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Development of Outdoor Service Robots

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Abstract: The outdoor service robots which we call OSR-01 and OSR-02 are presently under development intended for cleaning up urban areas by means of collecting discarded trash such as plastic bottles, cans, plastic bags and so on. In this paper, we mainly describe the architecture of OSR-02 which consists of hardware such as sensors, a manipulator, crawler structure, etc. for searching and picking up trash. After describing the systems, we show the result of open experiments in which OSR-02 collected plastic bottles in the special zone for robot research and development in Kitakyushu-city.

Keywords: outdoor service robot, separated collection, laser rangefinder, camera.

1. INTRODUCTION

Since November 28th of 2003, the Japanese government has designated the Fukuoka Prefecture, Fukuoka-city, and Kitakyushu-city as the one of the special zones for robot research and development. There researchers are allowed to operate their robots in public areas by applying for police permission. Thus, for example, in shopping areas in the city, we can take advantages of executing realistic experiments of outdoor service robots for cleaning up streets, welcoming customers, guiding them to a certain place, providing information about the shopping area, and so on. Under such circumstances, we have started developing the outdoor service robots called OSR-01 and OSR-02 intended for cleaning up shopping streets by means of the separated collection of discarded trash, such as plastic, glass, and steel, etc. on shopping streets. The OSRs are designed to search for trash while navigating a designated route in the shopping area, and to collect it by means of the manipulators. So far, several type robots for the cleaning work have been developed, however, they only vacuum on the specified route. On the other hand, since the developed robots aims to recognize the object in the shopping street etc. with person's traffic and to collect them with the manipulator, the technology that composes the robot and the algorithm of operation are greatly different. Although many operations have been programmed for the above task, we, in this paper, mainly show the sensor system and the manipulation system of OSR-02 for trash detection and distance measurement of the target after giving a briefing about the hardware of the robot.

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2. STRUCTURE

2.1 OSR-01

The specification of OSR-01 is shown in Table 1 and Fig. 1 (see [1]-[3] for detail). This robot is first prototype robot, and the kind of the sensor, the number of arms, and the run system, etc. are different from OSR-02 described as follows. From the experiments that used this robot, around the entrance of the arcade where strength of ambient light was greatly different and on the floor with the value of brightness and hue near that of trash, the problem that trash was not able to be recognized was clarified. Moreover, it turned out that running in the outdoors by OSR-01 equipped with the silicon tire was difficult. Therefore, OSR-02 was developed that aimed at the solution of these problems.

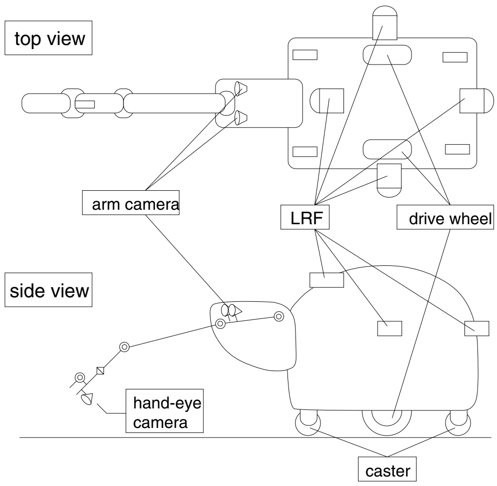
2.2 OSR-02

OSR-02 (Fig.2) has two manipulators and crawlers. The length of the manipulators is 850[mm] and they have

Table 1 Specification of OSR-01.

D.O.F.	manipulator	5
	hand	1
	drive wheel	2
dimension	height	600[mm]
	width	500[mm]
	depth	600[mm]
	manipulator length	750[mm]
weight	45[kg]	
running speed	1.8 [km/h]	
sensor	LRF	4
	color CCD camera	3

(a)



(b)

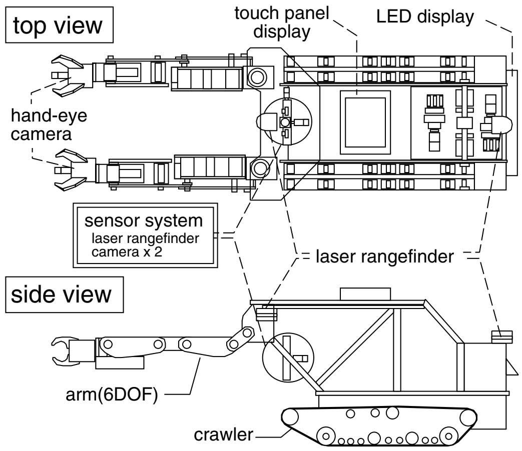
Fig. 1 Outdoor service robot OSR-01; (a) entire robot; (b) structure.

five degrees of freedom and a hand. The specification of OSR-02 is shown in Table 2. Moreover, five computers for control of the crawler, the manipulators, and the sensor system are installed in OSR-02, and they communicate via ethernet. Furthermore, in order to recognize the surrounding environment, and not to harm surrounding persons, several sensors have been installed in the robot.

Table 2 Specification of OSR-02.

D.O.F.	manipulator	5 (x2)
	hand	1 (x2)
	drive wheel	2
dimension	height	600[mm]
	width	500[mm]
	depth	800[mm]
	manipulator length	850[mm]
weight	90[kg]	
running speed	2.0 [km/h]	
sensor	LRF	3
	color CCD camera	4
	force sensor (hand)	2
	magnetic sensor (hand)	2

(a)



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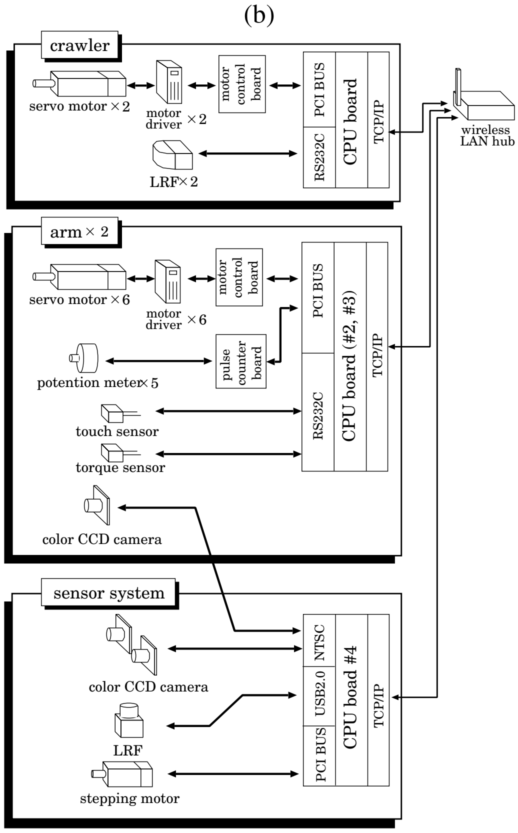


(c)

Fig. 2 Outdoor service robot OSR-02; (a) entire robot; (b) structure; (c) electric architecture.

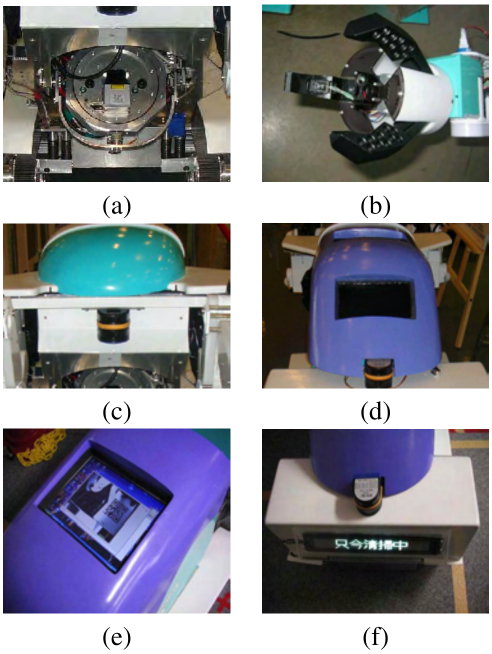


Fig. 3 Equipment of OSR-02; (a) sensor system; (b) hand with hand-eye camera, force sensor and magnetic sensor; (c) front LRF; (d) back monitor and back LRF; (e) laptop PC with touch panel; (f) publicity LED panel.

2.3 Equipment

The main equipment of OSR-02 is shown in Fig. 3. Fig. 3(a) shows the sensor system with three degrees of freedom, two CCD camera, and a LRF (Laser RangeFinder), and then the detection of trash and the inspection of running route are done by this device. Fig. 3(b) shows the hand of the arm, a CCD camera is installed in the center position and the image from it are used for the hand-eye system for grasping trash. Moreover, the magnetic sensor and the strain gage with a high resolution have been installed into the fingernail of the right and the left end effector (Fig. 4). The separated collection of the holding object can be done with these sensors, and it is possible to prevent the damage of the hand by controlling of the holding power. Fig. 3(c), (d) are LRFs for the obstacle detection of back and front of the robot, and each LRF can measure the range of 180 [deg] in surroundings by 10 [Hz]. The results of the image processing in the robot can be displayed on the back monitor shown in Fig. 3(d). It is possible to operate OSR-02 by using the laptop PC with touch panel (Fig. 3(e)) via wireless LAN, and this PC can be detached. The publicity LED panel (3(f)) displays the display of the content of the job of the robot and the advertisement of the shopping street.

2.4 Sensor system

The structure of the sensor system developed for OSR-02 and an example of result of the object detection are shown in Fig. 5. The sensor system can detect the object by the eigen space method [4], tracking by CAMSHIFT algorithm [5], measure distance by LRF and estimate the

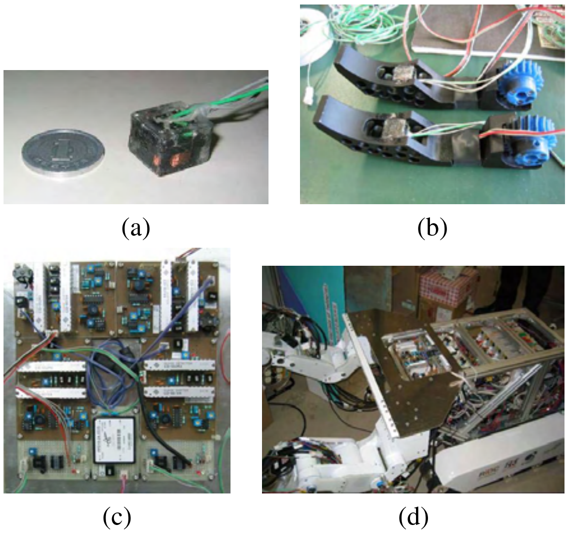


Fig. 4 Magnetic sensor for trash separation; (a) sensor; (b) hand with magnetic sensor; (c) sensor circuit; (d) the circuit is built into the robot.

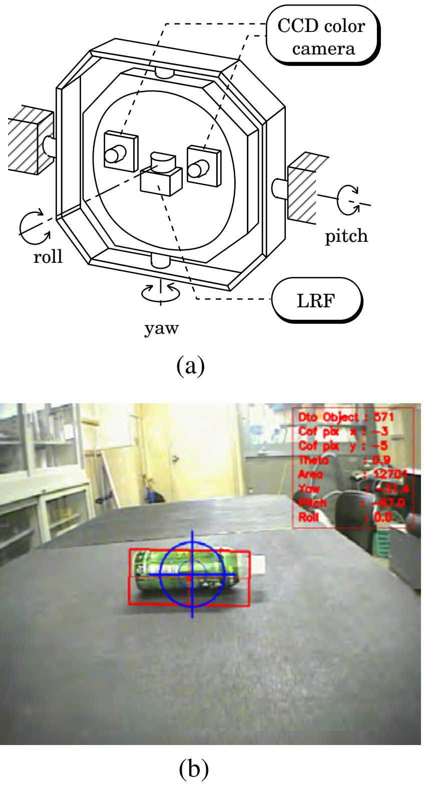


Fig. 5 Sensor system of OSR-02; (a) structure; (b) example of the camera image processing.

posture of the object (see [2] for detail of the object detection and the tracking algorithms).

2.5 Running control system

The control system for OSR-02 to approach the target object was constructed as follows (Fig. 6) [1], [3]. When the center of the object on the left camera image plane is $(x_d(t), y_d(t))$ at time t, the yawing angle $\theta(t)$ and the pitching angle $\phi(t)$ of the sensor system are controlled to turn to the front of the target object as follows,

$$\begin{bmatrix} \dot{\theta} \\ \dot{\phi} \end{bmatrix} = \begin{bmatrix} -k_{01} & 0 \\ 0 & 0 \end{bmatrix} \begin{bmatrix} \theta \\ \phi \end{bmatrix} + \begin{bmatrix} -k_{02} & 0 \\ 0 & k_{12} \end{bmatrix} \begin{bmatrix} x_d \\ y_d \end{bmatrix},$$

where $k_{01},\ k_{02},\ k_{12} > 0$ are gain coefficients and the bias between the rotation center of the sensor system and the optical center of the cameras is disregarded. Moreover, until the robot approaches a constant distance from the target object, the input angular velocity $\boldsymbol{w} \triangleq (w_l,\ w_r)^T$ is controlled as follows,

$$\boldsymbol{w} = \boldsymbol{R}_g \boldsymbol{v}, \tag{1}$$

where,

$$\boldsymbol{R}_g = \frac{1}{r_w} \begin{bmatrix} 1 & l \\ 1 & -l \end{bmatrix},\ \boldsymbol{v} = \begin{bmatrix} v_g \\ w_g \end{bmatrix}, \tag{2}$$

r_w is the radius of drive wheel in the crawler, and l is distance between the drive wheel and the center of rotation of the robot. Moreover v_g and w_g are the velocity and the angular velocity of the center of rotation of the robot, respectively. The velocity input in the robot coordinate system toward the target position is decided as follows,

$$\boldsymbol{v} = \boldsymbol{K} \left({}^r\boldsymbol{p} - \boldsymbol{m} \right), \tag{3}$$

where, ${}^r\boldsymbol{p} \triangleq ({}^rp_x,\ {}^rp_z)^T$ is the vector from the center of rotation of the robot to the center of the target object in the left camera image plane, and $\boldsymbol{m} \triangleq (0,\ m)^T$ is the vector represented by using the distance m from the center of the sensor system to the center of rotation of the robot. Moreover, $\boldsymbol{K}$ is represented as follows,

$$\boldsymbol{K} = \begin{bmatrix} k_r & 0 \\ 0 & k_\theta \end{bmatrix}, \tag{4}$$

where, k_r is the gain coefficient about the distance from the target object and k_θ is the gain coefficient about the yawing angle θ of the sensor system. The values of k_r and k_θ are adjusted according to the situation of the road. Therefore, the velocity of each wheel are determined by Eqn. (1) and Eqn. (3) as follows,

$$\boldsymbol{w} = \boldsymbol{R}_g \boldsymbol{K} \left({}^r\boldsymbol{p} - \boldsymbol{m} \right), \tag{5}$$

where the value of $\boldsymbol{w}$ does not exceed the maximum velocity set beforehand.

2.6 Object measurement by hand-eye system

The robot raises the arm above the target object and takes initial posture for the holding of the target object after approaching to a constant distance (cf. Fig. 10(b)). When the manipulator is in initial posture for the object holding, the robot views the target object by the hand-eye camera and measures the holding position and the posture of the object. The relation between hand-eye camera and the target object is shown in Fig. 7(a). The hand-eye image coordinate system and the hand coordinate system are represented as $\Sigma_i = \{{}^ix, {}^iy\}$ and $\Sigma_h = \{{}^hx, {}^hy, {}^hz\}$, respectively. For identifying the area of the target region in the hand-eye image to hold the target, the hue value obtained in a prior operation sequence is used. Namely, the area with the specific hue value tracked in a prior sequence is searched in the hand-eye camera image, and

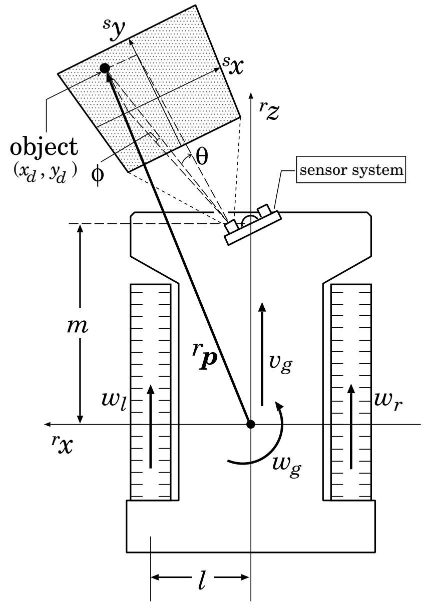


Fig. 6 Running control system of OSR-02.

only the area with the maximum size is analyzed. The minimum square that suits this area, the center position $(x_e, y_e) \in \Sigma_i$, and the posture angle θ_h of the target object are calculated. An example of the result of hand-eye image processing is shown in Fig. 7(b). Therefore, the holding position $(x_t, y_t, z_t) \in \Sigma_h$ of target object is able to be calculated from the height h_h(=const.) of initial posture of the hand and the height h_t of the target object estimated from the kind of trash as follows,

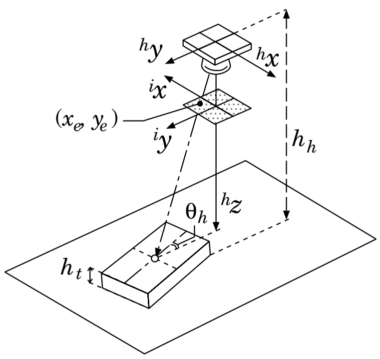
$$\boldsymbol{x}_t \triangleq \begin{bmatrix} x_t \\ y_t \\ z_t \end{bmatrix} = \begin{bmatrix} (x_e z_t)/f_h \\ (y_e z_t)/f_h \\ h_h - h_t \end{bmatrix}, \tag{6}$$

where f_h is the focal length of the hand-eye camera. The hand is controlled to be $\boldsymbol{x}_t \to 0$ and $\theta_h \to 0$. As mentioned above, the hand and arm are controlled for holding and collection of the object by the feed forward control system.

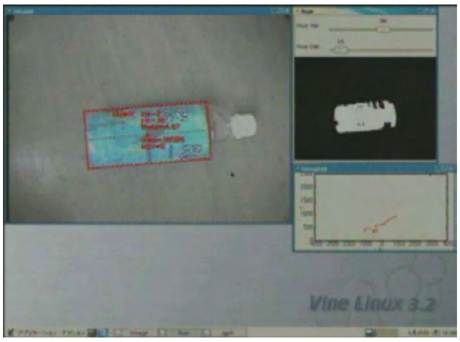
3. TRASH COLLECTION TASK

An operation sequence for the trash collection task of OSR-02 (Fig. 8) is shown as follows:

1. The robot searches for trash on the floor by controlling the posture of the cameras installed in the sensor system.
2. When a piece of trash is detected, the robot approaches the target trash as follows:
   (a) The posture of the sensor system is controlled to match the center of the target object and the center of the camera image.
   (b) The crawlers are controlled to approach constant distance from the target.
3. The robot stops moving near the target, measures the detail position of the target object by the stereo vision and the LRF, and raises the manipulator above it.



(a)



(b)

Fig. 7 Hand-eye : (a) relation of the hand-eye camera image coordinate system Σ_i and the hand coordinate system Σ_h; (b) example of calculating result of circumscribed rectangle of minimal area, center of gravity, posture, and distance of a target object.

4. The robot measures the position and the posture of the target by the hand-eye camera, and grasps and stores it into the trash box.

Since the appearance of trash changes according to the position, the posture of the camera, and the kind of trash, the robustness to the condition changing (mentioned above) is necessary for the method of detecting the object by this robot. Thus, we had employed a robust matching method compressing many template images by the Karhunen-Loeve (KL) expansion and obtaining normalized correlation approximately [4].

4. EXPERIMENTS

4.1 Driving performance

The driving performance of OSR-02 was tested under the outdoor environment. Here, since this test is for the evaluation of the driving performance, the robot was operated via wireless LAN. The robot was able to get over the ditch of 180 [mm] in width where running was difficult by the robot of the wheel drive (Fig. 9). It was confirmed that OSR-02 had a driving performance that was higher than OSR-01 of the wheel drive by this driving test.

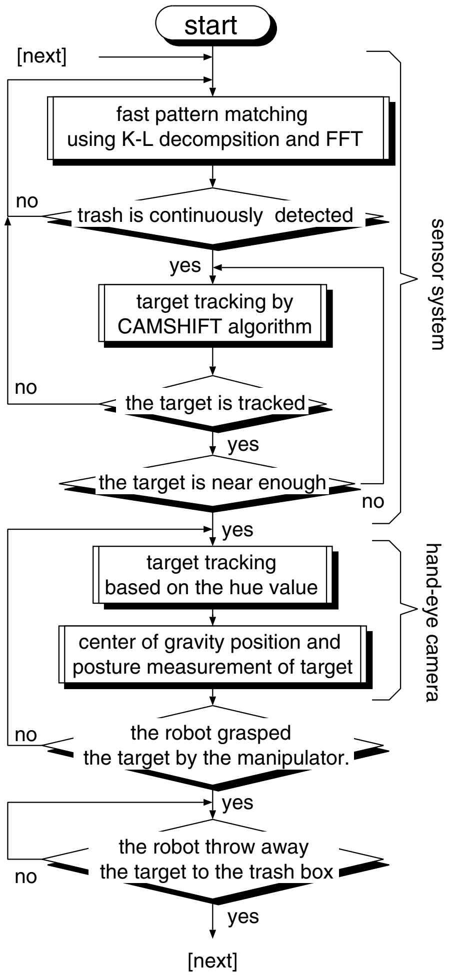
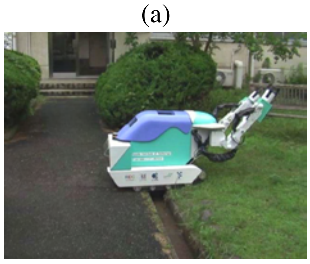


Fig. 8 Flowchart for image processing of the trash collection task.

(a)

(b)



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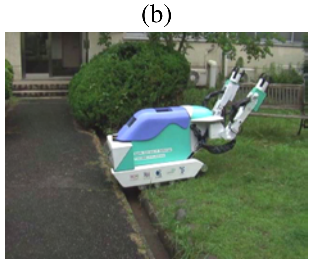
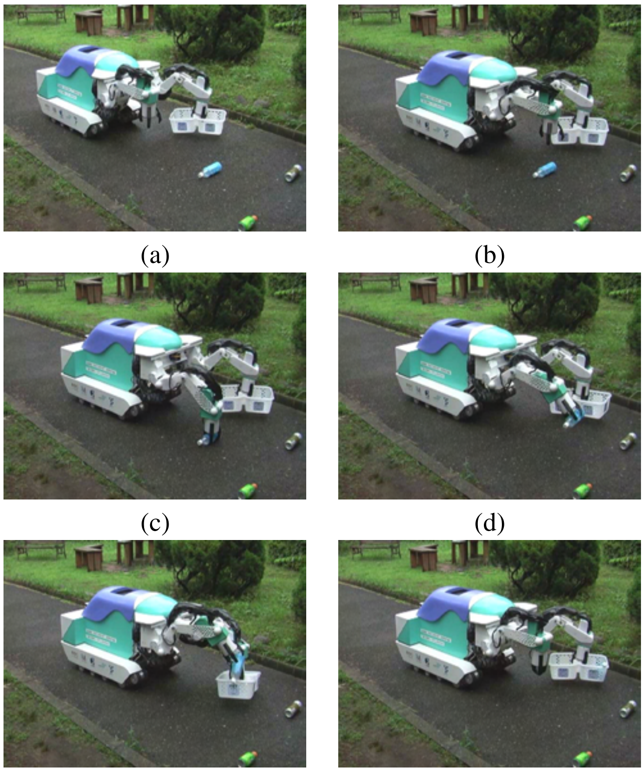


(d)

Fig. 9 Driving performance test.

4.2 Trash collection

The trash collection task of OSR-02 is experimented under the outdoor environment. A plastic bottle or a can was put forward of about 2 [m] of the robot, and the collection experiment was conducted. In this experiment,



(a) (b) (c) (d) (e) (f)

Fig. 10 OSR-02 collects up a plastic bottle; (a) a plastic bottle was discovered; (b) the initial posture for holding; (c) holding of the target object; (d) lift; (e) separated collection of the holding object; (f) searching for next trash.

the robot was programmed to classify the object by the right hand, and to store it into the trash box held by the left hand. It was the drizzle weather. The results of experiment are shown in Fig. 10. A series of operation sequence was confirmed from the result of these experiments, and it was confirmed that the separated collection task of trash is possible by the robot.

4.3 Experiment at the public space

We conducted the demonstrations of OSR-02 at a shopping arcade and a playground in Kitakyushu-city (Fig.11). The demonstration in which the robot patrolled the shopping arcade and the playground, and collected plastic bottles was executed several times. We confirmed that OSR-02 was able to detect the plastic and glass bottle and cans in the route, to approach, to collect accurately, and to avoid the pedestrian. Furthermore, it was found from these experiments that the calculation speed of the developed vision system was fast enough for the collection of trash.

5. CONCLUDING REMARKS

In this paper, we introduced the outdoor service robot OSR-01 and OSR-02. Moreover, we confirmed from the experiments in a real shopping street and a playground that the robots were able to detect the trash registered beforehand and to achieve the separated collection. Now, we are advancing improvement in the reliability and processing speed of the vision system and experimenting.

(a) (b)

Fig. 11 Example of demonstration of OSR-02; (a) at a shopping street; (b) at a playground.

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