Marking Robot in Cooperation with Three-Dimensional Measuring Instruments

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Abstract –

The marking robot has been developed for the purpose of streamlining marking operations at power plant construction sites and accelerating equipment installation work. This robot can draw line segments with accuracy of 1 mm or less on floors and walls of the construction site in cooperation with a three-dimensional measuring instrument. In addition, it is possible to write arbitrary characters such as position information of drawn line segments.

The marking robot is mainly composed of a marking mechanism and a wall traveling mechanism. The marking mechanism for drawing line segments and characters has been realized by a combination of a XY plotter and an ink jet printer. The small printer head is attached to the XY plotter instead of a pen. And a prism target for a total station is located just above the nozzle of the printer head. By moving the plotter to the four corners of its movable range and measuring its position, the command value of the cooperative operation of two axes of the plotter necessary for drawing an arbitrary line segment and characters is calculated.

On the other hand, by combining a vacuum suction device and a four wheel drive mechanism, the wall traveling mechanism which makes the marking robot of about 50 kg run on a concrete wall has developed.

In this report, we will report on structure of the marking robot, cooperation method of the robot and three-dimensional measuring instrument, and application case of the robot to construction site.

Keywords –

Marking robot; Three-dimensional measuring; Total station; XY plotter; Ink jet printer; Wall traveling mechanism

1 Introduction

In order to achieve requests for shortening construction period from customers and ensure construction quality in construction and remodelling work of thermal power plants and the like we the construction company actively introduces rationalization using the latest technologies such as IoT. This report relates to rationalization of marking work at the time of installation of equipment.

When installing equipment at construction sites we draw many lines on floors or walls of the sites as marks which indicate installation positions of equipment, for example positions of anchor bolts, by using surveying instruments such as automatic levels, transits, and tape measures. Normally, this marking work is carried out prior to the installation of each equipment, but as the construction progresses, the already installed equipment becomes interfering matter, which leads to decrease in efficiency of marking work and increase in the cause of mistake.

Therefore, we are planning to introduce a construction method to draw all the markings before the installation work starts. But in the construction work of a large-scale thermal power plant of 1,000 MW class, the number of the marking is more than thousands. Thus, efficient carry out of the marking work is needed for introducing the method. This is reason why we have developed a support system for marking work using a robot.

Here, some examples of previous studies on the marking devices for construction are shown below. First, Ohmoto et al. developed a marking system which consisted of a self-propelled marking robot that had a cross shape stamp, a laser range finder that guided the robot to the marking position, and a total station for accurately positioning of the stamp. By using this, they semi-automated the work to mark the cross lines with 2 mm accuracy on the floors of building construction sites. On the other hand, Yokoyama et al. developed a marking system to mark the positions of anchor bolts for ventilation jet fans mounted on the tunnel ceiling of highways. Their system consisted of a motor driven total station and a marking device. And the marking device had a cross line stamp on XY positioning mechanism at the tip of a cylinder mechanism extending to the ceiling. By using this, they realized high-place work of marking without scaffolding.

As described above, there are already some kinds of the marking system that use the total station to position the cross stamp at marking points. However, what can be obtained by the stamping method is information of "points". On the other hand, in some cases, information of "lines" indicating the installation orientation of the equipment etc. is also important. Furthermore, if the coordinate values of the marked points and lines, and the name of the equipment to be installed, etc. are not clearly indicated in the vicinity of the markings, there is a possibility of incorrect installation work. Therefore, in this research, we decided to develop marking system which can draw arbitrary line segments and characters on floors and walls of plant construction sites by linking with the motor driven total station.

2 Development of Marking System

2.1 Concept of Marking System

The basic requirement specifications considered in developing this system are shown below.

1. To draw arbitrary line segments and characters on indoor and outdoor concrete floors and walls.
2. To draw line segments with position accuracy of 1 mm or less.
3. Work efficiency equivalent to the conventional one.
4. Easy operation of the system.
5. Marking on walls without scaffolding

The basic concept of the system determined based on the above required specification is shown in Figure 1. The system consists mainly of the following three elements.

1. XY plotter type marking robot
2. Motor driven total station
3. Wireless controller of the system

First, the marking robot needs to draw arbitrary characters besides line segments, so we decided to adopt a relatively simple XY plotter system. In addition, to move on the floor and climb the wall the robot is needed a moving mechanism such as motorized wheels and a wall sticking mechanism using vacuum fan. Using the moving mechanism, we aimed to realize marking work on walls without scaffolding. In addition, we considered that the autonomous movement of the robot to marking points stated in the previous studies mentioned in section 1 was a future development item. Therefore, as our first step of the development, an operator of the system moves the robot to marking points with operation of a remote controller.

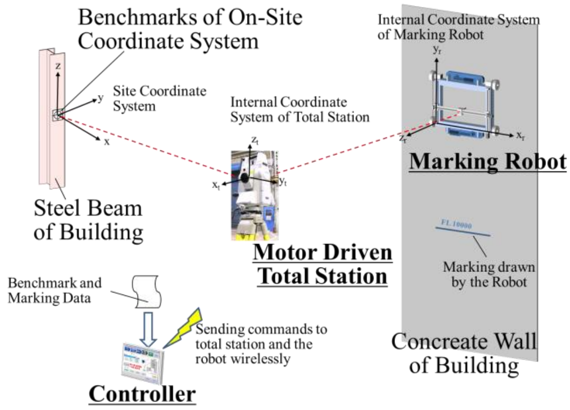


Figure 1. Schematic diagram showing the basic concept of the marking system

The total station is needed as a three-dimensional measuring instrument for grasping positions and orientations of the robot in on-site coordinate system. And the instrument is needed to have measurement accuracy higher than the marking target accuracy of 1 mm. Furthermore, a motor driven one is useful because that can collimate and track prism targets automatically. That can be adopted to automatic measurement of positions and orientations of the robot etc.

The wireless controller of the system is a general tablet PC on which software dedicated to this system was installed. From the controller, various commands to total stations and the robot are given wirelessly. The system operator inputs information such as coordinate values of benchmarks and line segments to be drawn to the controller in advance of the marking work. Based on the inputted information and measurement results of the benchmarks and the robot, the system gives the robot the motion command of the XY plotter necessary for marking.

2.2 Development of Marking Robot

The appearance of the marking robot developed based on the concept mentioned above is shown in Figure 2. And representative specifications such as external dimensions are shown in Table 1. On the other hand, the appearance of the total station adopted to the system is shown in Figure 3. And representative specifications such as measurement accuracy are shown in Table 2.

The robot consists mainly of a marking mechanism, a wall traveling mechanism, and a control unit of those two mechanisms. The following sections explain the concrete contents of each mechanism.

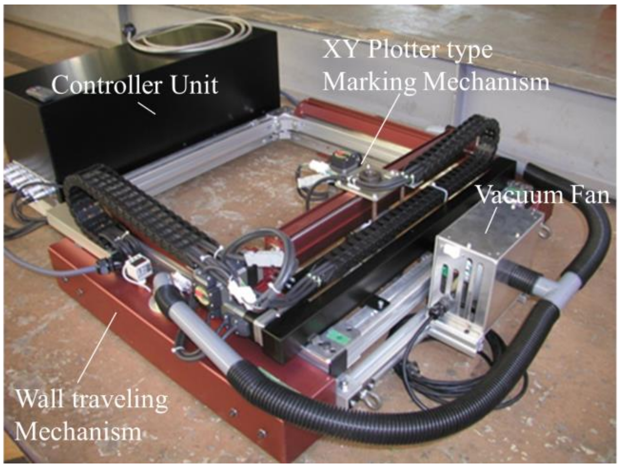


Figure 2. Appearance of the marking robot

Table 1. Specification of the marking robot

Item	Specification
Dimension (mm)	L:1,500 x D:1,000 x H:400
Weight (kg)	56
Main material	Aluminum
Power supply	A/C 100V

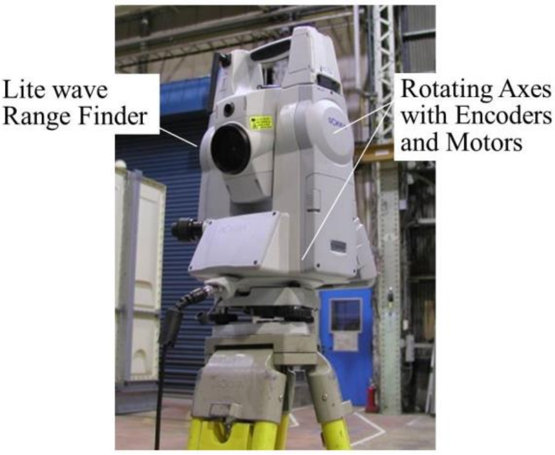


Figure 3. Motor driven total station used for the marking system

Table 2. Specification of the total station

Item	Specification
Manufacture / Model	SOKKIA / NET05
Accuracy of angle measurement	0.5”
Accuracy of distance measurement with using a prism	0.8mm+10^{-3}mm/m

2.2.1 Marking Mechanism

The appearance picture of the marking mechanism separated from the robot is shown in Figure 4. As shown (a), the overview of the mechanism is a two-axis linear motion device imitating an XY plotter of about 700 mm square. Here, the linear motion device is driven by stepping motors. However, as shown in (b), an inkjet printer was adopted instead of a drawing pen of XY plotter.

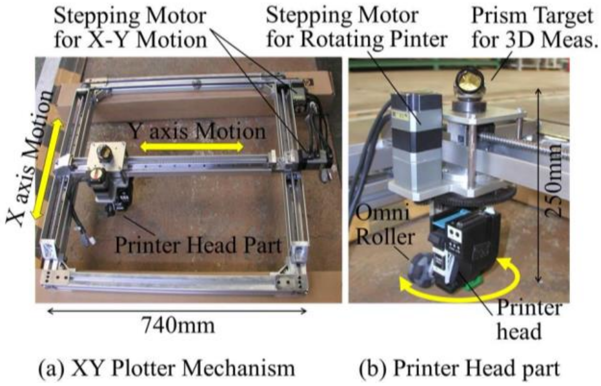


Figure 4. XY plotter type marking mechanism using the inkjet printer

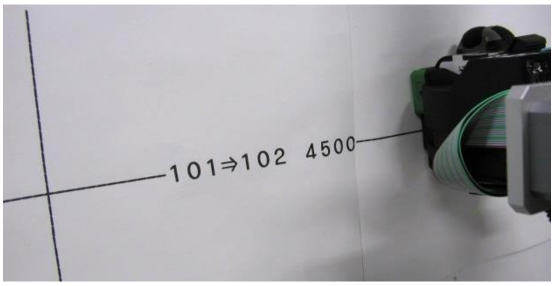


Figure 5. Example of line segments and characters printed by the inkjet printer

This special printer was developed for applications such as printing bar codes and letters on a cardboard box flowing through a production line. Using this, by simply running the XY plotter linearly, it is possible to print an arbitrary character string on the trajectory of the plotter. Incidentally, the height of the drawn characters is about 13 mm at maximum. Therefore, the efficiency of drawing characters is better than the original XY plotter, which needs to move the pen for the number of stroke counts of all the characters. In addition, control of the linear motion can be done simply by specifying only the coordinates of the start and end points and moving speed.

However, for proper printing without distortion, it is necessary to arrange the nozzles of the printer in parallel with the moving orientation of the XY plotter.

Therefore, as shown in (b), a stepping motor for turning the printer head was provided. Further, the printer head can move up and down so as to be able to absorb irregularities on the printed surface. In addition, a spring force acts on the print head in a orientation to press the head against the print surface. Depending on this spring force and an omni roller, the distance between the printing surface and the nozzle can always be kept at a distance suitable for printing. An example of line segments and characters drawn by the printer is shown in Figure 5.

On the other hand, a prism target for measuring the position and orientation of the robot by the total station was provided just above the nozzle of the printer head. This will be described in detail in the next section.

2.2.2 Marking Procedure in Cooperation with Total Station

The flow of the marking operation by the system is shown in Figure 6.

First, it is necessary to measure the benchmark which is the known point of coordinates in the on-site coordinate system by the total station and to obtain the transformation matrix between the internal coordinate system of the total station and the on-site coordinate system.

When after obtained this matrix, the controller of the system can command the motor driven total station to illuminate the work place where marking is drawn next with a built-in laser pointer. After that, a system operator moves the robot to the work place with the pointer as a guide.

Next, in order to draw line segments, it is necessary to obtain the transformation matrix of the internal coordinate system of the robot and the on-site coordinate system. Therefore, the system sequentially moves the XY plotter of the robot to the four corners of its operating range, and in each corner, makes the total station to measure the prism target described in the previous section. As a result, the position and orientation of the robot in the on-site coordinate system can be grasped, and a desired transformation matrix can be obtained.

By following the above procedure, the marking work can be executed by converting the start and end points of the line segments inputted as the coordinates of the on-site coordinate system into the local coordinate system of the robot as shown Equation (1).

$$(\boldsymbol{p}_{start} \quad \boldsymbol{p}_{End}) = f \cdot g \cdot (\boldsymbol{P}_{start} \quad \boldsymbol{P}_{End}) \qquad (1)$$

Here, $\boldsymbol{P}$ represents the coordinate values of the start and end points of the line segments described in the on-site coordinate system. And $\boldsymbol{p}$ represents those of the line segments expressed in the internal coordinate system of the robot. Also, f represents a coordinate transformation matrix between the total station and the robot, and g represents a coordinate transformation matrix between the on-site coordinate system and the total station.

Meanwhile, when marking on slopes, it is necessary to correct the start and end point coordinates of the line segments due to the influence of the height from the print surface to the prism target of the robot. The reason why the correction of the printing position on the slopes is necessary and the idea of the correction amount are shown as schematic diagram in Figure 7.

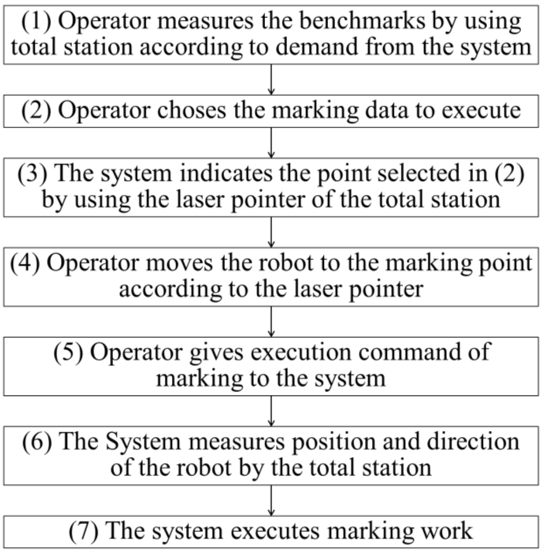


Figure 6. Marking work flow by the system

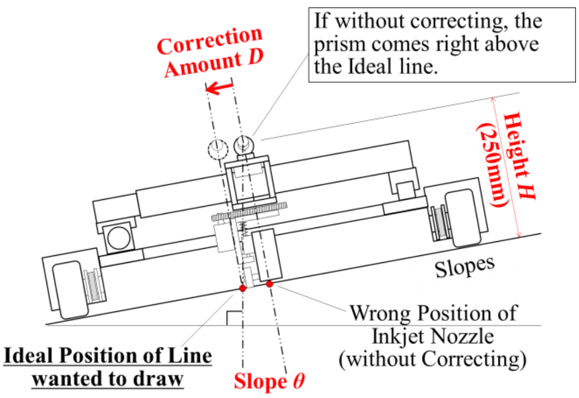


Figure 7. Schematic diagram showing the correction amount of the printing position required when marking on slopes

The prism target of the robot is located at the height H from the printed surface. Therefore, when drawing line segments on slopes, if the XY plotter is controlled so that the prism target passes right above target coordinates of the start and end points of the line segments, as shown in the figure, the lines wanted to draw and ones actually drawn have deviation.

Therefore, when measuring the robot position and orientation, the gradient θ of the slop is obtained, and the print position correction amount D shown in the expression (2) is calculated.

$$D = H \tan\theta \tag{2}$$

The results of the accuracy verification test of the marking mechanism are shown in Section 3.

2.2.3 Wall Traveling Mechanism

A picture of the bottom of the marking robot is shown in Figure 8. Both sides of the marking mechanism is the wall traveling mechanism. The inside of the left and right aluminum boxes is evacuated by a vacuum fan and the boxes are sticked to wall surface. And the mechanism travel the wall by motor driven wheels provided inside the boxes. By adopting four-wheel drive system that connects front and rear wheels with roller chain, not only going up and down but also turning by in-situ is possible.

Storing the wheels in the boxes makes it simple in structure, and since the reaction force from the wall surface by the suction is transmitted to all the wheels, a high payload can be obtained.

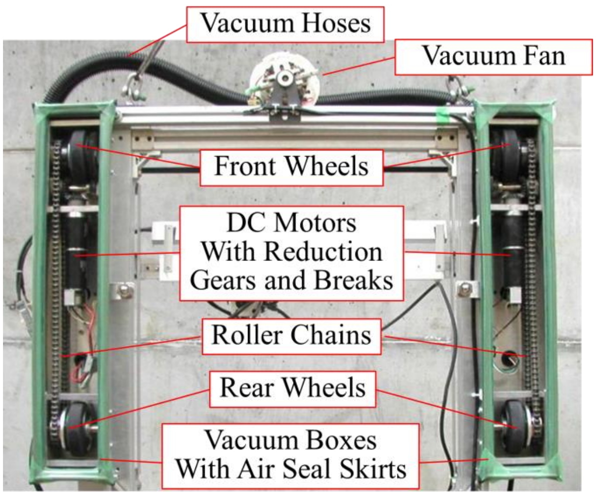


Figure 8. Bottom view of the marking robot

As shown in Figure 9, "skirt" which is the part that makes contact with the wall is made of rubber and sponge material and closely sticked to the wall without gaps. Furthermore, in order to reduce the friction between the skirt and the wall surface during running, a tape is affixed on the skirt.

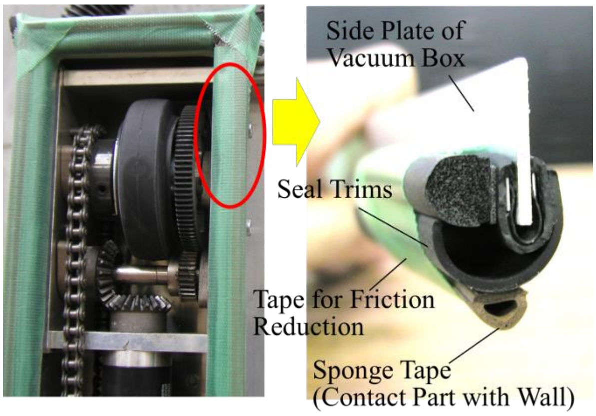


Figure 9. Cross-section shape of the air seal skirt

Table 3. Specification of the wall traveling mechanism

Item	Specification
Dimension of vacuum box (mm)	L:645 x D:100 x H:100 (Sticking Area: 0.065m^2)
Maximum pressure of Vacuum Fan (kPa)	-18
Output of motor for driving wheels (W)	150

Here, as shown in Figure 10, the force F required for the wall traveling mechanism to climb the wall at a constant speed while carrying the payload M (the mass of the robot) is obtained by equation (3).

$$\begin{aligned} F &= (m+M) + f_1 + f_2 = m + M + f \\ &= m + M + N\mu \end{aligned} \tag{3}$$

F: Driving force required to climb wall (N)
m: Mass of the wall traveling mechanism (N)
M: Payload (N)
f_1: Rolling resistance of the wheels (N)
f_2: Friction resistance between skirts and wall (N)
f: Wall climbing resistance (Summation of f_1 and f_2)
N: Wall sticking force (N)
u: Total coefficient value of rolling friction of wheel and static friction of skirt (-)

In addition, at this time, since the wheels must not slip, the driving force F must be equal to or less than the product of the static friction coefficient u_0 of the wheels at the time of rotation is restrained and the sticking force N, as shown in equation (4).

$$F \leq N\mu_0 \tag{4}$$

Here,
u_0: static friction coefficient of the wheels at the time of rotation is restrained (-)

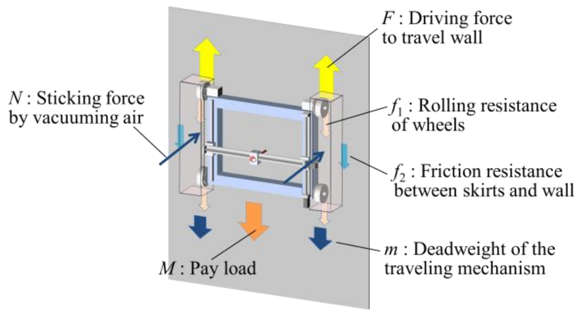


Figure 10. Schematic diagram showing the forces acting on the robot when climbing the wall with constant speed

Based on the relationship shown above, the maximum value of the payload that can be loaded on the wall traveling mechanism is represented by a linear function of the wall sticking force N as shown in Expression (5).

$$M_{mac} = N(\mu_0 - \mu) - m \quad (5)$$

3 Performance Verification of Marking System

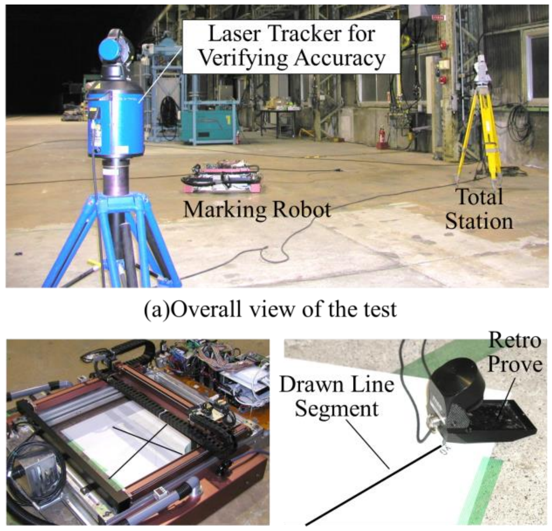
3.1 Verification Method

3.1.1 Verification Method of Marking Mechanism

Items to be verified for accuracy of the marking mechanism are shown below.

1. Repeatability of drawing: To confirm whether there is any deviation between line segments drawn when the orientation of the robot are changed.
2. Correction of drawing position at sloops: To confirm whether accurate line segments are drawn on sloops according to equation (2).
3. Position accuracy of line segments drawn: To confirm whether accuracy of drawing position of line segments satisfies development objective.

In order to confirm the three items mentioned above, we did marking work on the floor of an area assumed a construction site, and measured the position of line segments drawn by using a high-precision three-dimensional measuring instrument "laser tracker". Figure 11 shows pictures of the verification test. Here, the main specifications of the laser tracker are shown in Table 4.



(a)Overall view of the test

(b)Drawing of line segments by the robot on white paper put on floor

(c)3D measurement of end point of drawn line by using "Retro prove" which is one of tools for laser tracker

Figure 11. View of verification test on marking accuracy

Table 4. Specification of a laser tracker using the test

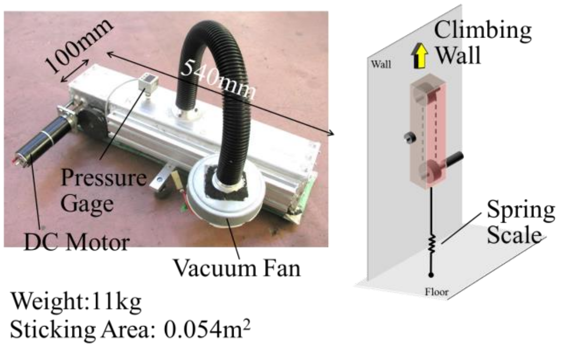
Item	Specification
Manufacture / Model	FARO / Xi
Accuracy of angle measurement	18um+3um/m
Accuracy of distance measurement by ADM	20um+1.1um/m

3.1.2 Verification Method of Pay Load of Wall Traveling Mechanism

In order to establish the design guidelines of the wall traveling mechanism to be mounted on the marking robot, we verified the payload of the mechanism by using a small test model.

(a) of Figure 12 shows the test model used the test. Area of the vacuum box and mounting position of the DC motor of the test model are different from ones of the marking robot shown in Figure 8. But the performance of the motor and the vacuum fan and the structure of the skirt are same of the robot.

As shown in (b) of Figure 12, we measured the reading of a spring scale which was connected between floor and rearward of the test model when the test model stopped to climb the wall because the driving force of the test model and the force of the spring scale was balanced. The test was repeated with changing the sticking force to wall by controlling output of the vacuum fan.



(a) View of the Test Model (b) Measurement Way of Payload

Figure 12. View of a test model of wall traveling mechanism and schematic diagram showing the way of measuring pay load

3.2 Result of Verification Test

3.2.1 Verification Result of Marking Mechanism

- Repeatability of drawing

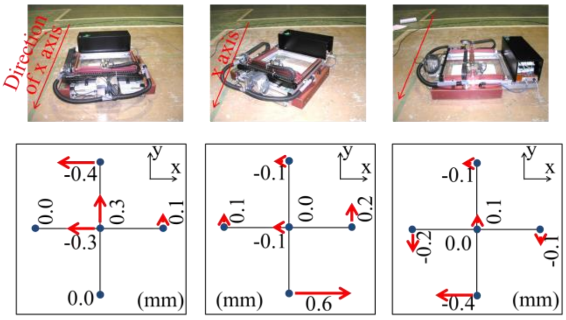
Figure 13 shows the result of the verification test. A cross shape line was drawn three times changing the orientation of the robot by about 45 degrees as shown in the upper photographs of Figure 13. After the drawing operation, positions of five points including the end points of each line segment and the intersections of the cross line were measured by the laser tracker. Here, length of each line segment is about 400mm.

Horizontal and vertical lines in the lower diagrams of Figure 13 show cross lines drawn. And numerals in the diagrams show the deviations between the target values and the measured values. In a similar way, arrows in the diagrams show the orientation of the deviations.

Among the three cross lines, 0.6 mm shown in (b) was the largest deviation. From this result, it can be said that the three cross lines were drawn in exactly the same place.

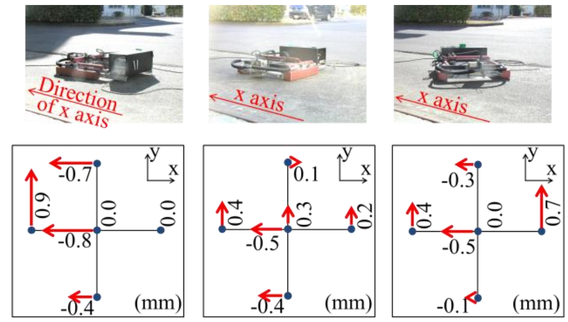
- Correction of drawing position at sloops

Figure 14 shows the result of the verification. As in the test mentioned above, a cross shape line was drawn three times on a sloop changing the orientation of the robot. Here, the angle of the sloop we used for the test was about 3 degrees. Thus, if correction is not done, 13mm of deviation between target values and measured values occurs according to equation (2). On the other hand, the deviation was 0.9 mm at the maximum as shown in (a). Thus, it was confirmed that the correction was performed correctly.



(a)Parallel with x axis (b)-45deg. rotation (c)-90deg. rotation

Figure 13. Confirmation results of repetitive positioning accuracy



(a)Parallel with x axis (b)90deg. rotation (c)135deg. rotation

Figure 14. Confirmation results of repetitive positioning accuracy on a slope

- Position accuracy of line segments drawn

Table 5 shows the evaluation results of the deviations between target values and measured values of coordinates of the intersection point of nine cross lines drawn on the horizontal floor. The maximum deviation from the target value was 0.7 mm, the average was 0.4 mm, and the standard deviation was 0.15 mm. Based on the above results, we judged that the development objective of the drawing accuracy 1 mm or less was achieved.

Table 5. Distance between the intersection of the nine crosshairs drawn by the robot and the true value

Maximum (㎜)	Average (㎜)	Standard Deviation (㎜)
0.7	0.4	0.15

3.2.2 Verification Results of Pay Load of Wall Traveling Mechanism

Figure 15 shows the result of pay load verification of the test model. This figure is a scatter diagram showing the relationship between wall sticking force and payload of the test model. The abscissa of the graph is wall sticking force, which is calculated by the product of the design value of sticking area of the test model and the measured value of the vacuum pressure, and the ordinate axis is the reading of the spring scale. In this case, the reading of the spring scale can be paraphrased as a payload of the test model.

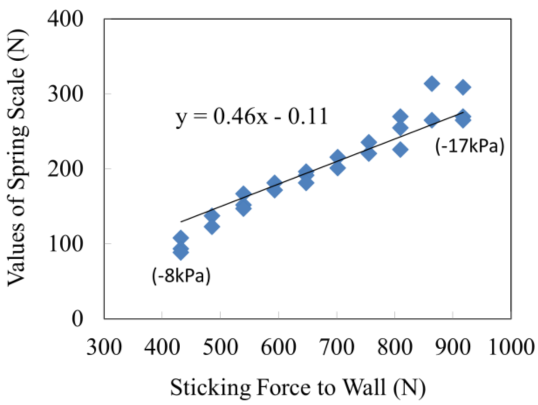
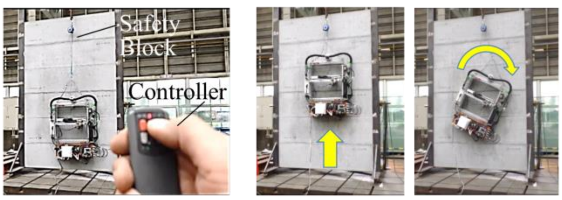


Figure 15. Verification result of pay load of the test-model wall traveling mechanism

As shown in the graph, the sticking force and the payload are almost linear relations. At vacuum pressure of -17 kPa, which is almost the maximum capacity of a vacuum fan, the sticking force was about 900 N and the payload was about 300 N. Since this result is the data of one traveling mechanism, about 600 N of payload will be obtain when two traveling mechanism are used.

A line segment in the figure is linear approximation result of the data. Here, with reference to Equation (5), the intercept of the linear equation was assumed to be 0.11 N of the weight of the test model. As a result, the term (u_0 - u) of the friction coefficient shown in the formula (5) was experimentally found to be 0.46.

With reference to the above results, in the design of the final version, the sticking area of the vacuum box was set to 1.2 times of the test model, taking into consideration the safety factor and the dimension of the marking mechanism. Pictures the marking robot climbing the wall is shown in Figure 16.



(a)The Robot Travels Wall by Wireless Control (b) Climbing Motion (c) Turning Motion

Figure 16. Traveling and marking on concrete wall with using the developed marking robot

4 Conclusion

In order to rationalize the marking work for equipment installation at plant construction sites, we have developed the marking system and got the following conclusions.

1. We developed the XY plotter type marking mechanism using an inkjet printer and made it possible to draw arbitrary line segments and characters by linearly moving the XY plotter.
2. As a result of the verification test of the marking accuracy, it was confirmed that the robot can draw line segments with an accuracy of 1 mm or less. Therefore, the development objective accuracy was achieved.
3. We confirmed that the wall traveling mechanism which sticks to walls by using vacuum fan and moves on wall with a four wheel drive mechanism realized the wall traveling of the marking robot with its own weight of 56 kg.

5 Future Prospects

We have already applied this system at two of our plant construction sites and drawing accuracy have been achieved. However, there are issues such as counter measures to cool the control unit of the robot in outdoor work and weight saving of the robot.

From now on, we are planning to apply the robot to construction sites in earnest and calculate concrete effect, while working on countermeasures for the above problem. Furthermore, we will also work on improving performance such as addition of autonomous running function of robot to marking position.

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