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# A Vision-Based Assistive Robotic Arm for People with Severe Disabilities

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**ABSTRACT**

This paper presents a vision-based assistive robotic arm for people with severe disabilities. This system is composed of a robotic arm, a microcontroller, its controller, and a vision-based unit. The main body of the robotic arm that can be contained in a briefcase is about 5 kg, including two 12-V lead acid rechargeable batteries. This robotic arm is also capable of being mounted on a wheelchair. To obtain position coordinates of an object, image processing technique with a single Web camera was used. Position errors in the order of few millimeters were observed in the experiment. Experimental results of drinking water task with able-bodied subjects showed that they could smoothly carry out the tasks. The present results suggested that the resultant position errors were acceptable for drinking water command.

**Keywords:** Assistive system, Robotic arm, Image processing, Web camera, People with severe disabilities.

# 1 INTRODUCTION

This paper deals with an assistive robotic arm system for people with severe disabilities. By the cause of stroke or spinal cord injury, there are many people who have paralyzed extremities and who need someone's help. Some of them have strong-minded to be independent of others and to live their own lives. We also live longer than we used to, in step with the advances in medical technology. Many of caregivers are getting older, and it is demanding for them to take good care of people with disabilities due to their advanced ages. It is of significant importance to support lives of elderly persons as one of common issues in developed countries.

Some robots to assist the disabled have been developed [1, 2]. For example, there are Manus Manipulator [3], Raptor wheelchair robot [4], manipulator mounted on wheelchair [5], Handy 1 [6], and My Spoon [7, 8]. People with disabilities using these systems are able to roughly manipulate an object. It is however difficult for the users with the Manus Manipulator and the wheelchair mounted assistive robots to have something to drink and eat. The Handy 1 and My

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Spoon require users to prepare foods to be cut and to use the dedicated tray for meals. In addition, they can hardly dine out with these systems.

In order to explore the optimum solution for the above-mentioned problems, we built a prototype of assistive robotic arm for people with severe disabilities [9, 10], such as stroke, spinal cord injury, and muscular dystrophy (MD). Our final goal is to realize and to provide a low-cost and useful assistive robotic arm system to them. The fundamental concept of our assistive robotic arm system is portability. The robotic arm's main body is small enough to put in a laptop computer's briefcase. The feature enables the user to go out to eat at a restaurant with his/her family, which leads to more desirable improvement of his/her quality of life (QOL). In our previous robotic arm system [10], there were some limitations that its motion and the positions of a plastic bottle, plates, and utensils had to be predetermined, because the system was an open-loop system and did not have any feedback device. We applied a vision-based control method with a single Web camera to the robotic arm system in this paper. To evaluate its performance, position coordinates calculations of a plastic bottle were experimentally carried out. Drinking water tasks with three able-bodied subjects were also performed.

This paper is organized as follows. Section 2 summarizes the proposed assistive robotic arm. Experiments are described in detail in Section 3. Sections 4 and 5 provide experimental results about calculations of position coordinates of the plastic bottle and drinking water tasks, and discussions. The final section concludes the paper.

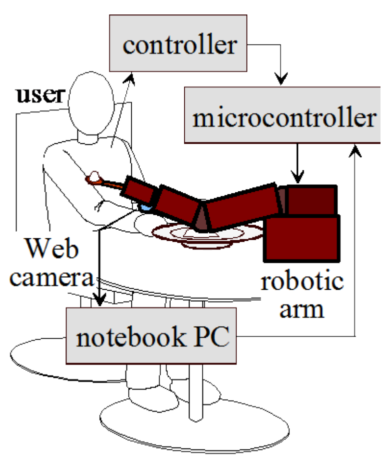



**Figure 1: System configuration of assistive robotic arm. The Web camera and notebook PC are used to calculate the position coordinates of an object, which is described in Section 2.2.**

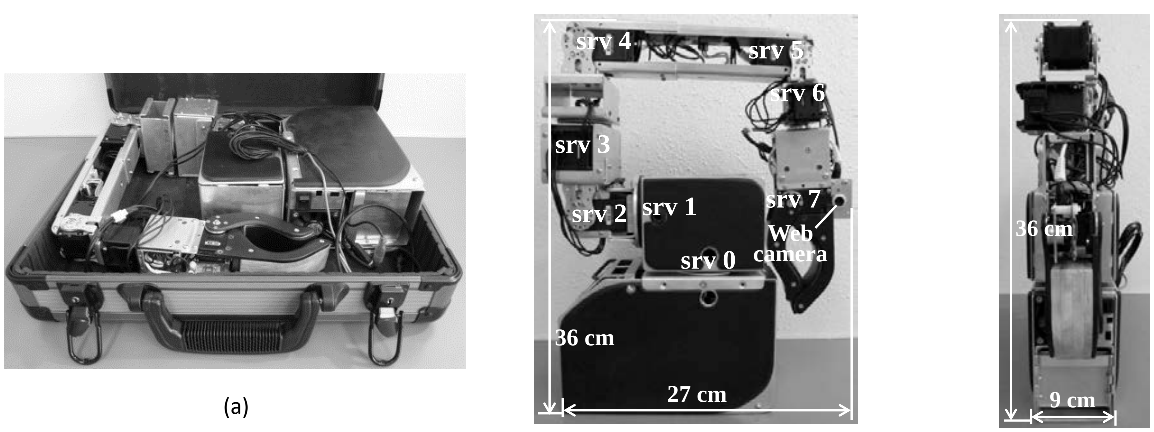
# 2 SYSTEM CONFIGURATION

## 2.1 System Overview

A system configuration of the proposed assistive robotic arm is illustrated in Figure 1. This system is composed of a robotic arm, a microcontroller, its controller, a Web camera, and a notebook computer. The microcontroller AT91SAM7S256 (Atmel Corporation) has a 32-bit ARM7TDMI RISC processor, which is low-power, small, cost-effective, and good real-time interrupt response. It is embedded to the system.

Figure 2 shows the prototype robotic arm. As can be seen in Figure 2 (a), the robotic arm's main body is totally contained in a laptop briefcase without removing any parts of the robotic arm shown in Figures 2 (b) and (c). The robotic arm also can be mounted on a wheelchair. One of the fundamental concepts for the robotic arm system is portability. This allows user to enjoy not only having dinner with his/her companions in his/her house but also eating out with them. The robotic arm system can be utilized when the user goes on a trip, which enables him/her to try some local dishes at restaurant as much as he/she wishes.

Some of the important technical specifications of the assistive robotic arm are summarized in Table 1. Except for a gripper, the robotic arm has seven servos, which are electromechanical devices in which electrical inputs determine the position of the armature of the motors. These servos are controlled by the microcontroller. The gripper (also called the end effector) is detachable. Its opening and grasping any objects are controlled by a servo (srv 7) which is attached to the wrist portion. The Web camera is fixed to the wrist part of the assistive robotic arm (see Figure 2 (b)). To reduce the weight of the end effector of the robotic arm, some lightweight materials, such as carbon plate, balsa wood, and low foamable vinyl chloride, were used [see Table 1]. We installed an emergency stop switch for emergency purposes. Turning this switch on allows users to immediately shut down the robotic arm system.




(a) (b) (c)

**Figure 2: Assistive robotic arm (a) when in a laptop briefcase, (b) its side and (c) rear views. Symbol "srv" in the figure stands for servo.**

**Table 1: Summary specification of proposed assistive robotic arm**

| | Specification |
|---|---|
| **Size when folded in a briefcase** | 36 x 27 x 9 cm |
| **Maximum working area in radius** | 71 cm |
| **Weight** | About 5 kg, including two batteries |
| **Microcontroller** | AT91SAM7S256, Atmel |
| **Battery** | Two 12-V lead-acid rechargeable batteries |
| **Degree of freedom** | 7 |
| **Web camera** | 0.3 megapixel |
| **Materials** | Aluminum mainly, low foamable vinyl chloride, balsa wood, carbon plate |

A control program written in the form of C language was developed with the gcc compiler. The program was then written into a flash memory of the microprocessor which was connected to the notebook PC using a USB cable.

## 2.2 Calculations of Joint Angles and Plastic Bottle Coordinates

In order to simplify the calculation for controlling the end effector of the robotic arm, its 3-link model in a Cartesian coordinate system in two dimensions is defined in this paper. We have an assumption that the assistive robotic arm is fixed on the user's right side. Figure 3 shows the robotic arm (top-down view) and its simplified 3-link model in two-dimensional Cartesian coordinate system with origin *O* and axis lines *x* and *y*. It is also assumed that the perpendicular line onto the origin *O* (*z* axis shown in Figure 5) coincides with the rotation axis of the servo srv 0, and the angles of servos srv 1, 2, 3, and 6 are fixed during the final stage of reaching an object. The fixation of these angles means that the end effector is moving parallel with the table on which the robotic arm is installed during the final approach to it. $l_1$, $l_2$, and $l_3$ are the link lengths.

A position vector of the tip point $P_3$ is the center of grasping position of the gripper. When the end effector coordinates $x_3$ and $y_3$ are detected, the angles $\theta_1$, $\theta_2$, and $\theta_3$ can be obtained by using inverse kinematics [11]. From Figure 3 (b), the point $P_3$ coordinates are given by

$$x_3 = x_2 + l_3 \sin\theta_{end} \tag{1}$$

and

$$y_3 = y_2 + l_3 \cos\theta_{end} , \tag{2}$$

where $\theta_{end}$ is the angle between $y$ axis and the link $l_3$, which is given by

$$\theta_{end} = \theta_{12} + \theta_{23} + \theta_3 . \tag{3}$$

The angle between $y$ axis and the position vector $P_2$, $\theta_{12}$, is also expressed as

$$\theta_{12} = \tan^{-1}(x_2 / y_2)\,. \tag{4}$$

By using the law of cosines, the internal angles $\theta_a$, $\theta_b$, and $\theta_{23}$ in the triangle $OP_1P_2$ are given by

$$\theta_a = \theta_{12} - \theta_1 = \cos^{-1}\left(\frac{l_1^{\,2} + l_{O2}^{\,2} - l_2^{\,2}}{2 l_1 l_{O2}}\right), \tag{5}$$

$$\theta_b = \pi - \theta_2 = \cos^{-1}\left(\frac{l_1^{\,2} + l_2^{\,2} - l_{O2}^{\,2}}{2 l_1 l_2}\right), \tag{6}$$

and

$$\theta_{23} = \pi - (\theta_a + \theta_b)\,, \tag{7}$$

where $l_{O2}$ is the length of the position vector $P_2$, which is expressed as

$$l_{O2} = \sqrt{x_2^{\,2} + y_2^{\,2}}\,. \tag{8}$$

We finally have the angles $\theta_1$, $\theta_2$, and $\theta_3$:

$$\theta_1 = \theta_{12} - \theta_a\,, \tag{9}$$

$$\theta_2 = \pi - \theta_b\,, \tag{10}$$

and

$$\theta_3 = \theta_{end} - \theta_1 - \theta_2\,. \tag{11}$$

These calculations are done in the microcontroller. Detecting plastic bottle's mouth coordinates by using the image processing techniques, the joint angles $\theta_1$, $\theta_2$, and $\theta_3$ are determined in this manner.

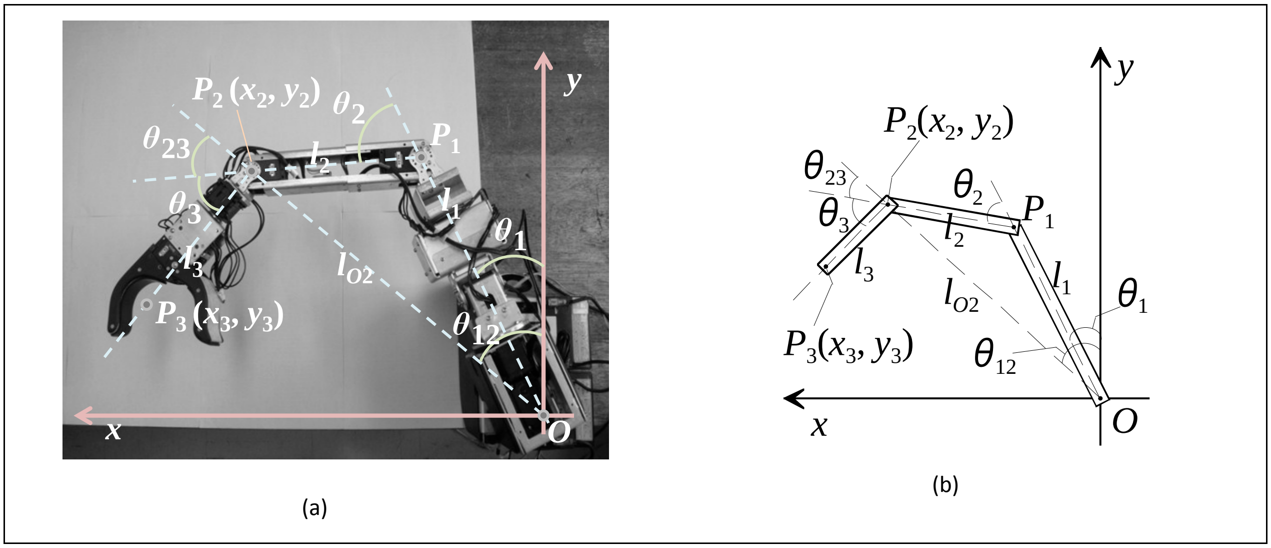



**Figure 3: Assistive robotic arm model for the calculation of joint angles in two-dimensional Cartesian coordinate system. (a) Its top-down view and (b) simplified 3-link model.**

A flowchart of the image processing to calculate the position coordinates of the plastic bottle is illustrated in Figure 4. First, we calibrate the Web camera set up in the wrist part of the robotic arm, and register the template model obtained from an image of a plastic bottle's mouth. Reading an image, we transform the RGB image into a gray scale image, enhance contrast of the image, and filter the enhanced image using Median filter [12] in the preprocessing stage. Secondly, the template matching with the registered template model is performed. When a matched area in the preprocessed image is found, calculations of the area and the center coordinates of the plastic bottle's mouth are carried out. We then calculate the height $z_h$ of the plastic bottle using the equation:

$$z_h = 0.211\ A_m + 8.576, \tag{12}$$

where $A_m$ is the area of the plastic bottle's mouth. This calculation is conducted in the notebook PC which is connected to the Web camera. We set a half of the calculated height coordinate as the *z*-coordinate on the final stage of reaching the plastic bottle.

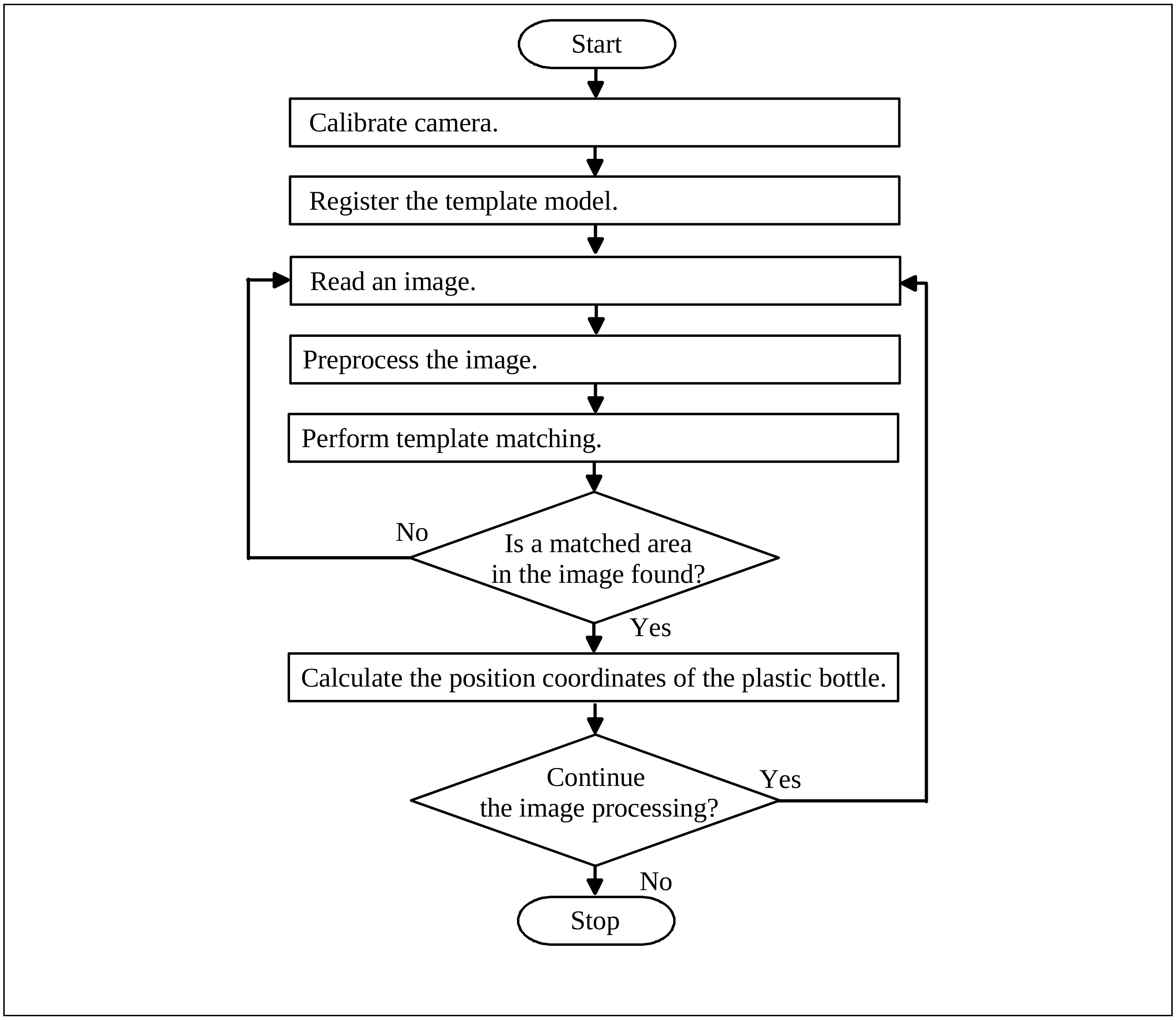



**Figure 4: Flowchart of image processing to calculate the position coordinates of the plastic bottle.**

# 3 METHOD

The experimental setup is shown in Figure 5. The robotic arm was placed at the right side. The distance between the camera and the surface on the table is set to approximately 50 cm, capturing an object on the table (Figure 5 (b)). The resolution of images obtained by the Web camera is fixed 352×288 pixels. A white paper is put on the table. Grid lines spaced at 5 cm intervals vertically and horizontally are drawn on it. The grid size is 15 cm long and 10 cm wide. A 500-ml plastic bottle with a black square-shaped coaster was put on 12 intersection points of the two grid lines, and using the image processing technique the mouth of the plastic bottle at each point was detected. The position coordinates of the plastic bottle were then calculated as shown in Figure 4. The height of the plastic bottle is 215 mm. The thickness of the coaster which is placed under it is 3 mm.

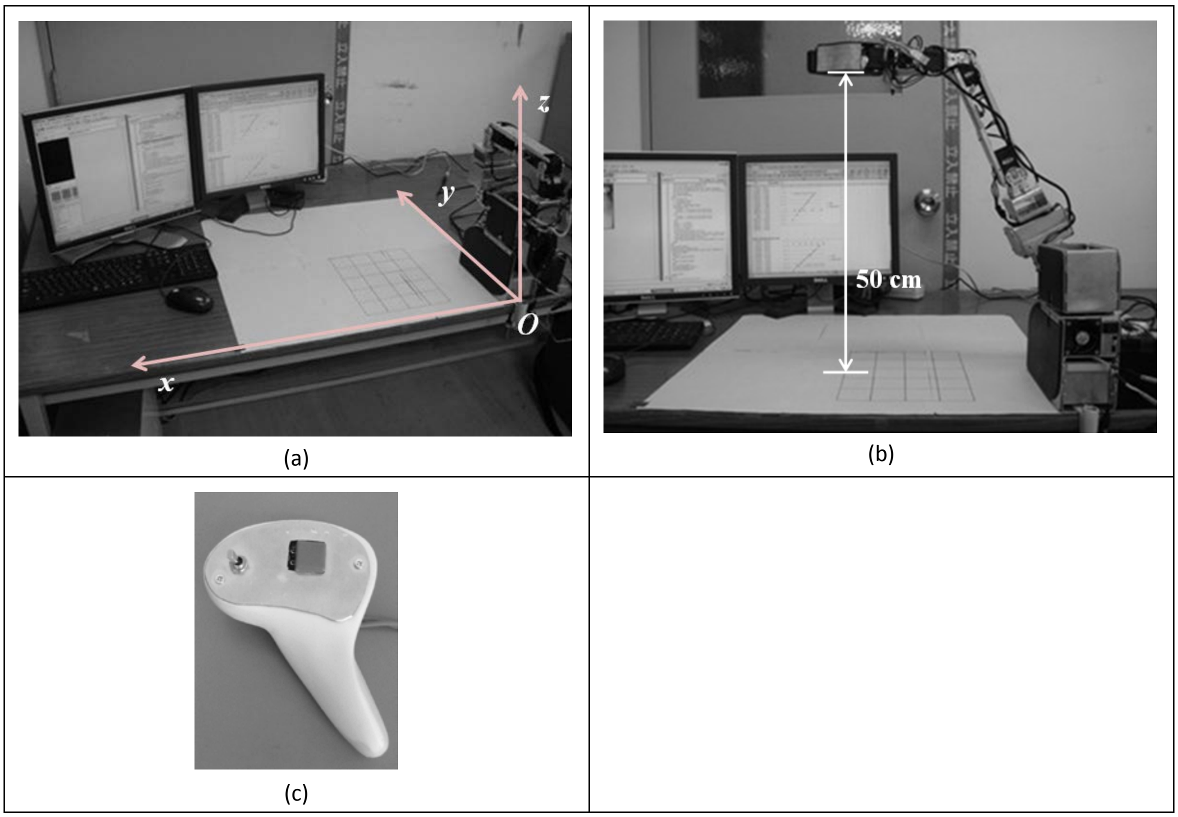



**Figure 5: (a) Experimental setup and three-dimensional Cartesian coordinate system, with origin *O* and axis lines *x*, *y*, and *z*. (b) Posture of the robotic arm when an object on the table is capture. (c) Controller used in the experiments.**

A drinking water task was carried out next. Experimental setup is the same as shown in Figure 5. Three able-bodied subjects (two males and a female) participated in the experiments. Subjects' age ranged from 22 to 45 years. We obtained informed consents from them. The robotic arm was also placed at subject's right side. Each subject was seated on a chair in front of the table. To issue a command to the robotic arm in the experiments, we made a controller for the subject as shown in Figure 5 (c). The left toggle switch is the emergency stop switch as described in Section 2.1. The right button is a push button for providing the assistive robotic arm with control commands. The experimental subjects were asked to drink water with the assistive robotic arm. The water was in a 500-ml plastic bottle which was commercially available. The experiments were recorded by a digital video camera.

# 4 RESULTS

Figure 6 shows examples of the calculated position coordinates of the plastic bottle. The position coordinates on the table where the plastic bottle was placed are indicated in the figure caption, while those of the plastic bottle's mouth obtained by the calculation are shown in the processed images. It was able to detect the plastic bottle's mouth from the images obtained by the Web camera. It could be seen that the position coordinates calculations of the plastic bottle's mouth were properly performed using our image processing method.

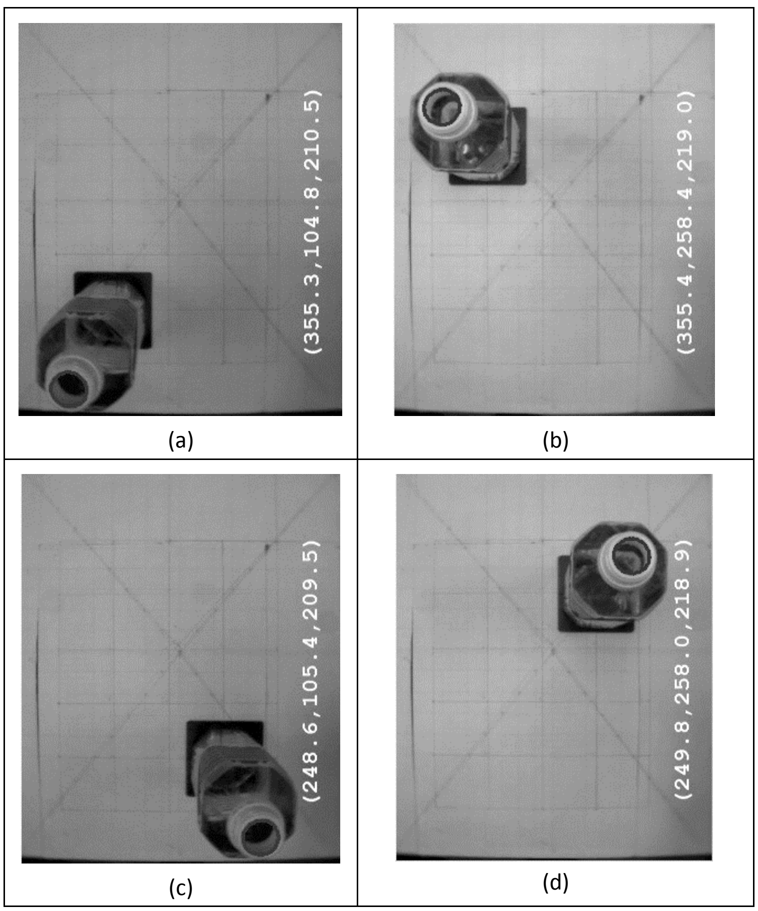



**Figure 6: Example results of the processed image with the calculated position coordinates of the plastic bottle's mouth. Its coordinates on the table where it was placed are (a) (350, 100, 0), (b) (350, 250, 0), (c) (250, 100, 0), and (d) (250, 250, 0), respectively. Numerical values in each image mean the calculated position coordinates where the plastic bottle's mouth was. The height of the plastic bottle with the coaster is 218 mm.**

Figure 7 represents example result of drinking water task captured from the video data. The elapsed time on each image is indicated in the figure caption. The subject A is drinking water in 19 s (see Figure 7 (d)). The other subjects could also manipulate the assistive robotic arm without any difficulties. It was clear from the experimental results that the subjects could appropriately drink water using the assistive robotic arm system.

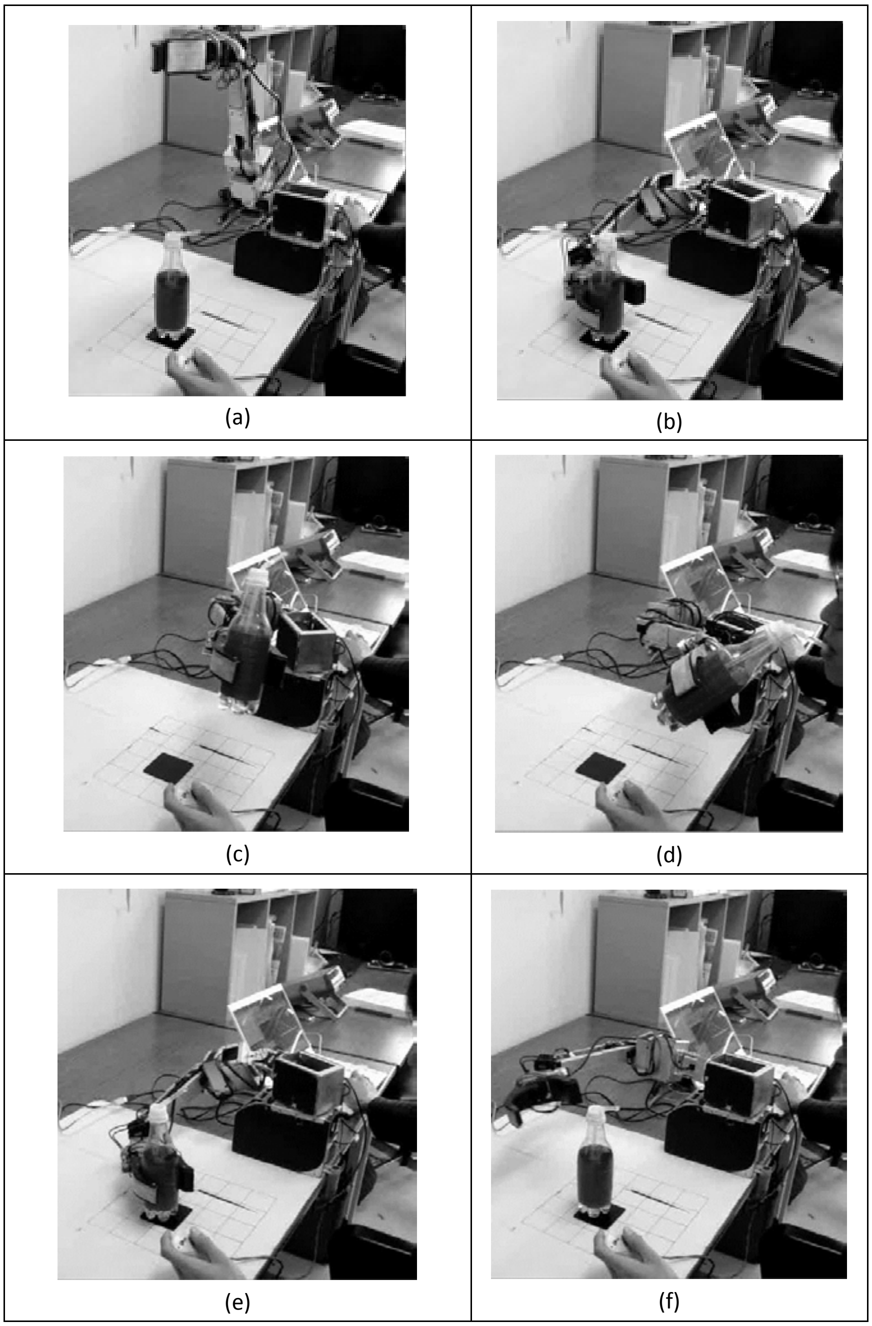



**Figure 7: Example of drinking water task performed by the subject A. The elapsed times of the experiment are (a) 0 s, (b) 7 s, (c) 15 s, (d) 19 s, (e) 33 s, (f) 37 s, respectively. These are captured from the video data.**

# 5 DISCUSSIONS

Table 2 lists the averaged errors (means and standard deviations; SDs) in position coordinates on each axis. It was seen from the processed images (Figure 6 and Table 2) that the plastic bottle's mouth at each point was appropriately detected, and that its position coordinates with the errors of few millimeters were obtained. The experimental results of drinking water tasks showed that the able-bodied subjects could grasp the plastic bottle and drink water from it by manipulating the vision-based assistive robotic arm. The time to drink water can be determined by each subject. Hence, it was found from the experimental results that our system allows users to drink water at their paces. In general, the number of drinking water a day is more often than that of eating meals. All the subjects made no error in operation during the drinking water task. It is suggested from the experimental results that the estimated plastic bottle's height coordinate using the proposed image processing method would be acceptable for grasping it. We have developed the controllers for assistive devices, e.g., head-controlled input device [13], eye-controlled input device [14], and single finger controlled user interface [15]. Connecting the assistive robotic arm with each device, preliminary experiments were done. The results showed that these controllers are applicable to control the assistive robotic arm.

It is possible effectively and efficiently to perform image processing with a typical microcontroller-based board such as a BeagleBone Black, or a Raspberry Pi in recent years. Substituting a microcontroller-based board for the notebook computer, which is our ongoing study, will lead to less power and more realistic assistive robotic arm system. A feeding assistance with assistive robotics is the most desired assistance for people with disabilities [1]. We could not complete a meal using our previous robotic arm system [10], because any foods on the table were not searched during the meal. An optimum control for eating task with the assistive robotic arm system should be needed for our future work. In order to deal with this, we need further considerations of both position coordinates calculations of any foods and how to reach to them to pick up. The proposed vision-based method in this paper would be applicable to the former coordinate calculations.

**Table 2: Averaged errors in position coordinates on each axis**

| | ***x*-axis [mm]** | ***y*-axis [mm]** | ***z*-axis [mm]** |
|---|---|---|---|
| **Mean** | 2.2 | 6.2 | -1.3 |
| **SD** | 2.9 | 1.3 | 3.9 |

SD: standard deviation

# 6 CONCLUSION AND FUTURE WORK

This paper described the demonstration of the assistive robotic arm. We built the robotic arm that could firmly grasp and hold up the plastic bottle of 500 ml. It was found that the plastic bottle's position coordinates with the acceptable errors can be obtained using the vision-based assistive robotic arm system. Further experiment with people with disabilities will be needed for the future work.

# ACKNOWLEDGMENT

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