Development and Application of a Fire Resistive Covering Spraying Robot to Building Construction Site

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Abstract –

Although the amount of building construction in Japan is not expected to decrease in the next few years, there has been a decrease in the number of fire resistive covering workers over the years. In this study, to overcome the shortage of construction workers, we developed a spraying robot for fire resistive covering. Optical sensors such as LiDARs and cameras may not work efficiently in dusty environments under spraying; therefore, we proposed a spraying method that would feasibly work without using them.

The robot is composed of traveling, lifting, and traversing devices, and a robot arm; it can move autonomously if a map of the working area is created in advance. We carried out several experiments to obtain the optimum spraying work data for each beam size in advance. Having the optimal spraying work data for each beam size, and grasping the position error and posture of the robot, the robot can spray accurately when sensing data for spraying is not available. By registering the work data in the work list according to the stop position and beam size, the robot can automatically spray multiple beams continuously.

We applied the developed robot to a building construction. After spraying, the shape of the sprayed covering was measured using a LiDAR, which verified the thickness. The specific gravity was observed to be higher than the regulation, and the quality was equivalent to that of workers. The spraying speed was approximately 80% of that of workers. In the future, the robot will have the potential of attaining the same construction speed as workers by making various improvements to it, as well as making it spray automatically.

Keywords –

Building Construction Robot; Fire Resistive Covering; Construction Automation; LiDAR

1 Introduction

In recent years, there has been a remarkable shortage of construction workers in Japan[1]. In particular, the number of workers for fire resistive covering spraying work in Japan has been significantly reduced because of poor working environments. In past study, the authors conducted a basic experiment of fire resistive covering spraying automatically using a robot arm and confirmed that the quality of fire resistive covering sprayed by the robot arm was equivalent to that sprayed by skilled workers[2]. As a next step, we developed a fire resistive covering spraying robot (hereinafter, spraying robot), and tested spraying. Subsequently, the spraying robot was applied in a construction site. This thesis describes the its development and results of its application.

2 Robot Development

2.1 Past Development Cases

In Japan, over 30 years ago, several companies had been developing spraying robots. Skilled workers taught those robots spraying motion and they could not move to the spraying position easily. However, the development was interrupted because the construction performance of robots were lower than workers[3]. There were various reasons for this, including the low level of technology at the time and the high cost of development and so on. In recent years, the robot arm has become cheaper, easier to use and an environment for easy development has been established. On the other hand, SLAM in the field of autonomous mobile robot has become available to anyone. There are two major methods of SLAM. One is a method using vision and the other is a method using shape matching with point cloud data. Both methods have been used in the construction field in recent years[4][5]. Therefore, we decided to start the development of the spraying robot in-house.

2.2 Robot Specifications

In order to replace a spraying worker with a robot, we assumed the work system shown in Figure 1. We set a high technical level goal where the robot could move, align and spray automatically by itself rather than be operated remotely by a dedicated operator.

The developed robot is shown in Figure 2, and its specifications are shown in Table 1. Table 1 shows the applicable construction sites. The targets of the robot's spraying are the girders and beams on the standard floors of middle or high-rise buildings. The robot is relocated to the upper floors by a crane or a construction elevator. The size and weight of the robot are such that it can be loaded on the platform of the construction elevator (2500kgf class). Because the robot sprays for girders and beams at a raised place, a lifting device is indispensable. Because widening the spraying area improves work efficiency, we install a traversing device that can move in the beam direction. In the case of large spans (more than 20 m), the maximum girder height is 1.5 m and the floor height is about 4.5 m; therefore, the workable floor height is set to 5.5m with some margin. We install to a travelling devise four mecanum wheels that can be finely adjusted in all directions when positioning the spraying robot. This is because the robot may move slightly in all directions.

2.3 Robot Control

The parameters involved in the spraying control of the robot include spraying distance, moving speed, pitch, and angle. The set value varies depending on the part of beams (lower flange bottom, its top, its edge, web, upper flange bottom, its edge), and changes according to the required fire resistive time specification of the fire resistive covering (specified coating thickness). We created a program that automatically assigns these control parameters to each beam size (beam height, beam width, plate thickness), and automatically creates robot work files. If we have structural design data in advance, it is possible to create spraying work files for all girders and beams of any construction without teaching by skilled workers.

We conducted an experiment in advance to evaluate the optimum parameters that could be used to effectively spray each part of the girders and beams in terms of quality. The spraying robot moves to the set girder and beam locations and aligns to them within a threshold. The working data of the spraying robot is corrected according to its stopping position error. The robot was operated on these principles.

If we create the map data of working area based on the distance data of the surrounding shape acquired by the two 2D-LiDARs installed at the diagonal corners of the robot and the initial position of the robot is specified, the position and direction of the robot are determined by SLAM. It can be calculated in the map using a

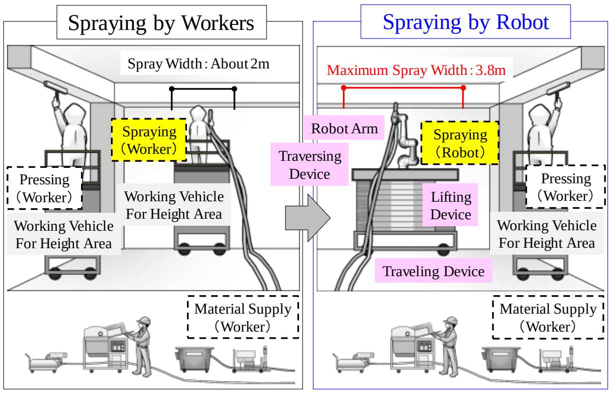

Figure 1. Spraying by Workers and Robot

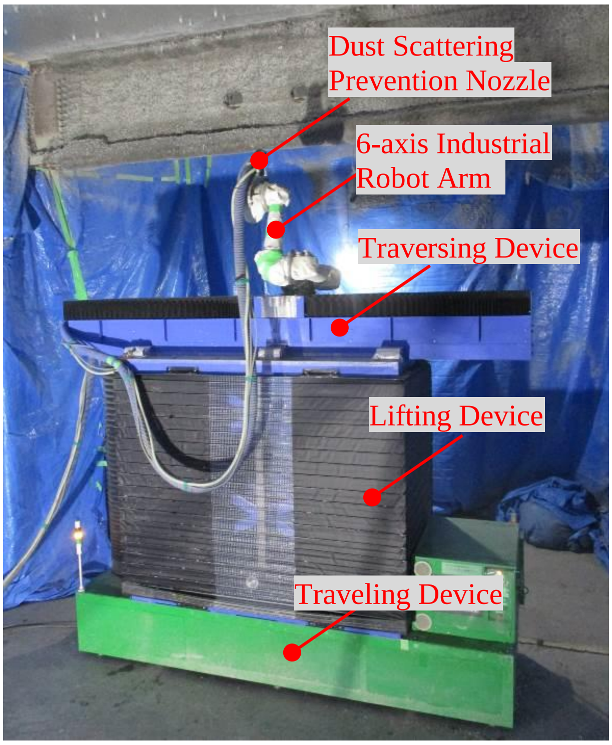

Figure 2. Fire Resistive Covering Spraying Robot

Table 1. Specifications of Spraying Robot

Structure	Traveling device, Lifting device, Traversing device, 6-axis Robot arm
Size	3.3 x 1.15 x 1.5 m
Weight	2350 kg
Workable floor height	5.5 m or less
Workable beam height	1.5 m or less
Maximum Spray Width	3.8 m or less

commercially available dedicated sensor.

2.4 Safety

Two 2D-LiDARs are installed to set the protection area and the alarm area; the robot stops when something breaks in the protection area, it slows down when in the alarm area. Additionally, a bumper sensor is attached around it to stop the robot when it contacts something. The situation when entering the set area and the operating status of the robot are clearly indicated by two warning lights, melody, alarm sound, etc, to make it easier for the surroundings to be understood.

2.5 Environmental Consideration

When spraying the fire resistive covering, a large amount of unwound rock wool discharged from the nozzle is scattered and suspended. For robots, there is a high risk that the scattered material will enter the joints and precision parts of the equipment and cause malfunctions. Therefore, to create an environment friendly to robot spraying, we developed the dust scattering prevention nozzle shown in Figure 3. By enclosing the discharged rock wool in a water mist, this nozzle can significantly reduce the amount of dust scattering and contribute to the stable operation of the robot. The results obtained from measuring the amount of dust scattering in the construction test confirmed that the amount was reduced to approximately one-third of the conventional spraying nozzle used by workers.

2.6 Spraying Experiment

After developing the robot, spraying experiments were carried out a few times at an in-house facility to confirm the thickness, and specific gravity of coverage sprayed by the robot. In the spraying experiments, the formation of high-quality coatings on each part of the H-section steel that is assumed to be a beam at a construction site, confirmed the robot control conditions proper. We also conducted an automatic construction test of the robot. Automatic construction is a series of spraying flow, in which the robot moves autonomously from the starting point to the spraying position, and after automatic alignment, sprays the fire resistive covering. In this test, we confirmed the optimum threshold value for the positioning error of the traveling device.

3 Application to a Construction Site

3.1 Purpose of Application

To collect the actual construction data, the robot sprayed the fire resistive covering on the girders and beams of a building construction site. Here, the actual construction data refers to the confirmation of sprayed quality, work efficiency, and verification of effectiveness of automatic construction.

Figure 4 shows steel girders and beams before spraying by the robot. Figure 5 shows the floor plan of the girders and beams to be sprayed, and Figure 6 shows the robot layout during spraying a girder. The spraying target was a total of thirty girders and beams with a floor height of 3.64 m and 1-hour fire resistive specifications. For both the girders and beams, the spraying area was divided into three to five parts on one side in the beam direction and sprayed at a total of six to ten positions on both of their sides. In each beam, a robot was placed on a line offset parallel to the center line, a traveling device ran in the girder or beam direction, and coating was sequentially sprayed onto the beam surface. The automatic construction procedure is shown below. The construction status is shown in Figure 7 and Figure 8.

1) Create a map of the construction area

2) Create a route for the autonomous movement of the

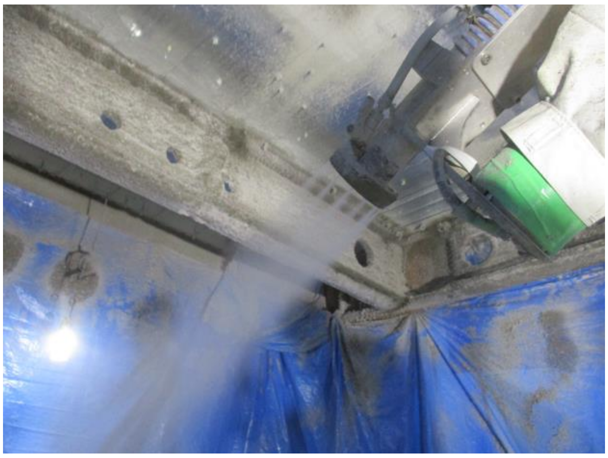

Figure 3. Dust Scattering Prevention Nozzle

Figure 4. Steel Girders and Beams Before Spraying

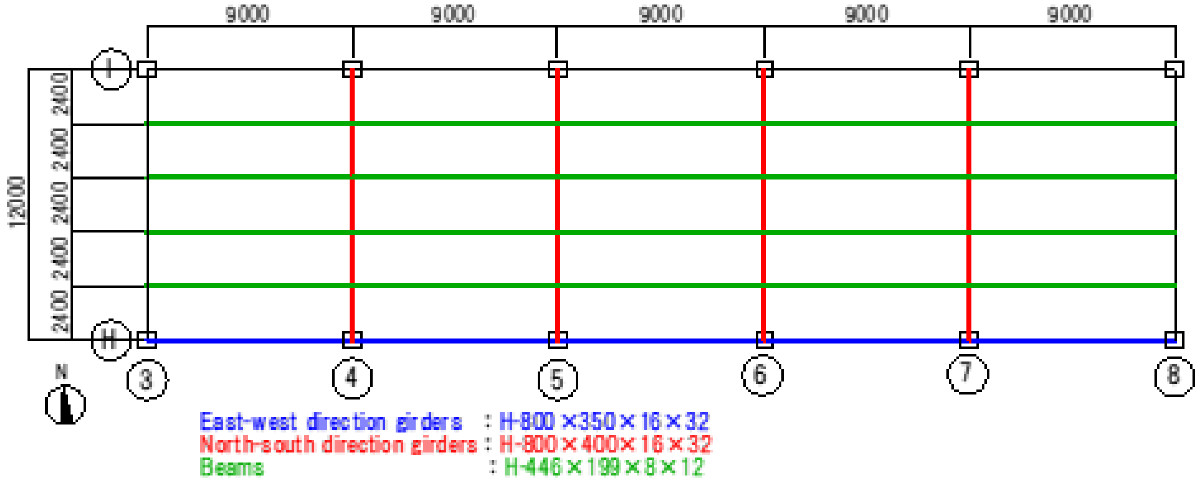

Figure 5. Plan View of Spraying Area

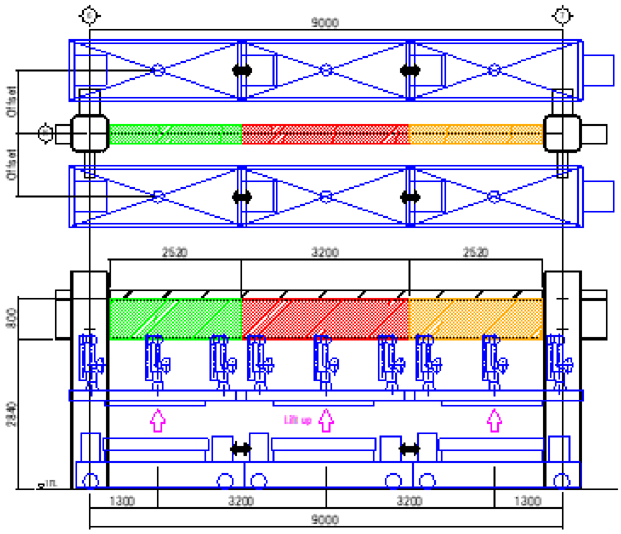

Figure 6. Robot Placement During Spraying a Girder

Figure 7. Autonomous Movement and Alignment of Robot

Figure 8. The Robot Under Spraying

robot, taking into consideration the layout of the girders and beams within the site.

3) Robot moves autonomously

4) Automatic alignment after moving to the spraying position

5) Spraying on one side of girders and beams

6) Spraying on the other side of girders and beams
After that, repeat 3) to 6)

7) Pressing sprayed fire resistive covering using trowel (by a worker)

3.2 Performance Assessment

We measured the fire resistive covering thickness and specific gravity of the sprayed covering after it was pressed by a worker using a trowel. The result of spraying girders and beams after pressing is shown in Figure 9. Two types of methods were used to obtain the measurements: randomly using a measuring pin, and overall using a laser scanner. Figures 10 and 11 show the measuring pin and laser scanner, respectively. The specific gravity of the sprayed covering was calculated from the weight of the sample taken from the dry sprayed covering.

Figure 9. Girders and Beams After Sprayed

Figure 10. Measuring Pin

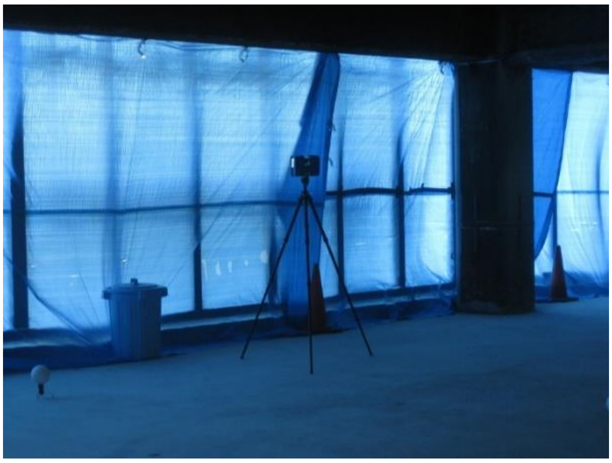

Figure 11. Laser Scanner

3.3 Application Results

3.3.1 Effect of Automatic Construction

To confirm the effect of automatic construction, we performed both automatic and manual construction. Automatic construction is a series of automatic running, automatic alignment, and automatic spraying. In manual construction, remote control is used to run, and align, whereas automatic control is used to spray. The construction efficiency between automatic and manual construction was compared.

3.3.2 Construction Quality

Figures 12 and 13 show the histogram and normal distribution of the measurement results of the covering thickness using a measuring pin. The average covering thickness was 45-50 mm, and both were well above the 1-hour fire resistive limit of 25 mm. The specified thickness of the girder and beam measurement points were exceeded at 97% or more.

Figures 14 and 15 show the measurement results of the covering thickness using laser scanners (typically between lines 4 and 5, and between lines 6 and 7 at the site). We obtained the measurements before spraying

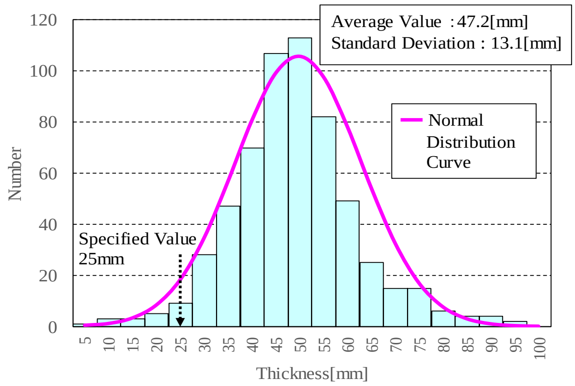

Figure 12. Results of Covering Thickness Measurement Using Measurement Pin (Girder)

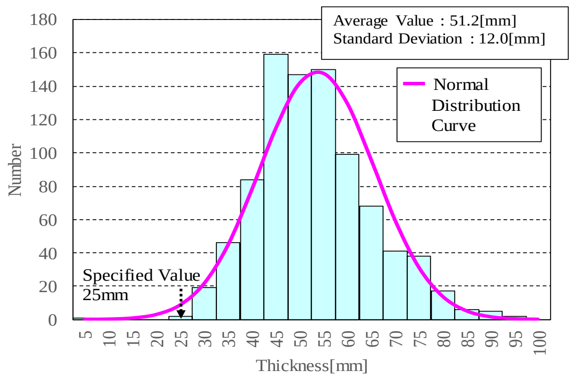

Figure 13. Results of Covering Thickness Measurement Using Measurement Pin (Beam)

the steel girders and beams, using a laser scanner. After spraying, we measured the surface of the covering again. After post processing the point cloud data, we calculated the difference between the point cloud data before and after spraying using software called CloudCompare. The heat map of the covering thickness calculated by this softwear is a view oriented from southwest to northeast. In these figures, the areas less than 25 mm of the an hour fire resistant specification are displayed in blue and the darkest green, and all other colors represent 25 mm thickness or more. A thickness less than 25 mm was found around the sleeves and around the stiffener of the north-south girder and beam joint, most of the other parts had a specified thickness of 25 mm or more. These data are consistent with the covering thickness measurements obtained using the measuring pin. After spraying using the robot, areas with insufficient thickness were repaired by workers.

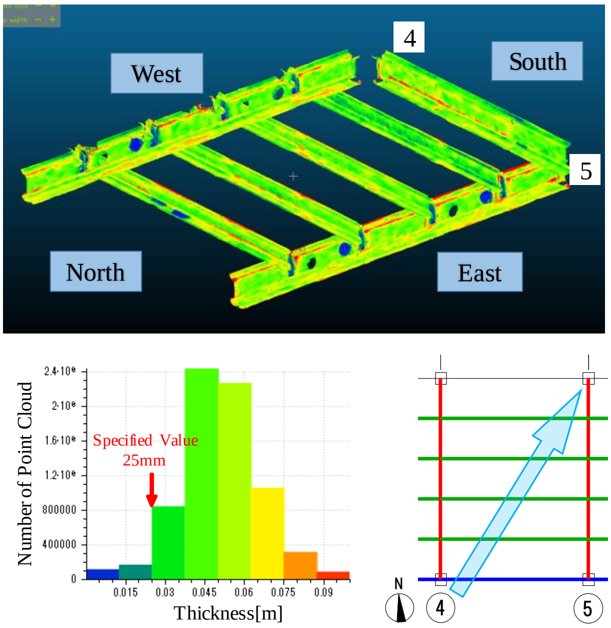

Figure 14. Results of Covering Thickness Measurement Using Laser Scanner (Between line 4 and 5)

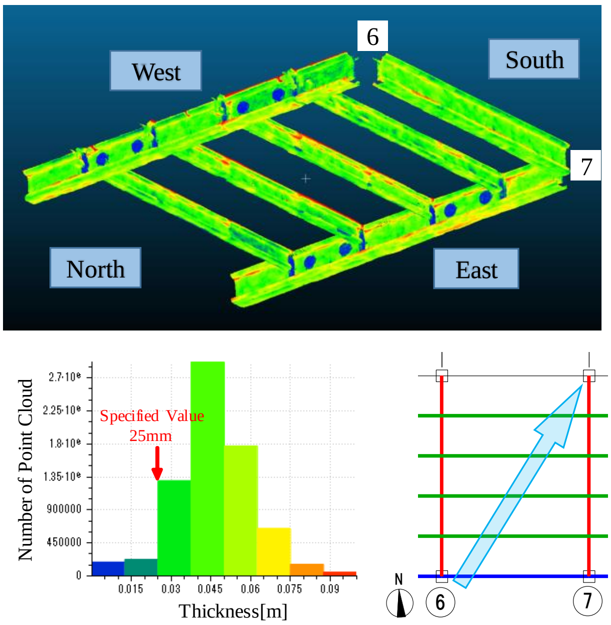

Figure 15. Results of Covering Thickness Measurement Using Laser Scanner (Between line 6 and 7)

The specific gravity measurement results were approximately 0.35-0.40, which did not fall below the construction management standard value of 0.28, during the entire construction period. There was no difference observed between the robot's manual construction and manual construction in both the coating thickness and specific gravity.

3.3.3 Working Time and Work Efficiency

Figure 16 shows the sprayed area per day of the automatic and manual construction. In this figure, the sprayed area per day of conventional spraying by a worker was set to 1. The sprayed area of the automatic construction was approximately 80% and the manual construction was approximately 50% of a skilled worker.

Figures 17 and 18 show the results of the automatic and manual construction, respectively. These figures shows the time ratio of spraying (=mondatory work), preparation/movement/alignment/nozzle cleaning (=subordinate work) and meeting/breaks (=other) when the time from beginning the work to the end of work is 100%. In manual construction, it took a lot of time to move and position the robot manually, and the spraying time per day (the net time when the material was discharged) was maintained at about 20%. In automatic construction, the spraying time per day was approximately 45%, which was an increase by roughly 25% compared to the manual construction. On the other hand, as shown in Figure 16, the sprayed area per day in automatic construction is around 80% of the necessary to reduce the time devoted to cleaning.

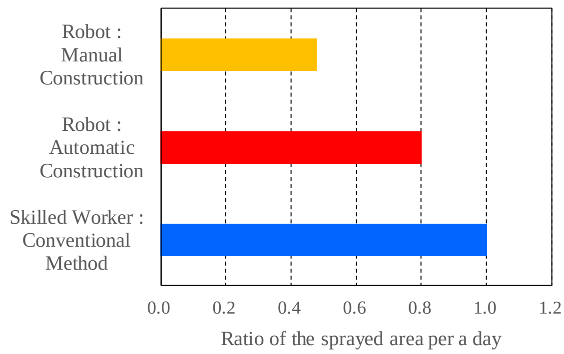

Figure 16. Comparison of Sprayed Area per Day

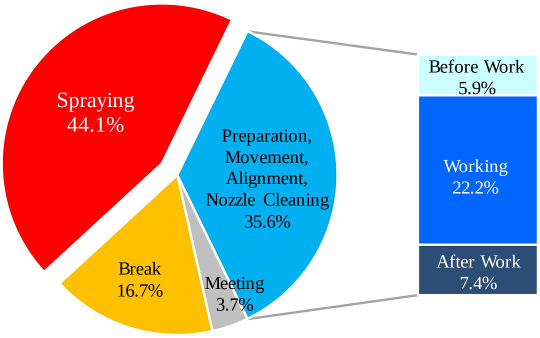

Figure 17. Working Time Analysis per Day (Automatic Construction)

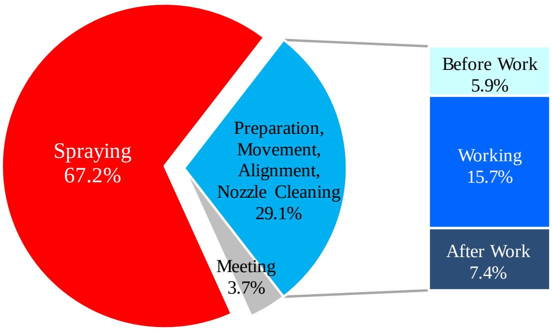

Figure 18. Working Time Analysis per Day (Automatic Construction with Improvement Plan)

4 Discussion

First, regarding the movement and alignment of the spraying robot, both were performed automatically and manually, and compared. Consequently, compared to the manual operation, the sprayed area per day in the automatic operation was improved by 70%. This indicates that work efficiency cannot be improved because movement and alignment take time by manual operation. So, it is essential for the spraying robot to travel automatically and to align automatically.

Next, regarding the measurement of the coating thickness, the measuring pin and the laser scanner were used in two ways. The normal distribution and average value of the covering thickness showed approximately the same value. From these results, the effectiveness of the measurement of the covering thickness by the laser scanner was verified. Because measurement using the measuring pin is manual work, a lot of man-power is required for post-processing. On the other hand, measurement using the laser scanner requires a long time for post-processing; moreover, it takes long time to obtain the results although most of the work is done automatically. From these strengths and weaknesses, work efficiency can be improved significantly by using the measuring pin to measure a part of area, getting immediate results, and obtaining the measurements later the rest of whole area by using laser scanners.

Finally, we describe the future productivity improvement. The nozzles were easily clogged with material, making the cleaning time long; thus, work efficiency did not improve. In the future, we plan to develop a new nozzle that does not require nozzle cleaning. It is also expected that this will improve work efficiency and exceed the sprayed area per day of skilled workers.

5 Conclusion

In this study, to save on labor in fire resistive covering work, a fire resistive covering spraying robot that sprays the fire resistive cover was developed through experiments and was applied at a construction site. The following findings were obtained.

1) The fire resistive covering sprayed by the robot at the construction site achieved quality results that satisfied the specified values for thickness and specific gravity.
2) The sprayed area per day of robot automatic construction is 1.7 times higher than that of manual construction. The effectiveness of automatic construction was confirmed.
3) Because it was necessary to secure the cleaning time of the spray nozzle, the sprayed area per day of automatic construction was approximately 80% of that of a skilled worker.
4) In the future, by developing a spray nozzle that does not easily get clogged by rock wool materials, and performing automatic construction, it will be possible to improve the sprayed area per day to a level equivalent to that of a skilled worker.

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