A Study on Wall Surface Mobile Robots*  
(Development of Moving Mechanism for Crawler-Type Wall Surface Mobile Robots with Vacuum Pads)

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We study the moving mechanism of a wall surface mobile robot for hazard maintenance under gravity. This robot can attach itself to a vertical wall or ceiling by vacuum pads. The vacuum pads are set on the crawler so as to enable rapid mobility on the surface. Each vacuum pad is simply designed. There is a mechanical valve set at each sucker, and every sucker is connected to an air duct inside the crawler belt. The valve opens mechanically when the sucker touches the surface, and the sucker clings to the surface. By this mechanism, the sucking control system becomes simple. The vacuum pad is made of flexible material in order to ensure sufficient sucking force even when the surface is rough. This robot also has an automatic pushing mechanism for the suckers and distribution mechanism. We designed, fabricated and tested the prototype. In the experiment, this robot succeeded in smoothly and rapidly climbing the surface of vertical walls and ceilings having both rough and smooth finishes.

Key Words: Robotics, Hazard Maintenance Robot, Wall Surface Mobile Robot, Vehicle, Crawler with Vacuum Pad, Mechanical Valve

1. Introduction

Some working environments are very difficult and dangerous for human beings; for example, those involving various kinds of plant equipment in such fields as atomic energy, petroleum, and chemistry. In order to prevent accidents in these situations, inspection and maintenance work is indispensable, and to this end, development of hazard maintenance robots is expected. In this paper, a robot for wall surface work is described. It does not fall from a wall surface or ceiling under the force of gravity. Development research on a mobile robot’s mechanism for wall surface work is performed.

The working environments of robots for wall surface work include those at great heights, such as on tanks and in pipes, as well as on large ships, outside walls of ultrahigh buildings and in narrow places between structures. Inspection of outside walls, repairs, painting, and cleaning are among the principal tasks performed by these robots. Robots are equipped with sensors and working functions, and automatization, labor-saving, and safety in this work can be achieved by independent control with a plant map. Those robots can work rapidly in situations such as rescue work at the time of a disaster in a building.

Robots which can move along walls are expected to be developed, and the problem in their development is how to realize smooth and high-speed mobility, reliability, safety, and efficiency. This paper focuses on the running mechanism which is the foundation of a wall surface working robot. In this paper, a crawler mechanism which possesses multiple suckers on a crawler surface is proposed, and prototype experiments on sucking force measurements on various wall
materials are conducted.

2. Design Condition of Running Mechanism and Its Basic Structure

In the design of the running mechanism of a wall surface mobile robot, the following 2 points become important.

(1) How to prevent the robot from falling due to gravity.

(2) How to make it move smoothly.

First, to achieve (1) above, a method using magnetic force\(^{(1)}\), an absorption method using a sucker\(^{(2)}\)–\(^{(4)}\), and a method of applying force to the wall surface by propelling power\(^{(5)}\) were previously proposed. The magnet method is characterized by a simple control system and possesses the advantage that standstill action is stabilized. However, there is a disadvantage in that the type of surface is limited. In the case of vacuum equipment, such as suckers, and inhalant mechanisms, there is a great advantage in that the wall surface need not be of a certain kind. Moreover, in the case of the method using propelling power, the burden on the controlling device becomes great with respect to the stability of standstill action.

Next, for point (2) above, a walking formula\(^{(6)}\)–\(^{(8)}\), a crawler formula\(^{(9)}\)–\(^{(11)}\), and a wheel formula\(^{(12)}\) have been proposed. The walking formula can overcome an obstacle, and in general, aims to achieve a speedy movement. On the other hand, this is not true of the crawler and wheel formulas. For a wall surface transfer robot, rapidness of work, safety, and labor-saving are important specifications, and in meeting the specifications, optimum form must be decided in designing a running mechanism.

In this paper, the surfaces of walls and ceilings are considered to be planes, and we consider the following conditions in designing the running mechanism of a wall surface mobile robot.

a. Type of wall surface is not specified.

b. Transfer speed is fast.

c. Control is easy.

d. Mechanism is lightweight.

e. Transfer to other walls is not considered.

As a result, of considering these points, we decided upon a suction formula with a sucker, and a transfer formula with a crawler. In this paper, a crawler mechanism possessing multiple suckers on a crawler surface is proposed as an optimum configuration.

This robot can cling to a vertical wall or ceiling by vacuum pads. The vacuum pads are set on the crawler so as to enable rapid mobility on the surface. In the previous research, the mechanism for suction was complex with many vacuum generators and electromagnetic valves. In this paper, each vacuum pad is simply designed. There is a mechanical valve set at each sucker, and every sucker is connected to an air duct inside the crawler belt. The valve opens mechanically when the sucker touches the surface; then the sucker clings to the surface. By this mechanism, the sucking control system becomes simple compared with the conventional one, and only one vacuum generator is required. The vacuum pad is made of flexible material in order to ensure a sufficient sucking force even when the surface is rough. This robot also has an automatic pushing mechanism for the suckers and distribution mechanism. With these mechanisms, a sucker clings to the wall securely. For design of the sucker, we have performed detaching experiments on the suckers for several walls made of different materials. These are the first attempts to design a wall surface mobile robot.

3. Details of Running Mechanism

3.1 Main body configuration

Figure 1 shows the structure of the proposed wall surface mobile robot equipped with suckers. In this paper, we consider forward and backward movement of the robot on the wall and ceiling. The main body is composed of a crawler with two pulleys in front and back, and one of the pulleys is driven by a DC motor. Multiple suckers are installed on the crawler belt, and the robot clings to the wall by contact of the suckers with the surface. The space for the payload can be set between the two pulleys. The proposed running mechanism can be used as a basic component, and combination of these components increases the total number of degrees of freedom.

3.2 Crawler configuration

Figure 2 shows the structure of the sucker-equipped crawler belt. The crawler belt is made of flexible rubber for the following reasons.

(1) To reduce the actuating power of the DC motor.

(2) To prevent the sucker from detaching from the wall due to the restoring force of the belt.

The weight of the robot should be distributed
over all suckers in contact with the wall to ensure the safety of its maneuvering. Hence, hooks made of aluminum alloy are installed on both sides of the belt, and the roller is set at the tip of each hook (Fig. 2). By these hooks rolling on the guide rail, the weight of the robot is distributed over the suckers which cling to the wall (distributed mechanism[6]).

3.3 Sucker configuration

The conditions for the suckers installed on the belt can be given as follows.

(1) They can cope with deformation of the crawler belt.

(2) They can cope with roughness of the wall surface.

For (1), we gave a sucker a flexible structure by using rubber and sponge, so that the sucker could deform in response to the crawler belt. When the belt is rolled up by the pulley, the sucker is peeled off from the surface in accordance with the deformation of the belt. For (2), we used a sponge pad at the contact surface of the sucker. When the suction inside the sucker starts, the sucker is pulled in the direction of the surface, and the sponge is attached to the wall so as to cover the gaps between the roughness of the wall and the sucker. Hence the sucker clings to roughly finished surfaces such as mortar and concrete without air leakage.

The sucker is designed with a circular configuration for ease of production (Fig. 2). The contact area of the sponge pad is designed so as to prevent leakage without losing durability. The prototype sponge pad is designed on the basis of experience.

3.4 Suction mechanism

Multiple suckers set on the crawler belt can be controlled individually by the contact sensor and electromagnetic valve, but this will make the system large and complex. Therefore, we consider simplification of the suction control system and aim at controlling the suckers mechanically. Basic ideas are summarized as follows.

(1) We build the air flow line inside the belt, and connect each chamber of the suckers (Fig. 2).

(2) We set a mechanical valve on each sucker. The valve opens automatically when the sucker comes into contact with the surface, and closes automatically when it detaches from the surface (Fig. 3). By this mechanism, the suckers in contact with the surface continue sucking while preventing air leakage at the other suckers. Thus, the suction control system is simplified.

To keep the air flow line inside the belt at low pressure, only one vacuum generator is required, and this can be set at the center of the crawler. We insert a spring in the air flow line to maintain the configuration. The spring is flexible enough to bend with the belt and rigid and rough enough not to cut off the air flow.

3.5 Pushing mechanism of the sucker

Because we installed a mechanical valve, the sucker must be pushed hard enough against the surface to open the valve. It is difficult for the sucker to be pushed against the wall and ceiling under the
gravitational effect. Therefore, we included the pushing mechanism shown in Fig. 4, which pushes the sucker against the surface actively. By this mechanism, the sucker near the front pulley is pushed by the tension force of the belt when the robot moves forward. Moreover, when the roller enters the guide rail, the sucker clinging to the surface is pulled against the wall, the volume of the sucker is increased and the suction force is stabilized.

4. Prototype Development of Suckers and Their Performance

4.1 Approximated suction force

We made a prototype of the suckers. The configuration of the sucker is designed as follows on the basis of experience.

- Inner diameter of the sponge pad = 0.032 [m]
- Outer diameter of the sponge pad = 0.046 [m]
- Height of the sucker = 0.08 [m]

Theoretical suction force is given by the following equation:

\[ F = -P_v \cdot A, \]  \hspace{1cm} (1)

where

- \( F \) : theoretical suction force [N]
- \( P_v \) : vacuum pressure \( = -0.0840 \) [MPa] (gauge pressure based on the atmospheric pressure \( 0.1013 \) MPa)]
- \( A \) : area of the sucker \( = 67.5 \) [N](6.88 [kgf])

The time taken to attain the vacuum level by the vacuum generator is experimentally given by the following equation:

\[ t = (1000 \ V/C) / 1.06, \]  \hspace{1cm} (2)

where

- \( t \) : time to attain vacuum level [s]
- \( V \) : volume inside the sucker [m³]
- \( C = 0.13 \) : (coefficient to attain vacuum level of \( -0.0800 \) MPa)

Vacuum generator: Myotoku CVD-M10HR: thus \( t \) equals 0.04 [s].

The pressure applied to the sponge pad is given as follows.

\[ f_p = F / a \]  \hspace{1cm} (3)

\( f_p \) : pressure applied to the sponge pad [N/m²]

\( a \) : contact area of the sucker [m²] thus \( f_p \) equals \( 7.88 \times 10^4 \) [N/m²].

These results are summarized in Table 1.

4.2 Experimental value of suction force

Next, we conducted suction force measurement experiments. The pressure level inside the sucker is set at \( -0.084 \) MPa (\( -603 \) mmHg), and we conducted experiments on (i) suction force in the vertical direction using one sucker (Fig. 5), (ii) suction force in the vertical direction using two suckers with the distribution mechanism (Fig. 6), (iii) suction force in the horizontal direction using one sucker (Fig. 7), (iv) suction moment using one sucker (Fig. 8), (v) suction moment of the sucker on the crawler belt (Fig. 9), for 4 walls of different materials (acrylic, steel, plywood, mortar). The roughness of the material increases in this order.

From Fig. 5, as the roughness of the wall increases, the suction force in the vertical direction

Table 1 Characteristics of a sucker (approximated value)

<table>
<thead>
<tr>
<th>Standard Atmospheric Pressure</th>
<th>0.1013 [MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vacuum Level (Gauge Pressure)</td>
<td>-0.0840 [MPa]</td>
</tr>
<tr>
<td>Theoretical Suction Force</td>
<td>67.5 [N]</td>
</tr>
<tr>
<td>Vacuum Time</td>
<td>0.04 [sec]</td>
</tr>
<tr>
<td>Pressure on a Sponge Pad</td>
<td>( 7.88 \times 10^4 ) [N/m²]</td>
</tr>
</tbody>
</table>

Fig. 4 Automatic pushing mechanism of a sucker

Fig. 5 Suction force in vertical direction
decreases. In the case of an acrylic surface, the suction force is almost the same as the theoretical value.

From the comparison of Fig. 5 and Fig. 6, the suction force in the case of two suckers is double that in the case of one. From this result, the distribution mechanism is judged to be effective.

From Fig. 7, it is seen that as the roughness of the wall increases, the friction force becomes greater, and the suction force in the horizontal direction becomes

Fig. 6  Suction force in vertical direction with distribution mechanism (Two suckers)

Fig. 7  Suction force in horizontal direction

Fig. 8  Suction moment of a sucker

Fig. 9  Suction moment of a sucker on the crawler belt


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strong.

From Fig. 8, it is seen that there are no extreme differences among suction moments of the different materials, but the mean value of the suction moment decreases as the roughness of the wall increases.

From Fig. 9, it is seen that it is easy to peel off the sucker by rolling the pulley compared with the case of applying the moment around the center of the sucker in Fig. 7.

The experimental sucking performance is summarized in Table 2, where the minimum values are taken into consideration for the material change.

5. Design of Running Mechanism

5.1 Design flow

Design factors of the robot are summarized as follows.

(1) Total weight of the robot
(2) Actuator selection
(3) Number of suckers

These factors affect each other. First, the length and height of the robot are roughly decided so that basic components such as the vacuum generator and the actuator can be attached to the robot. Then the actuator is selected. The total weight of the robot can be estimated, and the number of suckers is decided on the basis of Table 2.

5.2 Weight of prototype robot

The appearance of the prototype robot is shown in Fig. 10. The main body is made of aluminum alloy and is 490 mm in length; the length between the two pulleys is 514 mm. Tension force of the timing belt can be adjusted. The weight of the robot is given as follows.

- Main body 1.15 kg
- Vacuum generator (with a filter unit) 0.76 kg
- Crawler belt 1.20 kg
- Motor 0.98 kg
- Others (tube, cable, etc.) 0.41 kg
- Total 4.51 kg

5.3 Actuator selection

We use a DC motor. The relationship between driving force f transmitted to the crawler belt from the motor and motor torque is given by the following equation:

\[ f = T \cdot (1/n) \cdot (1/R) \cdot \eta, \]

where

\[ f \]: driving force transmitted to the crawler belt from the motor [N·m]
\[ T \]: motor torque [N·m]
\[ n \]: reduction ratio
\[ n = n_1 \cdot n_2 = z_1 \cdot z_2 \]
\[ r_1 \]: radius of the pulley transmitting driving force (motor side) [m]
\[ r_2 \]: radius of the pulley transmitting driving force (rear wheel side) [m]
\[ z_1 \]: number of teeth of the pulley transmitting driving force =12
\[ z_2 \]: number of teeth of the rear pulley =44
\[ R \]: radius of the rear pulley =0.44 m
\[ \eta \]: transmission efficiency of the belt
\[ \eta = 1 - \frac{1}{n_1 + n_2} \]

Efficiency \( \eta \) is designed to be \( \eta = 0.5 \). To obtain \( T \) from \( f \) we use the following equation.

\[ T = f \cdot n \cdot R \cdot (1/\eta) \]

The force and torque applied to the wall surface mobile robot are shown in Fig. 11, where

- \( f_1 \): shearing force produced by the robot's weight alone [N]
- \( f_2 \): force generated by the tension force and restoring force of the belt [N]
- \( f_3 \): force required to peel off the sucker [N].

From the experiment, \( f_1 = 44.13 \) [N], \( f_2 = 39.23 \) [N], and \( f_3 \) is calculated as \( f_3 = 3.187 \) [N], which is obtained by dividing the maximum torque of the pulley \( T_{\text{max}} = 0.127 [/N·m] \) by the radius of the pulley \( R \).

Here, \( f \) is the sum of \( f_1, f_2 \) and \( f_3 \), and substituting these values in Eq. (7), gives \( T = 1.89 \) [N·m], and the required motor torque is written as follows.

\[ T_{\text{req}} = 1.89 \text{[N·m]} \]
Table 3  Pressure change inside the belt for different wall materials units (Pa×10^3)

<table>
<thead>
<tr>
<th>Wall Material</th>
<th>Acrylic</th>
<th>Steel</th>
<th>Plywood</th>
<th>Concrete</th>
<th>Mortar</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vacuum Level (All Valves are Closed)</td>
<td>-80.7</td>
<td>-80.7</td>
<td>-67.7</td>
<td>-71.7</td>
<td>-80.1</td>
</tr>
<tr>
<td>Maximum Peak Vacuum Level at a Loss</td>
<td>-79.2</td>
<td>-78.9</td>
<td>-66.3</td>
<td>-76.3</td>
<td>-79.2</td>
</tr>
<tr>
<td>Minimum Peak Vacuum Level at a Loss</td>
<td>-25.9</td>
<td>-28.8</td>
<td>-1.3</td>
<td>-22.9</td>
<td>-25.9</td>
</tr>
<tr>
<td>Average Peak Vacuum Level at a Loss</td>
<td>-55.2</td>
<td>-59.6</td>
<td>-38.7</td>
<td>-57.9</td>
<td>-60.4</td>
</tr>
</tbody>
</table>

Fig. 11 Force and torque applied to the wall surface mobile robot

The DC motor used for the prototype robot is 2.16 N·m and 60 rpm, and this satisfies Eq. (8). As an actuation method, we utilized the PWM actuation method for both forward and backward motion.

5.4 Number of suckers

Required force for the sucker $f_s$ such that the robot can remain stationary on a vertical plane is calculated from the equations in section 5.3 as follows.

$$f_s \geq f_i = 44.13 \text{ [N]}$$  \hspace{1cm} (9)

The required force for the sucker $f_o$ such that the robot can remain stationary on the ceiling is calculated from the equations in section 5.2 as follows:

$$f_o \geq W \cdot g = 44.25 \text{ [N]},$$  \hspace{1cm} (10)

where $W$ : total weight of the prototype robot [kg].

From these, the condition for the robot not to fall is written as follows, by setting the safety number equal to 8.

$$n_p \cdot F_h/8 \geq f_s$$  \hspace{1cm} (11)

$$n_p \cdot F_v/8 \geq f_o$$  \hspace{1cm} (12)

$n_p$ : Number of suckers which are in contact with the wall

$F_h$ : Suction force of a sucker in horizontal direction [N]

$F_v$ : Suction force of a sucker in vertical direction [N]

From Table 2, we set $F_h = 47.04$ [N], $F_v = 48.51$ [N], and $n_p = 8$ so that Eqs. (11) and (12) are both satisfied. From these results, we determined the total number of suckers to be 20.

6. Running Experimental Results

An outline of the experimental system is shown in Fig.12. Here we do not consider transfer from one surface to another. First, we measured maximum speed on the acrylic surface, and the results are written as follows.

- Speed upward on the wall : 0.050 m/s
- Speed downward on the wall : 0.065 m/s
- Speed on tc ceiling : 0.050 m/s

Next, we measured pressure change inside the belt when the robot moves up the wall at an average speed of 0.025 m/s. The walls for the tests are made of acrylic, steel, plywood, concrete, and mortar, and tests are conducted three times for each. The main value of the pressure change (gauge value) inside the belt is summarized in Table 3. An example of the pressure change is shown in Fig.13 (concrete surface). When the sucker comes into contact with the surface, the valve opens and the pressure increases instantaneously, and spiked change of the pressure is
observed. We call this change loss in this paper. Table 3 shows the maximum, minimum, and average values of the spike. This spike change is not a serious problem for operation at the speed of 0.025 m/s. However, in the case of plywood, the pressure change is large and unstable, so the speed should be lowered. In the case of a plywood surface, air leaks through the plywood. So, if the period between spikes is short, it is quite difficult to recover the steady pressure level. From these results, this robot can be judged to have certain speed limitations, which are due to hardware limitations.

7. Points of Improvement

To increase the moving speed, the rotation speed of the belt should be increased. To accomplish this, the following points should be considered.

- Increase the actuator power.
- Reduce the weight and rigidity of the crawler belt.

To make the suction mechanism follow the rotation of the crawler belt, the vacuum level inside the belt should be maintained by the following improvements.

- Improvement of the time response of the valve.
- Improvement of the exhaust ability of the vacuum generator.
- Improvement of the sealing of the suction system.

The working environment of wall surface mobile robots is not always good for them. Pipes and steps present obstacles to the robot. To overcome these obstacles, we should consider improvement of the mechanical design as follows.

- Consider using two crawlers so that the robot can turn around by actuating each crawler in a different direction.
- Redesign the joint or change the configuration of the crawler itself.

These are subjects for future study.

8. Conclusions

In this paper, we suggested and produced an experimental running mechanism for a wall surface mobile robot. Through the running experiments, we demonstrated that the robot could move speedily and smoothly over a wall surface and ceiling. Characteristics of the running mechanism can be summarized as follows.

1. The type of wall surface (acrylic, steel, plywood, concrete, mortar) does not affect operation due to installation of multiple suckers on the crawler surface.

2. On/off control of a sucker is automatic, and the suction controller is simplified by installing a mechanical valve in each sucker.

3. With the pushing mechanism of a sucker and distribution mechanism, a sucker attaches securely to surfaces.

References


