DEVELOPMENT OF SMALL-SIZE WINDOW CLEANING ROBOT BY WALL CLIMBING MECHANISM

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Abstract: The objective of this research is to develop the small-size and light weight window cleaning robot. The prototype of window cleaning robot has been developed. The dimensions of prototyped robot are approximately 300mm x 300mm x 100mm and its weight is approximately 3 kg. The prototyped robot consists of two independently driven wheels and an active suction cup. The control system which includes traveling direction controller using accelerometer and traveling distance controller using rotary encoder and edge sensors ware installed for autonomous operation. This paper includes background and objectives of this research, prototyped mechanical systems, moving control system, experimental result of basic traveling control and window wiping motion by comparing to with or without of motioned control system, some discussions in each experiment and a conclusion.

Keywords: Climbing robot, window cleaning, wall climbing, attitude control, acceleration sensor.

1. INTRODUCTION

Recently, there have been many demands for automatic cleaning system on outside surface of buildings such as window glass by increasing of modern architectures. Some customized window cleaning machines have already been installed into the practical use in the field of building maintenance. However, almost of them are mounted on the building from the beginning and they needs very expensive costs. Therefore, requirements for small, lightweight and portable window cleaning robot are also growing in the field of building maintenance. As the results of surveying the requirements for the window cleaning robot, the following points are necessary for providing the window cleaning robot for practical use:

1) It should be small size and lightweight for portability.

2) Clean the corner of window because fouling is left there often.

3) Sweep the windowpane continuously to prevent from making striped pattern on a windowpane

4) Automatic operation during moving on the window.

The locomotion mechanism must be chosen to satisfy these demands, especially later two subjects. Here locomotion mechanism means the combination of adhering mechanism, traveling mechanism and a mechanism for changing a traveling direction.

First requirement brought the following specifications for designing the window cleaning robot.

- Weight: less than 5kg, including the weight of battery and washing water,
- Size: 300mm x 300mm x 100mm.

These were also defined by the results of surveying the demands from the cleaning companies. In previous researches, we have proposed outline of mechanical system for window cleaning robot for filling above mentioned demands. And we confirmed basic properties and its possibility by the experiments. That mechanical system consists of two-wheel centered differential drive specialized in making a right-angled turn at the corner of window and a suction cup with vacuum pomp as adhering method. By this mechanical system, window cleaning robot can move on vertical window with adhering smoothly. Fig. 1 is the rendering at a scene of practical use of proposed window cleaning robot. This robot adheres on a windowpane with cleaning as moving on large windows.

This paper deals with traveling control system in order that above mentioned mechanical system of window cleaning robot can be operated automatically. We know a lot of studies on wall climbing robot including window cleaning robot by various research groups[1]-[10], but there are few researches and development of motion control of wall climbing robot. However the environment of robot which moves on vertical or inclined plane is quite different from the robot moves on horizontal plane at conditions of motion control. This is due to difference of direction of

Fig. 1 Rendering of small-size window cleaning robot

gravity works on the robot.

In this paper, we explain window cleaning robot installed traveling control system and report results of basic traveling experiments and autonomous wiping motion on vertical window majored quantitatively.

This paper includes five chapters. The second chapter illustrates prototyped mechanical systems used for experiments and moving path of window cleaning. The third chapter explains statics model of the window on the vertical window and developed moving control system. The fourth chapter shows experimental result of basic traveling control and window wiping motion by comparing to with or without of motioned control system and says some discussions in each experiment. The fifth chapter gives a conclusion.

2. MECHANICAL SYSTEMS

In this study, we use climbing mechanism which consists of the two-wheel locomotion mechanism and adhering mechanism by a suction cup. This mechanism is reported in previous researches [11].

This mechanism was designed under focusing on the window cleaning robot for just a single windowpane. It is apparently necessary to cross over the window frame or joint line to use it at any window, but the single windowpanes like as a show window also exist as an important application.

A. Traveling path

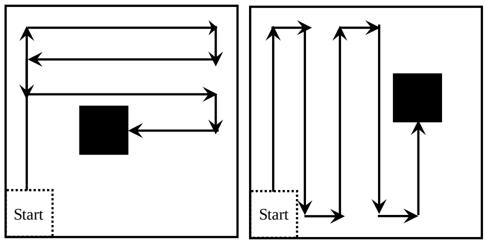
In order to sweep all over the window plane, two types of traveling paths shown in Fig. 2 were considered. Here we adopted type (A) in Fig. 2 because of energy efficiency and cleaning affectivity. Type (A) in Fig. 2 principally involves horizontal direction movements. The robot will climb up just once. On the other hand path of type (B) consists of mainly vertical direction movements, i.e. the robot must continue to climb up and go down the window recursively. Therefore type (A) is better on energy efficiency. And further, we must remember that the robot has a possibility to be in damage of bringing pollutions to where cleaned already, if the robot moves along the path of type (B).

B. Locomotion Mechanism and robot body

The robot moves on windowpane by two-wheel locomotion mechanism with holing the body on the surface using a suction cup vacuumed by a pump. The most important point in the mechanism is the friction coefficient of suction cup and tire against the adhering surface, e.g. high friction between the tire and the surface of window can transmits the torque, and low friction between the suction cup and the surface of window can achieves to move the robot with holding the body on the window. We selected PTFE (Polytetrafluoroethylene) for the materials of surface of a suction cup, and silicon rubber for the material of tires.

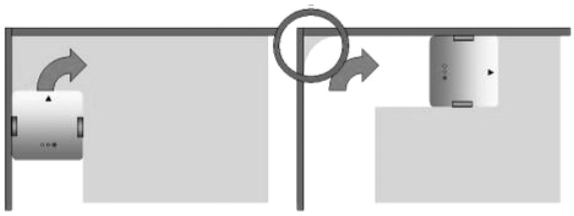
C. Turning Mechanism and robot body

Turning mechanism is a key to clean even at the corner of window. Fig. 3 shows the scenes that the robot changes its traveling direction at the corner. Fig. 3-(a) shows a usual turning way like as turning of motorcars. In this case, since the robot changes a direction as tracing an arc, it can not reach the end of corner of window. It needs the



(A) (B)

Fig. 2 Working path of window cleaning robot



(a) Conventional turning strategy

(b) Novel turning strategy, which enables to clean a corner

Fig. 3 Overview of small-size window cleaning robot

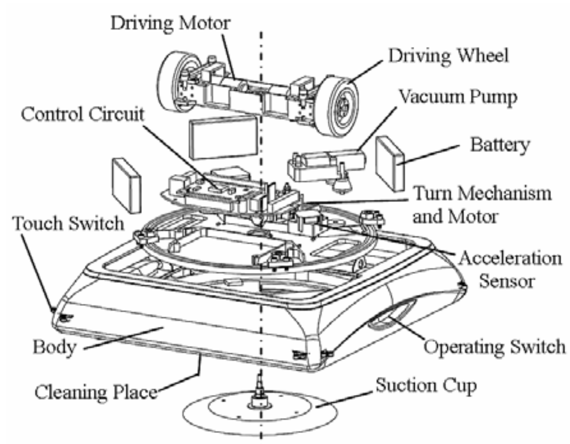


Fig. 4 Mechanism of small-size window cleaning robot. The top cover is removed for explanation

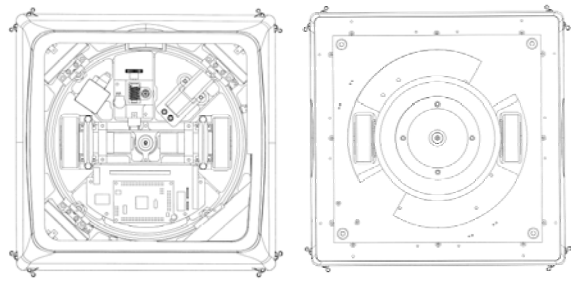


Fig. 5 Left drawing is top view of the prototype whose upper cover is opened, right one is bottom view.

Fig. 6 Prototyped window cleaning robot

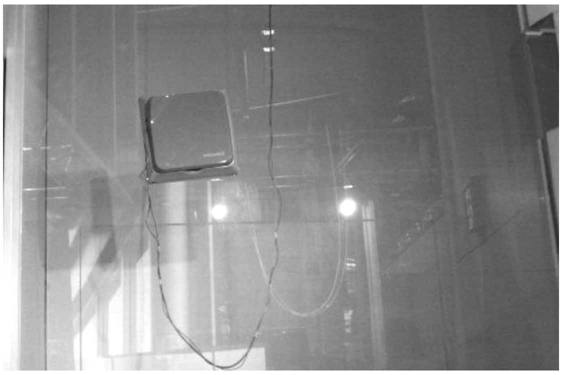


Fig. 7 Prototyped window cleaning robot moves on the window, the string was attached on the robots just for safe at experiment. This robot includes all the components such as batteries to work.

Table 1 Specifications of prototype

Motors	Wheel driving: DC servo motors x 2, Turn mechanism: DC motor x 1
Vacuum pump	Pressure: Maxmum -33.3 kPa, Flow volume: 2.5 l/min
Continuous work time	Approx. 1 hour
Power source	Li-Polymer Batteries, Actuators:14.4 V, Controller: 7.2 V
Dimensions (W x D x H)	Approx. 300 X 300 X 100 mm
Weight	Approx. 3 kg

complicated process as follows to clean the corner by such robot: first, the robot goes into a corner, next it moves back the distance to turn, then it changes its direction as tracing an arc. In case that the robot can change its direction at the end of corner as shown in Fig. 3-(b), the robot can clean a corner easily and rapidly. Round-shape robot is easily able to turn at the corner, but it unable to reach the end of corner. On the other hand, a quadrangular robot can clean to the end of corner, but never turn itself there.

To get a function to change direction as shown in Figure 3-(b), we designed the mechanism that a mobile unit and a cleaning part are rotatably connected at the center shaft as shown in Fig. 4.

3. TRAVELING CONTROL

The desired traveling trajectory when the robot cleans the window consists of the line of vertical and horizontal direction, shown in Fig. 9. However, the robot can not go straight to horizontal direction. This phenomenon means the robot can not move along desired lines. In consequence, the robot can not cover the window surface without any hole, or the robot come to dead end by going off the course therefore the robot can not continue operation any more shown as Fig. 8

It seems that this problem is caused by the gravity whose direction intersects with traveling direction of the robot at grade. It is a particular problem in traveling control of the robot moves on vertical or inclined plane like as windows. To determine this problem, we adopted attitude control using acceleration sensor. This chapter explains its control methods and outline of electronic system.

The attitude angle of window cleaning robot is controlled by proportional control method as shown in Fig. 11. In this control, input value is the desired attitude angle θ_0, output value is attitude angle of the robot θ which is measured by acceleration sensor whose characteristics are shown in Table 2 This sensor was installed into the robot body as shown in Fig. 10.

In order to control the attitude, the robot measures a direction of gravity since the related angle between gravity direction and robot body gives attitude angle. When the robot moves on the window, there is a possibility that the sensor detect convoluted value both the acceleration gravity and acceleration by the motion of the robot. But the robot will be operated with static and low velocity. Therefore the acceleration by motion of the robot is ever-smaller than acceleration gravity. So, in this control, we do not consider

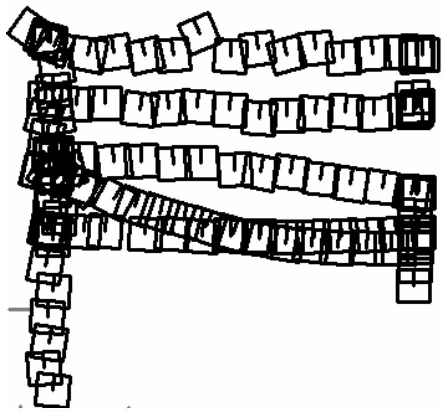


Fig. 8 Failed case: Moving trajectory of window wiping motion without attitude control

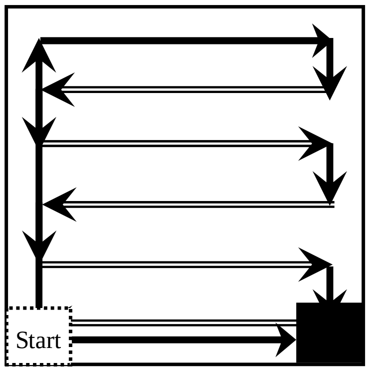


Fig. 9 Travelling path and control sequence. Bold single limes show tracer control part. Double lines mean attitude control part.

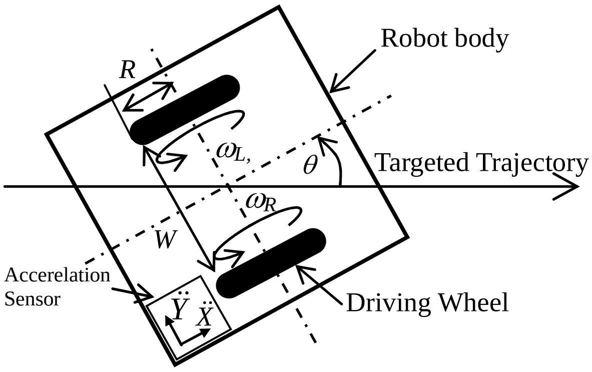


Fig. 10 Attitude control model with two-wheel locomotion

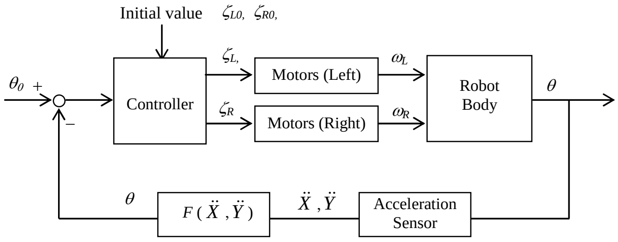


Fig. 11 Block diagram of attitude control

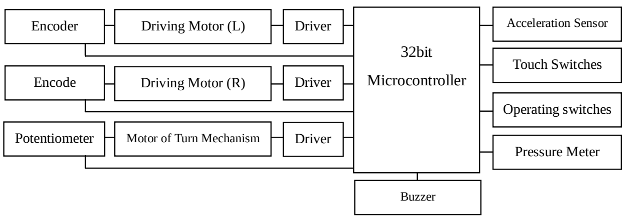


Fig. 12 Block diagram of the control system

Table 2 Specifications of acceleration sensor

Input range	±2 g ±5%
Zero g drift	±30 mV
Sensitivity	1 V/g ±5%
Non-linearity	±2% FS
Noise density	140 μg/Hz$^{1/2}$
Noise	1.0 mg rms
Bandwidth	DC-50 Hz ±5%
Dimensions	19.8 X 44.5 X 27.2 mm (W x D x H)
Weight	46 gm

the effect of acceleration based on the robot motion to measuring the gravity acceleration.

The relationship between angular velocity of attitude of the robot and angular velocity of left and right of driving wheels is given as following

A kinematics model for differential-drive robot is expressed as following:

$$\begin{pmatrix} V \\ \dot{\theta} \end{pmatrix} = \begin{pmatrix} R/2 & R/2 \\ R/W & -R/W \end{pmatrix} \begin{pmatrix} \omega_L \\ \omega_R \end{pmatrix} \quad (1)$$

where, V is a traveling velocity, $\dot{\theta}$ is angular velocity of the robot attitude. ω_L, ω_R are rotation velocity of left and right wheels. W gives tread. R is a radius of wheels [12].

The formula of controller shown in Fig. 11 is given as following:

$$\begin{pmatrix} \varsigma_L \\ \varsigma_R \end{pmatrix} = \begin{pmatrix} K_P(\theta-\theta_0) & 1 \\ 1 & K_P(\theta-\theta_0) \end{pmatrix} \begin{pmatrix} \varsigma_{L0} \\ \xi_{R0} \end{pmatrix} \quad (2)$$

where, $\zeta_{L,}$ and ζ_R gives output duty rate of PWM motor control. $\zeta_{L0,}$ and $\zeta_{R0,}$ give initial value of travelling velocity which is expressed as duty rate. K_P is feedback gain.

4. EXPERIMENTS AND DISCUSSIONS

This chapter reports experimental result of motion control of prototyped window cleaning robot installed attitude controller illustrated in Chapter III. This experiment consists of two kinds of experiments. One is measurement of performance of attitude control when the robot moves to horizontal direction and elevation angle of 45 degrees. The other is an experience of window wiping operation with attitude controller on actual window glass.

The robot was examined on the window stood vertically. The glass of the window is flat, clear and the thickness of 8mm. The glass is held by window frame made of aluminium. In all the experiment, the motions of robot measured by digital stereo vision camera, Bumblebee. This camera system can recode absolute position coordinate of the robot by measuring the position of colored light mounted on the two corners of the robot in darkroom. The experimental setups are illustrated in Fig. 9.

In this experiment, electric power is supplied form batteries placed in the robot, i.e. the robot is operated without any cables

Test 1: Horizontal direction

Moving of horizontal direction was measured as two conditions; one is without attitude control and the other is with attitude control using an acceleration sensor. Each experiment is measured in same position on the window, and same moving distance of 1.8 meters. At the starting point, the robot is attached on the window direct to horizontal direction shown as Fig. 14-(A).

Fig. 15 shows motion trajectory both controlled and uncontrolled by attitude control system. A square in the figure represents the position and attitude of robot body recorded every 1 second. Fig. 15 says that as the robot goes, its trajectory is decurved. The average moving velocities of controlled case is 0.199 m/s; uncontrolled case is 0.374 m/s.

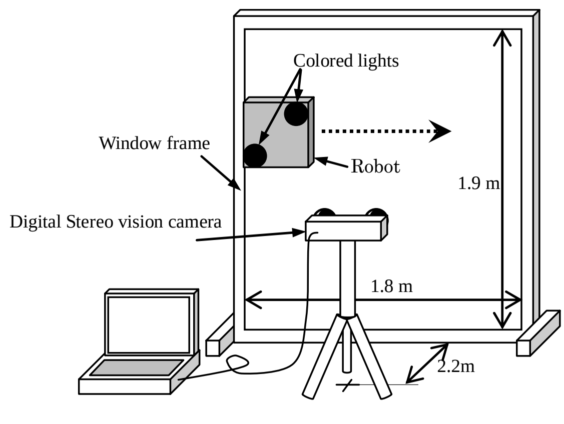
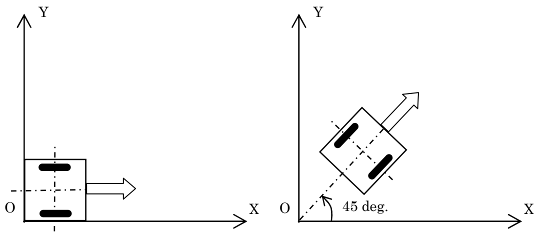


Fig. 13 Experimental setup with motion capture system



(A) Test 1 : Horizontal (B) direction of 45deg.

Fig. 14 Illustration of basic test of attitude control

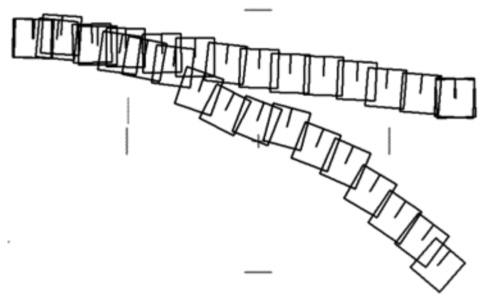


Fig. 15 Robot trajectory when the robot moves to horizontal direction.

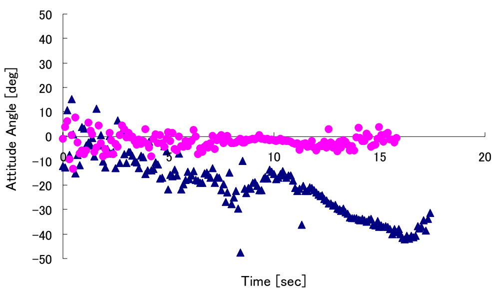


Fig. 16. Changing the attitude angle of the Robot when the robot moves to horizontal direction.

The trajectory of controlled case shift 0.226m of the –Y direction at goal point (X=1.80m). The trajectory of uncontrolled case shift 0.862m of the –Y direction at goal point (X=1.80m).Then the attitude of uncontrolled robot inclines to clockwise as the robot runs, shown in Fig. 16. On the other hand, attitude angle of controlled robot is stabilized around 0 degree with a margin of error of plus or minus 5 degrees as shown in Fig. 16.

Test 2: Direction of elevation angle of 45 degrees

In this experiment, control results of moving direction of elevation angle of 45 degrees were measured as test 1, shown in Fig 14-(B).

Fig. 17 shows motion trajectory of climbing to direction of elevation angle of 45 degrees. A square in the figure represents the position and attitude of robot body recorded every 1 second. The average moving velocity of controlled case is 0.138 m/s; uncontrolled case is 0.153 m/s.

Fig. 18 shows that attitude angle of the robot controlled is constant and stabilized at 43 degrees. On the other hand, the robot which was uncontrolled is increase up to approximately 100 degrees.

Test 3: Window Wiping Motion

Fig. 19 indicates moving trajectory of window wiping motion when the robot moved on the window toward a path shown in Fig. 8. The robot was started from the corner of

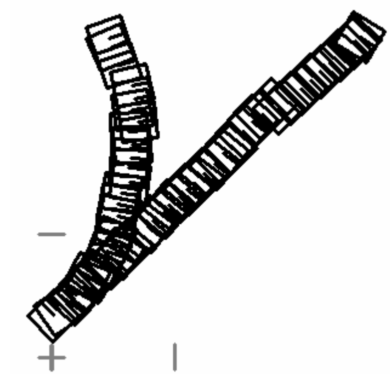


Fig. 17 Robot trajectory direction of parallel with elevation angle with 45 degrees

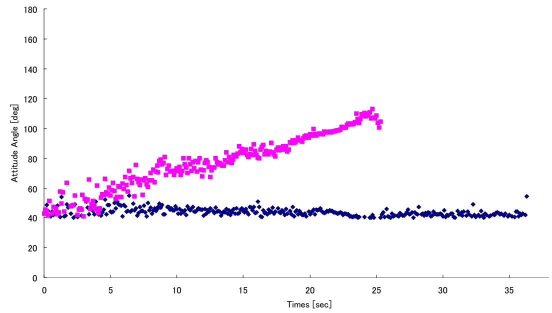


Fig. 18 Attitude angle of the robot when moves to elevation angle of 45 degrees

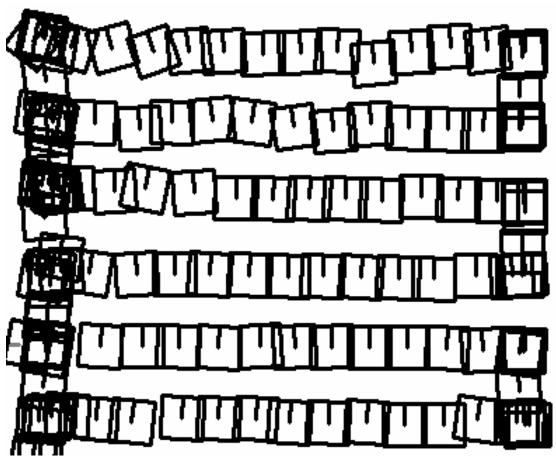


Fig. 19 Moving trajectory of wiping path controlled by attitude controller

lower left and climbed up toward window frame of left side, and it ran to horizontal direction toward window frame of top, next, the robot went down as the distance less than length of robot body. At the each corner, the robot changed the traversing direction at right angle using specialized turning mechanism.

A square in the figure represents the position and attitude of robot body recorded every 1 second.

5. CONCLUSION

This paper described an application of small-size and light weight wall climbing robots for window cleaning. The window cleaning robot consists of two-wheel locomotion mechanism and a suction cup. This robot moved on the

— 0.3m

window smoothly with adhering by a suction cup. And this robot has a function to change a traveling direction at right angle at the corner of the window. Above mentioned window cleaning robot was prototyped and its mechanism and some of characteristics were illustrated.

Next, we developed attitude control system which is important technology to operate automatically. This control system was installed into prototyped robot mentioned above. Then, in order to measure the specifications of widow cleaning robot with attitude control systems on the vertical window, some of the experiments have been done. And the trajectory of window wiping movement was recorded quantitatively. As the results of these examinations, we got result that the attitude angle of robot is under control, but robot trajectory is not fit with desired trajectory perfectly. Because, a robot has errors not only attitude angle, but also error of translation motion. To solve this problem, we will have to obtain the way to measure those errors and it control.

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