Improvement of Automated Mobile Marking Robot System Using Reflectorless Three-Dimensional Measuring Instrument

T. Tsuruta[a], K. Miura[a], and M. Miyaguchi[a]

[a]Research and development institute, Takenaka corporation, Japan
E-mail: tsuruta.takehiro@takenaka.co.jp, miura.kazuyuki@takenaka.co.jp, miyaguchi.mikita@takenaka.co.jp

Abstract –

In previous study we have already reported fully automated mobile marking robot system in construction site for streamlining marking work that is currently carried out manually. However, marking accuracy and efficiency were not satisfied compared to those of construction worker, further improvement was desired. This paper is the second report of the system. The purpose of this paper is to improve the marking performance of the system. The proposed system consists of a reflectorless three-dimensional measuring instrument and a mobile marking robot. The former accurately directs a measuring laser and measures a distance to the robot. The latter is a mobile robot which has a marking device and a special positioning sensor. It is important to navigate the marking robot to the designated marking position quickly and correctly. Two self-positioning estimation method is combined. The robot position is roughly estimated by the wheel odometry method during movement. On the other hand, it is accurately measured by the combination of a three-dimensional measuring instrument and the special positioning sensor just before drawing a mark on the floor. The marking device draws the mark exactly on the designated position based on the deviation between the designated position and the measured robot position. This paper describes the mechanism of proposed system and some experimental results. It also shows improvement of the marking performance compared to previous prototype.

Keywords –

Marking; Mobile robot; Reflectorless three-dimensional measuring instrument

1 Introduction

In Japan, a shortage of construction workers has become a major social issue. In 2015, the number of construction workers was about 73% of what it had been at its peak in 1997. Therefore, improvement of productivity in construction work is an urgent issue. In the construction process, marking work is indispensable. Before installing building material such as dry walls, free access floors and anchor bolts, construction workers have to draw marks and lines on the floors, walls, ceilings, and so on in construction site. They mean positions for installing building materials. In a big building construction, the number of marks and lines is more than thousands and it is currently carried out manually. Therefore, there is a great need for improving efficiency of the marking work.

The progress of surveying technology in recent years is remarkable. Some measuring instruments such as laser scanner and total station are already being used at construction site. Prior studies on the efficiency improvement for the marking work by using these instruments have already been reported. They are roughly divided into researches on support technology aimed at improving efficiency of marking manually [1-3] and those on automated marking robots [4-6]. If this work is fully automated with marking robots, construction workers will be able to concentrate on installing building materials and productivity will increase.

Several studies on automated mobile marking robot have already been done. Inoue et al. reported a system that combines a marking robot having a cross-mark stamp and a total station [4,5]. It is roughly navigated a designated marking position by using a laser range finder and its position and orientation is measured by the total station. After that, it stamps a cross mark accurately on the designated position. “Laybot” developed by DPR construction [6] can draw lines for installing drywalls on a floor. Its position is also measured by using a total station. Kitahara et al. reported a system that combines a marking robot having a XY plotter and a total station [7]. In the system, an operator of the system moves the marking robot to a marking position with operation of a remote controller. The total station measures its position and orientation and the mobile robot draws arbitrary figure on a floor based on the measured position.

All of them mentioned above need a total station that can collimate and track prism. However, this kind of the total station is generally very expensive. In author's view point the total station occupies most of the system cost. On the other hand, a reflectorless three-dimensional measuring instrument that does not track and collimate prism is less expensive. Cost is a very important factor for wide spread use of the marking robot system. Therefore, we propose a marking robot system with the reflectorless three-dimensional measuring instrument. As a first step, we intended to automate the marking work for installing free access floors. In our previous study, we reported a performance of a prototype system [8] [9]. The marking robot automatically moves to designated positions and draws cross marks in sequence. These marks mean positions where pedestal bases of free access floors are installed. We succeeded in marking 182 positions automatically in a 6m x 6.5m working area in construction site. Average deviation between drawn mark and designated position was 2.3 mm and average time required for marking a single position was 98 second. However, marking accuracy and efficiency were not satisfied compared to those of construction worker. Further improvement is desired in the working area, the time required for marking and the marking accuracy.

In this study, new marking robot system was developed. Two self-positioning estimation method is combined to improve marking performance. The wheel odometry method is used during movement. The combination method of the three-dimensional measuring instrument and the special positioning sensor is used just before drawing a mark on the floor.

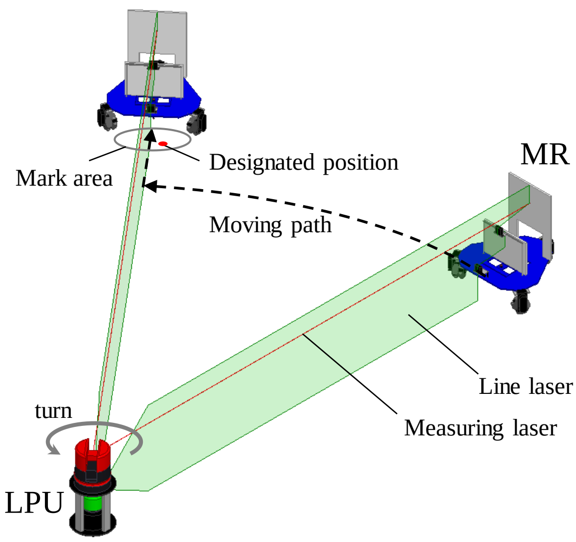


Figure 1. Outline of the marking flow using previous marking robot system

2 Proposed Marking Robot System

2.1 Problems in Previous Prototype

In our previous study, we proposed a line laser tracking navigation method using a laser positioning unit (LPU) and a marking robot (MR). As shown in Figure 1, the MR tracks a rotating line laser generated from the LPU in order to move to a designated position. The MR has two couples of screen and camera to detect the laser line projected on the screen. This method has two problems that deteriorate marking performance. First, when the MR is far from the LPU, the line laser light projected in the screen becomes weak and it is difficult to detect the laser line from a captured image. This is the reason that limits the working area and deteriorates the marking accuracy. Second, tracking path is a combination of the traveling on the circular path and straight path. This means that the MR does not move on the shortest path. Thus long time was required for moving to the designated position. For these reason we concluded that the usage of the line laser deteriorated the marking performance.

2.2 Automated Marking Flow

In order to improve marking performance, we stop using the line laser. The proposed system consists of a marking robot (MR) and a three-dimensional measuring instrument (3D-MI). The MR automatically moves to a marking position and draw marks on the floor. The moving path is a straight line connecting the current position and next designated position. The MR moves to the designated marking position by the combination of a straight traveling and a spin turn as shown in Figure 2. Two self-positioning estimation method is combined. The MR position is roughly estimated by the wheel odometry method during movement. On the other hand, it is accurately measured by the combination method of the 3D-MI and a special positioning sensor attached on the MR just before drawing a mark on the floor.

The 3D-MI is used for measuring the MR position and orientation. Like a motor driven total station, the horizontal and vertical axes of the 3D-MI can be motorized. This can direct a measuring laser parallel to the floor in the direction of the designated marking position and measure the distance to an object on which the laser spot is projected. Although it cannot collimate and track reflector such as prism target, it is less expensive than a motor driven total station used in previous studies already reported [4-7].

The MR is a two wheel differential drive robot with a caster wheel. A marking device is attached to the MR base flame. It is similar with a XY plotter. By controlling the marking device, an arbitrary mark, figure or character can be drawn on the floor. Furthermore, the MR has the special positioning sensor. It is a key device for measuring MR position and orientation accurately with reflectorless 3D-MI. The detailed measuring mechanism will be described in section 2.3.

In construction site, some benchmarks are already drawn on the floor just before installing building material. The coordinate of the 3D-MI in a construction site coordinate system Σw is calculated by resection. The coordinates of the target marks to be drawn on the floor in the Σw are set based on the floor plan. Automated marking is operated by repeating following steps as shown in Figure 3.

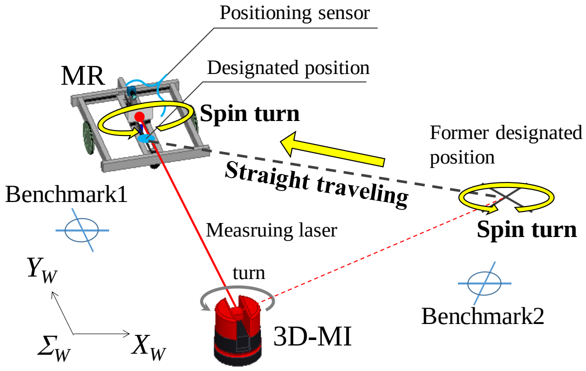


Figure 2. Move to the next designated position

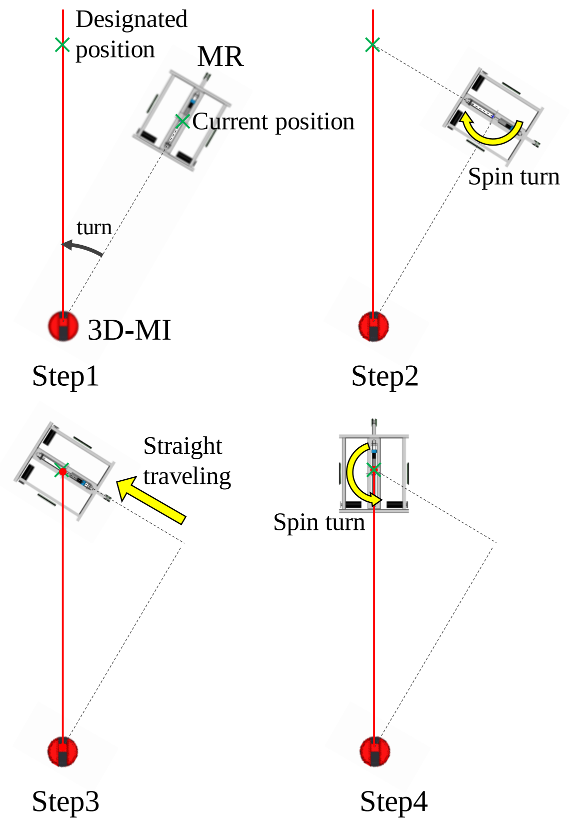


Figure 3. Automated marking flow

Step1: The 3D-MI directs the measuring laser parallel to the floor in the direction of the next designated position.

Step2: The MR makes spin-turn so that the orientation of the MR corresponds to the direction of the next designated position. The turning angle is estimated by the wheel odometry method.

Step3: The MR travels straight so that the MR reaches the next designated position. The traveling distance is also estimated by the wheel odometry method.

Step4: The MR makes spin-turn so that the positioning sensor is perpendicular to the measuring laser. After spin-turn, the MR position is not exactly on the next designated position. The MR position and orientation are accurately measured by the combination of the 3D-MI and the positioning sensor. The marking device is controlled based on the deviation between the measured position and the designated position so that a figure could be drawn exactly on the designated position.

2.3 Mechanism of the Marking with High Precision

The MR position is measured with combination of the 3D-MI and the positioning sensor. The positioning sensor consists of a light diffusion plate and a camera as shown in Figure 4. The measuring laser form the 3D-MI hits on the light diffusion plate. The 3D-MI measures the distance to the light diffusion plate. On the other hand, the camera captures an image of the laser spot projected on the light diffusion plate. The laser spot centroid is measured by an image processing described in section 2.5. After that, the positioning sensor moves y_f in the Y_R axis direction in the robot coordinate system Σ_R as shown in Figure 5. After that, the distance to the light diffusion plate and the laser spot centroid are measured again. By using these measured values before and after moving the positioning sensor, orientation α is calculated as below.

$$\alpha = tan^{-1}\left(\frac{x_{c0} - x_{c1}}{y_f}\right) \qquad (1)$$

Here,

Δy: The displacement of the positioning sensor

x_{c0}: The x-coordinate of the laser spot centroid in the Σ_R before moving the positioning sensor

x_{c1}: The x-coordinate of the laser spot centroid in the Σ_R after moving the positioning sensor

From the geometry relation as shown in Figure 6, the MR coordinate in the Σ_w x_{MR} and y_{MR} are calculated following equation.

$$x_{MR} = x_p + r_0 cos\theta_l - x_{c0} cos\phi \qquad (2)$$

$$y_{MR} = y_p + r_0 sin\theta_l - x_{c0} sin\phi \qquad (3)$$

$$\phi = \theta_l - \frac{\pi}{2} - \alpha \qquad (4)$$

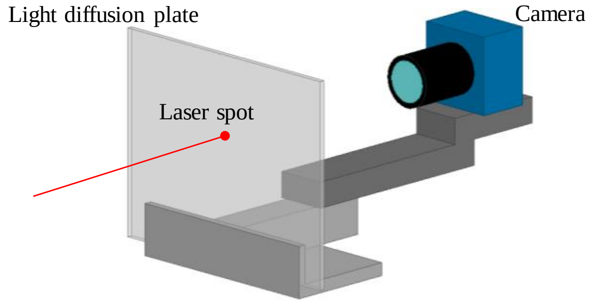
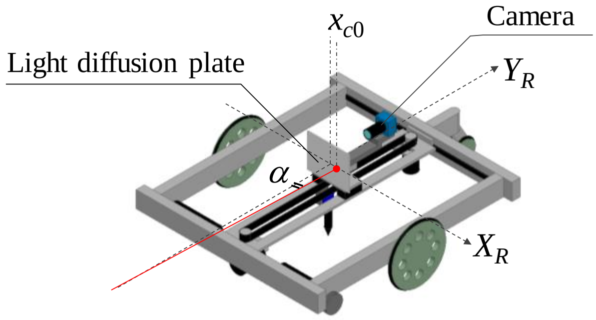
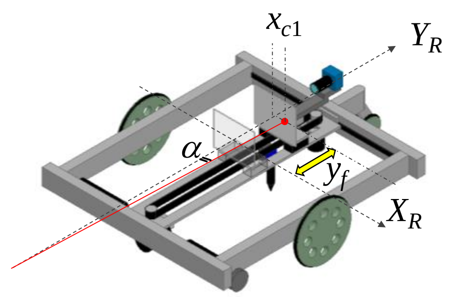


Figure 4. The positioning sensor



(a) Before moving the positioning sensor



(b) After moving the positioning sensor

Figure 5. Before and after moving sensor

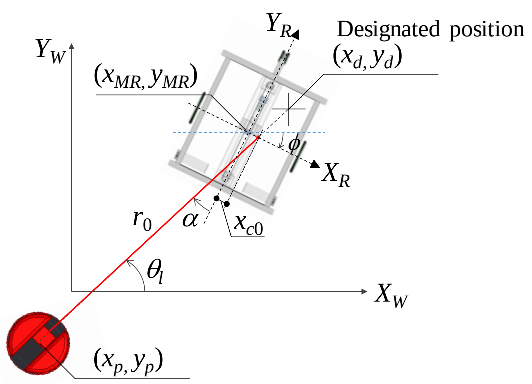


Figure 6. Explanation for calculating the x_{MR} and y_{MR}

Here,

r_0: The distance to the light diffusion plate from the 3D-MI before moving the positioning sensor

(x_p,y_p): The x and y-coordinate of the 3D-MI in the Σ_w

θ_l: An angle of the measuring laser to the X_W axis

ϕ: An angle of the X_R axis to the X_W axis

In proposed system, we prepare the figure to be drawn on the floor as a g-code data. It is commonly used in numerical control manufacturing such as milling and 3D printing. In this code, the start and end point coordinates of a line segment are defined. By controlling the movement of the marking pen based on this code, the figure can be drawn on the floor. In order to draw a designated figure exactly on the designated position with correct orientation, we need to rotate and translate the figure. The transformed coordinate of the point defined in the g-code data is calculated following equation (5). The values used in this equation are already calculated in equation (2)-(4).

$$\begin{pmatrix} p_t \\ q_t \\ 1 \end{pmatrix} = \begin{pmatrix} cos\phi & sin\phi & x_d - x_{MR} \\ -sin\phi & cos\phi & y_d - y_{MR} \\ 0 & 0 & 1 \end{pmatrix} \begin{pmatrix} p \\ q \\ 1 \end{pmatrix} \quad (5)$$

Here,

(p_t,q_t): Transformed coordinate in g-code data

(p,q): Original coordinate defined in g-code date

(x_d,y_d): The x and y-coordinate of the designated position in the Σ_w.

2.4 Component of the Marking Robot System

A photograph of the MR without controller is shown in Figure 7. Representative specifications such as external dimensions are shown in Table 1. As described in section 2.2, the MR is a two wheels differential drive robot with a caster wheel. The marking device is installed at the flame. The marking device consists of the XY movement stage and the pen unit which can move the marking pen in vertical direction by servo motor. By controlling the marking device, arbitrary figure can be drawn on the floor. The positioning sensor consisting of a camera and a light diffusion plate is also attached on the XY movement stage, thus it can move in the X_R and Y_R direction. On the other hand, a photograph of the 3D-MI is shown in Figure 8. Representative specifications such as some accuracies are shown in Table 2. System block diagram for proposed system is shown in Figure 9. Computer installed on the MR controls motor drivers for the vehicle and the XY plotter. Image processing on the captured image is also performed by the computer. 3D Disto is controlled by the computer through Wi-Fi communication.

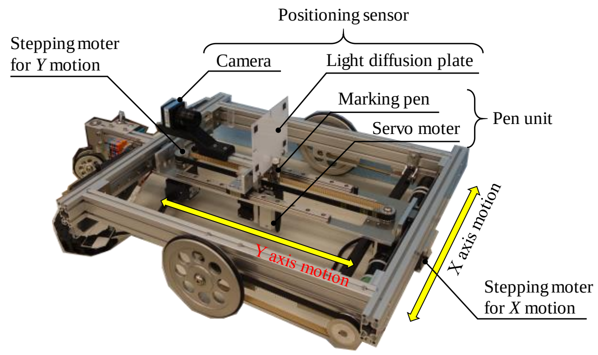


Figure 7. The MR without controller

Table 1. Specification of the MR

Item	Specification
Dimension(mm)	678x450x400
Weight(kg)	17
Power supply	lithium-ion battery

Figure 8. The 3D-MI

Table 2. Specification of the 3D-MI

Item	Specification
Manufacture / Model	Leica geosystems / 3D Disto
Accuracy of angle Measurement (Hz/V)	5”
Tie distance accuracy specified at 20 °C	Approx. 1mm at 10 m Approx. 2mm at 30 m Approx. 4mm at 50 m

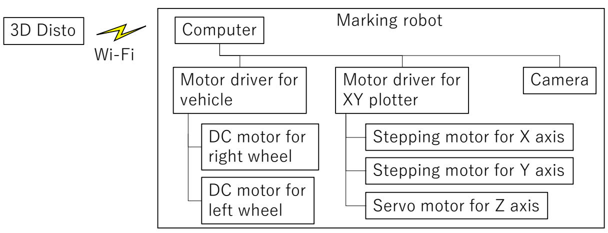


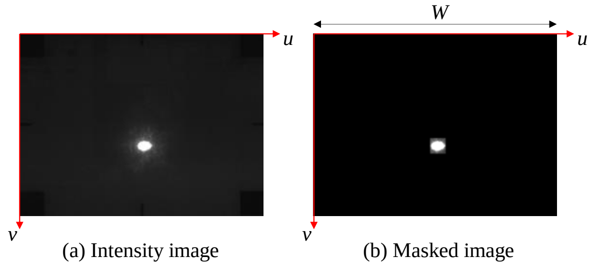
Figure 9. Block diagram for marking robot system

2.5 Detection Method of the Laser Spot

Since captured image includes the lens distortion and perspective distortion, they are removed by the same method previously reported [8]. Figure 10 shows images before and after removing these distortions. From this distortion-removed image, the position of the laser spot is measured. An intensity image as shown in Figure 11 (a) is obtained by averaging pixel intensity of red, green and blue channel image. On the other hand, a binary image is obtained from the intensity image by setting proper threshold level. Temporary laser spot position is obtained as the intensity center of gravity in the binary image. After that, the masked image as shown Figure 11 (b) is obtained by setting the pixel intensity to zero except for the 40 x 40 pixels centered on the temporary laser spot position in the intensity image. The horizontal camera coordinate of the laser spot, u_{max} is calculated as the intensity center of gravity in this masked image. The x_c, which is the x-coordinate of the laser spot centroid in the Σ_R is obtained from Equation (6).

(a) Before removing the distortion (b) After removing the distortion

Figure 10. Images before and after distortion removal



(a) Intensity image (b) Masked image

Figure 11. Images for measuring x_c

$$x_c = -(\frac{u_{max}}{N_H} - 1/2)W \quad (6)$$

Here,
N_H: Number of the horizontal pixel
W: Width of the image (See figure 10)

This image processing is mainly implemented by OpenCV 3.1 and conducted by the computer.

3 Experiment

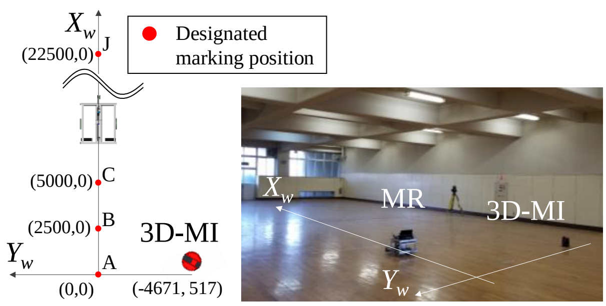
3.1 Performance of the Marking Area

In order to evaluate the performance of the marrking area, fundamental experiment was executed. The experimental layout is shown in Figure 12. The MR automatically drew cross mark from Position A to J in order. The distance between two adjacent positions was 2 m. After marking, the coordinates of the every cross mark center were measured by using a total station. Figure 13 shows Δr_w in each designated position respectively. Here, Δr_w is the deviation between marked position and designated marking position. Position J was 22.47m apart from the 3D-MI. The MR could automatically move to the position 22.47m apart from the 3D-MI and mark with an accuracy of within 1mm or less.

3.2 Performance of the Marking for Free Access Floor

In order to evaluate the marking performance for free access floor, a basic automated marking test was executed. The experimental layout is shown in Figure 14. In the 3m x 3m test area, we set 49 designated marking positions which were grid intersections at intervals of 0.5m. They imitated positions for installing pedestal bases of free access floors. The MR marked from Position A0 to G6 in order. After that, we measured all deviations in the same way described in the previous section.

Figure 15 shows the frequency distributions of Δr_w. Summarized result is shown in Table 3. For the purpose of comparison, the results obtained from previous system [9] are also summarized together. All of the marked positions are within less than 3mm deviation. However this result was obtained in the experiment in the test area which is not the construction site. Further evaluation in construction site is needed. The time required for per position was improved from 98 seconds to 33 seconds. In proposed system, the MR can move on the shortest path from current position to next designated position. As a result, the MR could perform automated marking faster than previous prototype.



(a) Experimental layout (b) View of the test

Figure 12. Experimental layout for evaluating marking area

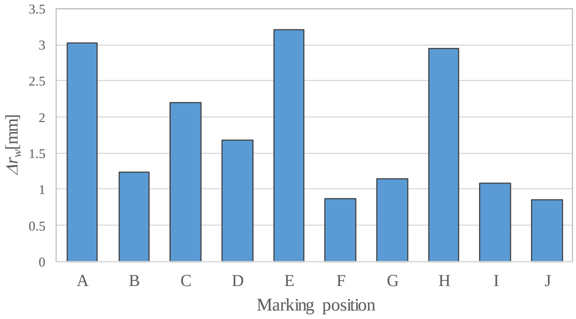


Figure 13. The Δr_w in each designated marking position

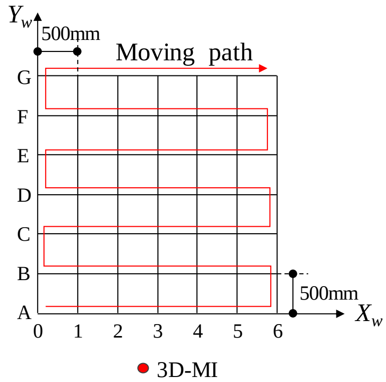


Figure 14. Experimental layout for evaluating marking for free access floor

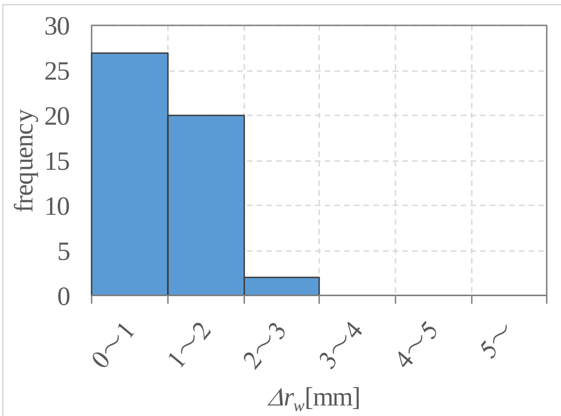


Figure 15. Frequency distribution of deviation between designated marking position and marked center

Table 3. Summarized result of the marking accuracy

Item	Proposed system			Previous system		
	Δx_w	Δy_w	$\sqrt{\Delta x_w^2 + \Delta y_w^2}$	Δx_w	Δy_w	$\sqrt{\Delta x_w^2 + \Delta y_w^2}$
Average deviation(mm)	0.6	0.5	1.0	1.7	0	2.3

Standard deviation (mm)	0.5	0.7	0.5	1.9	1.4	1.6
Maximum deviation (mm)	2.1	1.6	2.1	9.5	4.5	10.2
Percentage where deviation is within 3mm (%)		100			77	

4 Conclusion

In order to improve the efficiency of construction work, we have developed a fully automated mobile marking robot system. In this study, we obtained following conclusion.

- Proposed system is cost effective since it uses a reflectorless three-dimensional measuring instrument which cannot collimate and track prism.
- The MR automatically could move to the position 22.47m apart from the 3D-MI and mark with an accuracy of within 1mm or less. Previous studies did not reported marking area.
- Proposed system improved the marking performance compared to previous system. Average deviation was 1.0 mm. This result was comparable to that reported by Inoue et al. [5], and worse than that reported by Kitahara et al. [7]. Though the number of measured points in their study was 10 or less.
- Average time required for single marking for installing the pedestal bases of free access floors was 33 seconds. It is about 1/3 of that of the previous system. Ohmoto et al reported it took 2 minutes in their study [10]. In the case of 100 square meter marking, proposed system can finish all the marking about 4 hours.

Proposed system currently has some limitations.

- Since the MR cannot detect and avoid obstacles, it is available only in areas without obstacles. We can solve this limitation by using sensor such as laser range finder or bumper sensor.
- Some previous study reported floor inclination affected the marking accuracy [5], [7]. The MR does not measure its own tilt. Thus proposed system is effective in plane area. The inclination angle can be measured by tilt sensor. We can correct the marking position by measured value.

Since we only tested proposed system in a test field, we have to confirm the marking performance in construction site. In this study we reported the result of drawing cross mark for free access floor. If we change the figure to be drawn, the MR can draw arbitrary figure. We are now preparing the automated marking test for dry partition walls in construction site. Marking work for dry partition walls is more complicated than that for free access floors. We consider automated marking for dry partition wall with robot system is more effective for improving productivity.

In proposed system, we have to set the marking positions manually from a floor plan. This work is very laborious. Therefore, we need to develop a tool for making marking position data directly from CAD data.

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References

[1] Shintaro Sakamoto, Hiroki Kishimoto, Kouetu Tanaka and Yukiteru Maeda. 3D Measuring and Marking System for Building Equipment: Developing and Evaluating Prototypes. *Proceedings of the 26th International Symposium on Automation and Robotics in Construction*, 131-138, Austin, USA, 2009

[2] Shintaro Sakamoto, Naruo Kano, Takeshi Igarashi, Hiroki Kishimoto, Hirohiko Fujii, Yuji Oosawa, Kentarou Minami and Kousei Ishida. Laser Marking System Based on 3D CAD Model. *Proceedings of the 28th International Symposium on Automation and Robotics in Construction*, 64-69, Seoul, Korea, 2011.

[3] Shintaro Sakamoto, Naruo Kano, Takeshi Igarashi, Hiroyuki Tomita. Laser Positioning System Using RFID-Tags. *Proceedings of the 29th International Symposium on Automation and Robotics in Construction*, Eindhoven, The Netherlands, 2012.

[4] Fumihiro Inoue, Satoru Doi and Eri Omoto. Development of High Accuracy Position Making System Applying Mark Robot in Construction Site. *SICE Annual Conference 2011*, 2413-2414, Tokyo, Japan, 2011.

[5] Fumihiro Inoue and Eri Omoto. Development of High Accuracy Position Marking System in Construction Site Applying Automated Mark Robot. *SICE Annual Conference 2012*, 819-823, Akita, Japan, 2012.

[6] DPR construction, 'Laybot Shows Promise in Speed and Accuracy', 2013 [Online]. Available: https://www.dpr.com/media/news/2013
[Accessed: 22- Feb- 2018]

[7] Takashi Kitahara, Kouji Satou and Joji Onodera.

Marking Robot in Cooperation with Three-Dimensional Measuring Instruments. *Proceedings of the 35th International Symposium on Automation and Robotics in Construction*, 292-299, Berlin, Germany, 2018.

[8] Takehiro Tsuruta, Kazuyuki Miura and Mikita Miyaguchi. Development of automated mobile marking robot system for free access floor. *Proceedings of the 35th International Symposium on Automation and Robotics in Construction*, 622-629, Berlin, Germany, 2018.

[9] Takehiro Tsuruta and Mikita Miyaguchi. Evaluation of the automated marking system by cooperative operation of multiple robots (in Japanese), *The 18th Symposium on Construction Robotics in Japan*, O4-1.

[10] Eri Ohmoto, Fumihiro Inoue and Satoru Doi. Marking System applying Automated Robot for Construction Site (in Japanese), Reports of the Technical Research Institute Obayashi-Gumi Ltd, No76, 1-7, 2012