耐火被覆吹付けロボットの高機能化

上 田 航 平　　坂 上 　肇
瀬 川 紘 史　　池 田 雄 一

Upgrading Fireproof Coating Spraying Robots

Kohei Ueda　Hajime Sakagami
Hirofumi Segawa　Yuichi Ikeda

Abstract

At construction sites, fireproof coating spraying is particularly affected by a shortage of skilled workers because of the harsh working environment. Hence, a growing need exists for technologies that reduce the labor requirements in fireproofing operations. In this study, fireproof coating-spraying robots were developed and used in building construction projects. The autonomous movement function of the robot was improved, and a beam-recognition function was developed. The following conclusions are drawn from the study: (1) The improved autonomous mobility function enables full-day onsite operation. (2) The beam recognition function stabilizes the spray quality by correcting the spray path based on the relative position between the robot and the beam. Although positioning time increased, having each operator operate multiple robots improved overall productivity by approximately 1.4 times. We plan to continue these efforts toward practical implementation and further expand robot applications in building construction.

1.　Introduction

Fireproof coating spraying, particularly during summer, suffers from a significant shortage of skilled workers because of harsh working conditions. To address this issue, construction companies have actively developed technologies aimed at reducing the labor requirements in fireproof coating operations[1]. At Obayashi Corporation, we developed a fireproof coating spraying robot (hereafter referred to as "the robot," Fig. 1) to automate the spraying process in semi-dry sprayed rock wool fireproofing applications[2].

The robot was equipped with autonomous mobility functions. By registering the movement path and target beams in advance, the robot can automatically perform a series of operations, such as moving to the target beam, spraying, and then moving to the next beam. Based on previous field applications[3], productivity was found to improve by having one operator manage multiple robots rather than a single worker performing manual fireproofing work.

In a previous report[4], we changed the robot's autonomous navigation system from a simultaneous localization and mapping (SLAM) method using two-dimensional light detection and ranging (2D LiDAR) to a method that calculates self-location based on measurements of dedicated targets placed at known points. However, in actual construction sites, changes in lighting conditions sometimes prevent robots from recognizing their targets. To address this issue, we improved the autonomous mobility function to enhance the stability of automatic target recognition.

In addition, the sprayed finish is not always consistent because of various construction errors at the site, even when operations are performed based on design specifications, which presents another challenge. To address this issue, we developed a new function (the "beam recognition function") that stabilizes the sprayed finish by measuring construction errors and feeding them back to the robot.

In this report, we define these improvements as "functional upgrades" and describe the development process and application results in a high-rise building construction project. Furthermore, to verify the effectiveness and practicality of the upgrades, comparative evaluations of the sprayed finish were conducted with and without improved functions.

Fig. 1　Fireproof coating spraying robot

2. Identified Issues and Robot Improvements

2.1 Summary of Issues and Robot Improvements

The autonomous mobility function is presented in Figs. 2 and 3. The robot was equipped with a measurement unit consisting of a laser rangefinder, camera, and rotating platform. By measuring the distance and angle between the robot and two targets placed at known points, the robot calculated its own position, as illustrated in Fig. 4.

First, the robot and targets are placed in their initial positions, and their relative positions are registered. Next, information regarding the movement path and target beams (such as beam height, width, and floor height) is registered. As the robot moves along a registered path, it measures the targets distances and angles, and calculates its position. If the calculated position (robot center) deviates significantly from the registered stopping point, the robot performs corrective movements toward the designated stopping point. Subsequently, it performs the spraying operation and moves again along the registered path. This procedure is then repeated.

In actual construction sites, lighting conditions vary significantly, and in certain instances, the measurement unit fails to automatically recognize the target. Consequently, the robot cannot calculate its position and is unable to perform corrective movements. If spraying is performed without correction, deviations from the intended position adversely affect the spray quality.

Even when the robot navigates accurately, construction errors in the beam and slabs can cause the relative position and angle between the robot and target beam to deviate from the design specifications, which leads to subpar spray quality.

To address these issues, the autonomous mobility function was improved to enhance the stability of the automatic target recognition. Additionally, a new function was developed to measure the relative position and angle between the robot and target beam to correct the spray path accordingly.

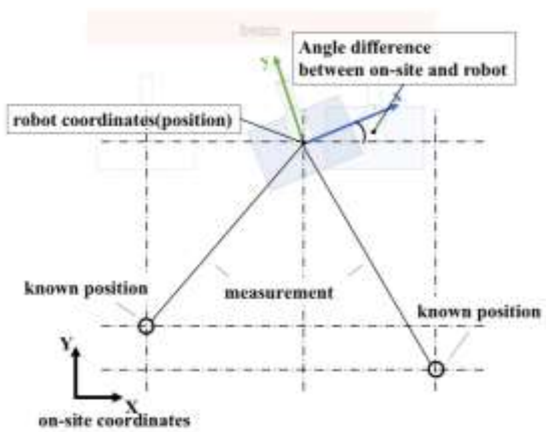

Fig. 2 Schematic of the self-location measurement method

2.2 Improvement of Autonomous Mobility Function

The robot failed to automatically recognize the targets primarily due to the significant difference between the indoor development (Fig. 5) and the actual construction site

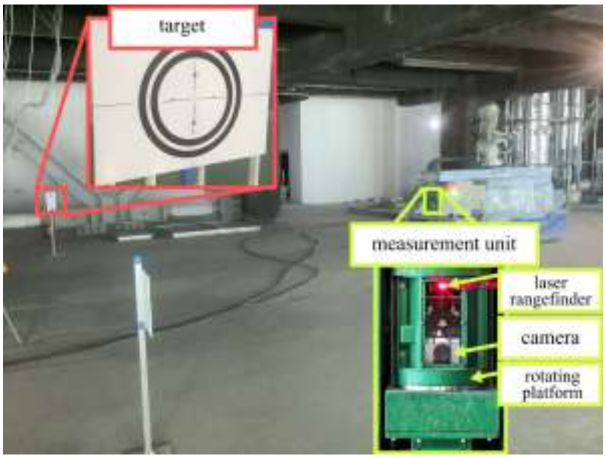

Fig. 3 Crafted target and measurement unit

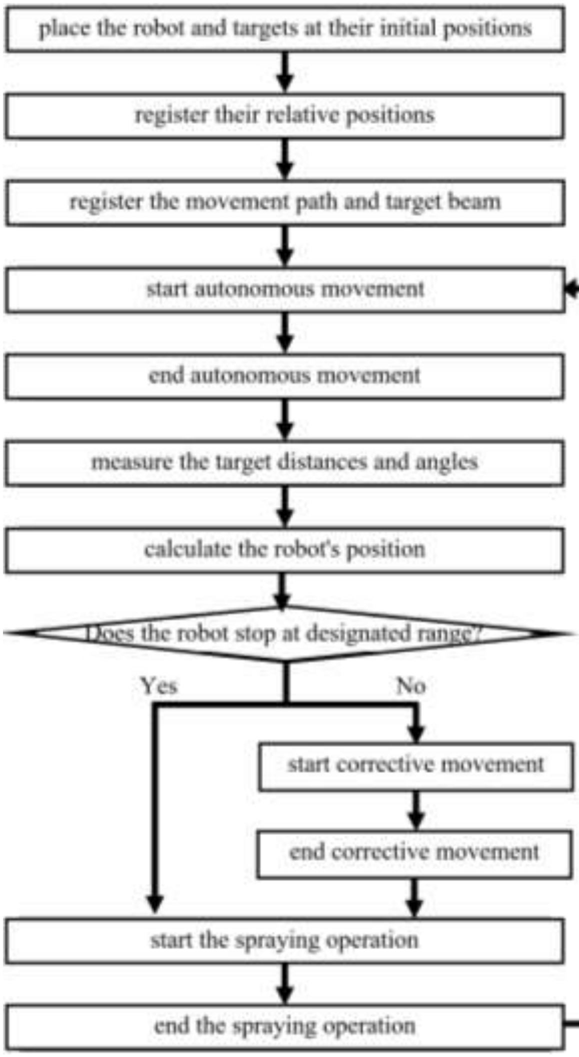

Fig. 4 Workflow of the autonomous mobility function

environment (Fig. 6). For example, while lighting in the indoor development environment was constant, the brightness at the construction site varied greatly depending on weather conditions (e.g., sunny or cloudy) and the time of day.

Although the development process considered differences in lighting sources and brightness, actual site conditions often exceeded these expectations. Therefore, we collected image data of the targets under various conditions (weather, time of day, etc.) at the actual site. By analyzing these images and adjusting the threshold values used in image processing, we enhanced the stability of the automatic recognition rate.

2.3 Implementation of the Beam Recognition Function

A laser rangefinder was mounted on the tip of the robot arm used for spraying. By moving the robot arm along the transverse and vertical axes, as shown in Fig. 7, the robot measured its distance from the beam. This allowed the system to calculate the relative position (Δy, Δz) and relative angles (ΔRx, ΔRy, ΔRz) between the robot and the beam to correct the spray path accordingly.

By adjusting the spray path based on the values calculated by the beam recognition function, the robot achieved a spray quality that matched the design specifications in terms of relative position and angle. In the verification experiments conducted after implementing the beam-recognition function, the robot was stopped at various relative positions and angles, and the values calculated by the function generally matched the actual stopping positions.

3. Application to High-Rise Mixed-Use Building Construction Project

3.1 Overview of the Construction Project

Table 1 outlines these construction projects. The target building is a 31-story mixed-use facility. The lower floors are commercial spaces, and the standard office floors are located from the 8th to the 30th floor. The fireproof coating thickness was 60 mm (3 h fire resistance (up to the 17th floor)), 45 mm (2 h fire resistance (18th to 27th floors)), and 25 mm (1 h fire resistance (28th floor and above)).

3.2 Application Plan

3.2.1 Robot's Target Areas The robot was assigned even-numbered floors from 8th to 26th. These floors required either 3 h or 2 h fire resistance. Fig. 8 shows the target areas of the robot on each floor. The spray targets included both small and large beams within the designated office area. The target area of the robot per floor was approximately 400 m².

Fig. 5 Indoor environment during development

Fig. 6 Construction site environment during spraying

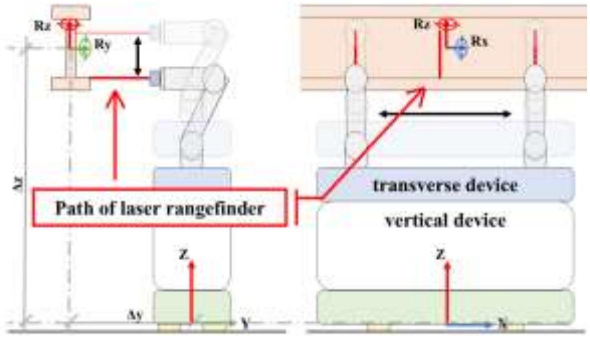

Fig. 7 Schematic of beam recognition measurement

Table 1 Outline of construction project

Number of stories	31-story
Building use	Commercial facility, Office
The robot's application area per floor	400 m² / floor
The floor(s) targeted for robot (Fire resistance rating)	8to16(even-numbered only) (3 hours) 18to26(even-numbered only) (2 hours）

3.2.2 Construction System

The construction system consisted of a robot, a robot operator, and an assistant cleaner. The robot operator was responsible for handling errors or unexpected events during spraying and manually moving the robot in areas where targets could not be placed, making functional upgrades infeasible.

Since the office area was divided into ceiling chambers, troweling and slurry spraying were required after the fireproof coating was applied. Considering overall work efficiency, a workflow was planned such that after the robot completed spraying, manual workers performed touch-ups and slurry spraying (Fig. 9).

3.2.3 Layout Planning

Fig. 10 shows an example of a robot layout during beam spraying. For small beams, the spraying area was divided into two sections along the 7.2 m span, with spraying performed on both sides of the beam at four locations in total. The robot was positioned parallel to the beam centerline and moved along the beam axis using a transverse device for efficient spraying.

Fig. 11 illustrates an example of the robot and target layout and movement path where functional upgrades are applied. The targets were placed in a span adjacent to the robot, with approximately one target in every three spans.

3.2.4 Collection Operational Data

The accuracy of the autonomous navigation was evaluated by measuring the robot's center position before and after corrective movement. The stability of the automatic target recognition was assessed by recording the number of successful and failed recognitions.

The quality of the beam recognition function was evaluated by measuring the sprayed finish using a laser scanner and comparing the results with and without the spray path correction. The relative position and angle values calculated using the beam recognition function were also recorded.

Since enabling functional upgrades added steps such as target and beam measurement, the time needed to reach the spraying position would increase (seconds from the top in Fig. 9). Therefore, the productivity per unit time was recorded. Additionally, because much of the work was performed during summer, potential mechanical issues due to high temperatures were closely monitored.

4. Results of Application

4.1 Construction Quality

The thickness was adjusted to at least 0.28, as required by the standards. All measured values ranged from 0.29 to 0.30, exceeding the required threshold.

Fig. 8 Robot target areas

Fig. 9 Workflow of robot and manual workers

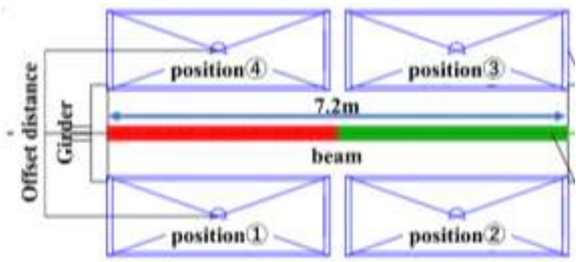

Fig. 10 Robot layout during beam spraying

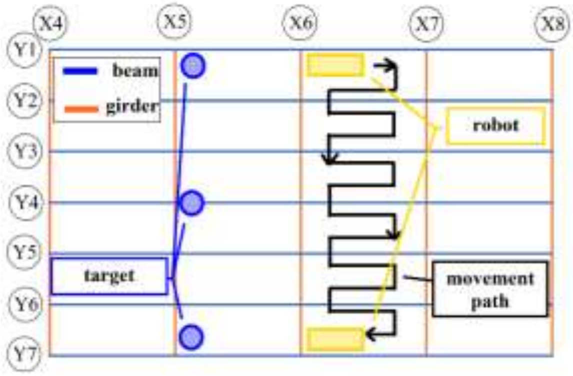

Fig. 11 Robot and target layout and movement path

4.2 Positioning Error of Autonomous Mobility Function

The positioning errors before and after corrective movement are shown in Fig. 12 and Table 2. In Fig. 12, there is a significant reduction in the spread after corrective movement. Comparing the errors in the x- and y-directions, the standard deviation in the x-direction is larger. This is attributed to the orientation of the mecanum wheels installed on the driving unit. These wheels behave differently when moving in the travel direction (y-axis) versus the transverse direction (x-axis), particularly under site conditions affected by dust and rainwater, which may cause slippage and prevent accurate positioning.

4.3 Impact of Beam Recognition Function on Spray Quality

Table 3 presents the relative errors between the beam and robot. After corrective movement, the robot's positioning error in the y-direction (Δy) has a mean of -0.3 mm and a standard deviation of 2.1 mm. However, the relative error calculated using the beam recognition function was larger, with a mean of 5.0 mm and a standard deviation of 23.8 mm.

This discrepancy is likely caused by a slight unevenness in the slab, which tilts the robot during vertical movement and introduces measurement errors.

To analyze the impact of the beam recognition function on s pray quality, point-cloud data obtained via laser scanning wer e used (Fig. 13). Fig. 14 compares the coating thicknesses at t he lower edge of the upper flange, where the spray angle error s were most pronounced. The results indicate that enabling the beam recognition function slightly increases the average coati ng thickness and reduces the frequency of areas below the req uired thickness. This improvement is attributed to correcting t

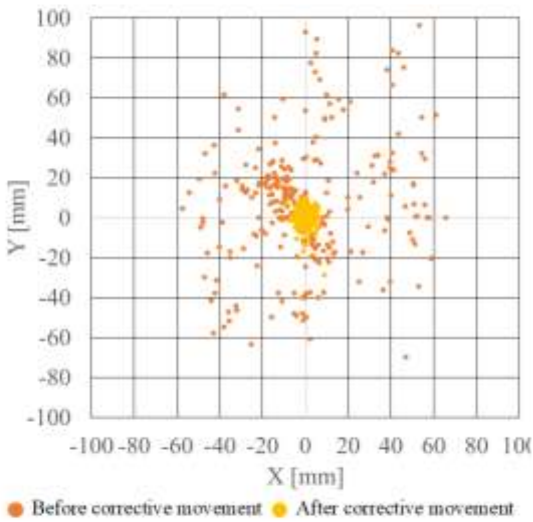

Fig. 12 Errors before and after corrective movement

Table 2 Errors before and after corrective movement

Before corrective m ovement(mm)	Δx	Δy	ΔRz
Average	2.9	-0.4	0.0
Standard deviation	24.2	19.2	0.3
After corrective movement(mm)	**Δx**	**Δy**	**ΔRz**
Average	-0.1	-0.3	0.0
Standard deviation	3.2	2.1	0.0

Table 3 Relative errors for the beam and robot

Measurement results(mm)	Δy	Δz	ΔRx	ΔRy	ΔRz
Average	5.0	-14.6	0.1	0.0	-0.2
Standard deviation	23.8	9.6	7.7	1.1	1.2

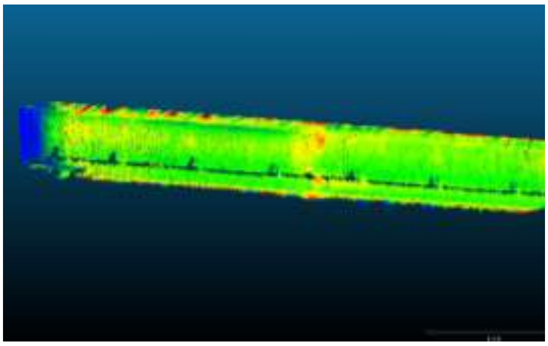

Fig. 13 Point-cloud data after beam spraying

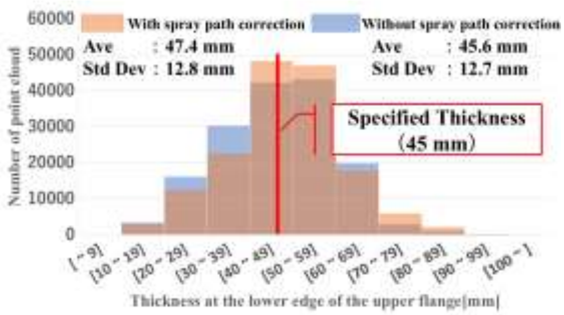

Fig. 14 Comparison of coating thickness

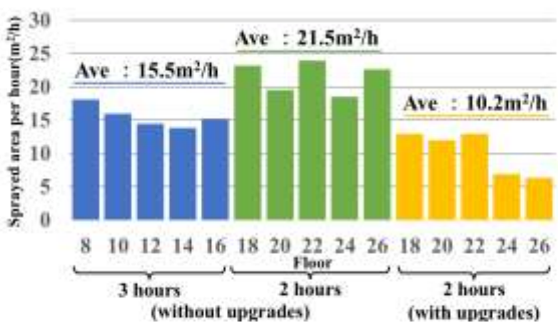

Fig. 15 Productivity summary of spraying per floor

he spray path to match the design specifications. Areas with in sufficient thickness were manually repaired by fireproofing workers.

4.4 Productivity

Fig. 15 summarizes the productivity of the spraying operations per floor, comparing cases with and without functional upgrades. For 3 h fire resistance floors without upgrades, the robot achieved an average productivity of approximately 15.5 m²/h, which is a 35% improvement over manual fireproofing. For 2 h fire resistance floors, an average productivity of approximately 21.5 m²/h was obtained, representing a 50% improvement. The thinner coating required for the 2 h resistance reduced the spraying time, contributing to higher productivity.

In contrast, with functional upgrades enabled, the productivity of 2 h fire-resistance floors averaged only 10.2 m²/h, approximately 70% of the manual fireproofing productivity attributed to the additional time spent on target and beam measurements.

Despite lower productivity, the autonomous operation of the robot reduced the workload of the operators, enabling one operator to manage multiple robots. This approach is expected to increase overall productivity per operator beyond that of manual workers. For example, operating two robots at 70% productivity would result in a combined productivity that is approximately 1.4 times higher than that of a single manual worker. Additionally, the beam-recognition function is expected to improve spray quality.

Manual worker productivity tends to decrease by 10%–20% during summer under heat stress. However, during this project, which involved extensive summer work, no decline in robot productivity was observed, demonstrating the stability of the robotic operations.

5. Conclusion

The fireproof coating spraying robot was improved by enhancing the stability of automatic target recognition and developing a beam recognition function. The effectiveness of these upgrades was confirmed in a high-rise mixed-use building construction project.

Regarding the improvement in the autonomous mobility function, the enhancement successfully stabilized the automatic recognition rate of the targets. The development of the beam recognition function contributed to an improved and stabilized spray quality.

Although the implementation of functional upgrades led to a decrease in productivity of approximately 70% compared to manual fireproofing because of the need for measurements of dedicated targets and beams before spraying, it also reduced the workload of robot operators. This reduction in labor enables the simultaneous operation of multiple robots by a single operator.

Consequently, the overall productivity per operator is expected to exceed that of manual fireproofing. For instance, operating two robots at 70% productivity would yield a combined productivity that is approximately 1.4 times higher than that of a single manual worker. In addition, the beam recognition function is expected to stabilize the spray quality.

References

1) Riku Matsuda, Takeshi Yoshida, et al.: Study on the Robotization of Fireproof Coating Spraying Work (Part 1 to Part 3), Proceedings of the Architectural Institute of Japan 2025 Annual Convention (Kyushu), pp.1405–1410, September 2025.
2) Kohei Ueda, Yuichi Ikeda: Development and Field Application of Fireproof Coating Spraying Robot, The 24th Symposium on Automation Technology in Architecture, March 2024.
3) Kohei Ueda, Hirofumi Segawa, et al.: Study on the Automation of Fireproof Coating Spraying Work (Part 8, Part 9), Proceedings of the Architectural Institute of Japan 2024 Annual Convention (Kanto), pp.1145-1148, August 2024.
4) Hirofumi Segawa, Kohei Ueda, et al.: Development of the Second-Generation Fireproof Coating Spraying Robot and Its Application to High-Rise Building Construction, Obayashi Technical Research Institute Report, No.88, 2024.
5) Kohei Ueda, Hajime Sakagami, et al.: Development of Fireproof Coating Spraying Robot, The 23rd Construction Robot Symposium, October 2025.