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CONTROL SYSTEM FOR A MOBILE ROBOT WITH OBJECT GRASPING ARM BY COMBINING MANUAL OPERATION WITH VISUAL SERVOING

Yoshitaka Matsuda[1,*], Yoshitaka Sato[2], Takenao Sugi[3], Satoru Goto[3]
and Naruto Egashira[4]

[1]Institute of Ocean Energy
[2]Department of Advanced Technology Fusion
Graduate School of Science and Engineering
[3]Department of Electrical and Electronic Engineering
Faculty of Science and Engineering
Saga University
1, Honjo-machi, Saga 840-8502, Japan
[*]Corresponding author: ymatsuda@cc.saga-u.ac.jp
ysato.1025.anchor@gmail.com; { sugi; goto }@cc.saga-u.ac.jp

[4]Department of Control and Information Systems Engineering
National Institute of Technology, Kurume College
1-1-1, Komorino, Kurume, Fukuoka 830-8555, Japan
naruto@kurume-nct.ac.jp

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Abstract. *In this paper, a control system for a mobile robot with object grasping arm is developed. The control system mainly consists of mobile robot, object grasping arm, USB camera, distance sensor, microcomputer and control PC. To recognize the target object to be grasped, an image processing method for the extraction of the target object is introduced. The mobile robot is controlled by two kinds of methods: manual operation and autonomous control. The manual operation of the mobile robot is done according to the command of human operator. The autonomous control of the mobile robot is realized by the assignment of the velocities of wheels, where the velocities are determined by a proportional integral control law with control error represented by the angle information of image. For the verification of the usefulness of the proposed control system, experiments using an actual robot system were conducted. The experimental results demonstrated that the action of object grasping could be successfully achieved even if some conditions such as lighting condition were different.*

Keywords: Mobile robot, Object grasping, Visual servoing, Manual operation

1. **Introduction.** In recent years, teleoperation technology [1] has been introduced to the works in hazardous environments such as disaster areas, outer space and harmful substances. However, in teleoperation, in general, communication delays occur. Therefore, human operation is difficult in accurate works. For this problem of operability, a method of switching manual remote operation and autonomous control appropriately has been considered [2-7]. In [2], a teleoperation system of industrial articulated robot arm was proposed by combining force-free control [8] for manual operation with template matching [9] for autonomous control via visual servoing [10]. In [3], the teleoperation system proposed in [2] was evaluated through experiments from the viewpoint of human operator perception. In [4], the image processing for autonomous control in [2, 3] was improved

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by adding the target selection function. In [5], not only the autonomous control but also the manual operation was further improved by introducing the position measurement function via angle-pixel characteristics of the camera and visual supporting function for human operator to watch some useful items for manual operation. In [6], the generation of the template image for autonomous control was improved by the automatic template generation technique. Furthermore, in order to expand the working area, a mobile robot was also implemented. In [7], the reproducibility of the autonomous control was improved by taking account of the turning radius determination based on angle information of image. However, the system still has a problem that the image processing sometimes failed by the influence of lighting condition. In addition, the task considered in [2-7] was for the tip of robot arm to press a button, which was so simple and limited. Here, it is noted that, in [11], a prototype of a military robot for object tracking using PID controller and computer vision was developed. This system has a gun to shoot the enemy. However, it does not have an object grasping function as in this paper. Some related works on image processing and system integration for robots are explained in [5-7].

On the other hand, object grasping by using robot arm has been paid much attention for recent years [12-21]. In [12], a detection method to apply to the robotic grasping was proposed by using visual and tactile sensing based on deep network. In [13], a detection method for the robotic grasping under complicated background situation was considered by using structured edge and superpixel contrast. In [14], a stable and repeatable grasping technique for flat objects on hard surfaces was developed by using passive and epicyclic mechanisms. In [15], mechanical damage by robotic grasping for harvesting robots was comparatively studied. In [16], a method of deep belief neural network parameter determination was investigated to apply to robot object recognition and grasping. In [17], a scheme to compute optimal grasping and manipulation forces for dexterous robotic hands was considered by employing a quadratic optimization problem and an artificial neural network. In [18], a flexible manipulator inspired by octopus to apply to grasping various objects was developed. In [19], a grasp quality measure was proposed by considering some physical limits of robot hands. In [12-19], the works on the object grasping have mainly focused on the development of advanced grasping techniques under the condition that the grasping system was fixed on the working environment. In [20, 21], the mobile bin picking using an anthropomorphic service robot (Cosero) was investigated. Since the robot autonomously behaved based on object recognition and navigation, the human intention for the selection of a desired target was not considered. However, it is important that the mobile robot realizes the object grasping and the target selection based on the human intention simultaneously.

In this paper, control system for a mobile robot with object grasping arm is developed by introducing the concept of combining manual operation with visual servoing.

A brief organizational overview of this paper is as follows. In Section 2, the system configuration for a mobile robot with object grasping arm considered in this paper is explained. In Section 3, the control system to control the mobile robot with object grasping arm is introduced. In Section 4, experimental results to check the behavior of the proposed control system are shown. In Section 5, the discussion about the control system is provided. Finally, in Section 6, the conclusion of this paper is stated.

2. System Configuration.

The system configuration of control system for a mobile robot with object grasping arm is depicted in Figure 1.

The system consists of mobile robot, object grasping arm, USB camera, distance sensor, microcomputer and control PC. The USB camera and the object grasping arm are directly connected to the control PC. The mobile robot and the distance sensor are connected to

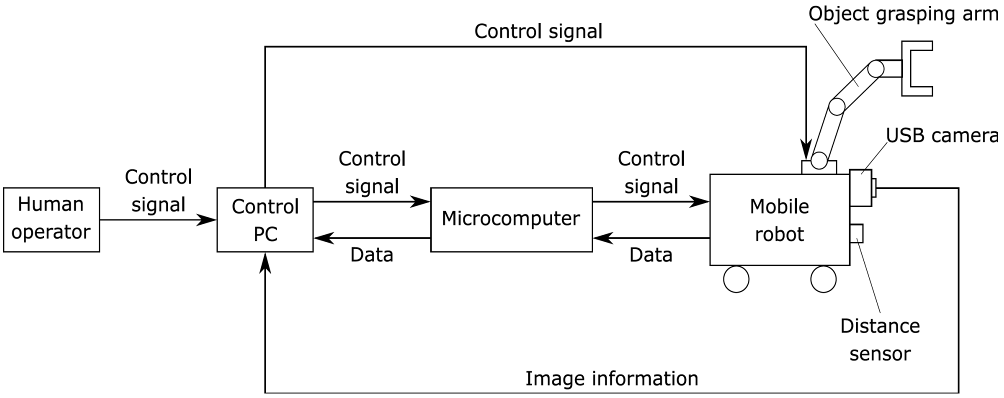


Figure 1. System configuration

the control PC through the microcomputer. The control PC can be operated by human operator. The mobile robot is controlled by specifying both the left and right wheel speeds. The object grasping arm is controlled by suitable control commands for the torque, position and velocity of its servomotors. Image information from the USB camera mounted on the mobile robot is used to determine the rotational speed of the mobile robot wheels and detect the target position.

3. Control System.

The control system is constructed to control both the mobile robot and the object grasping arm. The mobile robot is controlled by two methods: manual operation by human operator and autonomous control using visual servoing, where the visual servoing is performed based on the object recognition via image processing. The control for the object grasping arm is realized by the control of servomotors specified in advance.

3.1. Object recognition.

In order to recognize the target, template matching was used in the previous works [2-7]. However, in the previous works [2-7], it was not possible to accurately recognize the target due to the brightness changes of the room, and the recognition was sometimes failed. Therefore, in this paper, for target recognition we adopt two representations of HSV and RGB. To construct the image processing environment, OpenCV [9] is used.

The color of each pixel in camera image is represented by three components of HSV (hue, saturation and value) or RGB (red, green and blue).

Here, let us check the relationship between RGB and HSV [22]. Throughout this paper, images are assumed to be represented by 8-bit, i.e., $0 \leq R \leq 255$, $0 \leq G \leq 255$ and $0 \leq B \leq 255$. First, the components R, G and B are scaled as $0 \leq \tilde{R} \leq 1$, $0 \leq \tilde{G} \leq 1$ and $0 \leq \tilde{B} \leq 1$. Then, the components $\tilde{H}$, $\tilde{S}$ and $\tilde{V}$ are calculated by

$$\tilde{V} = \max\left(\tilde{R}, \tilde{G}, \tilde{B}\right)$$

$$\tilde{S} = \begin{cases} \left(\tilde{V} - \min\left(\tilde{R}, \tilde{G}, \tilde{B}\right)\right) \Big/ \tilde{V} & \text{if } \tilde{V} \neq 0 \\ 0 & \text{otherwise} \end{cases}$$

$$\tilde{H} = \begin{cases} 60\left(\tilde{G} - \tilde{B}\right) \Big/ \left(\tilde{V} - \min\left(\tilde{R}, \tilde{G}, \tilde{B}\right)\right) & \text{if } \tilde{V} = \tilde{R} \\ 120 + 60\left(\tilde{B} - \tilde{R}\right) \Big/ \left(\tilde{V} - \min\left(\tilde{R}, \tilde{G}, \tilde{B}\right)\right) & \text{if } \tilde{V} = \tilde{G} \\ 240 + 60\left(\tilde{R} - \tilde{G}\right) \Big/ \left(\tilde{V} - \min\left(\tilde{R}, \tilde{G}, \tilde{B}\right)\right) & \text{if } \tilde{V} = \tilde{B} \\ 0 & \text{if } \tilde{R} = \tilde{G} = \tilde{B}, \end{cases}$$

respectively, where if $\tilde{H} < 0$, then $\tilde{H}$ is replaced by $\tilde{H} + 360$. Since $0 \leq \tilde{V} \leq 1$, $0 \leq \tilde{S} \leq 1$ and $0 \leq \tilde{H} \leq 360$, the values are finally converted to the 8-bit representation: $0 \leq V \leq 255$, $0 \leq S \leq 255$ and $0 \leq H \leq 255$.

Thresholds for the binarization to assign the color of white to the target object in camera images are given so that the color of the target is successfully captured. From the logical product for three binarized components the target object is extracted.

As the target position in camera images with width W and height H (See Figure 2), the centroid (x_G, y_G) of the white-colored region corresponding to the target object is calculated by

$$(x_G, y_G) = \left(\frac{m_{1,0}}{m_{0,0}}, \frac{m_{0,1}}{m_{0,0}} \right), \tag{1}$$

where the image moment $m_{p,q}$ for the luminance $f(x, y)$ at (x, y) is defined by

$$m_{p,q} = \sum_{x=0}^{W-1} \sum_{y=0}^{H-1} x^p y^q f(x, y). \tag{2}$$

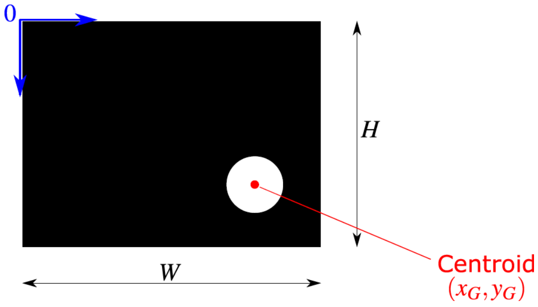


FIGURE 2. Position detection of target object

In this paper, the centroid (x_G, y_G) is used as the target position to determine the control command for the mobile robot, where the mobile robot is controlled so that the difference between the centroid x_G and the center of camera image becomes zero.

Furthermore, the horizontal distance between the mobile robot and the target object is detected by distance data acquired from the distance sensor. The detected distance is used to stop the movement of the mobile robot.

3.2. **Control of mobile robot.**

3.2.1. *Manual operation.* In the manual operation by human operator, the mobile robot is operated according to the inputs from keyboard. The correspondence of the inputs to the movement of the mobile robot is shown in Figure 3, where W, X, A, D, Q and E stand for forward, backward, leftward, rightward, left rotation and right rotation, respectively.

3.2.2. *Autonomous control.* The mobile robot is controlled by specifying the speeds $v_L(t)$ and $v_R(t)$ of the left and right wheels shown in Figure 4:

$$v_L(t) = \left\{ r(t) + \frac{D_c}{2} \right\} \omega(t) \tag{3}$$

$$v_R(t) = \left\{ r(t) - \frac{D_c}{2} \right\} \omega(t), \tag{4}$$

where D_c is the distance between wheels, $\omega(t)$ is the angular velocity and

$$r(t) = \frac{v}{\omega(t)} \tag{5}$$

is the turning radius. In this paper, the translational speed v is assumed to be constant. It follows from (3), (4) and (5) that the wheel speeds $v_L(t)$ and $v_R(t)$ can be determined by giving the angular velocity $\omega(t)$ appropriately.

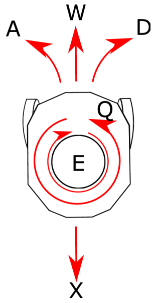


FIGURE 3. Movement of mobile robot for manual operation

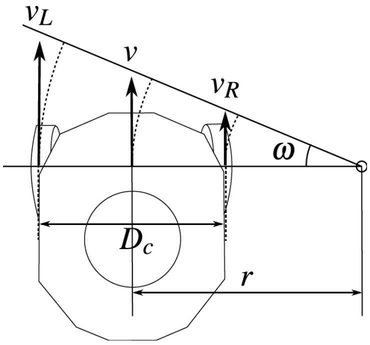


FIGURE 4. Wheel speeds of mobile robot

In this paper, a proportional integral (PI) control law

$$\omega(t) = K_P \left\{ e_x(t) + \frac{1}{T_I} \int_0^t e_x(\tau)\, d\tau \right\} \tag{6}$$

is proposed to assign the angular velocity $\omega(t)$, where $e_x(t)$ is the control error:

$$e_x(t) = \beta_x^{ref}(t) - \beta_x(t). \tag{7}$$

The angle $\beta_x(t)$ to specify the target object position shown in Figure 5 is detected by the object recognition using image information, where the angle $\beta_x(t)$ is derived from

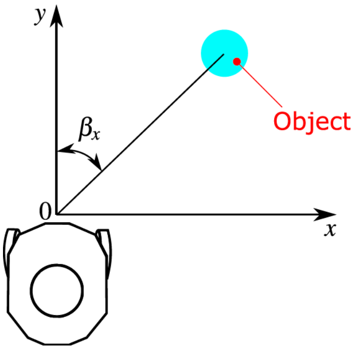


FIGURE 5. Definition of angle to specify target position

the angle-pixel characteristics [5] of USB camera. The reference angle $\beta_x^{ref}(t)$ is set as $\beta_x^{ref}(t) = 0$ so as for the USB camera image of the mobile robot to capture the target object in the center.

3.3. **Control of object grasping arm.** The object grasping arm is controlled by manipulating its servomotors for the end effector to grasp the target object successfully according to the commands specified in advance. The control commands are appropriately given corresponding to the required action. As the commands for object grasping arm, target angles are, for example, inputted to each servomotor.

4. Experimental Results.

In order to verify the usefulness of the control system proposed in this paper, experiments to grasp an object by a mobile robot were conducted.

The specifications of components in the control system used for experiments in this paper are listed in Table 1, where the size of images from USB camera was 640 × 480 [pixel], and as the lighting condition, illuminance of Room A and Room B was 597 [lx] and 293 [lx], respectively.

Table 1. Specifications of components in control system for experiments

Component	Specification
Mobile robot	Megarover (Vstone Co., Ltd.) with microcomputer (VS-WRC103), I/O board (VS-WRC007), 2 DC motors and 2 encoders
Object grasping arm	CRANE+ (RT Corporation) with 5 axes by 5 servomotors
Distance sensor	GP2Y0E03 (SHARP)
USB camera	C920r (Logicool)
Control PC	ProBook 430 G3 (HP)
Target object	Blue-colored ball

4.1. **Experimental results of color recognition.** Thresholds for the binarization to assign the color of white to the target object in camera images were chosen by performing some experiments. Indeed, lower and upper thresholds for components H, S and V were selected as $(80, 96)$, $(65, 220)$ and $(40, 240)$, respectively. On the other hand, lower and upper thresholds for components R, G and B were selected as $(0, 90)$, $(100, 255)$ and $(90, 255)$, respectively. These thresholds were determined to successfully capture the target object in both rooms explained later.

Extracted results in 2 rooms (Room A and Room B) of target object by RGB color recognition and HSV one are shown in Figure 6 and Figure 7, respectively, where the distance between the mobile robot and the target object was 0.15 [m]. In this paper, experiments in 2 rooms were conducted to verify the robustness of the proposed control system for lighting condition. In Figure 6 and Figure 7, the left image is original data and the right one is the extracted result.

Since the extracted results in Figure 6 and Figure 7 indicate that the HSV color recognition is suitable for the detection of target object, in the control experiments explained later, the HSV color recognition was adopted.

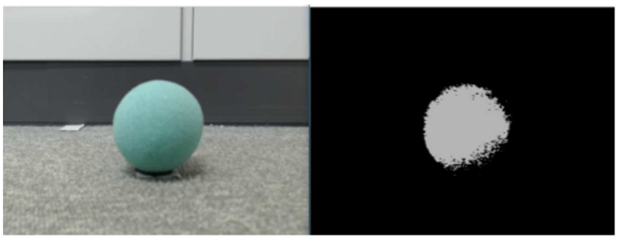
4.2. **Experimental results of control.** The procedure for control experiment is shown below.

1) The mobile robot is moved by manual operation from the initial position shown in Figure 8 to the position where the ball is captured by the USB camera.

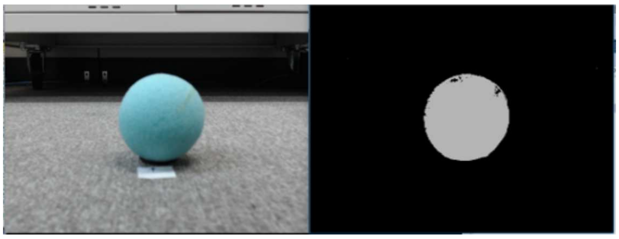
(a) A result of binarization in Room A via RGB

(b) A result of binarization in Room B via RGB

FIGURE 6. Results of extracted target object by RGB color recognition



(a) A result of binarization in Room A via HSV



(b) A result of binarization in Room B via HSV

FIGURE 7. Results of extracted target object by HSV color recognition

2) Then, the autonomous control for the mobile robot to approach the target object based on image processing starts, where the control scheme is changed from manual operation to autonomous control by clicking mouse on the target object in camera image.
3) The mobile robot stops when the distance between the mobile robot and the target object detected by the distance sensor becomes 0.01 [m].
4) The object grasping arm starts the action of grasping the target object according to the control command which is set in advance.

Here, the definition of success of this experiment is that the object grasping arm successfully captures the target object. Otherwise, the experiment is said to be failed.

In this paper, 20 experiments with different manual operations were performed in Room A and Room B. The parameters K_P and T_I in (6) were given by $K_P = -0.059$ [rad/(deg·s)] and $T_I = 50$ [s], respectively, where the parameter K_P was determined such that the

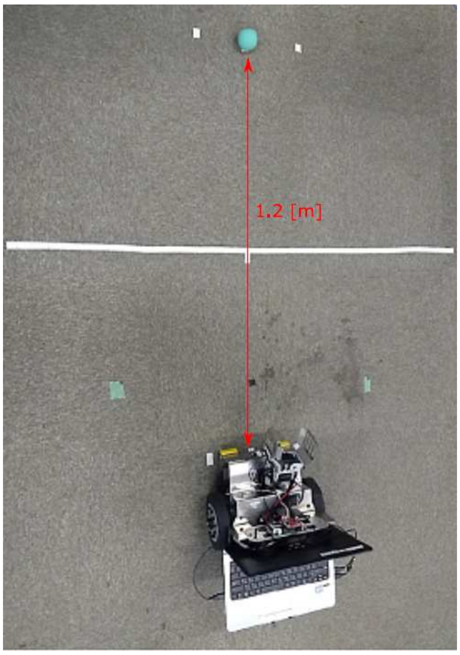
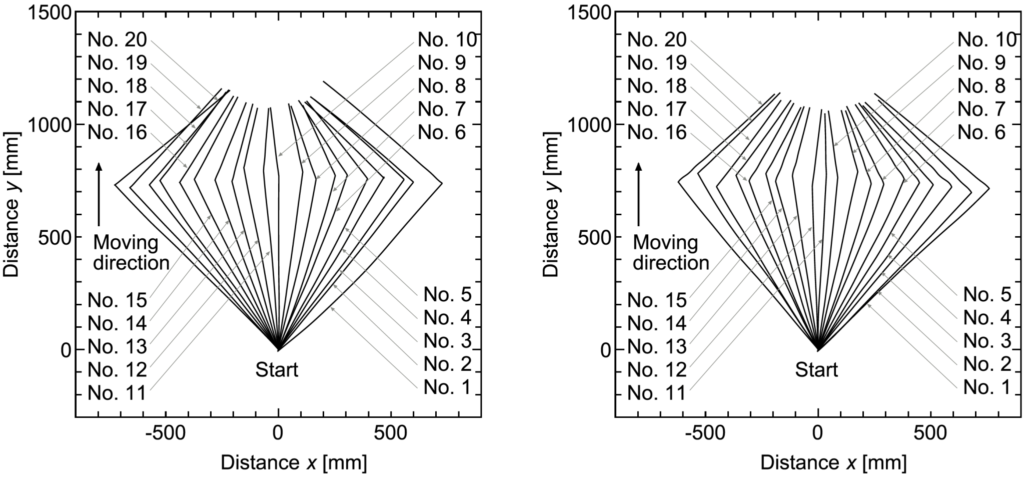


Figure 8. Initial position of experiments

Table 2. Experimental results

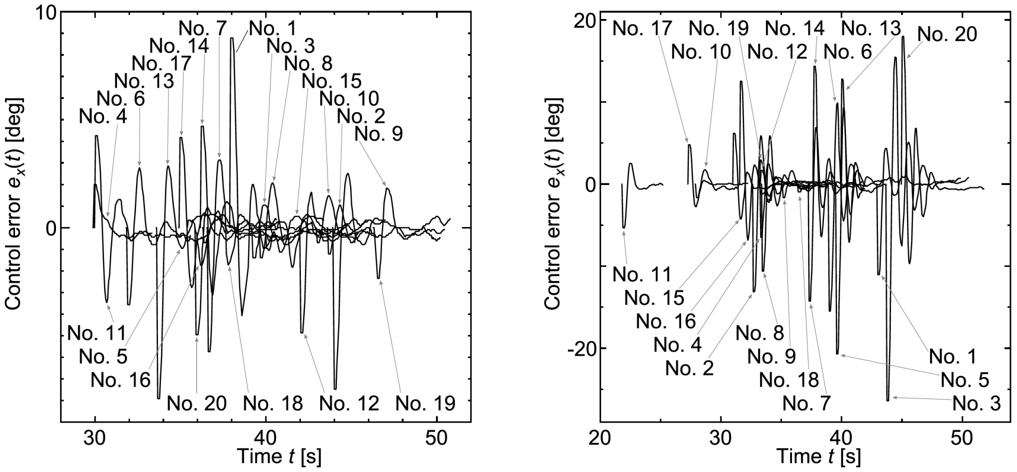
No.	Room A	Room B
1	○	○
2	○	○
3	○	○
4	○	○
5	○	○
6	○	○
7	○	○
8	○	○
9	○	○
10	○	○
11	○	○
12	○	○
13	○	○
14	○	○
15	○	○
16	○	○
17	○	○
18	○	○
19	○	○
20	○	○

mobile robot rotated right with the error $e_x = 30$ [pixel], the speed $v = 80$ [mm/s] and the turning radius $r = 500$ [mm]. Thus, the translational speed v was given by $v = 80$ [mm/s].



(a) Experimental results in Room A (b) Experimental results in Room B

Figure 9. Trajectories of mobile robot



(a) Experimental results in Room A (b) Experimental results in Room B

Figure 10. Control error $e_x(t)$

In Table 2, 20 experimental results in both Room A and Room B are listed, where the notation ○ indicates success of the experiment. This shows that the success rate of experiments by the control system in this paper was 100%.

Furthermore, the trajectories of the mobile robot for 20 experiments are shown in Figure 9, where the control method was switched at the point that the direction of trajectory changed drastically. In Figure 10, the control error $e_x(t)$ is depicted.

5. **Discussion.** In the control systems of previous works [6, 7], the mobile robot has the limitation on the movement from its ability. On the other hand, in this paper, the mobile robot Megarover has resolved this problem. Furthermore, although in previous works [2-7] only the action of pressing a button was executed, the control system in this paper can realize the action of grasping an object by improving not only the components as the hardware but also the image processing as the software.

In fact, although the recognition accuracy based on the RGB color recognition was not good, the HSV representation brings higher reproducibility and easy selection of thresholds. This may come from the property of the HSV representation which is strong against brightness changes.

In the previous works [6, 7], the horizontal distance between the mobile robot and the target object was detected from the area of the white region. Furthermore, the characteristics of the distance must be derived from the experiments in advance. On the other hand, in the experiments of this paper, the distance detection was directly carried out by using distance data from the distance sensor. This change of detection method may lead to the improvement of accuracy of experimental success since this strategy is not affected by lighting condition of the environment.

On the other hand, as the mobile robot, Roomba was used in the previous works [6, 7]. Since the mobile robot Roomba has some limitations on the movement performance, it could not be controlled accurately. To solve this problem, in this paper, the mobile robot was changed to another mobile one, Megarover. By using Megarover, the movement performance was improved.

As mentioned in Section 1, in [12-19], the works on the object grasping were made under the condition that the grasping system was fixed on the working environment. In [20, 21], the robot behaved autonomously without human intention for the selection of a desired target. However, in this paper, the control system for the mobile robot to realize both the object grasping and the target selection with the human intention was successfully constructed as shown in the last section.

Here, from Figure 9 and Figure 10 we can see that the successful results could be obtained for all experiments even if the movements of the mobile robot by manual operation were different. The different manual operation results also show the robustness of the proposed control system. Since the success rate of experimental results in the previous work [7] depended on the movements by manual operation, this fact implies that the reproducibility of successful action could be improved.

6. **Conclusion.** In this paper, a control system for a mobile robot with object grasping arm was developed based on the integration of manual operation with autonomous control. In the autonomous control, turning movement of the mobile robot was realized by image processing using HSV representation. On the other hand, to avoid the influence of the lighting condition, the distance between the mobile robot and a target object was detected by distance sensor without image processing. The experimental results using an actual mobile robot with object grasping arm clarified that object grasping task could be perfectly done by the proposed control system for various kinds of manual operations. Although the control system in this paper was developed under the ideal situation without any obstacles, the extension to the system considering some obstacles must be important as a potential future research direction.

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Author Biography

Yoshitaka Matsuda received his B.E., M.E. and Ph.D. degrees from Kyoto Institute of Technology in 2002, 2004 and 2007, respectively. He worked at Japan Mint from 2007 to 2010. He is currently an associate professor at the Institute of Ocean Energy, Saga University, where he was an assistant professor at the Department of Electrical and Electronic Engineering, Saga University from 2010 to 2020. His research interests include plant systems control and mechatronic systems control. He is a member of IEEE, the Institute of Systems, Control and Information Engineers, the Society of Instrument and Control Engineers and the Japan Society of Mechanical Engineers.

Yoshitaka Sato received his B.E. degree from Tokai University in 2018 and M.E. degree from Saga University in 2020. His research interests include control of mobile robot using image processing.

Takenao Sugi received his B.E., M.E. and Ph.D. degrees from Saga University in 1992, 1994 and 1999, respectively. Since 1995, he has been affiliated with Saga University, where he was a research associate at the Department of Electrical Engineering from 1995 to 2002, a lecturer from 2002 to 2004 and an associate professor from 2004 to 2021 at the Institute of Ocean Energy, Saga University. He has been a professor in the Department of Electrical and Electronic Engineering since 2021. His research interests include plant system control and biomedical control. He is a member of IEEE, the Society of Instrument and Control Engineers of Japan, the Japanese Society for Medical and Biological Engineering, Institute of Complex Medical Engineering, the Japanese Society of Sleep Research and the Japanese Society of Clinical Neurophysiology.

Satoru Goto received his B.E. and M.E. degrees in applied physics and Ph.D. degree from Osaka University in 1988, 1990 and 1995, respectively. Since 1990, he has been affiliated with the Faculty of Science and Engineering, Saga University, where he was a research associate at the Department of Electrical Engineering from 1995 to 1996, a lecturer from 1996 to 1998, an associate professor at the Department of Advanced Systems Control Engineering from 1998 to 2007 and he has been a professor since 2007. His research interests include control theory and its applications to real systems. He is a member of the Society of Instrument and Control Engineers of Japan, the Robotics Society of Japan, and the Institute of Systems, Control and Information of Japan, the Japan Society for Precision Engineering and IEEE.

Naruto Egashira received his Ph.D. degree from Saga University in 1999. He has been a teacher at Saga Prefectural Taku High School in 1986. Since 1992, he has been affiliated with the Department of Control and Information Systems Engineering, National Institute of Technology, Kurume College, where he was a research associate from 1992 to 1996, a lecturer from 1996 to 2000, an associate professor from 2000 to 2006 and he has been a professor from 2006. His research interests include measurement and control using network and mechatronic systems control. He is a member of the Society of Instrument and Control Engineers of Japan.