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CONTROL SYSTEM FOR OBJECT TRANSPORTATION BY A MOBILE ROBOT WITH MANIPULATOR COMBINED WITH MANUAL OPERATION AND AUTONOMOUS CONTROL

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Abstract. *In this paper, a control system of a mobile robot with manipulator for object transportation is developed by using image processing and distance measurement. As the control methods, manual operation and autonomous control are considered. First, mobile robot is operated manually until USB camera captures a target object to be transported. Then, the control method is switched from manual operation to autonomous control. In the autonomous control, to detect the target object, HSV color recognition is used. A distance sensor is used to measure the distance between the target and the mobile robot when the mobile robot sufficiently approaches to the target. The target object is grasped by the manipulator. Secondly, a destination object for the target object to be put into is detected by USB camera and distance sensor after the mobile robot is manually operated. Then, the mobile robot is controlled autonomously to transport the target object. The usefulness of the proposed control system was verified by experiments.*
Keywords: Autonomous control, Manual operation, Object transportation, Mobile robot, Image processing

1. **Introduction.** In recent years, robot remote control technology has been introduced to work in disaster areas, construction sites and environments with hazardous substances. The technology has been developed by the progress of network systems and robotics [1]. However, in remote operation, the operability problem due to communication delay generally hinders accurate works. Therefore, skilled operation techniques are required for accurate works. On the other hand, image processing has been recognized as an effective tool for detecting objects. For example, in [2], a method of detecting objects jumping in front of car was considered using deep learning. The authors have investigated whether the operability problem can be solved by switching from manual remote operation to autonomous control [3, 4, 5, 6, 7, 8, 9]. In [3], a system for the teleoperation of robot

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arms was developed by using forcefree control and template matching [10], where forcefree control [11] realizes the passive motion of robot arm without any changes to the built-in servo controller. To evaluate the teleoperation system, in [4], experimental evaluation was conducted by the human operator perception. In [5], the target selection function in the template matching was added to the teleoperation system. In [6], angle-pixel characteristic was newly introduced to the image processing of the teleoperation system, where visual supporting function to assist the manual operation was also added. In [3, 4, 5, 6], the robot arm was fixed on the environment, and was not movable. In order to improve this situation, in [7, 8], a mobile robot was introduced. In [7, 8], the recognition of an object during autonomous control was performed by template matching. The mobile manipulator was operated by P (proportional) control, and the operation of pushing a target button was realized. However, it was clarified that template matching could not cope with brightness changes sufficiently and P control was not performed well due to the limited performance of the mobile robot. Therefore, in [9], the recognition of object was changed to HSV color recognition and improved by obtaining the target position from recognized color area. By improving color recognition, it was made less sensitive to changes in brightness. Furthermore, the hardware was replaced so that it could be operated with PI (proportional integral) control. The movement of grasping an object was also realized by introducing a manipulator.

Here, it is noted that the task of transportation of object is important [12, 13, 14, 15, 16, 17, 18, 19]. In [12], transportation of convex polygonal object was considered by multi mobile robots caging based on fuzzy sliding model control. In [13], cooperative mobile robots to transport a payload were designed. In [12, 13], the use of camera images was not considered. In [14], a transportation robotic system for a simulated factory was proposed by using a multipurpose enhanced cognitive architecture. The system was not applied to the control in real environment. In [15], a control strategy of mobile robot to transport an aluminum tube by the collaboration of operator and mobile robot was proposed. The mobile robot was autonomously worked. In [16], a path tracking control method for an indoor transportation robot was proposed. The effectiveness was confirmed through simulations. However, any manipulation tasks were not included. In [17], visual communication system for a human robot cooperation was developed. A stereo camera was used for image processing, and the transportation of selected items was done. However, almost all of the control of mobile robot was realized autonomously. In [18], a robot programming method using augmented reality and stereo camera was proposed. The effectiveness was verified by an experiment of pick and place operation. In this system, a robot arm fixed on the environment was used. As checked above, most of the existing studies investigated the autonomous control systems, and did not consider the possibility of the combination of manual operation and autonomous control sufficiently. It is also noted that in image processing of this paper the angle-pixel characteristic is adopted. On the other hand, the literature about the transportation robotic systems mentioned above did not use it. This is just a difference from this paper.

Since the control systems for the mobile robots with manipulator developed by the authors have never had the transportation function, in this paper, the control system of a mobile robot with manipulator for object transportation is constructed based on the combination of manual operation and autonomous control. The contribution of this paper is to propose the control system for object transportation by using not only the manual operation via human operator but also the autonomous control via image processing.

The rest of this paper is organized as follows. In Section 2, the configuration of mobile robot with manipulator is explained. In Section 3, object recognition method using image processing and distance sensor is shown. In Section 4, the movement of mobile robot with manipulator for object transportation is explained. In Section 5, experimental results using an actual mobile robot with manipulator are shown to confirm the effectiveness of the constructed control system. In Section 6, concluding remarks are stated.

2. Configuration of Mobile Robot with Manipulator.

The configuration of mobile robot with manipulator in this paper is shown in Figures 1 and 2. The mobile robot with manipulator consists of a control PC, a mobile robot (Megarover made by Vstone Co., Ltd.), a manipulator (CRANE+ made by RT Corporation), a USB camera (C920r by logicool) and a distance sensor (GP2Y0E03 made by SHARP Corporation). The mobile robot, the manipulator and the USB camera are connected to the control PC. The distance sensor is connected to the microcomputer of the mobile robot. The mobile robot can be controlled by specifying both the left and right wheel speeds. The moved distance of the mobile robot can be calculated by using data obtained from encoders for left and right wheels. The manipulator has a 5-axis configuration with 5 servo motors, and each servo motor can be controlled by torque, position and speed. The mobile robot with manipulator acquires image information from the USB camera and distance sensor information, and determines wheel rotation speed of the mobile robot and target angle of each servo motor of the manipulator.

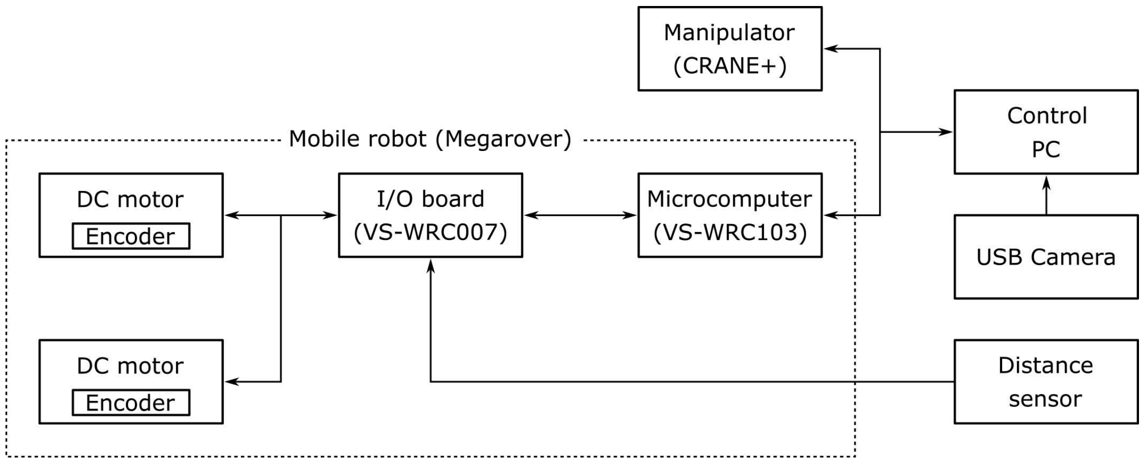


FIGURE 1. Configuration of mobile robot with manipulator

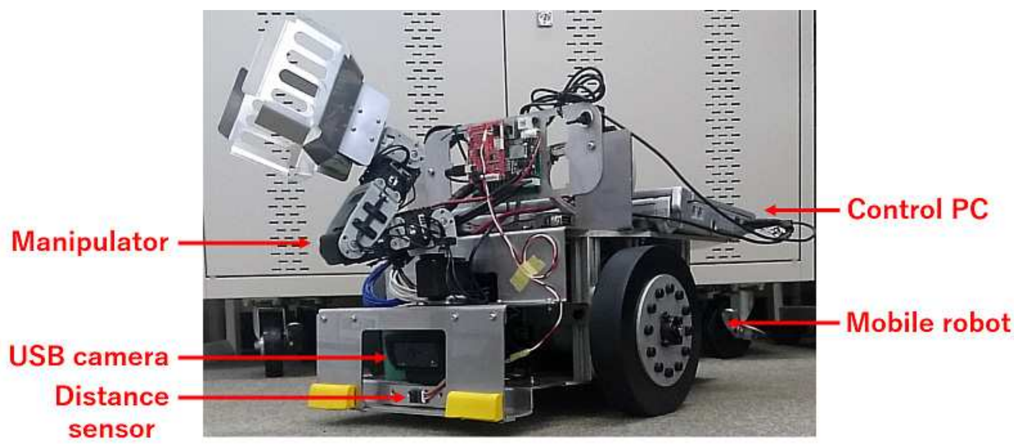
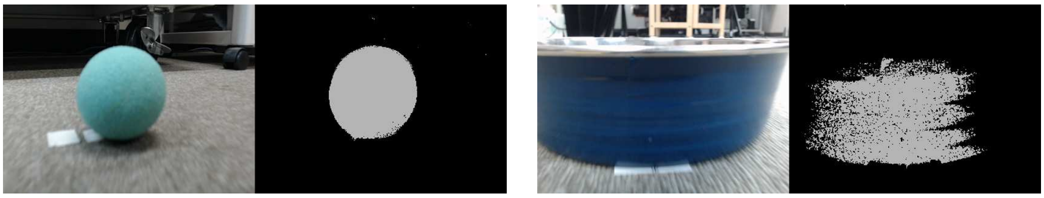


FIGURE 2. Mobile robot with manipulator

3. Object Recognition.

3.1. Image processing. In the previous works [7, 8, 9], template matching or HSV color recognition was used to recognize objects. In this paper, in order to grasp and transport an object, the target object and the destination object for the target object to be put into are recognized by HSV color recognition. A binarization condition for assigning white to the object in camera image is given so that the target is captured successfully. By the logical product for the binarized components of H, S and V, the target color is extracted. Figure 3 shows an example of extraction results. The centroids of the extracted region in images of not only the target object but also the destination object are calculated to calculate the control inputs to the mobile robot. The procedure for the calculation of the control inputs is the same as that in [9]. Although the shape of the destination object is different from that of the target object, the destination object can be detected by giving the thresholds for image processing appropriately. This is the reason why the proposed control system adopts the same procedure for the calculation of the control inputs as in [9].



(a) Object color extraction (b) Container color extraction

FIGURE 3. An example of color extraction results

3.2. Distance sensor. The horizontal distance between mobile robot and objects is detected by distance data acquired from distance sensor. In the conventional method [7, 8], the horizontal distance was detected by the size of white area of recognized object as shown in the right of Figure 3(a). Since the recognition area increases as the mobile robot approaches to the object, the distance was measured by counting the number of pixels. However, in the method, the recognition area depends on the direction at which the object is recognized and the environment in which the mobile robot with manipulator is operated.

Therefore, in this paper, a distance sensor to measure the exact distance is used. The distance sensor is installed in such a way that the irradiation point of distance sensor coincides with the center of camera image horizontally. This makes it possible to accurately capture the center of object. The distance sensor is used to stop the motion of mobile robot. Here, the distance sensor used in this paper was applicable in the range of 40-500 [mm] from its specification.

4. Movement of Mobile Robot with Manipulator for Object Transportation.

In [9], a control system for grasping an object using a mobile robot with manipulator was developed. The mobile robot was operated by manual operation until the target object was included in camera image. Then, the control method was switched to autonomous control to perform the object grasping motion.

In this paper, by repeating the switching action, a control system for transporting an object is newly developed.

First, the mobile robot is operated by manual operation until the target object is captured in camera image. Then, the control method is switched to autonomous control when the operator clicks the camera image. When the mobile robot sufficiently approaches to the target object, the mobile robot stops, where the distance between the mobile robot and the target object is measured by the distance sensor. Then, the manipulator grasps the target object. The manual operation, the autonomous control and the control of manipulator are realized by the similar manner as in [9]. After the manipulator grasps the target object successfully, the control method is switched to manual operation.

Secondly, the mobile robot is operated by manual operation until the destination object is included in camera image. Then, the control method is switched to autonomous control when the operator clicks the camera image. The control methods of manual operation and autonomous control using image processing are both the same as that in [9] except that the target image in image processing is different. When the mobile robot sufficiently approaches to the destination object, the mobile robot stops. The distance between the mobile robot and the destination object is also measured by the distance sensor. Then, the manipulator starts to put the transported object into the destination object. This manipulation is performed by manipulating the servomotors of the manipulator so as for the end effector to successfully put the grasped object into the destination object according to the predetermined commands for the required action.

The manual operation, the autonomous control and the control of manipulator are summarized below.

4.1. **Manual operation.** The manual operation of the mobile robot is realized by keyboard inputs corresponding to the movements of forward, backward, left and right rotations, leftward and rightward. The keyboard inputs are given by human operator.

4.2. **Autonomous control.** The mobile robot is controlled by using the image processing result and the distance data from distance sensor. To realize the suitable movement of the mobile robot, speeds of both left and right wheels are specified, where the speeds are determined by the angular velocity. The angular velocity is calculated by a proportional integral (PI) control law whose input is the control error between the current position and the reference position of the target image.

4.3. **Control of manipulator.** The manipulator is driven by controlling the servomotors to realize the motions of grasping, transporting and releasing the target object. The control commands for each action are specified in advance as shown in Figure 4 and Figure 5, where the motion of transporting the target object is realized by maintaining the posture in Figure 4(c).

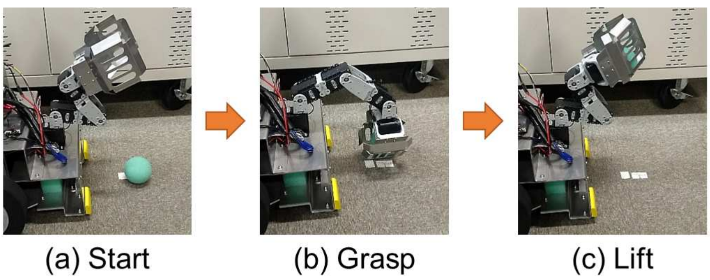


FIGURE 4. The motion of grasping target object by manipulator

5. **Experimental Verification.** In order to verify the usefulness of the control system developed in this paper, experiments were conducted in which a mobile robot with manipulator grasped and transported an object. A blue ball was used as the object, and

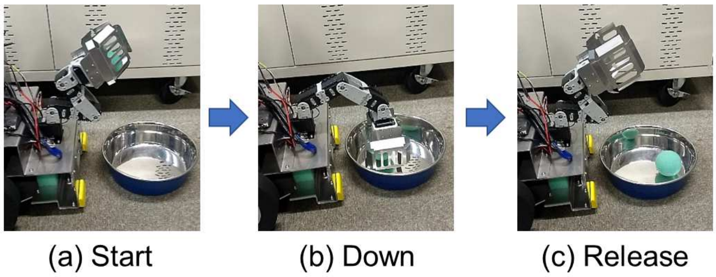


Figure 5. The motion of releasing target object by manipulator

a stainless steel container was used as the destination object. In this paper, the conditions for the recognition of the blue ball and the container were given by H: 80-96, S: 65-220, V: 40-240 for the blue ball, H: 105-111, S: 150-240, V: 29-100 for the container, respectively.

5.1. **Experimental procedure.** The experimental procedure is shown below.

1) The mobile robot moves manually from the initial position shown in Figure 6 to the position where the ball is captured by USB camera. After reaching the position at a number marked on a white line, the mobile robot stops at the position of the white line and turns so as for the camera to capture the ball in the image. The numbers as the target position were written on the white line with the interval 50 [mm] which was sufficiently small for manual operation.
2) By left-clicking the object on the camera image, the control method switches from manual operation to autonomous control for grasping the object, and the mobile robot approaches to the object by autonomous control based on image processing.
3) The mobile robot stops when the distance to the object reaches 100 [mm], and the manipulator starts to grasp and lift the object according to preset control commands.
4) If the object is successfully grasped, manual operation is performed again to transport the object. After reaching the position at the same number on the white line, the mobile robot stops at the position of the white line. Then, it turns so that the container is captured by the camera.
5) By right-clicking the container on the camera image, the control method is switched from manual operation to autonomous control, and the mobile robot approaches to the container by autonomous control based on image processing.
6) The mobile robot stops when the distance to the container reaches 60 [mm], and the manipulator puts the object into the container according to the preset control command.

The experimental success is defined as the success of the placement of the object in the container, and otherwise the failure. In this paper, 20 object transportation experiments were carried out in room A or room B. The number of 20 of experiments was determined from the limitation on the applicable range of the USB camera.

5.2. **Experimental result.** Table 1 shows the results of 20 experiments in room A or room B. Here, the notation ◯ indicates the success of the experiment, and the notation × indicates the failure of the experiment. Therefore, the overall success rate of the experiment using the control system in this paper was 95%. Figure 7 shows the trajectory of the mobile robot in each room. The black line is the success trajectory, and the red line is the failure trajectory. The reason for the failure in room B was that the ball could not be grasped by the manipulator.

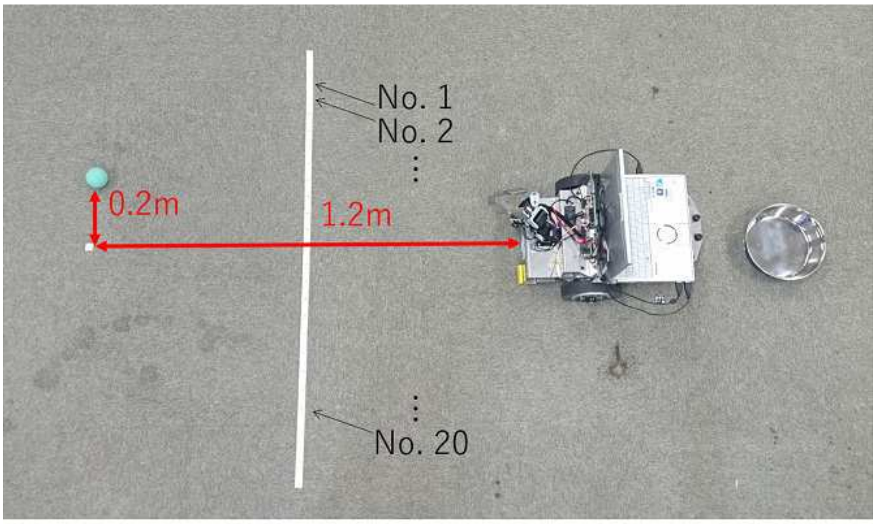


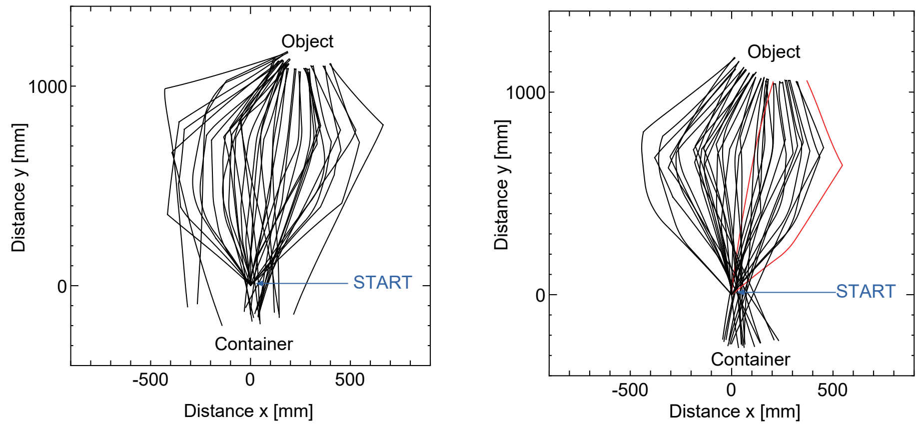
FIGURE 6. Experimental setup

TABLE 1. Experimental results

No.	Room A	Room B
1	○	×
2	○	○
3	○	○
4	○	○
5	○	○
6	○	○
7	○	○
8	○	○
9	○	×
10	○	○
11	○	○
12	○	○
13	○	○
14	○	○
15	○	○
16	○	○
17	○	○
18	○	○
19	○	○
20	○	○

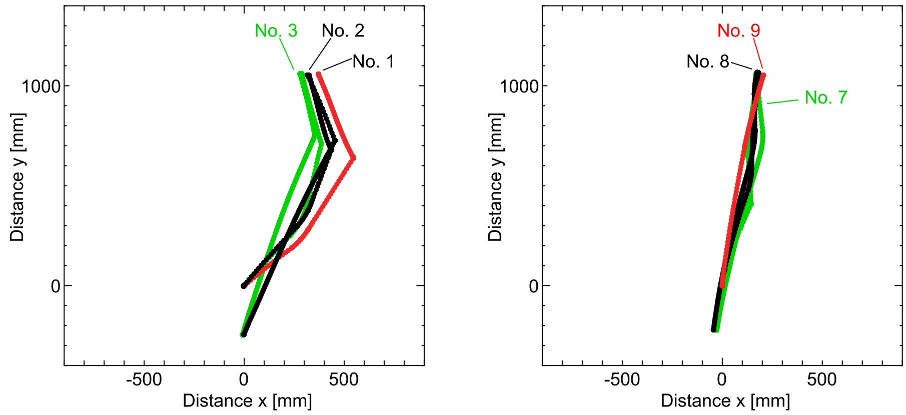
Here, let us compare two failures in room B with those that were operated in the closest trajectory. Figure 8 shows the comparison of the trajectories. As shown in Figure 9 of the data obtained from the distance sensor, it is confirmed that all of them stopped properly at the distance 60 [mm]. Figure 10 shows the control error (β_x [deg]) obtained from the camera image. This shows that there is a slight difference between success and failure. Figures 11-12 show actual camera images (left) and image processing results (right). From these images, it is confirmed that the failure was slightly off to the right compared to the success. Furthermore, let us compare experimental results in this paper with those in [9].

As verified above, the success rate in this paper was 95%. On the other hand, that in [9] was 100%. Therefore, the control technique of this paper could achieve not only the action of grasping the target object but also that of transporting and releasing it successfully.



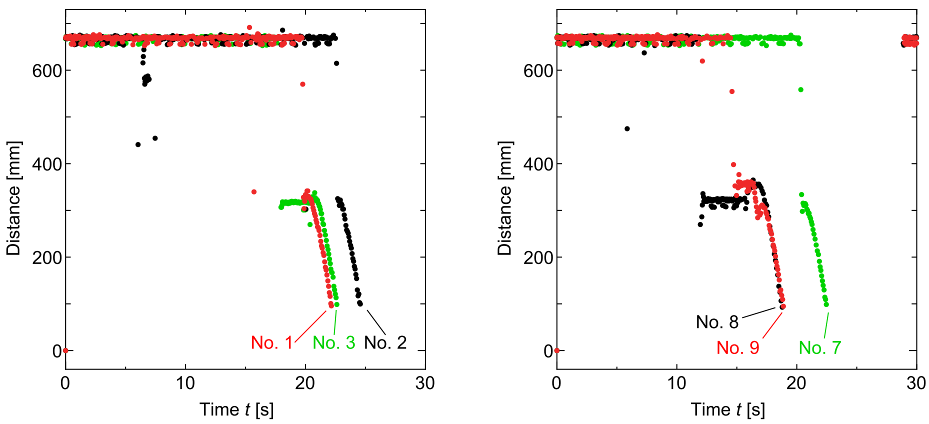
(a) Room A (b) Room B

Figure 7. (color online) Horizontal trajectory



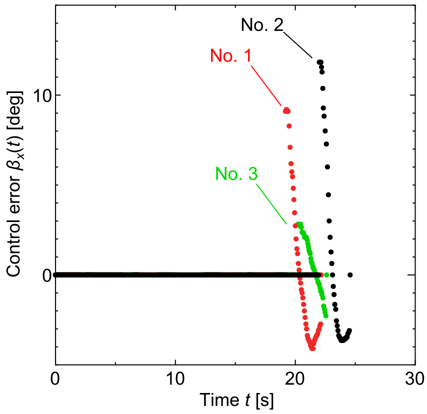
(a) Comparison of Nos. 1-3 (b) Comparison of Nos. 7-9

Figure 8. Horizontal trajectory for comparison

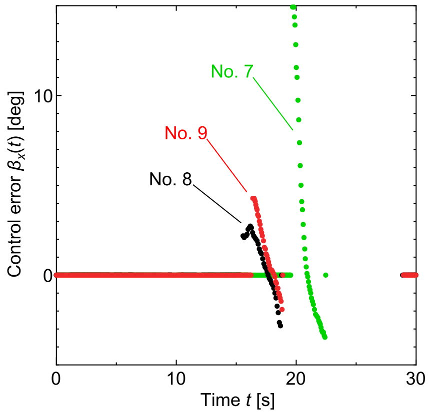


(a) Comparison of Nos. 1-3 (b) Comparison of Nos. 7-9

Figure 9. Distance for comparison

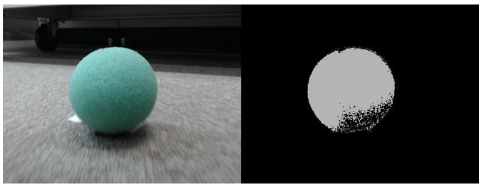


(a) Comparison of Nos. 1-3

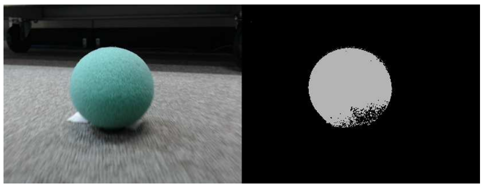


(b) Comparison of Nos. 7-9

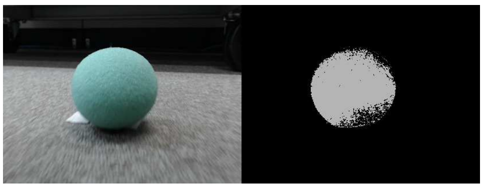
FIGURE 10. Control error for comparison



(a) No. 1

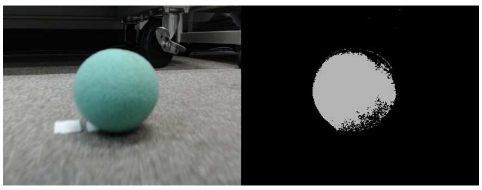


(b) No. 2

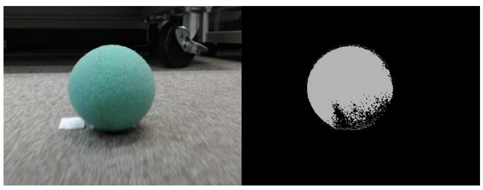


(c) No. 3

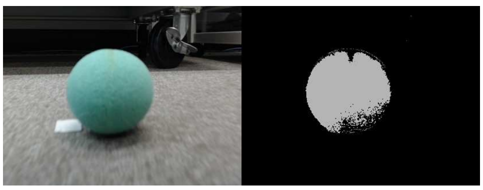
FIGURE 11. Comparison of stop position camera images Nos. 1-3



(a) No. 9



(b) No. 8



(c) No. 7

FIGURE 12. Comparison of stop position camera images Nos. 7-9

6. **Conclusion.** In this paper, a control system for transportation of object by mobile robot with manipulator based on image processing was developed. The system was constructed by improving the existing system from the viewpoint of software. The results of

the experiment of grasping and transporting the target object by the system developed in this paper showed that the mobile robot with manipulator could work well by the proposed control method.

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