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Development of an Autonomous Beach Cleaning Robot "Hirottaro"

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***Abstract* - This paper discusses the development of a small beach cleaning robot. The paper discusses two aspects of the robot: the refuse collection mechanism and the autonomous navigation system. In order to enable effective collection of refuse from a sandy surface, we developed a mechanism that mimics cleaning of a floor using a broom and dustpan. To identify its own position, the robot was equipped with a scanning range finder, which measured the position of two poles placed at the corners of the designated work area. The navigation system calculated the position and orientation of the robot using the sensor information and corrected any errors in the path.**

Index Terms* - *Beach cleaning robot, autonomous navigation, scanning range finder, self-localization.

I. Introduction

To date, large beach cleaning machines have been widely used for cleaning beaches before the beginning of the tourist season [1], [2]. However, these machines are not always available in the season itself because of cost limitations and safety concerns, resulting in most of the refuse collection being performed by volunteer groups, or the beach being otherwise left unattended. To address this problem, small beach cleaning robots have been developed [3], [4]. However, most of these robots are remote controlled and require a human operator. In this paper, we discuss the development of an autonomous beach cleaning robot named "Hirottaro," which is suitable for use on crowded beaches.

Our robot was designed to be capable of collecting refuse from populated beaches. The refuse collection mechanism was based on the action of cleaning floors with a broom and dustpan.

We also developed an autonomous navigation system on beach. The navigation system calculated the position of the robot using a scanning range finder and poles. This sensing system allowed the robot to move autonomously around the area delimited by the poles.

II. MECHANISMS OF HIROTTARO

A. *Driving Mechanism*

Figure 1 shows the autonomous beach cleaning robot comprising a driving mechanism, a refuse collection mechanism, and a control system. The length, width, and weight of the robot are 1350 mm, 600mm, and 220 kgf, respectively. The robot can work for about one hour by using a lead-acid battery. We intend to use a lithium-ion battery to increase the operation time of the robot in future.

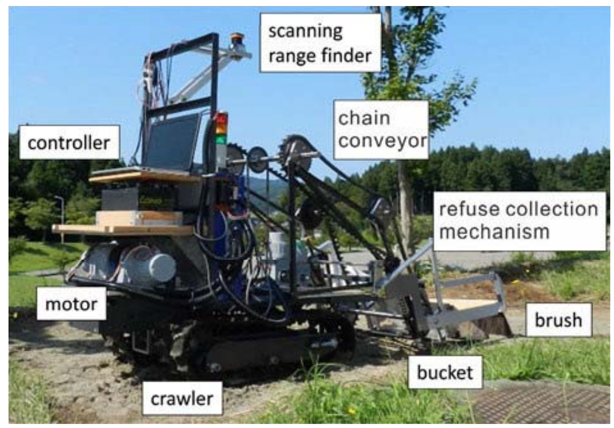


Fig. 1 Autonomous beach cleaning robot "Hirottaro."

The driving mechanism comprised two rubber crawlers, driven independently by variable-speed motors (Nissei Corporation. VGLD28-100N400L4, 400 W, gear ratio 1/400). The robot was capable of traveling stably over sand with a maximum speed of 0.65 km/h.

B. *Refuse Collection Mechanism*

The refuse collection mechanism was designed to work steadily on uneven terrain using a brush. Figure 2 shows the concept of the refuse collection. When a floor is cleaned by a human using a broom and dustpan, items are swept toward the dustpan by pressing the broom against the floor. The broom must be returned to its initial position without scattering refuse around the dustpan. To replicate this function, we designed a link mechanism driven by a single motor, as shown in Fig. 3.

A rotating driving lever moved the brush back and forth through a four-link mechanism. While the driving lever was not touching the up–down lever, around point A, the brush was kept in contact with the sandy surface by its own weight. In contrast, when the driving lever depressed the up–down lever, around point B, the brush was raised. The tip of the

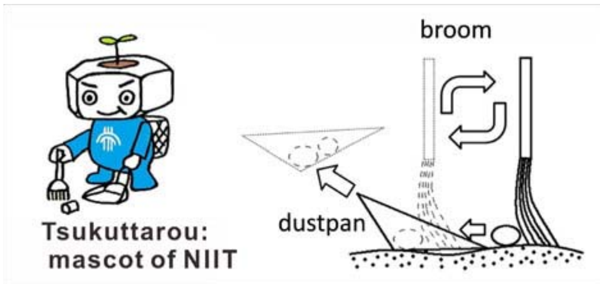


Fig. 2 Concept of the refuse collection.

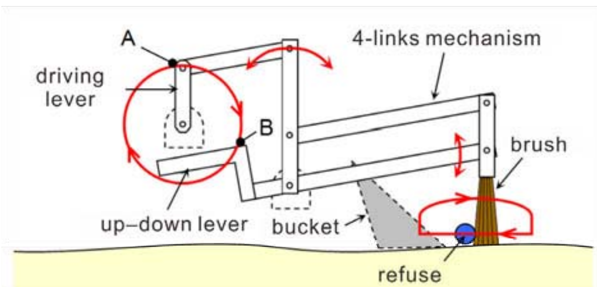


Fig. 3 Refuse collection mechanism.

brush thus traced the path shown in Fig. 3, driven by the rotation of the motor.

This mechanism allowed the brush to follow the uneven surface and sweep steadily. The refuse was then transferred to a collection box by a chain conveyor.

III. AUTONOMOUS NAVIGATION SYSTEM

A. The Concept of the Autonomous Navigation System

As shown in Fig. 4, the robot moved forward and turned repeatedly around a rectangular work area. The main movement was described by a long straight path between the sides of the area. After the straight path had been determined, it was divided into sections by subgoals. The collection mechanism cleaned the section between the two subgoals on each straight path. When each subgoal was completed, the robot stopped temporarily and transferred the collected refuse to the collection box placed at the rear of the robot. Thus, the control followed an intermittent pattern.

A mobile robot driven by open loop control cannot precisely follow a planned path when moving across uneven terrain such as a beach. This issue is mostly addressed using the odometric dead reckoning method; however, this method is only suitable for short distances because errors tend to accumulate over longer distances. By using closed loop control, "Hirottaro" was able to track its own location at each subgoal on the straight path and then correct its path when moving to the next subgoal. This allowed the robot to trace the planned path without any accumulation of error.

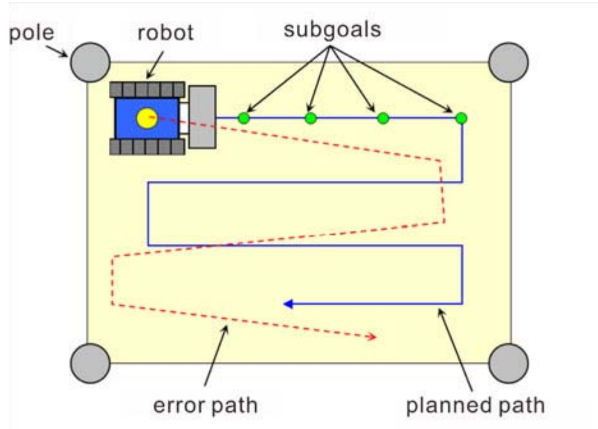


Fig. 4 Planned path for beach cleaning.

B. Self-localization Using a Scanning Range Finder and Two Poles

Global positioning systems are widely used to determine the self-location of a robot in outdoor environments [5], [6]. However, we adopted a simpler method using a scanning range finder. The range finder measured the positions of poles arranged at the four corners of the assigned rectangular area. This allowed the robot to determine its location with reference to the poles.

Self-localization using a scanning range finder requires identification of local landmarks [7], and insufficient natural landmarks are available on beaches. Therefore, we introduced a self-localization method based on trilateration using a scanning range finder (UTM-30LX, Hokuyo Automatic Co., Ltd.) and two poles as artificial landmarks. The sensing system allowed the robot to estimate its location at any point within the 20 m × 20 m rectangle because the scanning range finder had a range of 30 m.

Figure 5 shows the self-localization method using the scanning range finder and two poles. The scanning range finder measured the distances d_1, d_2 and angles α_1, α_2 to the two poles. Because the range finder detected the shortest distances d_{s1}, d_{s2} to the surfaces of the poles, the distances d_1, d_2 were corrected as follows:

$$d_1 = d_{s1} + r \tag{1}$$

$$d_2 = d_{s2} + r, \tag{2}$$

where r is the radius of the poles.

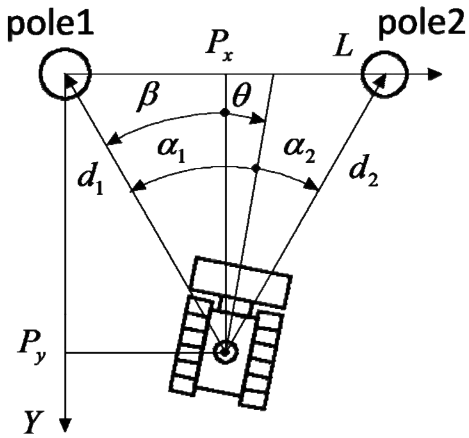


Fig. 5 Self-localization using a scanning range finder and two poles.

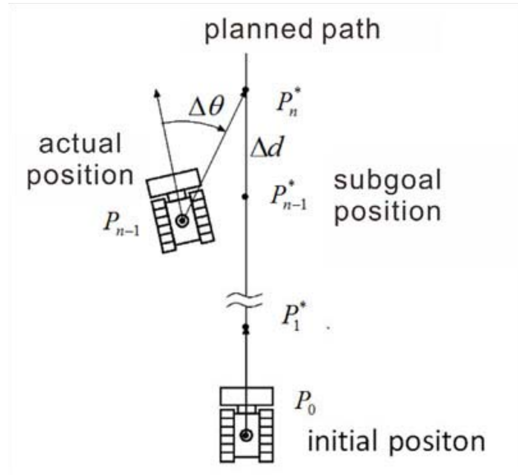


Fig. 6 Course correction based on self-localization.

Using trilateration, the position of the robot was calculated as

$$P_x = \frac{L^2 + d_1^2 - d_2^2}{2L} \tag{3}$$

$$P_y = \sqrt{d_1^2 - P_x^2}\ , \tag{4}$$

where the distance L between two poles is given by

$$L = \sqrt{d_1^2 + d_2^2 - 2d_1 d_2 \cos(\alpha_1 + \alpha_2)}\ . \tag{5}$$

The orientation θ of the robot was calculated by (6) and (7).

$$\theta = \alpha_1 - \beta \tag{6}$$

$$\beta = \tan^{-1}\left(\frac{P_x}{P_y}\right)\ . \tag{7}$$

This did not require the distance L between the two poles to be set precisely because it was obtained from (5). The line connecting the two poles was set to be orthogonal to the straight path. Although the rectangle was delimited by four poles, only two poles were used at any time for self-location. A further advantage of this approach is that the work area can be changed by moving the poles.

C. Course Correction Based on Self-localization

The control system comprised a main computer and a sub-computer. The main computer was a notebook PC, used for self-localization and path generation; the sub-computer was an “Arduino Mega” microcontroller, used for travel control. The sub-computer controlled the two crawlers in response to the desired turning angle $\Delta\theta$ and traveling distance Δd sent by the main computer.

To guide the robot to each subgoal, the control system made the robot turn by $\Delta\theta$ in the direction of the subgoal and then travel Δd , calculated from the subgoal and the actual position (see Fig. 6). The system repeated this motion until the end of the straight path was reached.

Basically, obstacles such as beach umbrellas in a work area are cleared in advance. When a human, however, goes into the work area, the sensing system of self-localization detects the human as the third local landmark except the two poles. In this case, the robot rescans the work area after the human goes out of the area.

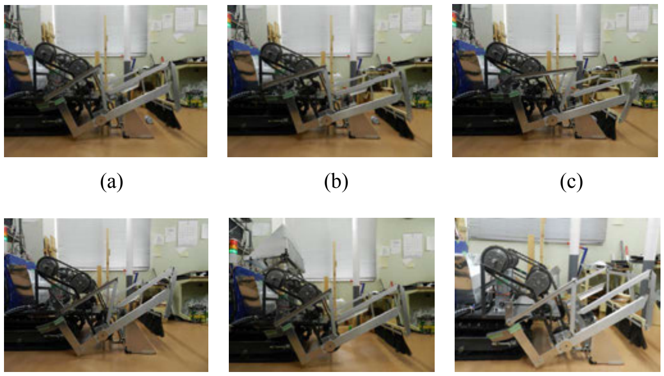
To detect a human around the robot, we intend to equip the robot with short range sensors (e.g., ultrasonic sensors). By using the sensors, the robot can detect that the human is on a planned path. And then, after announcing a warning to the human, the robot suspends its motion until the planned path is cleared.

Since the closed loop control of this robot is performed sequentially through the above main and sub-computer, the control cycle is not constant. The operation time of each section between the subgoals is approximately 30 s.

IV. EXPERIMENTS

A. Experiments on Refuse Collection

Experiments were conducted using the following sequence of movements to collect empty cans and plastic bottles. The robot was first moved ahead, lifting the brush. Next, the brush was pressed against the ground while the robot was in motion. The refuse was swept into the mesh bucket by the brush. The brush was then lifted and returned to its initial position. After this process had been repeated several



(a) (b) (c)

(d) (e) (f)

Fig. 7 Experiments on refuse collection. (a) The robot moved forward, lifting the brush. (b) The brush was pressed against the ground. (c) The brush swept refuse to the mesh bucket. (d) The brush was lifted. (e) The chain conveyor raised the mesh bucket to transfer the refuse to the collection box. (f) The mesh bucket was dropped to the ground.

TABLE I

EXPERIMENTAL RESULTS FOR SELF-LOCALIZATION.

robot position		position error		
P_x [cm]	P_y [cm]	Δx [cm]	Δy [cm]	θ [deg]
250	200	-1.0	2.8	0.65
	400	-4.8	2.6	0.01
	600	-3.5	2.0	0.05
	800	-3.0	5.0	0.09
	1000	4.5	-3.0	0.12

times, the robot stopped and the mesh bucket was raised to transfer the refuse to the collection box. The results of the experiments, shown in Fig. 7, confirmed that the collection mechanism worked effectively.

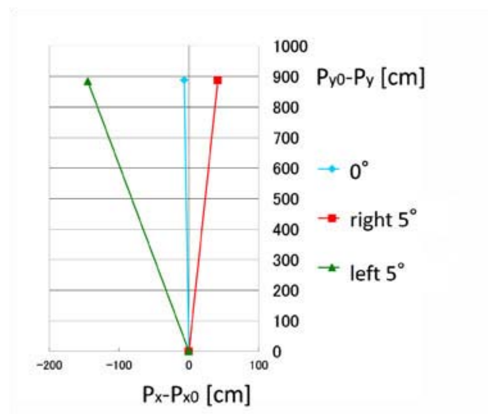
B. *Experiments on Self-localization*

The proposed self-localization method was also tested experimentally. The scanning range finder used was able to scan objects at each step angle of 0.25° in the scanned range, to a maximum angle of 270°. The pole needed to have a sufficiently large diameter to allow scanning. A pipe with a diameter of 11.4 cm and a length of 2 m was used for the poles in these experiments.

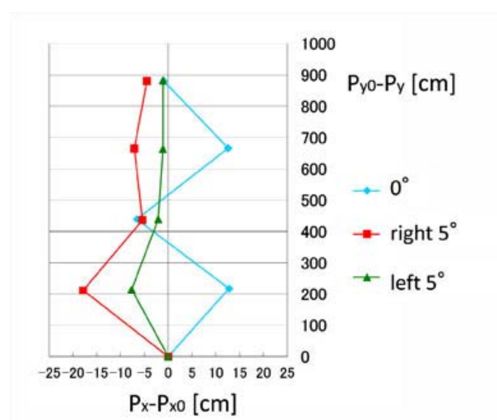
The robot was placed on the coordinate system defined by two poles separated by a distance of 500 cm (see Fig. 5). P_x was fixed at the center of the two poles and the robot faced forward to the two poles (θ = 0°). P_y was changed from 200 cm to 1000 cm, and the position (P_x, P_y) and orientation θ of the robot were measured by the sensing system.

Table 1 shows the experimental results. As P_y changed, the errors of the position and orientation fell within the range

Fig. 8 Field for the running experiments.



(a) Without correction.



(b) With correction.

Fig. 9 Results of the running experiments.

±5 cm and 1°, respectively. This error level is acceptable for the cleaning task because the width of the robot is almost 1 m.

C. Running Experiments

We tested the proposed navigation system by performing autonomous running experiments on a straight path (see Fig. 8). The distance between the two poles was the same as in the previous experiment. The desired path was a straight line from an initial position (P_x = 2.5 m, P_y = 10 m) to a final position (2.5 m, 1 m). The path was divided into four sections by three subgoals. Initial orientation errors of 0°, 5°, and −5° were set in these experiments.

Figure 9(a) presents the experimental results without course correction. Although the robot was able to arrive near the goal, errors of P_x at the final positions became large by the initial orientation errors.

Figure 9(b) presents the experimental results following course correction. Although a maximum position error of 20 cm occurred in the x-axis direction, the robot was able to trace the planned path without any accumulation of the error. The results confirmed the validity of the proposed navigation system.

IV. CONCLUSIONS

In this paper, we presented an autonomous beach cleaning robot called "Hirottaro." The refuse collection mechanism of this robot is less complex than conventional ones and can be used even on uneven terrain.

We introduced an autonomous navigation system using a scanning range finder and a grid of poles to allow "Hirottaro" to operate autonomously. Experimental results confirmed that the robot was able to trace a planned path without accumulated error.

In future work, we will conduct realistic experiments on refuse collection and autonomous navigation on a sandy beach.

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