International Journal of Innovative Computing, Information and Control
Volume **20**, Number **3**, June **2024**
 ISSN 1349-4198
pp. **795–806**

OBSTACLE AVOIDANCE SYSTEM FOR AN OBJECT TRANSPORTATION ROBOT BASED ON SHAPE MEASUREMENT

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Received October 2023; revised February 2024

Abstract. *In this paper, a control system for a transportation robot of an object with obstacle avoidance function is developed. First, by manually inputting the location of the target object and goal object, the robot moves straight to the target object. When the target object is captured by the camera, the robot approaches it. Once close enough, the target object is grasped by the manipulator. After that, the robot moves to the goal object in the same manner. When the robot is close enough to it, the robot releases the grasped target object. If an obstacle prevents the movement, obstacle avoidance is performed. In the obstacle avoidance, the robot uses a distance sensor to measure the length between the robot and the obstacle and detect the location of the obstacle. The robot moves according to the control command generated by using the obstacle information. The usefulness of the developed control system was verified by experiments using an actual transportation robot.*
Keywords: Mobile robot, Manipulator, Distance sensor, Obstacle avoidance, Object transportation, Shape measurement

1. **Introduction.** Many autonomous control technologies for mobile robots have been developed. In the real world, there are many obstacles that hinder the robots' movement, and robot control system to take these obstacles into account is needed.

As one of the methods for avoiding obstacles, a geometric obstacle avoidance algorithm, Follow the Gap Method (FGM), has been proposed for safety-critical local navigation in [1, 2]. In this method, the positions of obstacles to pass through the gaps between them were detected. In particular, in [2], FGM was improved by proposing another algorithm, Follow the Obstacle Circle Method (FOCM). Obstacle avoidance by optical flow was proposed as an algorithm for visual obstacle avoidance in [3]. In this method, the information obtained from camera images was used. In other methods, fuzzy control is often used to control mobile robots [4, 5, 6, 7]. In [4], an image of the floor in front of the robot acquired with a CCD camera was used as input to the fuzzy controller in the experiment. In [5], a behavioral decomposition approach to rule selection and control was proposed. In [6], by

DOI: 10.24507/ijicic.20.03.795

using a neuro-fuzzy approach, the rules and membership functions were automatically obtained for control of mobile robot. In [7], experiments were conducted for implementation of fuzzy logic system in a warehouse. This system has a problem that the construction of control rules is not easy. Another major method is the potential method [8, 9, 10, 11]. In [8], a method called vector field histogram was developed to control a mobile robot for a target position while avoiding unknown obstacles by applying a potential method. In [9], harmonic functions were introduced to construct the population potential field, and experiments were conducted in known environments. In [10], an evolutionary population potential approach was used to optimize obstacle avoidance paths. In [11], a modified Artificial Potential Field (APF) approach was proposed for mobile robot to avoid collision with fixed obstacles and reach the target in an optimal path, where the modified APF approach improved the APF algorithm. In recent years, neural network has also been used [12, 13, 14, 15]. In [12], path planning was performed using Q-learning and neural networks within an environment containing both static and dynamic obstacles. In [13], a Guided Autowave Pulse Coupled Neural Network (GAPCNN) approach is proposed for path planning. In [14], three ultrasonic distance sensors based on backpropagation neural networks and a camera were used for obstacle avoidance. In [15], a neural network approach equipped with statistical dimension reduction techniques to perform exact and fast robot navigation, as well as obstacle avoidance was considered, where this technique heavily depends on the training data to obtain successful results. Here, it should be noted that, in [16], a method to optimize the obstacle avoidance trajectory and positioning error of robotic manipulators was proposed based on multigroup ant colony and quantum-behaved particle swarm optimization algorithms.

On the other hand, control systems were developed in [17, 18, 19, 20, 21], in which a mobile robot automatically recognized and grasped an object using image and distance information, and transported the object while avoiding obstacles. In [17], a visual servo remote control system was developed. In [18], a control method was proposed to determine the turning radius based on the angle information of the acquired image. In [19], an automatic object search system with automatic transportation function was developed. In [20], an autonomous control system using a USB camera and distance sensors was developed. In [21], a distance sensor-based obstacle avoidance system was developed. However, this system could not deal with unknown obstacles because the avoidance actions for shape and placement of obstacles were predefined. Here, it is noted that the situation of predetermined avoidance action is limited to the system in [21]. In some of the literature explained above, the avoidance path was determined by considering the space around obstacle. On the other hand, in this paper, the shape and placement of obstacle itself is used for the determination of avoidance path.

In this paper, we develop a system that measures the shape and placement of obstacles and avoids them using distance sensors by improving the system in [21]. In [21], the shape of obstacles was not confirmed during operation of mobile robot. Therefore, the object avoidance action might not be successfully done when the shape of obstacles during operation was different from that measured in advance. Such a problem can be solved by the proposed system. Furthermore, an object tracking system by inputting the target position in advance is newly introduced.

The rest of this paper is organized as follows. In Section 2, the system structure of the mobile robot considered in this paper is explained. In Section 3, an avoidance system based on obstacle measurement is introduced. In Section 4, an object tracking system is developed. In Section 5, experimental results to verify the effectiveness of the proposed system were shown. In Section 6, the discussion on the proposed system is provided based on the experimental results. In Section 7, the concluding remarks are given.

2. **System Structure.** The mobile robot used in this paper is a two-wheeled transportation robot equipped with a manipulator, a USB camera, a control PC, and a distance sensor. As the transportation robot, Megarover (Vstone Co., Ltd.) was used. The mobile robot has the structure of two wheels with caster. The motion of wheels is controlled via the communication between the control PC and the transportation robot. Figure 1 shows the overall view of the mobile robot used in this paper. Figure 2 shows the system structure.

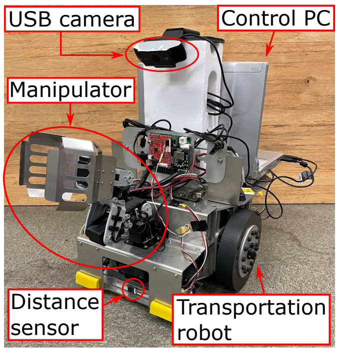


FIGURE 1. Overall view of mobile robot

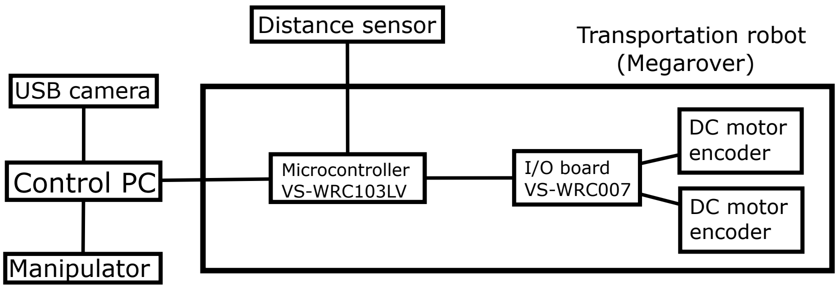


FIGURE 2. System structure

The microcomputer is used to transmit the distance information detected by the distance sensor and the encoder values of the DC motors for the left and right wheels to the control PC. The I/O board is attached to the microcontroller and connected to the DC motors of the left and right wheels. USB camera detects an object. The object detection method is to convert the image acquired by the USB camera into the HSV color space and binarize only specific color components with white color as shown in Figure 3.

(a) Original image (b) Binarized image

FIGURE 3. Binarization of images using HSV color space

The object to be grasped is considered to be found when the white area in the converted image exceeds 500 [pixel]. After the object is grasped, the target container is considered to be found when the white area exceeds 3700 [pixel]. If the robot finds a target object, the speed commands for the left and right wheels are given from the control PC so that the center of gravity of the target object is centered in the camera image. The robot arm can be controlled by giving angle commands from the control PC to each manipulator's servo motors.

As shown in Figure 4, the manipulator consists of five servo motors which are assigned unique IDs. The manipulator has five states: initial state, grasping state, holding state, releasing state, and final state. The drive angle of the servo motor in each state is shown in Table 1.

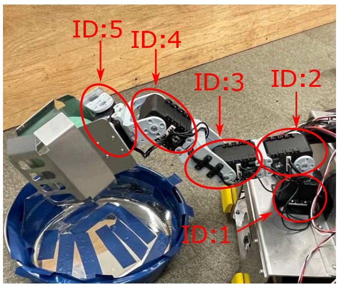


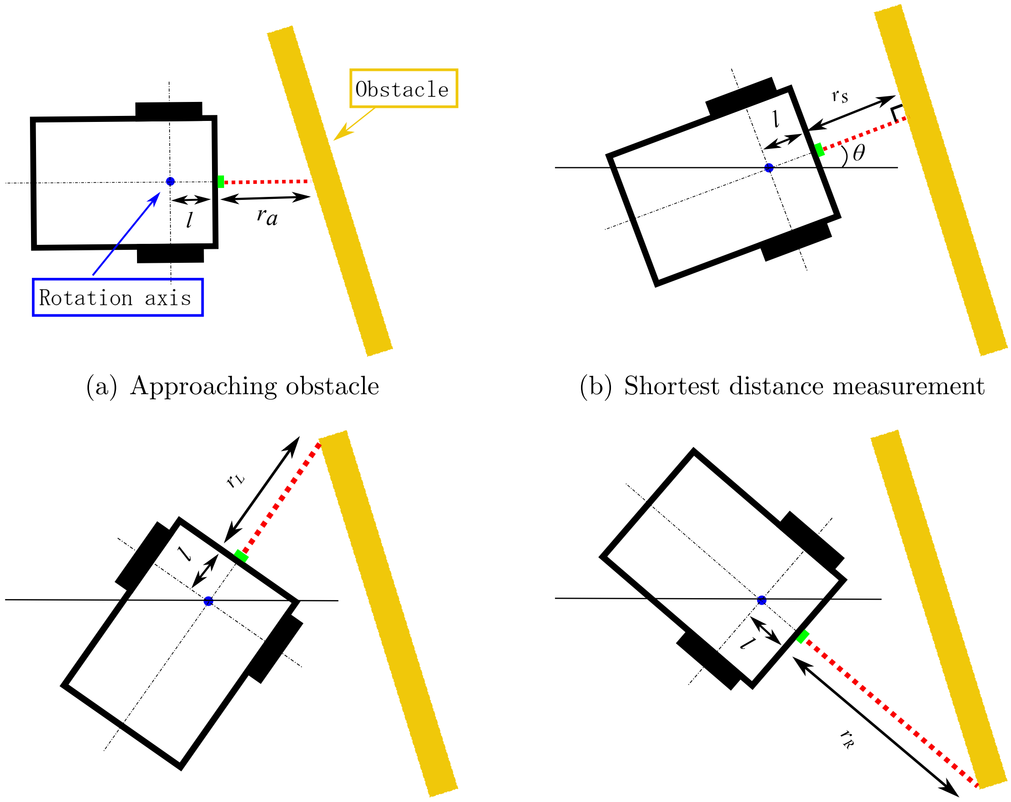
FIGURE 4. Manipulator

TABLE 1. The drive angle of the servo motor

	The drive angle [deg]				
State	ID1	ID2	ID3	ID4	ID5
Initial state	235	240	235	100	120
Grasping state	155	220	90	95	190
Holding state	235	225	235	40	190
Releasing state	150	240	200	70	120
Final state	150	230	280	40	120

3. **Obstacle Measurement System.** In order to realize the avoidance motion corresponding to the shape and placement of the obstacle, a function to measure the shape of obstacle is added to an existing control system in [21]. In this paper, as the environment, indoor environment is assumed. When the distance between the robot and the obstacle reaches r_a, the robot turns to the left or right, measures the length and placement of the obstacle by distance sensors, and then performs an evasive maneuver corresponding to the shape of the obstacle. The parameter r_a is determined from the specification of distance sensor and the size of mobile robot. Figure 5 shows the procedure for obstacle measurement. In Figure 5, l is the distance between the rotation axis of mobile robot and the distance sensor.

1) As shown in Figure 5(a), when the distance between the obstacle and the distance sensor attached to the front of mobile robot reaches r_a, the obstacle measurement starts with counterclockwise rotation.
2) As shown in Figure 5(b), the distance r_s and the angle θ are recorded when the distance to the obstacle is the shortest.



(a) Approaching obstacle (b) Shortest distance measurement

(c) Measured to one end (d) Measured to another end

FIGURE 5. Procedure for obstacle measurement

3) As shown in Figure 5(c), counterclockwise rotation is kept until one end of the obstacle is measured, and the distance r_L between the distance sensor and one end of the obstacle is recorded.
4) As shown in Figure 5(d), the direction of rotation is changed to clockwise and the distance r_R to another end of the obstacle is recorded by the same procedure as in Figure 5(b) and Figure 5(c).

After recording both ends of the obstacle, the smaller length of the obstacle

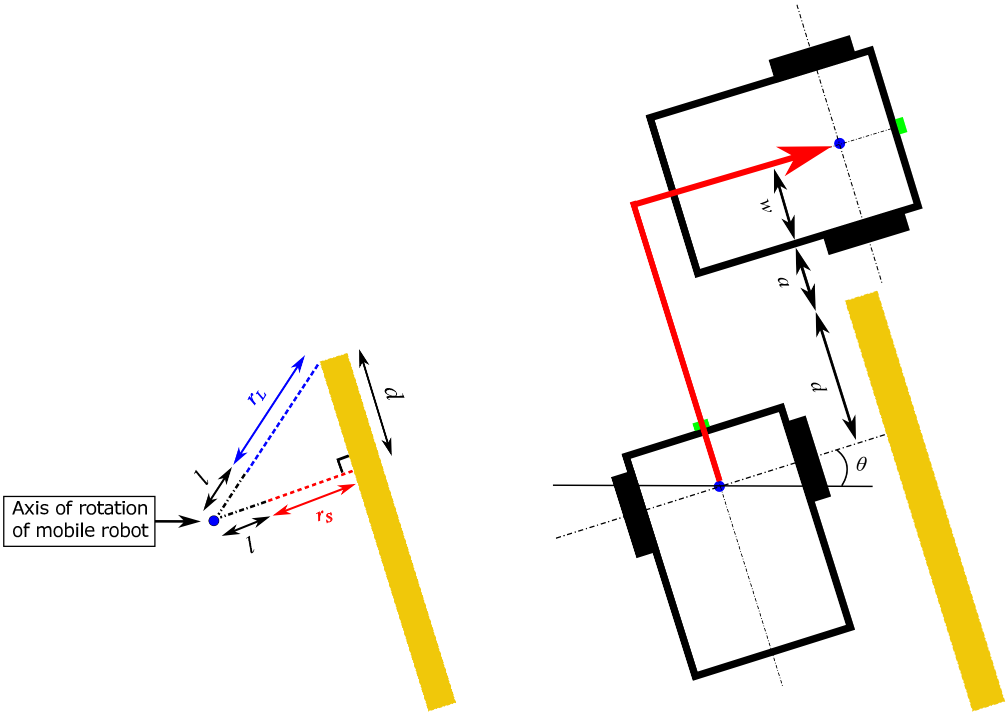
$$d = \begin{cases} \sqrt{(l + r_L)^2 - (l + r_s)^2} & (r_L < r_R) \\ \sqrt{(l + r_R)^2 - (l + r_s)^2} & (r_L > r_R) \end{cases} \tag{1}$$

is calculated as shown in Figure 6(a).

As shown in Figure 6(b), mobile robot moves forward $w + a + d$ along the obstacle to avoid it, where w is the half width of mobile robot and a is the distance between the obstacle and the mobile robot. The parameter a is determined from the length and width of mobile robot.

In the above method, it may be seemed that the rectangular (or linear) shape of obstacles can only be dealt with. However, since two ends are used to detect the objects, the method may be applicable to the object whose shape is not rectangle if two ends can be detected appropriately.

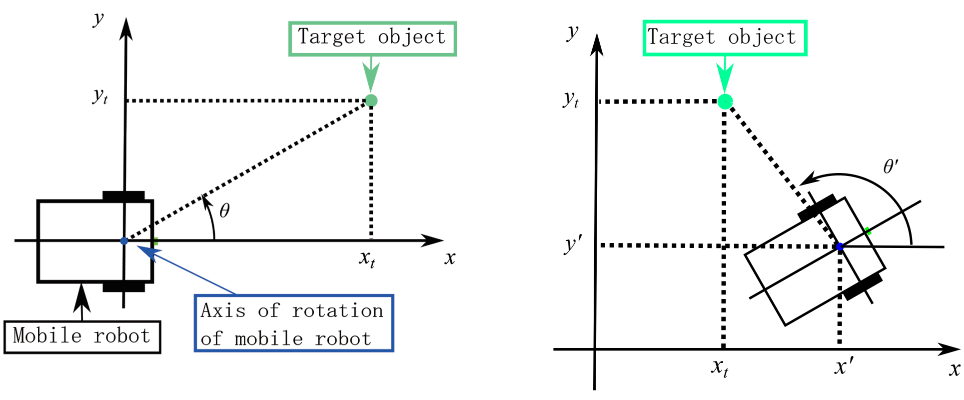
4. **Object Tracking System.** In the control system of previous work [21], the robot might lose the object when the robot was far away from the object after avoidance action. To cope with this problem, it is necessary to introduce a function that can keep track of the target object's position and follow it. Therefore, in this paper, an object tracking



(a) Calculation of distance d required for avoidance

(b) Avoidance motion after obstacle measurement

FIGURE 6. Avoidance motion after obstacle measurement ($r_L < r_R$)



(a) Calculation of the angle of travel

(b) Object tracking

FIGURE 7. Procedure for object tracking

system based on coordinate input is newly added. This system calculates the positional relationship between mobile robot and the object by inputting the position of the object in advance for the mobile robot to automatically run to the target object. The procedure for the object tracking is shown in Figure 7.

1) The position (x_t, y_t) of the target object is manually inputted before the start of mobile robot operation.
2) Calculate the angle θ shown in Figure 7(a) by the following manner. Since

$$\tan^2\frac{\theta}{2} = \frac{1-\cos\theta}{1+\cos\theta} = \frac{1-\frac{x_t}{\sqrt{{x_t}^2+{y_t}^2}}}{1+\frac{x_t}{\sqrt{{x_t}^2+{y_t}^2}}} = \frac{{y_t}^2}{\left(\sqrt{{x_t}^2+{y_t}^2}+x_t\right)^2}$$

or

$$\tan\frac{\theta}{2} = \frac{y_t}{\sqrt{{x_t}^2 + {y_t}^2} + x_t},$$

we have

$$\theta = 2\tan^{-1}\left(\frac{y_t}{\sqrt{{x_t}^2 + {y_t}^2} + x_t}\right)[\text{rad}] = \frac{360}{\pi}\tan^{-1}\left(\frac{y_t}{\sqrt{{x_t}^2 + {y_t}^2} + x_t}\right)[\text{deg}]. \quad (2)$$

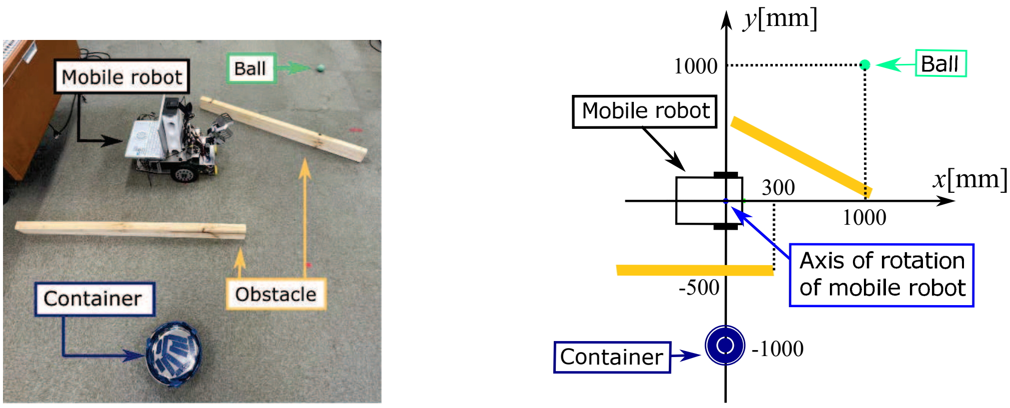
In this paper, a function atan2 was used for the calculation of inverse tangent in (2).

3) Mobile robot turns to the calculated angle θ and travels automatically to the location of the target object.
4) If the position of mobile robot changes due to obstacle avoidance, repeat Step 2) again by calculating the angle θ' in Figure 7(b) to the target object after the movement:

$$\theta' = \frac{360}{\pi}\tan^{-1}\left(\frac{b}{\sqrt{a^2 + b^2} + a}\right)[\text{deg}], \quad (3)$$

where $a = x_t - x'$ and $b = y_t - y'$.

5. **Experimental Results.** To verify the effectiveness of the control system developed in this paper, avoidance experiments by obstacle measurement using a mobile robot, obstacles, a ball, and a container were conducted. The experiment is judged to be success if the robot places the ball into the container without touching any obstacles; otherwise it is judged to be failure. The experiment was repeated 10 times. The ball and the container as the target objects were located at $(x, y) = (1000, 1000)$ and $(x, y) = (0, -1000)$, respectively. Here, it should be noted that the target object at the beginning of operation was the ball, and the target object was changed from the ball to the container after the manipulator grasped the ball.



(a) Photograph (b) Location

FIGURE 8. Experimental setup

The experimental results showed the success rate of 90% as listed in Table 2. Figure 9 shows the trajectories of the mobile robot. The mobile robot placed the ball into the container in all experiments, but the second one was judged as failure because the robot touched the side of the obstacle during the last avoidance action. Figure 10 and Figure 11 show experimental results for No. 1 and No. 2, respectively. In these figures, (a) shows the measured distance by distance sensor, (b) the white area (or area of target) in images, (c) the time evolution of position x, and (d) the time evolution of position y. In Figure 10(a)

TABLE 2. Results of target object tracking experiment

No.	Judgement	Note
1	○	
2	×	Touch on the obstacle
3	○	
4	○	
5	○	
6	○	
7	○	
8	○	
9	○	
10	○	
Success rate	90%	

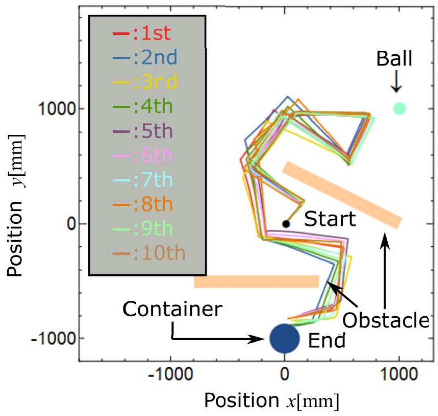
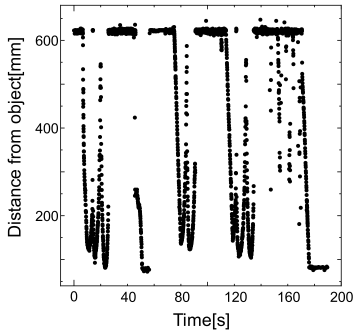


FIGURE 9. Trajectories of mobile robot

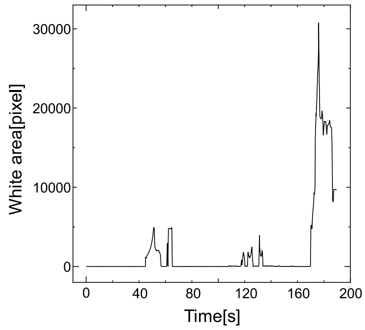
and Figure 11(a), the obstacle measurement was performed in time duration 0-30 [s], 70-100 [s] and 110-140 [s]. Figure 10(b) and Figure 11(b) show that the condition to grasp the ball was satisfied about 60 [s], where the condition was given as follows: The white area was greater than or equal to 4600 [pixel] and the distance between the robot and the ball was less than 100 [mm]. These figures also indicate that the condition to release the ball was met about 180 [s], where the condition was given as follows: The white area was greater than or equal to 14000 [pixel] and the distance between the robot and the container was less than 100 [mm].

6. **Discussion.** In the obstacle measurement system, the shape is measured by using distance sensor. Therefore, obstacle avoidance action corresponding to the shape and the position of obstacles can be realized. In the object tracking system, a solution to the problem of losing target object in the past work [21] is given by assigning the target position appropriately. Thus, these systems provide the autonomous action of the mobile robot for the system in [21].

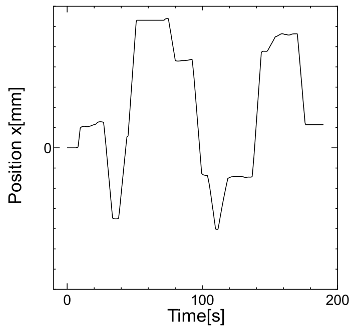
Table 2 shows that the ball was placed into the container without touching any obstacles at the success rate of 90%. The fact that the ball was able to be placed into the container on all results indicates that this system worked well as the transportation robot. This success rate could be achieved because the measured data of distance was directly used different from the techniques in some literature explained in Section 1. However, in the result No. 2, mobile robot came into contact with the side of an object present at the



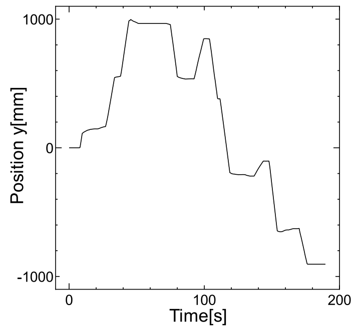
(a) Measured distance



(b) White area in images

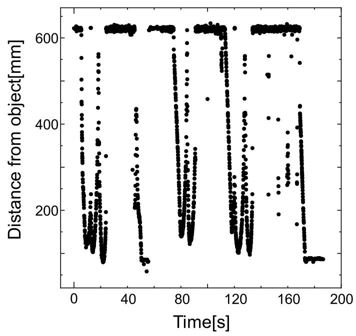


(c) Position x

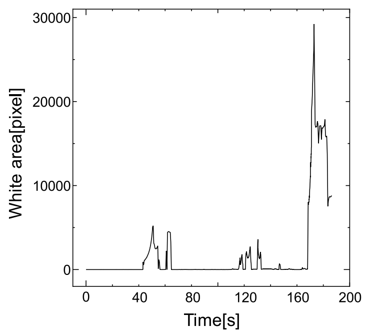


(d) Position y

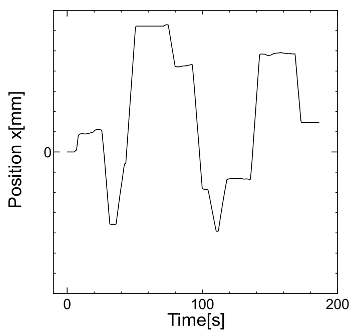
FIGURE 10. Experimental result (No. 1)



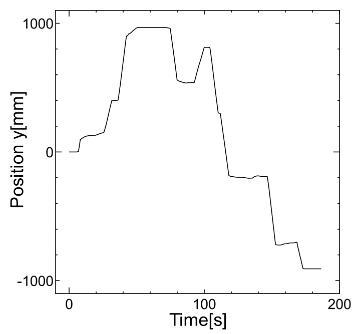
(a) Measured distance



(b) White area in images



(c) Position x



(d) Position y

FIGURE 11. Experimental result (No. 2)

end of the operation, as shown in Figure 9. Indeed, the position y in Figure 10(d) was different from that in Figure 11(d) at 140 [s]. On the other hand, we see from Figure 10(a) and Figure 11(a) that the measurement of distance could be done successfully. Therefore, this difference of position y indicates that the touch on the obstacle in experiment No. 2 was caused by the lack of turning action of mobile robot. Thus, the reproducibility of the successful action of this system should be improved.

In the proposed system, the positions of the target object are manually given before the start of operation. Therefore, it is necessary to develop a system that allows mobile robot to automatically search for the object without entering the positions.

7. **Conclusion.** In this paper, we developed an obstacle measurement system and an object tracking system to avoid unknown obstacles using a mobile robot which are the contributions of this paper. In the obstacle measurement system, the distance sensor measured the shape and placement of obstacle, and the mobile robot achieved suitable avoidance. In the object tracking system, the mobile robot autonomously ran to the target object by inputting the location before starting the movement. The experiments were successful, as the success rate was 90%. As one of the application scenarios, the utilization of the proposed system in logistics factory may be meaningful because the system does not require additional improvement of facility itself. In the future, in order to achieve more flexible avoidance, we will develop a system that can deal with dynamic obstacles.

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