Control of Movement on Stairs for a Cleaning Robot

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Abstract: An autonomous cleaning robot is proposed so as to move on all floors including stairs in a building. In human living environments, it is often the case that the cleaning area is a three-dimensional space such as a high-rise building. However, many of cleaning robots cannot clean and move on stairs, because they are not considered to move on places between floors. The proposed cleaning robot possesses L-shaped legs on the both sides of the body frame of a rectangular solid. The robot climbs down stairs by rotating the body so that the top and bottom sides of it may be reversed using L-shaped legs. In this paper, the mechanism and its control method are described for translational movement on stairs.

Keywords: Cleaning robot, Stairs, Translational movement.

I. INTRODUCTION

Recently, various robots that support and act for the work have been developed to be utilized in various fields. One of such robots is the autonomous cleaning robot [1], [2]. The automation of cleaning by robots reduces labors and saves energy for a cleaning task, so that there is an increasing need for it in large areas such as stations and airports.

In human living environments, it is often the case that the cleaning area is a three-dimensional space such as a high-rise building. However, many of cleaning robots are not considered to move on places between floors. Tajima et al. [3], [4] have developed a robotic system in which the cleaning robot cooperated with the elevator to clean floors in a high-rise building. The cleaning robot was equipped with an optical transmitter to communicate with the elevator. The elevator accepted requests from the robot, opened the door and moved to the designated floor carrying the robot. However, this system did not consider the cleaning of stairs. Also, the several types of vehicle using crawlers, wheels and legs were proposed to move on stairs [5], [6]. However, those vehicles were not assumed to turn and keep posture level on the tread board of stairs during moving on stairs.

The objective of this study is to automate of cleaning in a three-dimensional space to develop a cleaning robot which can move on stairs. A cleaning robot has been already proposed, where its structure was divided into two mechanisms for climbing down stairs and translational movement [7]. The proposed cleaning robot climbed down stairs by rotating the body so that the top and bottom sides of body may be reversed using L-shaped legs which are attached on the both sides of the body frame of a rectangular solid. It was also confirmed that the robot was able to climb down stairs keeping a stable posture through a simulation. In this paper, the mechanism and a control method are further described for translational movement on stairs in detail.

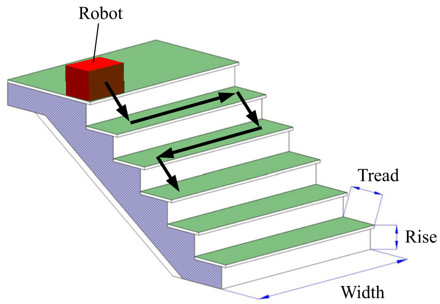


Fig. 1. Outline of stair cleaning by robot

II. CONCEPT OF CLEANING ROBOT FOR STAIRS

In this study, stair movement is assumed to climb down stairs. As shown in Fig. 1, whenever the robot moves on step of stairs, it needs to move in the perpendicular direction to a direction of movement. In the followings, several items are considered to design a cleaning robot for stairs:

- The cleaning from the upper floor to the lower floor is efficient for the stairs cleaning.
- The size and shape of the robot are based on the form of stairs for cleaning each step of stairs.
- The simple mechanism of a cleaning robot for stairs is desirable because of control design and weight saving.
- A cleaning area is a flat surface in indoor environment.

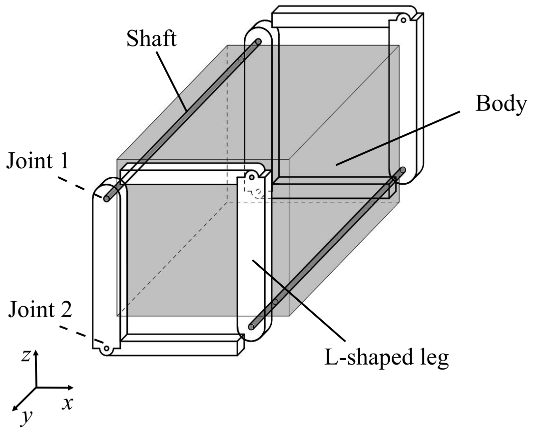
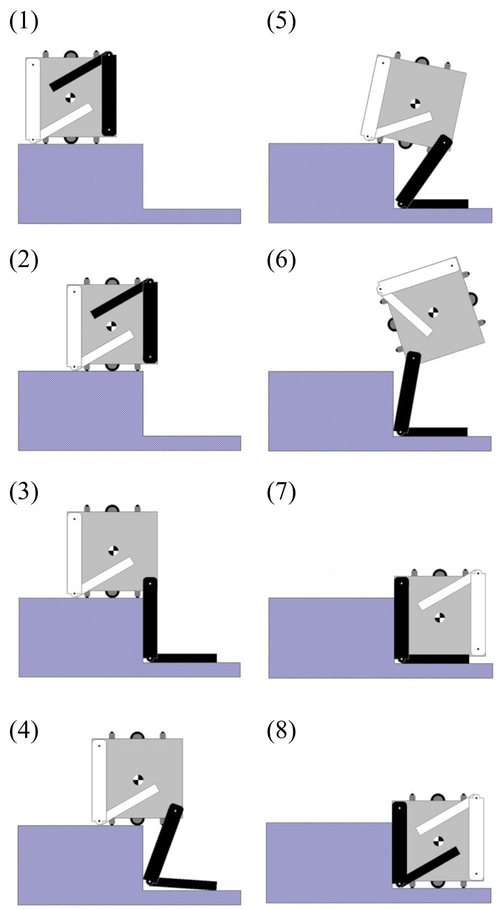


Fig. 2. Mechanism for climbing down stairs



(1) → (2) : Move to an dege of stairs.
(2) → (3) : Rotate legs by 180 degrees.
(3) → (5) : Move the CG of the robot to the support polygon.
(5) → (7) : Rotate the body keeping the CG of the robot in the support polygon.
(7) → (8) : Bend legs for translational movement.

Fig. 3. Algorithm of climbing down stairs using L-shaped legs

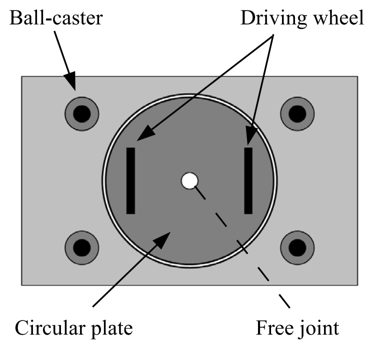


Fig. 4. Mechanism for translational movement

1. Mechanism for Climbing Down Stairs

Fig. 2 shows the proposed robot for climbing down stairs. The robot consists of the body frame of a rectangular solid and four L-shaped legs, where the leg has two degrees-of-freedom. The center of gravity (CG) of the robot is set to the center of the body. The posture of the robot remains in stable, if the CG of the robot is kept within the support polygon. Also it is assumed that this robot does not cause the displacement in y-axis direction for climbing down stairs, because the motion in a pair of L-shaped legs fixed in a shaft is synchronous. Fig. 3 shows the algorithm of stair climbing down stairs. The following is the relation between climbing motions and the number in the figure.

First, the robot moves to the edge of stairs in Fig. 3(1) to Fig. 3(2). The robot is located in the thickness of leg forward from the edge of stairs in Fig. 3(2). Secondly, rotate legs by 180 degrees in Fig. 3(2) to Fig. 3(3). Third, move the CG of the robot within the support polygon using the legs for stability in Fig. 3(3) to Fig. 3(5). The support polygon is to be a convex region surrounded by the sole of leg contacting with floor. Fourth, rotate the body keeping the CG of the robot within the support polygon in Fig. 3(5) to Fig. 3(7). Finally, bend the legs not so as to contact with the floor on the way of translational movement in Fig. 3(7) to Fig. 3(8).

2. Mechanism for Translational Movement

It is assumed that a cleaning robot is used in the indoor environment that is flat such as wooden floor or tile floor. The robot performs translational movement using wheels. The corner of the robot may collide with the wall and the riser of stairs when turning around, because the robot shape is a rectangular solid. Therefore an omnidirectional mobility is adopted to move and turn around keeping a posture.

For some of omni-directional mobile mechanisms with wheels, there are mechanisms with omni-wheel, mecanum wheels, etc. Since the robot climbs down stairs by rotating the body so that the upper and lower sides of body may be reversed, two mechanisms for moving are attached to the top and bottom of the robot. To

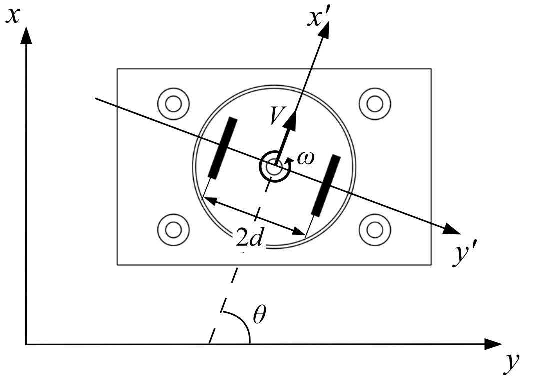


Fig. 5. Kinematic model of two-wheel-drive mechanism

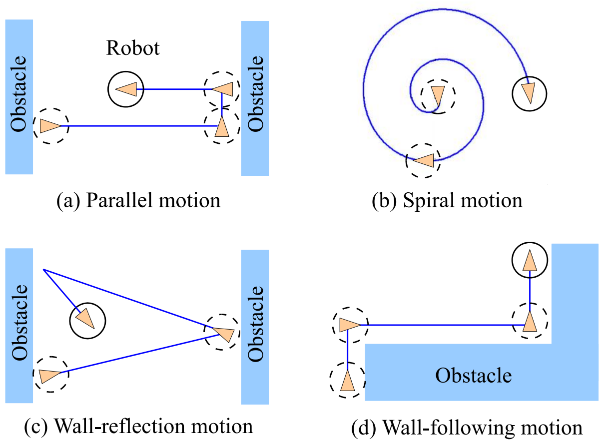


Fig. 6. Basic motion for cleaning robot

reduce the robot weight, it is desirable to use the fewest possible actuators. Fig. 4 shows the proposed mechanism for translating on stair treads. The mechanism consists of four ball-casters and two driving wheels that are attached on a circular plate with a free joint. This locomotive mechanism is attached to the top and the bottom of the robot body. Also the robot bends legs not so as to contact with the floor during translational movement.

Fig. 5 shows the kinematic model of the mechanism for translational movement. The velocity V and the angular velocity ω of the robot are given by

$$\begin{bmatrix} V \\ \omega \end{bmatrix} = \begin{bmatrix} \frac{r}{2} & \frac{r}{2} \\ \frac{r}{2d} & -\frac{r}{2d} \end{bmatrix} \begin{bmatrix} \dot{\theta}_R \\ \dot{\theta}_L \end{bmatrix} \quad (1)$$

where θ_R and θ_L are the rotational angles for the left and right wheels, r is the wheel radius, $2d$ is the distance between wheels. The kinematic model is given by

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} \frac{r}{2}\sin\theta & \frac{r}{2}\sin\theta \\ \frac{r}{2}\cos\theta & \frac{r}{2}\cos\theta \\ \frac{r}{2d} & -\frac{r}{2d} \end{bmatrix} \begin{bmatrix} \dot{\theta}_R \\ \dot{\theta}_L \end{bmatrix} \quad (2)$$

where x and y are the position of the robot, and θ is the turning angle of a circular plate.

III. LOCOMOTION CONTROL

1. Locomotion Process

The locomotion of commonly-marketed cleaning robots is classified into four basic motions [8], [9] as shown in Fig. 6. Parallel motion is a repeated motion combining advance and 90-degree turns. Spiral motion is of moving toward outside on a spiral path. Wall-reflection motion is of changing the direction at random when having an obstacle collision and going straight ahead. Wall-following motion is of moving along an obstacle when having an obstacle collision.

Spiral motion and wall-reflection motion are unsuitable for the stair cleaning, because one step of stairs is narrow and it takes time to complete the cleaning. On the contrary, parallel motion and wall-following motion are suitable for the stair cleaning, because the shape of step is a rectangular form. In this study, the parallel motion will be adopted.

2. Range sensor

The range sensor is used for the robot to recognize and face stairs. A position sensitive detector (PSD) SHAPE GP2D120 is used as the range sensor. Table 1 shows the electro-optical characteristics of the PSD.

Table 1. Electro-optical characteristics of the PSD

Parameter	Symbol	Value	Unit
Operation supply voltage	V_{cc}	4.5 ∼ 5.5	[V]
Average dussupation current	I_{cc}	33	[mA]
Distance measuring range	L	40 ∼ 300	[mm]
Measurement period	T	38.3	[ms]
Output terminal voltage	V_o	0.25 ∼ 0.55	[V]

The PSD outputs the value that converts a one-way distance to an object into DC voltage. Also, the PSD has less influence on the color of reflective objects and the reflectivity, because it is an optical sensor by applying a triangulation method. In addition, the PSD has less influence on the outside light, because the operational environment is assumed to be indoor in this study.

IV. OPERETIONAL CHECK

An operational check of the robot was conducted with stopping and turning actions in the edge of a step for recognizing stairs.

1. Mobile Robot

Fig. 7 shows the topview of the mobile robot used in experiment. Table 2 shows its specification, where

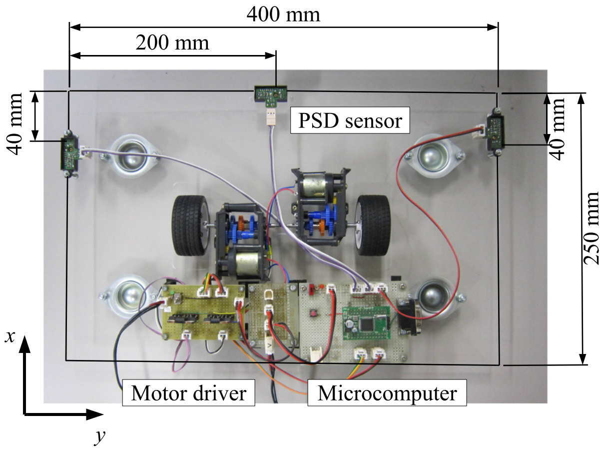


Fig. 7. Topview of mobile tobot

Table 2. Specification of mobile robot

Prameter	Value	Unit
Width	400	[mm]
Length	250	[mm]
Vehicle height	20	[mm]
Mobile velocity	15	[cm/s]

the robot consists of two driving wheels and four boll-casters. Three PSDs were attached to the downward. The robot is located in the thickness of leg forward from the edge of stairs with two PSDs attached on both sides of the robot. The thickness of leg is assumed to be 40 mm. The DC voltage is converted from the analog information to the digital information by using an A/D converter of H8/3664 microcomputer, where the resolution of the A/D converter is 10 bits with 5 V. The motor can be controlled in normal and reverse rotation, stop and braking by using a motor driver.

2. Condition

The size of stairs is assumed as follows: the width is 1200 mm, the tread is 270 mm, and the rise is 180 mm. A threshold was defined to recognize stairs with 300 in A/D converted value as shown in Fig. 8. The robot recognized stairs when the threshold was less than or equal to 300.

In stop actions using all PSDs, the robot stops if any one of PSDs reacts. In turning actions using PSDs attached on both sides, if one of PSDs reacts, then the robot turns in the direction so that the other PSDs react.

3. Result and Consideration

As a result, it is confirmed that the robot stopped and turned to recognize stairs using PSDs. However, there was a case that the ball-caster had fallen from stairs before stopping the motor. This problem will be overcome by changing the layout and attached angel of PSDs for securing the distance enough to brake. Also, the robot will be controlled to slow down near the edge of stairs.

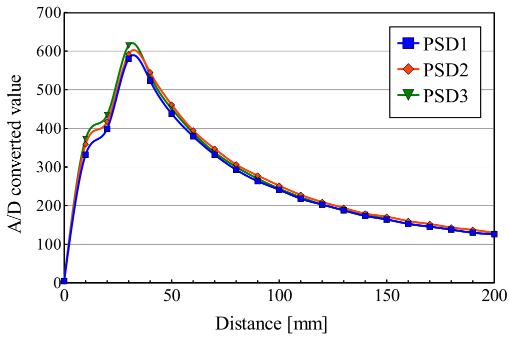


Fig. 8. Relationship between distance to a reflective object and A/D converted value of output voltage

V. CONCLUSION

A cleaning robot to climb down stairs has been developed for cleaning three-dimension space. In particular, a mechanism and a locomotion control method were proposed for the robot to clean and climb down stairs. The operational check of the robot was conducted for recognizing stairs. In the result, it was confirmed that it needs to change the layout of PSDs and control to slow down near the edge of stairs.

As future work, a stair cleaning robot will be developed to solve the above problem, together with making a real robot.

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