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BIPEDAL WALKING ROBOT CAPABLE OF MOVING ON A VERTICAL WALL FOR INSPECTION USE

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ABSTRACT

A robot capable of moving on a vertical or overhanging wall has been expected for inspection use of the outer walls of tall buildings, dams, and some other vertical walls. For the purpose, the sucking force produced by the negative pressure in the suckers is available to sustain the robot on the surfaces. To adopt a robot to the various types of irregular surfaces, a walking mechanism is suitable. A bipedal walking model which has a sucker on each leg is considered. When it is walking on a vertical wall, a sucker has to sustain the whole weight, then it is very important to examine its safety condition. To develop a control system of walking, a numerical simulation is carried out and safety of walking is investigated. By these studies, a model was constructed and tested. The safety of walking on a vertical wall and transition from the wall to the ceiling were confirmed by the experiments.

1. Introduction

Development of a mobile robot capable of moving on a vertical wall of tall buildings, dams, etc. has been expected for a long time. Since 1965 we have built a few mobile robot models of this type. Some of them are presented in Ref. (1). They have a sucker which has a relatively small vacuum pressure and a pair of crawlers as a moving mechanism. These types can be utilized on flat and wide vertical walls.

There are many types of irregularities on the vertical walls of buildings and dams in general, so that a walking mechanism is suitable to step over them and it has a wider applicability.

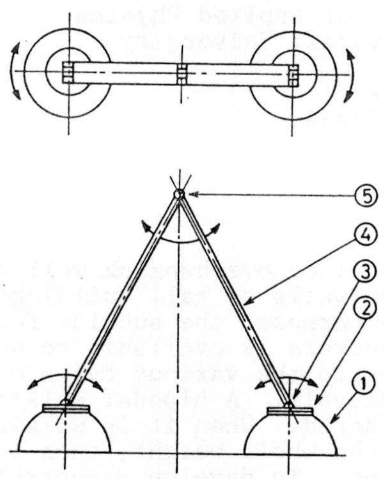
Bipedal walking model with a sucker on each leg is considered, and its mechanism is discussed in the following chapter. The safety conditions of a sucker is very important and it is discussed in chapter 3. To develop a control system of walking, a numerical simulation is carried out.

Based on these preliminary studies, a model was constructed and tested. Safety of moving on a vertical wall and ceiling was confirmed by the experiments.

2. Mechanism of the robot

2.1 Walking mechanism

There are many types of irregularities on the vertical wall of tall buildings, such as frames of window, eaves, etc., and on the wall of dams, such as ladders, stairways, etc., respectively. The walking mechanism is preferable to a robot to climb up these surfaces, since it can step over these obstacles. A bipedal walking model was considered. The mechanism of it is shown in Fig. 1. It has a sucker and two hinges and a pivot on each leg, so that this model has five degree of freedom. The walking form is given in Fig. 2. The rotation at the ankle and inclination at the ankle and crotch are combined to walk on a vertical wall and the path of the free leg is controlled to decrease the moment acting on the fixed cup.



① Sucker, ② Pivot, ③ Hinge at ankle,
④ Leg, ⑤ Hinge at crotch
Fig.1 Walking mechanism.

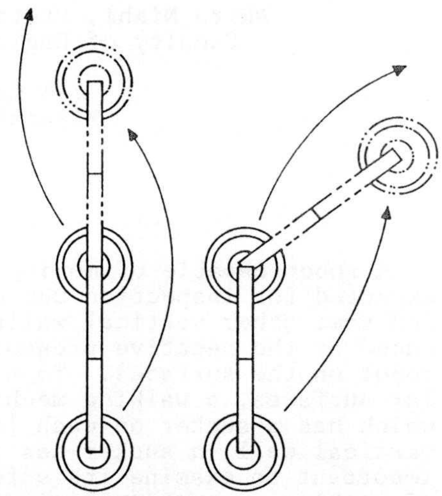


Fig.2 Walking form.

2.2 Sucker and blower

The sucking force can be produced without power when the air tight is kept at the periphery of the suction cup. This condition, however, is not always attained for the rough wall surface. Therefore an active method to keep the cup in negative pressure, must be employed in order to utilize it as a robot component. The sucker can be divided into two categories, that is, higher negative pressure and lower ones. For the former a vacuum pump or ejector is used and a conventional blower can be utilized for the latter. A smaller sucker can be used to sustain the dead weight for the former, as a higher negative pressure produces a larger sucking force. The air tight, however, must be kept severely. For a lower pressure cup the air flow of the blower is larger than a vacuum pump, then small amount of air leakage into the cup from the periphery is allowable.

An AC motor driven conventional vacuum cleaner blower is utilized for the model. As the rotational speed of the motor depends on the required torque of the fan, the smaller air mass flow brings the higher rotational speed, then the higher pressure rise. This is a typical characteristic of high speed blower, and its performance curve gives a sharp decrease with increasing the air mass flow. This blower has a merit of light weight, but it has a defect of comparatively small range of allowable air mass flow change. An expected blower characteristic is a small pressure change for a certain amount of air mass flow variation, and this depends on the types of blowers.

Section of a cup is shown in Fig. 3 as an example. A flexible lip at the periphery of the cup is effective to tight the leakage. Both the spring effect of the rubber lip and the force produced by the pressure difference of outer and inner surfaces of the lip prevent the air leakage. The inner lip is usefull to sustain the dead weight of the robot by the friction force.

3. Safety Conditions of a Sucker

When the model is walking on a vertical wall, a sucker has to sustain the whole dead weight, therefore the safety conditions of it is very important. There are two types of danger on the wall---slipping and falling, depending on the position of center of gravity. Although the slipping can be stopped at the biginning by controlling the pressure in the sucker, the falling is fatal and it must be avoided.

The rotational slipping is a combined motion of simple slipping and rotation produced by the gravitational force and moment respectively. When the position of center of gravity is inside of the radius, $\ell/r < 1$, the motion is close to a simple slipping, and for $\ell/r > 2$ it can be seen as only a rotation by the moment of ℓW. In Fig. 4 an experimental result of rotational slipping is presented.

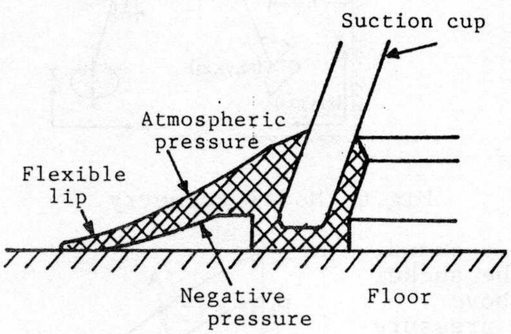


Fig.3 Section of a cup.

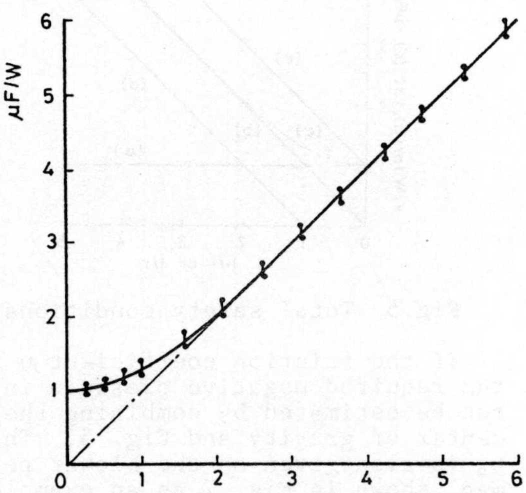


Fig.4 Experimental results of rotational slipping.

The total safety conditions are summarized by the following relations and these are shown in Fig. 5. The upper side of each curve gives a safety reange.

(a)	Simple slipping ;	$\mu F/W \geq 1$	(1)
(b)	Simple falling ;	$F/W \geq h/r$	(2)
(c)	Rotational slipping ;	$\mu F/W > 1$ for $\ell/r < 1$	(3)
		$\mu F/W > l/r$ for $\ell/r > 2$	
(d)	Falling off on the floor ;	$F/W \geq l/r - 1$	(4)
(e)	Falling off from the ceiling ;	$F/W \geq l/r + 1$	(5)

where F is a sucking force, W a dead weight of a robot, G a position of center of gravity, μ a frictional coefficient, r a radius of a circular sucker, ℓ and h are shown in Fig. 5. Slipping and falling occur independently, and the most severe condition is a falling off from the ceiling, so that the pace of walking on the ceiling must be smaller. The second is a rotational slipping on a vertical wall.

When the model is moving on a wall or on a way of transition to the opposite wall, the center of gravity must be calculated to examine the safety conditions at any time. It can be done by using the model geometry, which is shown in Fig. 6, and the angles of α , β , γ and δ are measured by the sensors and h and ℓ can be calculated with these angles.

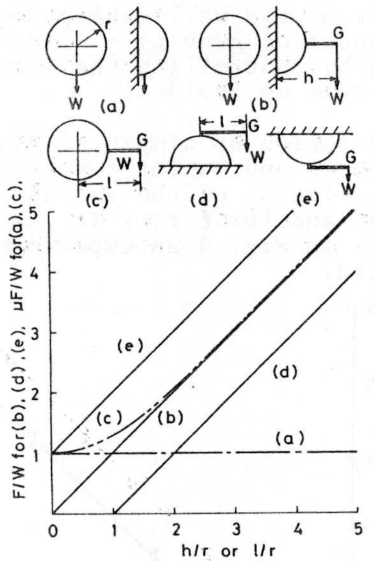


Fig.5 Total safety conditions.

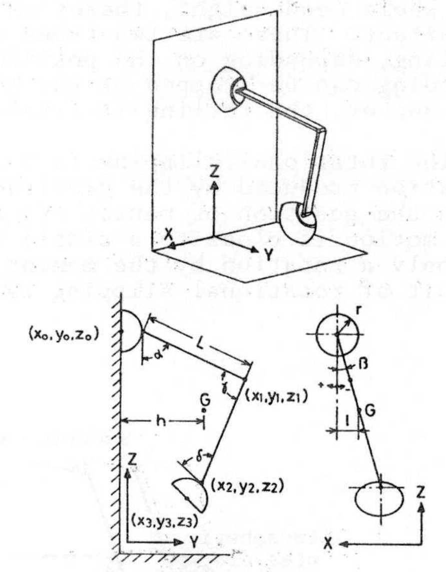


Fig.6 Model geometry.

If the friction coefficient μ is assumed, the required negative pressure in the sucker can be estimated by combining the above center of gravity and Fig. 5. This pressure p_0 is also given on the blower performance map, shown in Fig. 7 as an example. On the other hand, just after a cup is fixed on the wall, the pressure is measured, which is p in Fig. 7 for example. It is a little larger than p_0 , so that the input voltage V must be increased to rise the pressure to get a certain margin. But in this case it is important to know whether p is on the curve of A or B. If it is on B, the maximum pressure margin, $S_B = p_2/p$ is less than the case of A, $S_A = p_1/p$, so that the fixing position has to be changed, if S_B is not enough. For the larger air leakage, curve B, the required input voltage is higher for the same pressure p. Therefore the maximum pressure margin can be calculated by using the blower performance map, which is given beforehand in the computer memory.

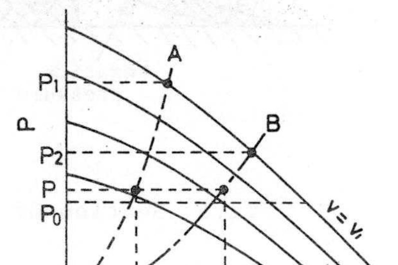


Fig.7 Blower performance map.

4. Control System of the Model

The model is shown in Fig. 8, and its dimensions are presented in Table 1. A small blower is set in each cup and five DC motors are used at each hinge and pivot.

4.1 Assumed environment

To build up a control system the following environment is assumed as a basic one.

(1) It is composed of the combined flat walls.
(2) On each wall there is at least a place where a sucker can be fixed on it.
(3) There are no obstacles on the wall.

The followings are measured by the robot itself.

(4) All rotation and inclination angles at the ankle and crotch.
(5) The negative pressure in the cup.
(6) The distance and angle to the opposite wall.

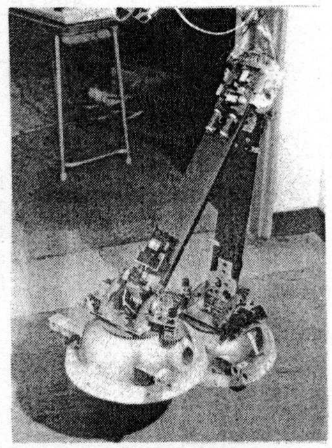


Fig.8 Robot model.

4.2 Control procedure

Firstly, on a vertical wall the negative pressure in the fixed cup is checked whether the pressure margin is enough or not, and the input voltage of the blower motor is controlled if necessary.

Secondly, the another sucker is parted from the wall and forced to move upward. The path of the moving is selected as decreasing the moment acting on the fixed cup by a combined adjustment of rotational motion at the ankle and inclinations at both ankle and crotch. The base plane of the cup is moved parallel to the wall surface. At the end of the movement, the cup is pushed to the wall and the clearance is controlled by using a pair of photo-electronic distance sensors which are set in the cup. Then the blower motor is started and the cup is fixed on the wall easily. The negative pressure is checked and the same controll system starts again.

Therdly, when the robot approaches to the opposite wall, the distance and angle to the wall are measured by a pair of ultrasonic sensors, which are set on each cup. And the pace of walking is adjusted before the wall, since an appropriate distance is required to transfer to the opposite wall depending on its mechanical restriction at the ankle. The next step is a transition. Now, as the distance from the fixed cup to the opposite wall is measured, the required angles of each hinge and pivot can be calculated. After moving according to these angles, the moving cup is pushed to the opposite wall, and a fine control is carried out with the feed back signals of the photo-distance sensors.

4.3 Control units

The main control unit is an off-boad 8-bit micro-computer, and other sensors and sub-units on the robot are given in Table 2. They are connected to I/O ports of the computer.

5. Numerical Simulation

To buid up a control program, the walking motion is simulated by a computer. Two cases are treated. One is a walking on a vertical wall,

Table 1 Dimensions of the model.

Sucker	weight	3.65 kg
	radius	16.5 cm
	rotational angle	-180° ~ +180°
Leg	weight	2.35 kg
	length	70 cm
Total weight		12.0 kg

Table 2 Control units.

Motor	DO	Relays
Blower	AO	Triac
Angle	AI	Potentiometers
Pressure	AI	Pressure-sensors
Forward distance	DIO	Ultra-sonic sensors
Cup-to-wall distance	DI	Photo-distance sensors

D: digital, A:analog, I:input, O:output

and the other is a transition from a vertical wall to the ceiling. In Fig. 9 the analyzed motion on a vertical wall is presented and for each station the force acting on the fixed sucker is shown in Fig. 10 by the corresponding letters. The abscissa is a relative distance and h and ℓ are same as ones in Fig. 5.

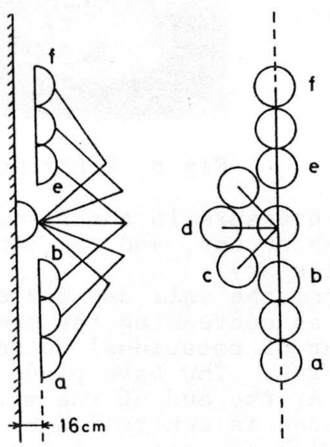


Fig.9 Analyzed motion on a vertical wall.

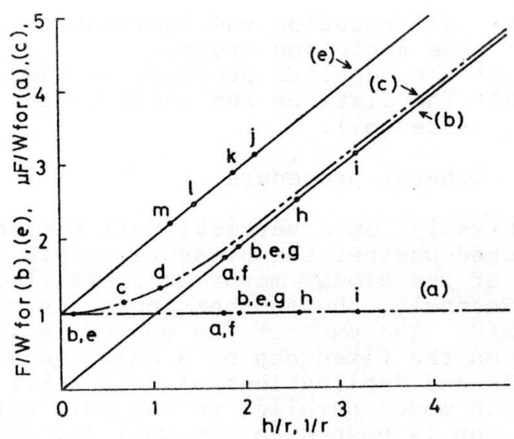


Fig.10 Forces acting on a fixed sucker.

The transition process from a vertical wall to the ceiling is shown in Fig. 11. It is seen that the most severe condition is point i or j from this figure and it is verified in Fig. 10, that is, the largest value of F/W is obtained for the point i or j.

The required negative pressure for each point is shown in Fig. 12 on the curve of blower performance. Assumed curves of A and B correspond to less and larger leakages respectively. The amount of leak air depend on the relation between the wall surface roughness and the shape of peripheral lip. If the surface is flat and smooth, the leak is small, and the higher pressure can be obtained for the same motor input voltage. As the air flow through the fan is utilized for motor cooling, the small amount of leak air brings a severe condition in regard to motor cooling. On the other hand, a higher input voltage produces a larger negative pressure margin, therefore a safer situation is obtained. To compromise these opposite conditions, the input voltage is controlled to get twice margins of the required pressure for a given situation. On the curve of B in Fig. 12, points i, j, and k are not satisfactory on this view point, and these situations are avoided in practical experiments by adjusting the fixing position on the ceiling.

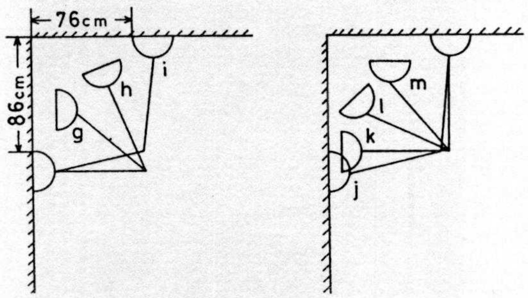


Fig.11 Transfer motion from wall to ceiling.

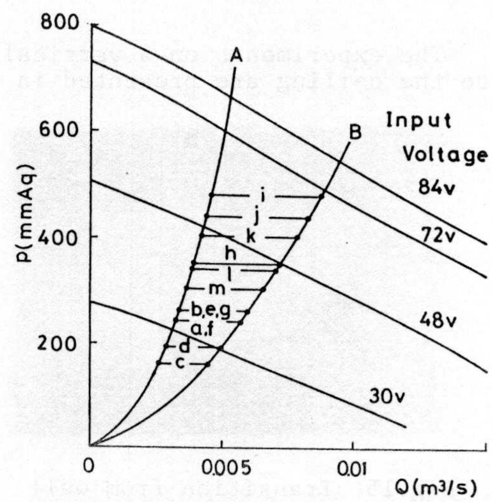


Fig.12 Required pressure on a blower performance.

6. Experiments of Walking

A control program was built up based on above simulations. The continuous walking from the floor to the ceiling through the vertical wall was examined. It was easy to walk on the floor, vertical wall and ceiling according to the control program, and the safety of walking was confirmed by these experiments. However, the transition from the floor to the vertical wall or vertical wall to ceiling was a little difficult to control. On the last two steps before the opposite wall, the pace of walking was adjusted to leave a certain distance from the fixed cup to the wall. After that the angle between the direction of motion and opposite wall was corrected to be right angle, and the leg was stretched. When the moving cup approached to the wall, the clearance between the base of the cup and wall surface was controlled. But this fine regulation was difficult by a backlash of gear at the ankle and deformation of legs. A half of trials succeeded for transfer walking in the experiments. For a case of failure, a little help of manual control was required to accomplish the mission.

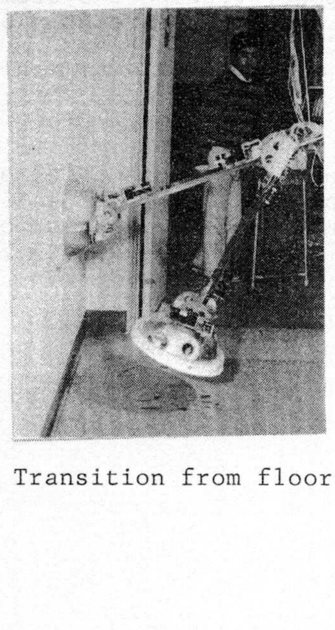


Fig.13 Transition from floor to wall.

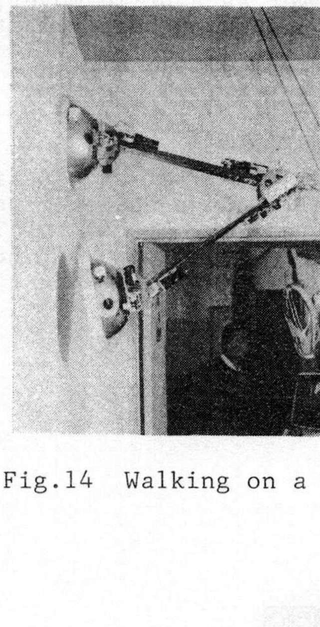


Fig.14 Walking on a wall.

The experiments on a vertical wall and transfer walking from a wall to the ceiling are presented in Figs. 13, 14, 15 and 16.

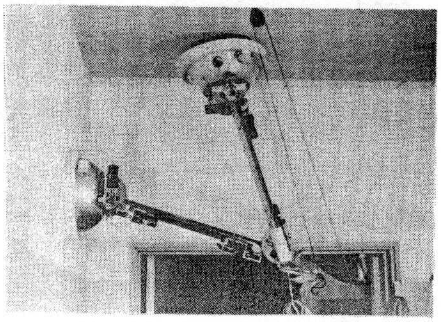


Fig.15 Transition from wall to ceiling.

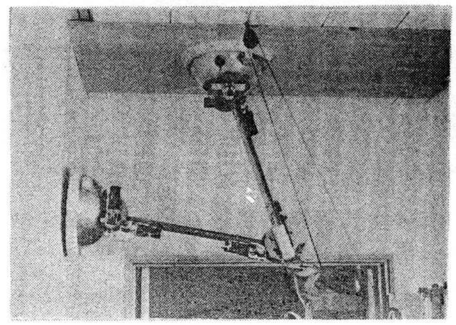


Fig.16 Transition from wall to ceiling.

7. Conclusions

To climb up the vertical wall for inspection use, a bipedal walking robot model was constucted and tested. By the investigation the followings are summarized.

(1) A bipedal walking mechanism of the model has an attructive characteristic to move on a vertical wall and ceiling safely.
(2) The safety conditions of a sucker are obtained and that of rotational slipping is acertained by the experiment.
(3) To develop a control system of the model, a numerical simulation was carried out, and a basic controller was built up.
(4) The safety of moving of the model on a vertical wall or ceiling was confirmed by the experiments.
(5) The continuous transfer from the floor to the wall and the wall to the ceiling could be achieved in the experiments.

A self-powered and self-controlled robot is expected for practical use. As a future development of this type robot, a model with a small engine and blower as a prime mover, pneumatic power transport system to the actuators and on-boad computer controll system is currently being investigated.

References

(1) Nishi A., et al., Design of a robot capable of moving on a vertical wall, Advanced Robotics, Vol. 1, No. 1, 1986, pp. 33-45.
(2) Nishi A., Eguchi H., Two-legs walking robot with suction cups (in Japanese), Bull. of the Faculty of Eng., Miyazaki Univ., No. 31, 1985, pp. 119-127.