# Fundamental Study on a Wall-climbing Robot

Kiichi Ikeda, Taketoshi Nozaki
Vehicle Engineering Division, Machinery Department
Mechanical Engineering Laboratory, AIST, MITI
1-2 Namiki, Tsukuba-shi, Ibaraki-ken, 305 Japan

Saburo Shimada
Chemical Housing Co.,Ltd.
2-15-1-418 Dogenzaka, Shibuya-ku Tokyo, 150 Japan

Yoshio Tajima
No.1 Group Future Business Development Department,
R&D Division . Yokohama Rubber Co.,Ltd.
2-1 Oiwake, Hiratsuka-shi, Kanagawa-ken, 254 Japan

## ABSTRACT

There is a great need for the development of a robot to perform painting and cleaning of high-rise buildings and tanks and similar dangerous tasks. The Mechanical Engineering Laboratory has been developing a wall-climbing robot (MEL-SPIDER) which can adhere to rough-finished walls using vacuum suction cups and can move up and down as well as to the right and left. Two prototypes were studied: a separate type (MSII) and a self-contained type (MSIII). For the separate type, the power/control unit was set on the ground separated from the main mobile unit. Power and control signals were supplied to the main mobile unit by pneumatic tubes and electric cables. The MSII has eight legs and each leg terminates with a vacuum suction cup. Each cup comprises a metallic disk with a closed-cell foamed rubber sealing ring around the edge. The vacuum for the suction cup is supplied by a vacuum pump in the power/control unit. The eight legs are in two groups of four legs each. Climbing is achieved by moving the two groups alternately while synchronizing the suction and release control signals for their suction cups. Movement is achieved by DC servo motors. The MSII weighs 17 kg and its dimensions are 85 cm(L) 55 cm(W) 25 cm(H). Climbing experiments on vertical walls of concrete buildings were successful, and many points to be improved concerning adhering and climbing methods were found. These improvements were incorporated in the development of the MSIII which carries all devices including the power source and controller. The MSIII uses an engine to drive both a generator and vacuum pump and its movement is remotely controlled by the operator. The MSIII weighs 35 kg and its dimensions are 100 cm(L) 58 cm(W) 32 cm(H). Climbing tests on the wall were successful, and the technical possibility of this moving method on vertical walls was presented.

## 1. INTRODUCTION

The tasks of cleaning and inspecting outside vertical walls of high-rise buildings are presently undertaken by human operators with the aid of suspended gondolas or set-up scaffolding. These tasks , however, involve dropping and falling hazards and where scaffoldings are set up, high costs as well. The development of robots to do such tasks has lately been urgently demanded.[1]-[5]

The Mechanical Engineering Laboratory has been developing a robot which can move around on walls as a part of the large-scale national R&D project,"Advanced Robot Technology", promoted by the Agency of Industrial Science and Technology of the Ministry of International Trade and Industry. A wall-climbing robot named MEL-SPIDER (hereafter abbreviated to MS) oriented for application over rough-finished wall surfaces is being developed there. MS clings to a wall surface with its vacuum suction cups, and uses a walking ( or climbing ) action via its leg mechanism to traverse the wall up and down as well as right and left.

## 2. BASIC CONSTRUCTION

The basic construction of MS is shown in Figure 1. Two types of robot are studied : the separate type that installs the power unit, controller, drive unit and vacuum pump on the ground, and the self-contained type that incorporates the power unit and so on. We will first present features common to both types.

### 2.1 Mechanical Structure

Figure 2 shows the fundamental mechanism of MS. It consists of a main body and eight telescoping legs which end in suction cups. The part marked ○ is a spherical joint, and that marked ⊙ is a joint rotating around the perpendicular axis to this paper surface. Two symbols, ╧╤ and ⊏ are the parts making linear movements by means of actuators. Since a self-locking function is necessary for each linear movement part, a screw mechanism is used.

The representative point S of the suction cup makes two kinds of motions, $L_1$ and $L_2$, shown by the broken lines. Motion $L_1$ is made by combining the linear movements of mechanisms A and B. Similarly, motion $L_2$ is done by combining the movements of mechanisms B and C. When MS walks, the eight suction cups are in two groups: one set of the four inner cups and the other set of four outer ones. The walking movement is achieved by alternately moving two sets of cups in a step fashion synchronized with their suction and release operations. For motion $L_1$, MS moves forward and backward, and motion $L_2$ moves it sideways.

Mechanism A is operated by a DC servo motor. The positions of the inner and outer sets of legs are detected by two limit switches attached to both ends of mechanism A. Each mechanism B is operated by a DC servo motor, and its extending and retracting length is detected by a potentiometer. DC servo motors used in mechanism C on rear are larger than those on the front because the applied loads between them are different. The position of a cup is detected by three limit switches which are attached to both ends and in the middle of mechanism C.

### 2.2 Suction System

Figure 3 shows the construction of a vacuum suction cup. The cup is constructed of a circular metallic plate of 8 cm diameter and a ring-shaped elastic material (closed-cell foamed rubber) surrounding the outer edge of the plate. The suction is applied as follows. First, the cup is pressed slightly on the wall by the extension of the leg. When the clearance between the elastic material and wall becomes smaller, the air in the cup is removed by a vacuum pump. The cup is able to adhere tightly to rough wall surfaces of up to 2 mm unevenness and its suction force is about 28 kgf. Closing of the clearance between wall and cups is detected by measuring the electric current of the motor used in mechanism B.

Figure 4 shows the construction of the suction system. MS uses eight suction cups, which are grouped into two sets of four and four. Each cup is linked to the vacuum pump by air tubes, and alternately adheres to the wall surface as synchronized with the walking movement of MS. The pressure in the cup is detected by a pressure switch.

### 2.3 Control Method

Figure 5 shows the forward walking movement of MS. Suction and release are performed at each step (3) and step (6). Backward movement is achieved by reversing this sequence. Sideways movements are achieved by driving mechanism C instead of mechanism A.

Figure 6 shows the operating sequence of each actuator while MS is walking. Motors A and B are used respectively in mechanisms A and B. There are two important points. First, the suction release of one set of cups must be performed after sufficient adherence of the other set of cups.(#1) Second, the length of mechanism B must be slightly adjusted after completing its suction .(#2) The reason is that the extension length of mechanism B differs with each movement because soft elastic material is used. The walking movement is controlled by a micro processor.

This describes a climbing phase, but for a descending phase, motor A simply runs in reverse. For a lateral movement, motor C runs instead of motor A.

## 3. SAFETY CONDITIONS

This paragraph discusses the relationship between the suction force of cup required to allow MS to climb a wall and its total weight.

In Figure 5, states (3) and (6) represent the most severe dynamic requirements for MS to adhere to a wall surface. The states involve one set of suction cups fully adhering to the wall and the other set just starting to adhere. The various forces applied to MS in these states are shown in Figure 7. The symbols used here signify the following:

$N_{f1}$, $N_{f2}$, $N_{r1}$, $N_{r2}$ : Reaction forces exercised by the wall on suction cups

$f_{f1}$, $f_{f2}$, $f_{r1}$, $f_{r2}$ : Frictional forces between suction cups and the wall

$W$ : Weight of the main mobile unit of MS

$L_s$ : Stride of walking movement

$L$ : Spacing of suction cups

$h$ : Distance from the wall to the center of gravity G

$F_s$ : Suction force of suction cup

$\mu$ : Maximum static frictional coefficient

$F$ : Pressing force of suction cup

By assuming 1) $\mu$, $F$ and $F_s$ respectively to be fixed, 2) $N$ and $F$ to be applied concentrically to the center of suction cups, and 3) point A to be located on the wall surface, the following equations must be satisfied for these forces to be balanced, namely

X-axis direction :

$$2N_{f1} + 2N_{f2} + 2N_{r1} + 2N_{r2} - 4F_s = 0 \quad \ldots\ (1)$$

Y-axis direction :

$$2f_{f1} + 2f_{f2} + 2f_{r1} + 2f_{r2} - W = 0 \quad \ldots\ (2)$$

Moment around point A :

$$-2N_{f1}(L + L_s) + 2(F_s - N_{f2})\,L - 2N_{r1}L_s - W\,h = 0 \quad \ldots\ (3)$$

The frictional force may be expressed as follows:

$$f_{f1} \leq \mu\, N_{f1} \quad \ldots\ (4)$$

$$f_{f2} \leq \mu\, N_{f2} \quad \ldots\ (5)$$

$$f_{r1} \leq \mu\, N_{r1} \quad \ldots\ (6)$$

$$f_{r2} \leq \mu\, N_{r2} \quad \ldots\ (7)$$

First, we obtain the condition for MS not to slide off the wall. It is given by the equation below eliminating N and f from equations (1), (2), and (4) through (7).

$$W \leq 4\,\mu\, F_s \quad \ldots\ (8)$$

Next, we obtain the condition for MS not to fall off the wall. Firstly, a fall-off limit coincides with zero reaction forces applied to suction cups, then $N_{f2}$ and $N_{r2}$ may be expressed as follows:

$$N_{f2} = N_{r2} = 0 \quad \ldots\ (9)$$

By substituting equation (9) in equation (1) and (3), we find the reaction forces $N_{f1}$ and $N_{r1}$ to be given by the equation below.

$$N_{f1} = \left(1 - \frac{2L_s}{L}\right) F_s - \frac{h}{2L} W \quad \ldots\ (10)$$

$$N_{r1} = \left(1 + \frac{2L_s}{L}\right) F_s + \frac{h}{2L} W \quad \ldots\ (11)$$

Since equations (10) and (11) assure $N_{r1} > N_{f1}$ at all times, the fall preventive conditions are given as follows by replacing $N_{f1}$ in equation (10) with F and reorganizing it:

$$W = \frac{2L}{h}\left\{\left(1 - \frac{2L_s}{L}\right) F_s - F\right\} \quad \ldots\ (12)$$

Figure 8 shows the safety regions acquired by substituting the parameters of MS in equations (8) and (12), where the values of parameters are shown in Table 1. Zone (IV) in Figure 8 represents a region to assure no fall-off or slide-off, and zone (I) conversely a region where both fall-off and slide-off occur. Zones (II) and (III) are situated in between the above two. Marks ⊗ indicate suction force and weight of the main mobile units of MSII and MSIII that we have built trially. Their levels reveal an ample load capacity against the given suction force.

To achieve a still higher load capacity of the robot, equation (12) teaches us the below described possibilities.

1) The load capacity may be increased by reducing h , F and $L_S$.

2) The load capacity will be reduced by increasing $F_S$ and L.

## 4. HARDWARE AND EXPERIMENTS

### 4.1 Separate Type (MSII)

The our first phase, we placed foremost emphasis on its light weight. The basic construction of MSII is shown in Figure 9. The portion in the broken line border has been built into the main mobile unit, and the remainder, consisting of the drive unit and controller as well as the vacuum pump and other components, is set on the ground.

Figure 10 gives the whole view of MSII thus built. The main mobile unit is 85 cm long, 55 cm wide, and 25 cm high, and weighs 17 kgf. Its vertically climbing speed is 0.5m/min and its lateral shifting speed is 0.25 m/min, which prove its good performance.

But some problems have been revealed by the tests. The first problem is a negative pressure drop-down phenomenon occurring at suction cup switching as in steps (3) and (6) in Figure 5. To elaborate, since the inner and outer suction cups simply branch out from the vacuum pump as shown in Figure 4, when solenoid valve switches on to make the outer suction cups cling to the wall, it significantly lowers the negative pressure in the inner suction cups. This is a serious issue that affects the safety of MSII.

The second problem is about the pressing force of suction cup. The higher the pressing force, the better the sealing performance. But the force acts to pull the other set of suction cups off the wall and reduces the safety margin of MSII. Therefore, an elastic material that provides adequate vacuum sealing at minimal pressing force is required.

### 4.2 Self-contained Type (MSIII)

Based on the test results with MSII, we designed the self-contained type. Its basic specifications are the same as those of MSII except its 35 kg weight.

The basic construction of MSIII is shown in Figure 11. For its primary power unit, an internal combustion engine is employed that drives a vacuum pump and DC generator. The vacuum pump operates the suction cups, and the DC generator and a built-in storage battery energize various actuators, such as DC servo motors and solenoid valves. In designing the mechanism of main mobile unit, a space has been provided in the middle of mechanism A for mounting the engine and DC generator and so on.

To prevent the negative pressure drop described earlier, it is necessary to provide a sufficiently large volume of the piping from solenoid valve to the vacuum pump, as compared with the combined volume of suction cups and the piping from the solenoid valve to suction cups. For this purpose, an accumulator has been provided between the solenoid valves and vacuum pump.

The travel control is exercised only over its four directional movements, up/down and right/left, by the operator using remote radio control. In designing the controller, particular attention has been paid to prevent interference of the engine noise. For the power subsystem, there were three approaches: a generator, a battery, and a generator plus a battery. The third approach has been selected because of its higher capabilities to withstand electric load variations and its lighter weight.

Figure 12 shows the MSIII climbing the concrete wall of a building. The MSIII overall dimensions are 100 cm long, 58 cm wide, and 32 cm high, and it weighs 35.4 kgf. Table 2 shows the list of actuators and sensors used in it.

Figure 13 shows sample data acquired from the walking tests of MSIII on the vertical concrete wall, where. [1] are records of the DC generator output current, and [2] through [6] the outputs in response to the signal inputs of [1] through [5] shown in Figure 6. Due to the engine drive, noise is superimposed on the signals. Its lateral movements have also checked out satisfactorily, and the feasibility of a self-contained wall-climbing robot has now been assured.

## 5. CONCLUSIONS

The Mechanical Engineering Laboratory has developed a self-contained wall-climbing robot, MEL-SPIDER, and has showed the technical possibilities by walking tests on vertical walls. There are several tasks for the future: 1) to develop a transfer mechanism necessary for MEL-SPIDER to move continuously from the floor to the wall, 2) to increase the locomotive speed of MEL-SPIDER, 3) to improve the performance of suction cups and suction system.

In closing we extend our sincerest appreciation to Mr. M. Abe, Deputy Director-General, Dr. T. Yada, Director-General of the Machinery Department, and Dr. E. Nakano, Professor of Tohoku University, for their valuable suggestions and guidance in pursuing this research objective.

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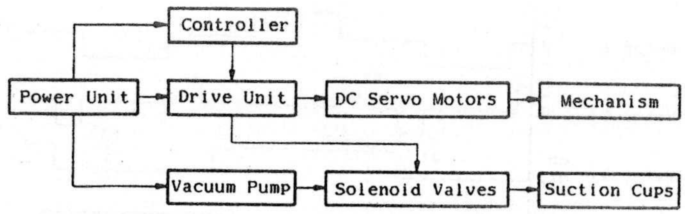


Fig.1 Basic construction of MS

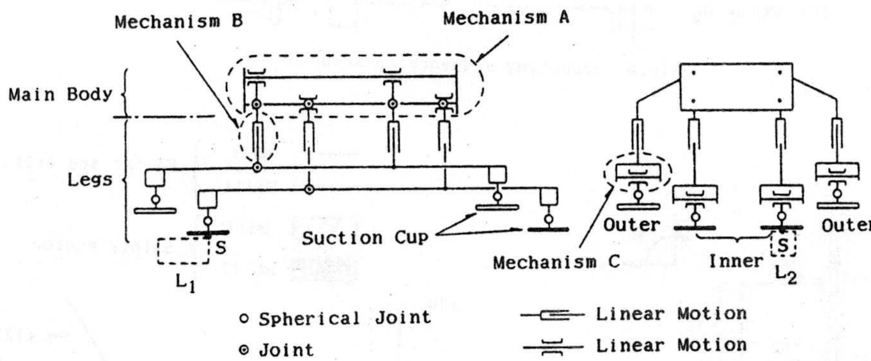


Fig.2 Fundamental mechanism of MS

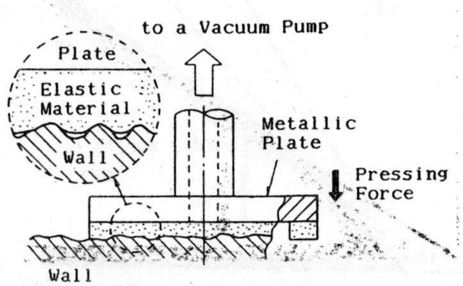


Fig.3 Construction of vacuum suction cup

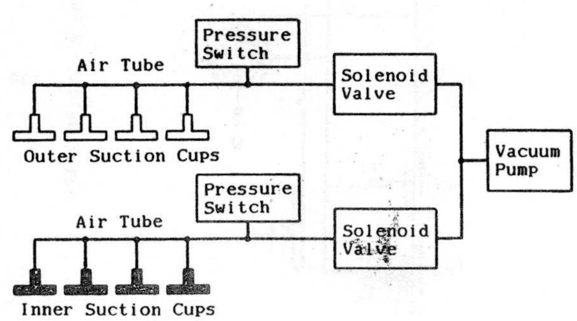


Fig.4 Construction of suction system

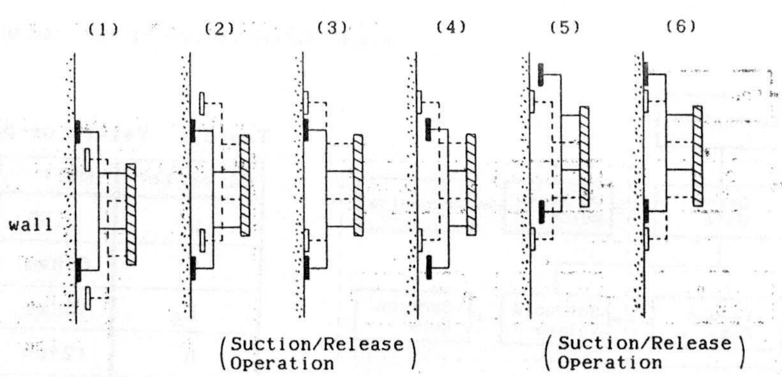


Fig.5 Walking movement of MS

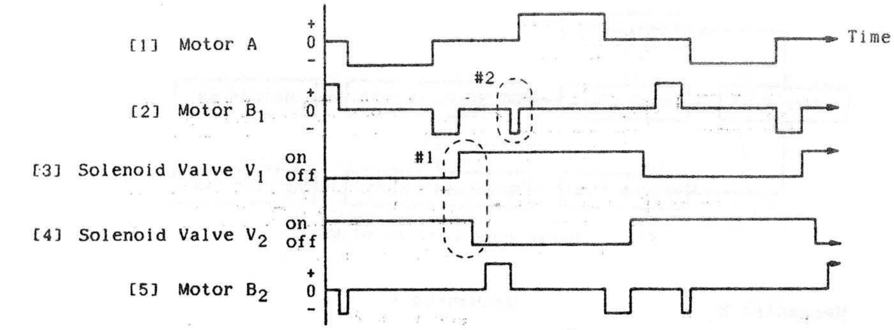


Fig.6 Operating sequence of actuators

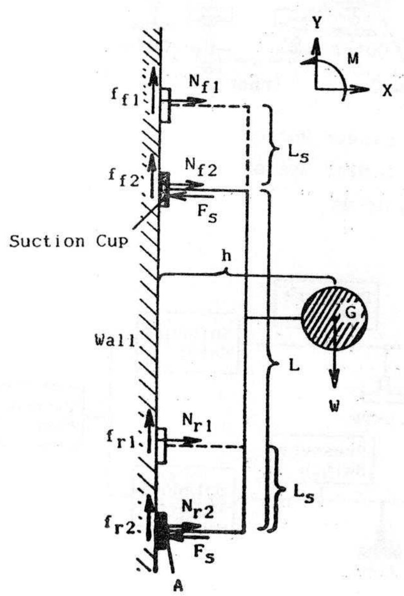


Fig.7 Various forces applied to MS

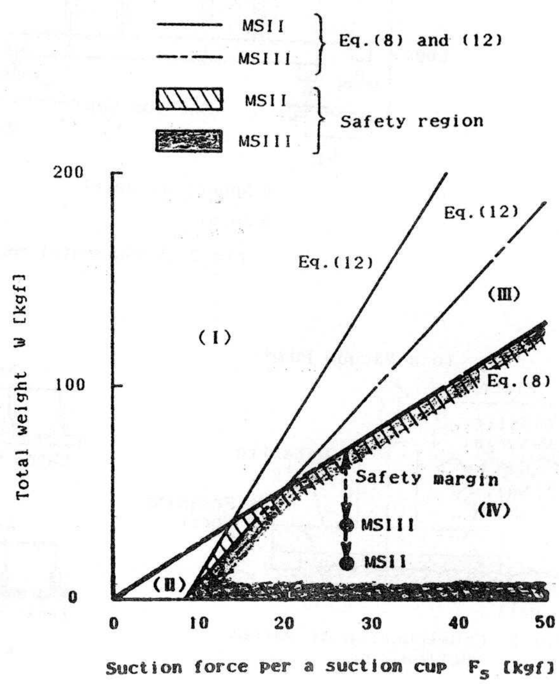


Fig.8 Safety regions of MSII and MSIII

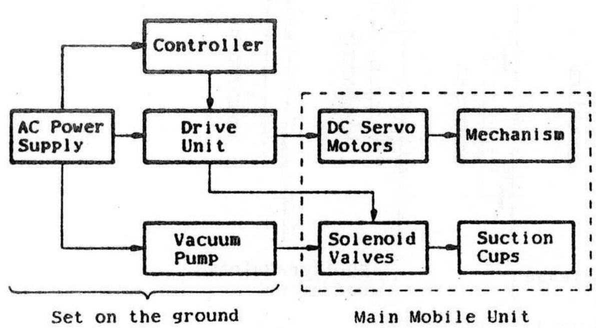


Fig.9 Basic construction of MSII

**Table 1 Values of parameters**

| Parameter | MSII | MSIII |
|---|---|---|
| $\mu$ | 0.65 | 0.65 |
| L | 660mm | 770mm |
| $L_s$ | 130mm | 150mm |
| h | 120mm | 210mm |
| F | 5kgf | 5kgf |

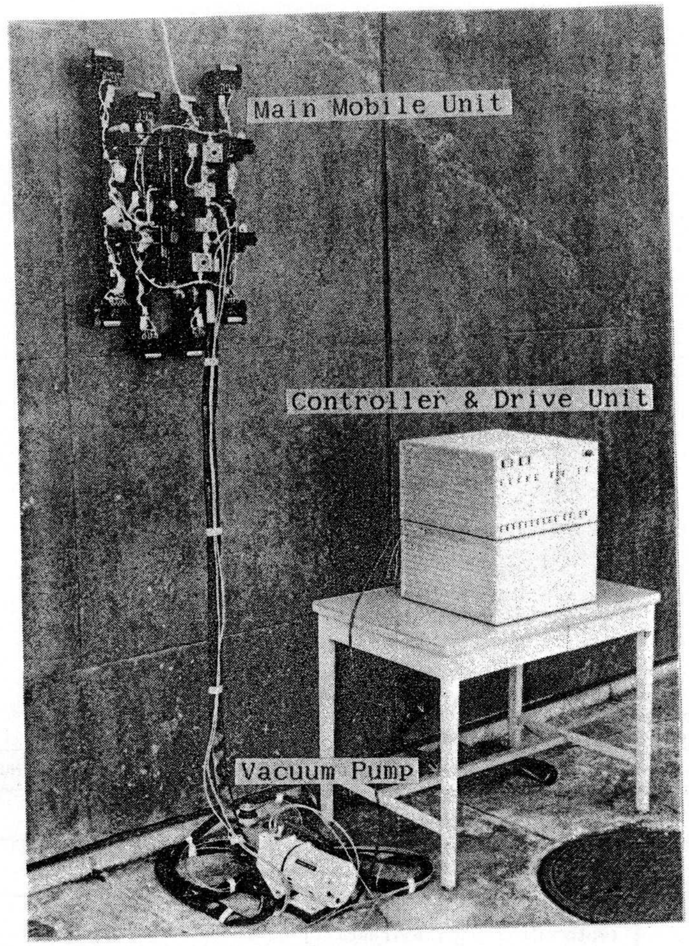


Fig.10 Whole view of MSII

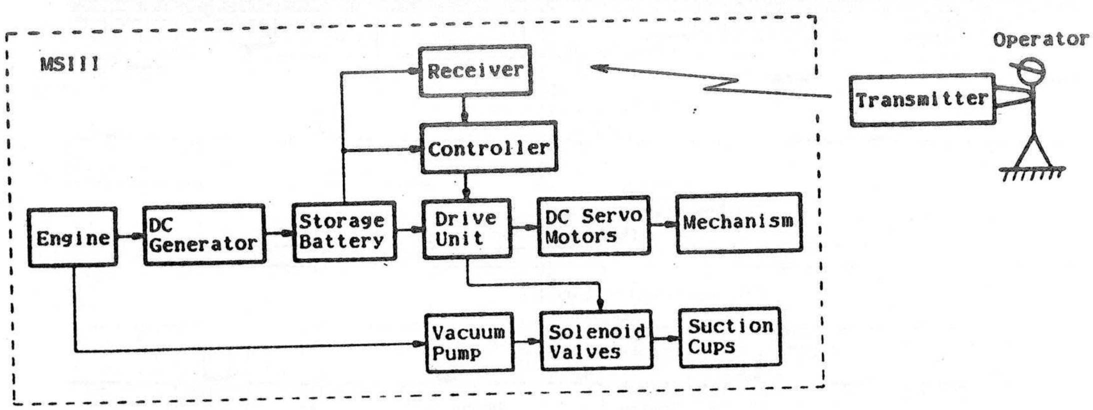


Fig.11 Basic construction of MSIII

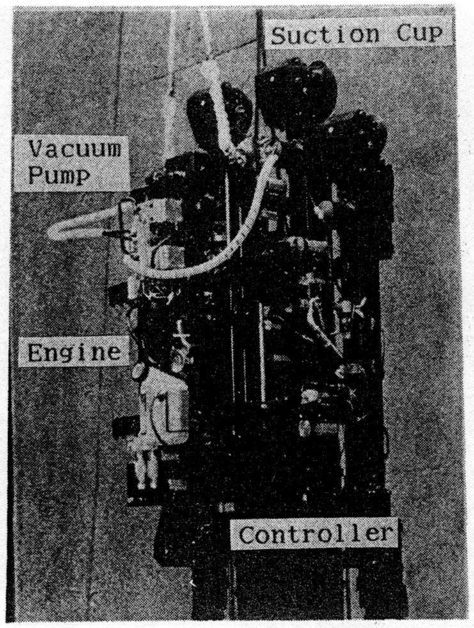


Fig.12 Whole view of MSIII

Table 2 Actuators and sensors used in MSIII

| Component / Mechanism | Actuator | | | Sensor | |
|---|---|---|---|---|---|
| | Kind | Reted power | Number | Kind | Number |
| Mechanism A | DC Servomotor (Motor A) | 100W | 1 | Limit switch | 2 |
| Mechanism B | DC Servomotor (Motor B) | 4W | 8 | Potentiometer | 8 |
| Mechanism C | DC Servomotor (Motor C) | 4W(front)<br>7.6W(rear) | 4<br>4 | Limit switch | 24 |

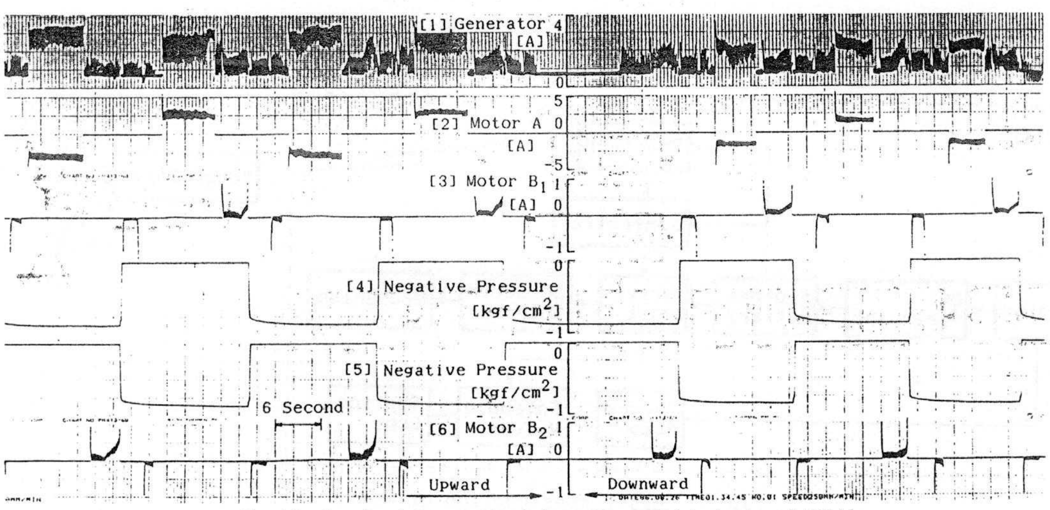


Fig.13 Sample data acquired from the walking tests of MSIII