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# Development of multi-purpose mobile robot capable of traveling along columns and beams

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**Abstract**

Steel frameworks are conventionally erected by tradesmen working on scaffolding at heights, and the process is therefore dangerous to a certain extent and is dogged by the problems of a lack of skilled workers and the need for safety improvements. Recognizing such problems, we have been developing a new mobile robot that can travel freely along columns and beams to automate erection work, welding inspections, etc. The robot travels vertically and horizontally as an inchworm does and can shift from column to beam and vice versa, changing its posture.

Tests of the mobile robot's ability to support itself have shown that its basic performance is satisfactory.

## 1. INTRODUCTION

One way to automate dangerous work at construction sites, such as erecting steel frames at heights, could be to use robots: robots on mobile scaffolds, or robots able to move around the framework of a building. The goal of this project is to develop a multi-purpose mobile robot able to travel along columns and beams, making possible the automation of steel frame erection, welding inspection, and other tasks.

This paper outlines an experimental mobile robot and the results of evaluating the capability of its self-support mechanism.

## 2. OBJECTIVES

Figure 1 is a sketch of the proposed robots in use. The objective of our development project is to produce a robot able to make its way freely along the columns and beams that frame a structure and which can accomplish the tasks expected of it. Thus it must have two broad types of capability: task-performance and mobility. The goal for the first stage of development is to design and build a basic machine possessing the required capacities listed below, and to evaluate its performance.

- Self-support: the ability of the robot to stop at a given location on a column or beam and support its own weight
- Vertical and horizontal mobility: the ability to traverse columns and beams

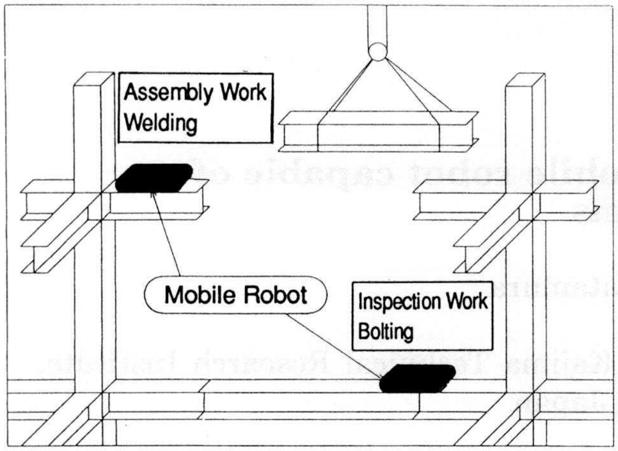


Figure 1. Mobile Robots in Use

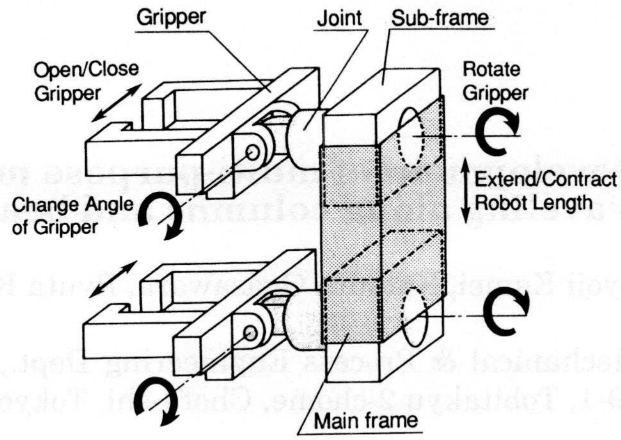


Figure 2. Mobility Mechanism

- Column-beam shift: the ability to shift position from column to beam and vice versa

## 3. MOBILITY MECHANISM

### 3-1 Structure

Figure 2 is a sketch of the robot's mobility mechanism, designed as a result of our study to provide the requisite capabilities mentioned above.[1]

Each of the two grippers shown in the figure has a mechanism which acts along one axis with one degree of freedom and generates the force needed to hold a column or beam. The sub-frames include a mechanism which acts along the main frame with one degree of freedom and extends or withdraws the sub-frame and thus changes the total length of the robot. Each joint has two degrees of freedom in rotation, and can change the angle of the gripper relative to the length of the robot and rotate it so the unit can shift itself (for example) from column to beam.

### 3-2 Action

The specific actions of which the robot is capable are described below.

*a. Self-support*

The robot supports itself by using the friction force generated by holding a column or beam with its grippers.

*b. Vertical and horizontal mobility*

The unit resembles an inchworm as makes its way vertically or horizontally, by repeating this process: opening the lead gripper, extending its length, closing the

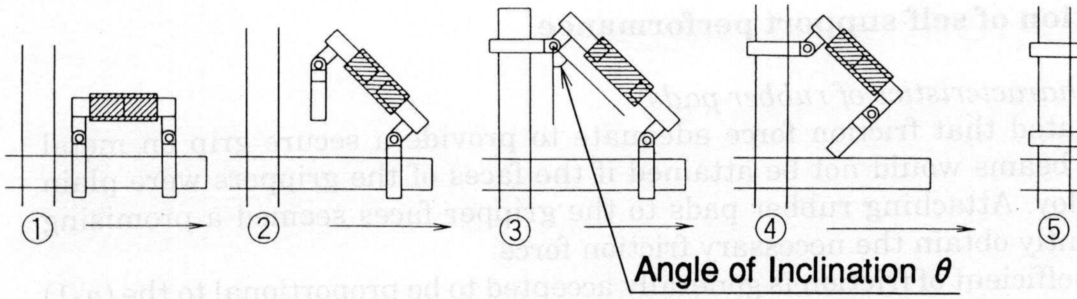


Figure 3. Shift from Beam to Column

lead gripper, opening the trailing gripper, contracting its length, and closing the trailing gripper.

*c. Column-beam shift*

Figure 3 is a series of sketches showing the robot shifting itself from a beam to a column: the robot lifts its front end, the lead gripper is rotated into place and grasps the column, the robot contracts, and the trailing gripper grasps the column.

This combination of capabilities permits the robot to move freely throughout the frame of a building, as indicated in Figure 1.

# 4. DESIGN OF EXPERIMENTAL UNIT

## 4-1 Design of main body

The following basic specifications for an experimental unit were set forth.[2]

*a. Dimensions of columns and beams*

As simplified models of columns and beams, 150-mm square pipes were to be used. The columns and beams were to be free of obstructions.

*b. Drive unit*

For controllability, an electric motor was to be used. Power and control signals were to be sent to the robot through wires.

*c. Form and dimensions of main frame*

The grippers were to be sufficiently longer than the depth of columns and beams so that fall-prevention hooks could be added to the end of each gripper arm. The form and dimensions of the robot's main frame were to be determined from the size of the grippers, on the basis of the mobility mechanism sketched in Figure 2. The main frame was to be made of aluminum alloy for light weight.

The power needed for each subset of the mobility mechanism was calculated using a simulation tool, and then the main frame was designed.

## 4-2 Evaluation of self-support performance

*a. Spring characteristics of rubber pads*

We anticipated that friction force adequate to provide a secure grip on metal columns and beams would not be attained if the faces of the grippers were plain aluminum alloy. Attaching rubber pads to the gripper faces seemed a promising way to efficiently obtain the necessary friction force.

Rubber's coefficient of friction is generally accepted to be proportional to the $(n\text{-}1)$ power of the compressive load, the value of $n$ varying roughly from 3/4 to 8/9 depending upon conditions.[3] Because we needed to know beforehand the spring characteristics of rubber under the conditions in which it was to be used, experiments were performed to measure rubber's characteristics when subject to shear and compressive force, as indicated in Figure 4. Knowing the spring characteristics of rubber subjected to compressive force made it possible to predict the force a gripper could exert as a result of compressing its rubber pads.

Figure 5 shows the results of an experiment in which the spring characteristics of a rubber pad 60 mm long, 50 mm wide and 20 mm thick were measured by applying shearing force. The solid line in the graph is the characteristic curve for such a pad compressed by 2 mm ($d$=2 mm), and the broken line is the characteristic curve for compression by 4 mm ($d$=4 mm). When the pad was compressed by 2 mm it slipped against the plate when shear deformation increased to just over 9 mm, and when it was compressed by 4 mm it slipped when shear deformation increased to roughly 10 mm. Consequently, shear deformation limits ($X_c$) were set at 8 mm and 9 mm for such a pad compressed by 2 mm or 4 mm, respectively. The load corresponding to the shear deformation limit was defined as permissible load $F_a$.

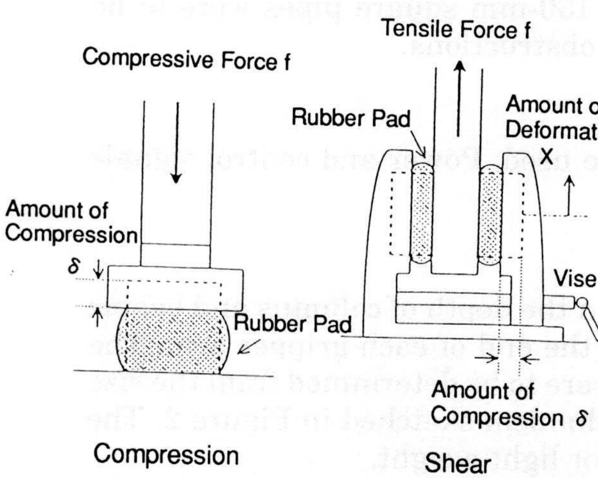


Figure 4. Experiment on Spring Characteristics of Rubber Pads

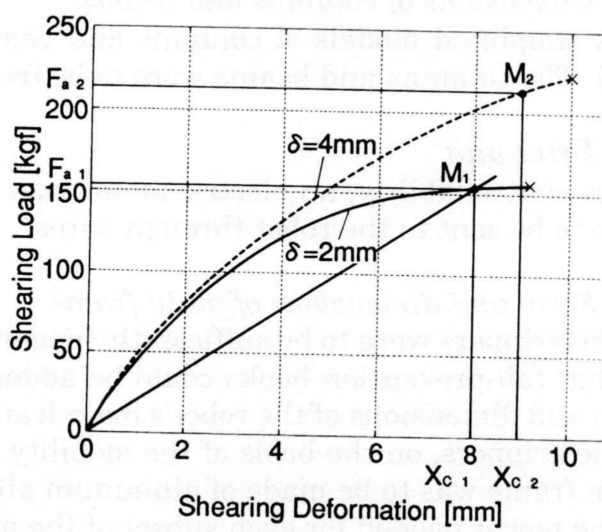


Figure 5. Spring Characteristics of Rubber Pad under Shearing Force

*b. Evaluation of self-support capability*

To evaluate the validity of the self-support mechanism adopted for this robot, the results of the experiments on the spring characteristics of the rubber pad described above were incorporated in an analysis of the robot's self-support mechanism.

Figure 6 is a sketch of the self-support mechanism which was analyzed. In this configuration the gripper has two rubber pads on each face and balls to provide additional support for the moment produced by the robot's weight. This mechanism was analyzed using the analytical model shown in Figure 7. The analysis did not, however, take into account the effects of rubber pad being twisted; only the equation of static equilibrium was calculated.

In Figure 7, points A and B denote the rubber pads and point C the ball, point G indicates the robot's center of gravity, and points A', B', C' and G' show respective positions of these points in a state of equilibrium (∠OC'O'=$\theta$). $L_A$ and $L_B$ represent amount of deformation, and $F_A$ and $F_B$ the shearing loads, of the rubber pads, while $F_C$ indicates the reaction exerted on the ball. It is assumed that the ball bears no vertical force.

$L$ represents the distance from point O to the robot's center of gravity. Changes in $L$ can be related to changes in the attitude of the robot (or in load) caused by rotation around the gripper-angle axes. $L$ reaches its minimum or maximum value when angle of inclination $\theta$ is 0° or 90°, respectively.

Equations 1 and 2 describe equilibrium of forces and Equation 3 the equilibrium of the moment about point C' for this model.

$$0 = F_{CX} - F_{AX} - F_{BX} \tag{1}$$

$$0 = F_{AY} - F_{BY} - W \tag{2}$$

$$\begin{aligned} 0 = {} & F_{AX}\left[L_3 \cos\theta + (L_1 + L_2)\sin\theta\right] - F_{AY}\left[(L_1 + L_2)\cos\theta - L_3 \sin\theta\right] \\ & + F_{BX}(L_3 \cos\theta + L_2 \sin\theta) - F_{BY}(L_2 \cos\theta - L_3 \sin\theta) - W(L\cos\theta - L_3 \sin\theta) \end{aligned} \tag{3}$$

As Figure 5 indicates, the characteristics of the rubber pad are nonlinear. This means it is difficult to extract a general solution using Equations 1–3. Self-support capacity was therefore evaluated using the simplified method described below, substituting a linear spring for the rubber pads.

Referring to Figure 5, let us take the case of $d$=2 mm as an example. First draw a line $OM_1$ from the zero point to $M_1$, which falls on the shearing deformation limit of 8 mm in the spring characteristic curve. Then assume a linear spring whose spring characteristic is the line $OM_1$ in every direction in the $x$-$y$ coordinate plane, and which is represented by Equation 4.

$$F = \left(\frac{F_{a1}}{X_{c1}}\right)L \tag{4}$$

Next, substitute the linear spring for the rubber pad in Equations 1–3 above and solve for $F_A$ and $F_B$. If these solutions are smaller than the allowable shearing load, the robot can hold its own weight.

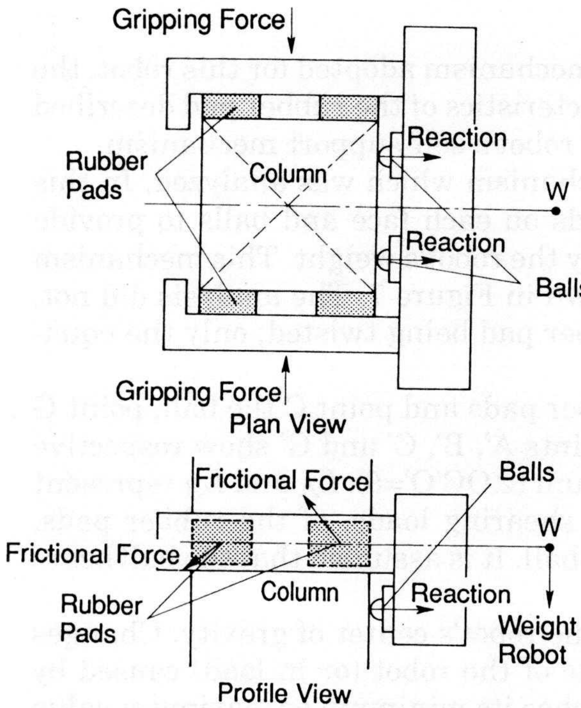


Figure 6. Self-Support Mechanism

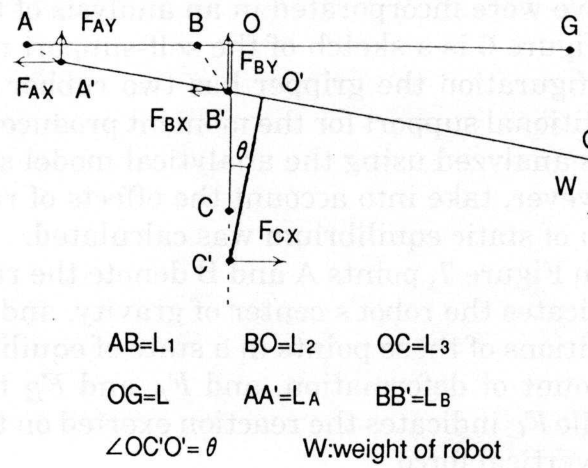


Figure 7. Analytical Model

Figure 8 shows the results of an evaluation using this method. Since shearing load $F_B$ on rubber pad B is always larger than $F_A$ on rubber pad A because of the equilibrium conditions, self-support capacity was evaluated in relation to rubber pad B only.

Figure 8 clearly shows that, with this pad, the robot cannot support its own weight if the angle of inclination is greater than 75° when the amount of compression is 4 mm ($d$ = 4 mm). But since the maximum angle of inclination in a shift from column such as that shown in Figure 3 is 45°, we conclude that the mechanism provides adequate self-support performance.

### 4-3 Experimental robot

The experimental robot which was constructed based on the results of our studies is shown in Photo 1. The robot is made of aluminum alloy and weighs 70 kg. DC servomotors are used as drive units with two installed in each of the grippers, two each for changing gripper rotation and angle relative to the length of the robot, and one more for extending and contracting the length of the robot, for a total of nine servomotors.

Basic tests of the experimental robot have confirmed that it has the necessary basic functions such as moving the grippers, and that it is able to exert the expected gripping force. Other tests have demonstrated that its self-support capacity is similar to that predicted by analyses.

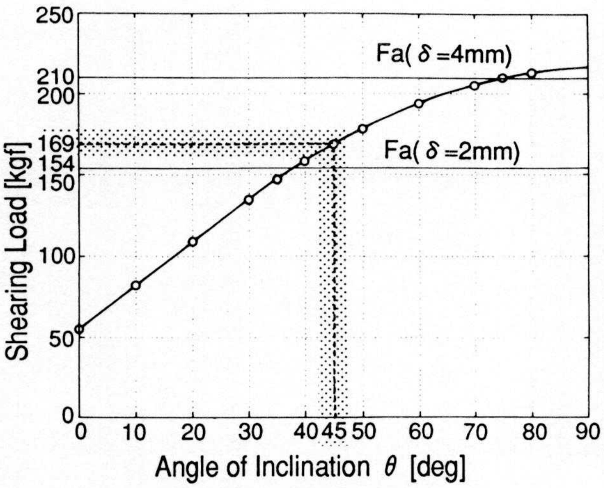


Figure 8. Self-Support Capacity

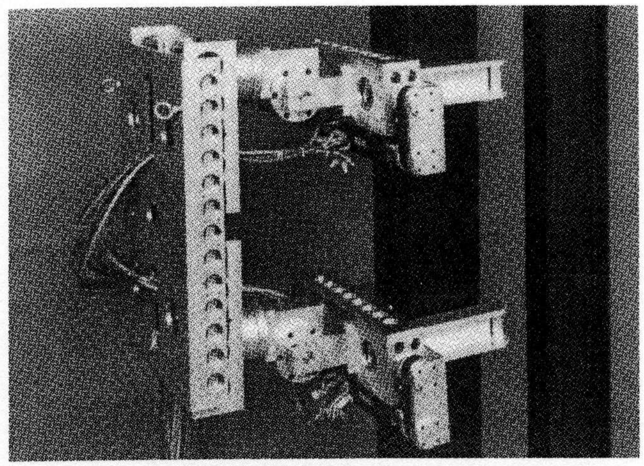

Photo 1. Experimental Mobile Robot

## 5. CONCLUSION

The mechanism of a multi-purpose mobile robot able to travel along columns and beams was devised, and its validity confirmed.

The next stages of this project will involve tests to verify the robot's mobility—its ability to move horizontally and vertically and to shift itself from column to beam and beam to column—and attitude control of a moving robot.

## REFERENCES

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