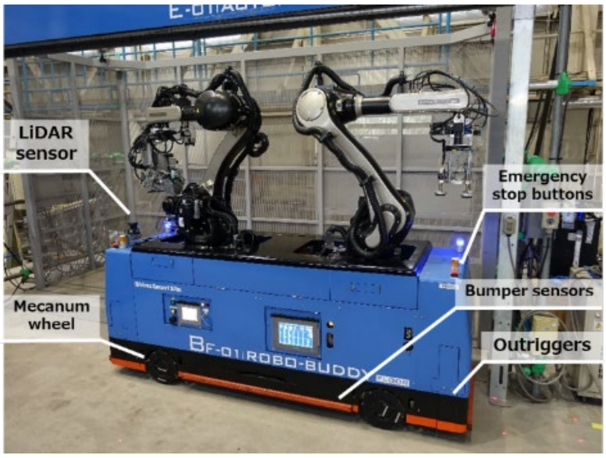

Figure 7. Floor construction robot.

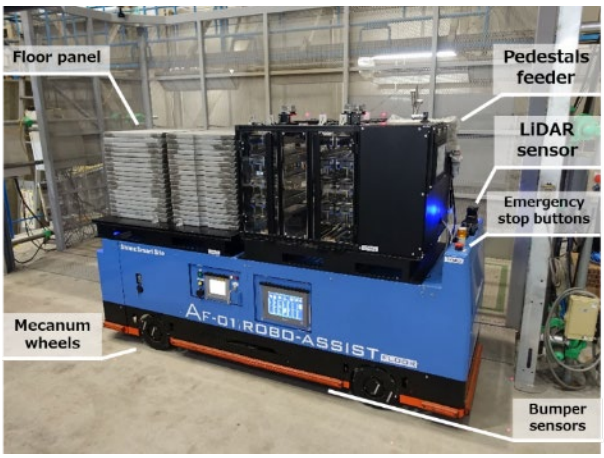

Figure 9. Assist robot for floor construction robot.

are automatically supplied to the floor construction robot. In addition, a container is installed at the top to contain the adhesive to be applied to the bottom of the pedestals picked up by the robot.

Table 2 Specification of floor construction robot and assist robot for floor construction.

	Floor construction robot	Assist robot for floor construction
Dimensions [mm] L × W × H	2,500 × 800 × 1,750	2,500 × 800 × 1,700
Weight [kg]	1,460	1,125
Power supply	Battery-powered (Lithium-ion recharge battery)	
Control interface	Tablet	
Communication	Mobile or Wi-Fi	
Materials	Panels, pedestals, adhesive	

The components of the PLCs are the same as those of the ceiling construction robot and assist robot for ceiling construction robot. We have also been commonly developing other units, such as those for controlling traveling and sending and receiving commands from tablet applicable to these robots. The floor construction robot has a separate computer for processing the data obtained from the camera and laser distance sensor, and the processing result is sent to its PLC. In addition, the feeder of the assist robot for floor construction robot has a PLC to control the device to feed the pedestals.

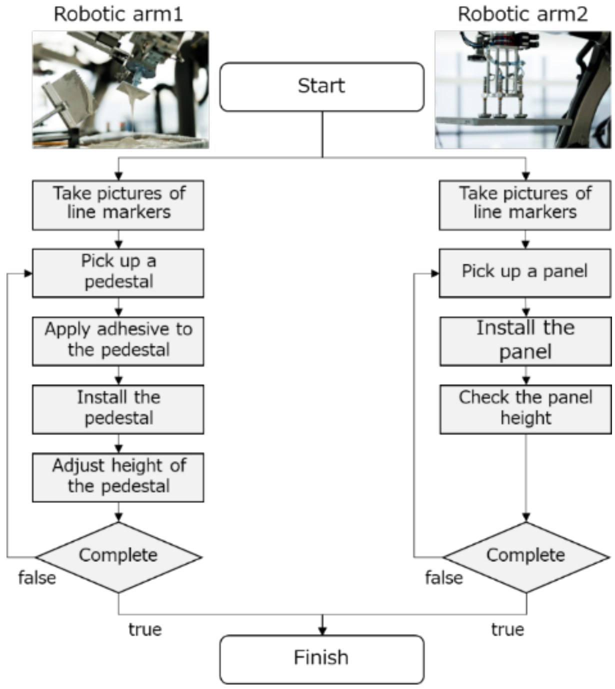

Figure 10. Flowchart of floor construction robot.

3.2 Construction procedure

In preparation for construction, first, perform floor marking on the floor slab for the raised floor installation. Since this floor marking is also necessary for the workers to perform their tasks, it can be done in the same work environment as the workers. Next, set up the laser level and adjust the height to the desired floor level.

Like ceiling construction robots, workers can generate work commands using a tablet and operate the robots through the cloud server. When the robot reaches the target position, it starts installing the raised floor.

Figure 10 shows a flowchart of the raised floor construction by the robot. When no pedestals are in place, only the robotic arm1 repeats the tasks of installing the pedestals. When four or more pedestals are placed, and the panels are ready to be laid, the robot performs the pedestal and panel installation simultaneously. First, the robotic arm1 takes pictures of the floor line markings and identifies the target position. Once the robotic arm1 completes taking pictures, the robotic arm 2 starts to take pictures of the floor markings. Since the robotic arms share their status and posture, they can move without interference from each other. The robotic arm1 picks up the pedestals supplied from the pedestal feeder of the assist robot. The position of the pedestals can be identified by recognizing the relative position from the marker on the feeder.

When the robotarm1 picks up the pedestal, the robotarm1 dips into the adhesive to bottom surface of the pedestal. A box containing adhesive is prepared on the assist robot. The adhesive is applied to the bottom surface based on information on the adhesive surface height measured by the laser distance sensor. In addition, a comb is prepared at the top of the box to remove excess adhesive.

Next, the pedestals are installed according to the floor line markings, and the pedestal height is adjusted according to the height of the laser level.

Once the pedestals are installed, the robotic arm2

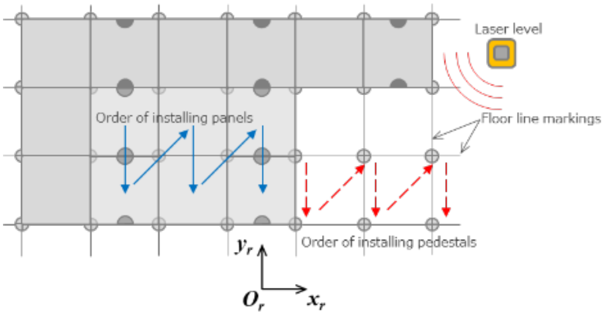

Figure 11. The order of the pedestal and panel installation

picks up the panels on the assist robot and installs the panel on the pedestals. Finally, measure the height of the panel edge installed to ensure correct installation. If not, skip the installation of the surrounding panels to avoid failure of the laying of adjacent panels. This process prevents the error propagation.

As the pedestals are installed, the target area to install the panels increases, so the robotic arms can communicate signals with each other using a PLC and work simultaneously, avoiding interference. Figure 11 shows the order of installing the pedestals and the panels when the robot works most efficiently. Each robotic arm places the panels and pedestals in the direction of each arrow. At this time, the center of the robot body is located on the center line of the panel to be installed last. Once the six panels and pedestals have been installed, the robot moves parallel in the x_r direction and starts the installation again.

3.3 Case study

The floor construction robot and the assist robot were applied to construction sites in Japan. They were applied at another site, and the area of 425 m^2 was covered in 10 days, excluding the perimeter of walls and pillars. The workers generally perform floor marking on the floor slab, install pedestals, and install panels step by step. Unlike the robotic construction procedure, the panels are usually installed over the entire work area after installing the pedestals instead of simultaneously laying the pedestals and panels. Therefore, it is not easy to compare work efficiency, but based on the production rates of all processes, the daily output per robot corresponds to the daily output per worker. The workers generally lay materials such as particleboard where the panel size does not fit, such as the area alongside the wall. Since these materials need to be sized according to the site dimensions, it is a labor-intensive work that requires measuring, cutting, and installing. By replacing workers with robots in simple tasks, workers can focus on these time-consuming and highly skilled tasks.

4 Conclusion

We have developed two types of autonomous robots. Ceiling construction robots can install ceiling boards automatically and floor construction robots can install the pedestals and panels automatically. These robots can move at construction sites using the self-localization system with 2D-LiDAR and safety devices. Each of the robots performed the installation at the construction sites and showed the usefulness of installation of the robots. The ceiling construction robots can perform the work of two operators in eight hours. The number of workers required is reduced to one operator. Moreover, the unit labor cost can be reduced as no special skills or physical strength are required. The floor construction robots can perform the work of one worker in one day. As with the ceiling construction robots, this has the effect of reducing labor costs.

Construction sites involve a variety of tasks. In ceiling work construction, the works include a lot of tasks such as installing suspension bolts in the upper floor slab, constructing the ceiling foundation, fixing the plasterboards with screws, installing the finishing board, and installing the equipment. In floor construction, the works also include many tasks such as marking lines on the floor slab, installing the raised floor, laying the floor mat, and installing the cable. However, the amount of work that can be automated is small because our robots target only a single task. Therefore, it is still difficult to obtain cost advantages. Our future work is to expand the types of work that can be performed by the robots to realize more productive construction and more cost benefits.

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