ON MECHANICS OF CLIMBING ROBOT

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ABSTRACT

The paper is devoted to the climbing robot developed in the Institute for Problems in Mechanics, USSR Academy of Sciences. This robot has a number of pneumatic grippers and can move along vertical walls. Several versions of this robot were created which can be used for purposes of inspection, painting, cutting, maintenance, fire fighting etc. Conditions of equilibrium of the robot on a wall are discussed. Both rigid and flexible structures of robots subject to different external forces and torques including dry friction are considered. Maximal loads are estimated that the robot can carry maintaining reliable contact with the surface of the wall.

1. Introduction

Mobile robots used now in industrial processes and in hazardous environment mostly have wheels or legs and can move along surfaces which do not differ greatly from a horizontal plane. However, in many cases it is necessary for a robot to move along surfaces with a great slope, along vertical planes (walls) and horizontal planes from below (ceilings). Such climbing robots are needed for a number of operations (painting, assembly, inspection, cutting, cleaning etc.) in construction, maintenance and repair of buildings and structures. These robots can be also useful in shipbuilding industry,for fire fighting and other applications.

Climbing robots have special grippers (feet) that fix the robot to the surface along which it moves. These grippers may be either magnetic or pneumatic (vacuum), see [1-4]. Magnetic grippers can be used only for surfaces made of ferromagnetic material. Vacuum, or pneumatic grippers are more universal and can serve for any smooth enough surfaces made of metal, tile, ceramics, concrete, for painted surfaces etc. The main requirement that the climbing robot must satisfy is a reliable contact with the surface: at each instant of time the robot must be firmly attached to the surface. In this paper we analyze this requirement, derive equilibrium conditions for the climbing robot and estimate its carrying capacity. Before that we describe briefly climbing robot developed in the Institute for Problems in Mechanics, USSR Academy of Sciences.

2. Structure of the climbing robot

Several versions of climbing robots were developed. Each of them consists of two mobile platforms 1, 2 and two groups of grippers 3, 4 attached to these platforms, see Fig. 1. Both platforms are parallel to the surface along which the robot moves, and can move with respect to each other in the direction parallel to their planes. One of the platforms 1 carries the payload 5 containing the technological equaipment which depends on the operation that the robot performs. The grippers can move in the direction perpendicular to the planes of the platforms. Each group can have different number of grippers. In one version one group has four grippers, and the other one has only one big central gripper. In other version both groups have four grippers. In any case, each group of grippers must be capable to carry the whole weight of the robot. All motions of platforms and grippers are performed by means of pneumatic drives consisting of cylinders and pistons. Each gripper has a rubber sucker; vacuum can be created between the sucker and the surface.

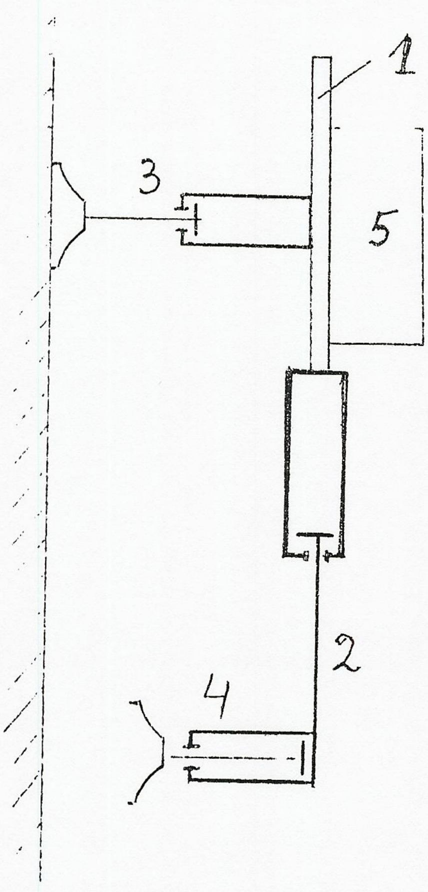

Fig. 1. Parts of the climbing robot

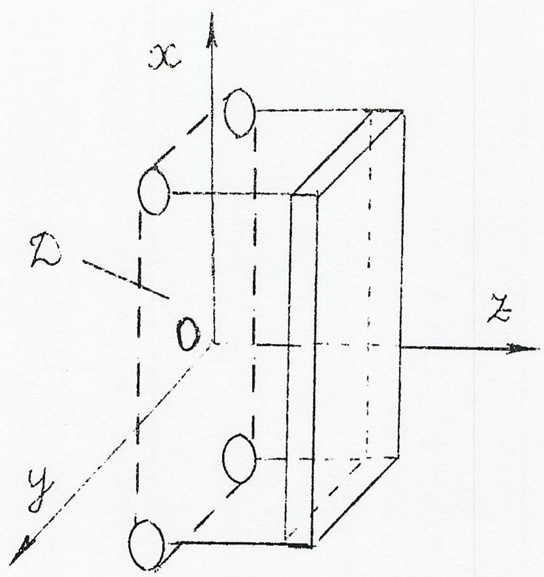

Fig. 2. The robot and the frame of reference

3. Algorithm of motion

At any instant of time one group of grippers is attached (sucked) to the wall. For instance, let the grippers 3 (and thus the platform 1) be fixed to the wall due to vacuum supported between these grippers and the surface of the wall. Then the platform 2 moves with respect to the platform 1 by means of pneoumatic drives. After that the grippers 4 approach the wall, touch it and are sucked to it due to vacuum created between these grippers and the wall. Then vacuum in the grippers 3 is removed, these grippers detach from the wall and move closer to the platform 1. Now the platform 1 moves with respect to the platform 2 which is fixed to the wall. Thus the robot makes a step; then the process is repeated, and so on. In such a way the robot moves in some direction. Special mechanism makes it possible to change the direction of motion. More details about the structure and algorithm of motion for climbing robots see in [4].

4. Equations of equilibrium

Consider a mobile robot attached to a plane by means of n vacuum grippers, see Fig. 2. Let a frame of reference $Oxyz$ be connected with this plane. Axes Ox and Oy lie in this plane, and the robot is situated in the half-space $z \geq 0$. Denote by x_i, y_i co-ordinates of the centres of grippers. The following forces act on the robot in the state of equilibrium :

1) external active forces (weight, tension of cables etc.) with a total force (R_x, R_y, R_z) and a torque (M_x, M_y, M_z) with respect to the point 0;

2) normal reactions $N_i \geq 0$ of the surface, $i = 1,\ldots n$;

3) tangential reactions of the surface with x, y - components X_i, Y_i satisfying Coulomb's law of dry friction (f is a constant coefficient of friction)

$$(X_i^2 + Y_i^2)^{1/2} \leq fN_i, \qquad i = 1,\ldots,n \qquad (1)$$

4) vacuum forces

$$\Phi_i = (p - p_i)S_i > 0, \qquad i = 1,\ldots,n \qquad (2)$$

directed against the axis z . Here p is the armospheric pressure, p_i is the pressure under the ith gripper, S_i is area of that gripper.

Equations of equilibrium can be divided into two groups containing different unknown forces (N_i and X_i, Y_i)

$$R_x + \sum (N_i - \Phi_i) = 0, \qquad M_x + \sum p_i(N_i - \Phi_i) = 0$$

$$M_y - \sum x_i(N_i - \Phi_i) = 0 \qquad (3)$$

$$R_x + \sum X_i = 0, \qquad R_y + \sum Y_i = 0,$$

$$M_z + \sum (x_i Y_i - y_i X_i) = 0 \qquad (4)$$

All sums are taken for all $i = 1,\dots,n$.

5. Conditions of equilibrium

In the state of equilibrium the unknown reactions N_i, X_i, Y_i satisfy equations (3), (4) and inequalities $N_i \ge 0$ and (1). Define K as a point in the plane Oxy with coordinates

$$x^* = \frac{\sum x_i\Phi_i + M_y}{\sum \Phi_i - R_z}, \qquad y^* = \frac{\sum y_i\Phi_i - M_x}{\sum \Phi_i - R_z} \qquad (5)$$

The moment of all external active forces and forces Φ_i with respect to K , has zero x, y - components. It can be shown that equations (3) have a solution $N_i \ge 0$ if and only if

$$\sum \Phi_i > R_z, \qquad K = (x^*, y^*) \in D \qquad (6)$$

where D is a convex hull of all grippers in the plane Oxy, see Fig. 2. Conditions (6) are necessary and sufficient for a rigid robot not to lose contact with the surface.

However, conditions (6) do not guarantee that equations (4) have a solution X_i, Y_i satisfying inequlities (1). It means that if (6) are satisfied the robot can still slide along the surface without losing contact with it.

Analysis of conditions (4), (1) for given positive reactions $N_i > 0$ shows that the robot will not slide along the surfacve if and only if

$$\sup_{x,y} Q \le f, \qquad Q = \frac{M_z - xR_y + yR_x}{\sum \rho_i N_i}$$

$$\rho_i = [(x - x_i)^2 + (y - y_i)^2]^{1/2}, \qquad i = 1,\ldots,n \tag{7}$$

Here sup is taken with respect to all x, y. If for some N_i all conditions (6), (7) are satisfied then the climbing robot is in equilibrium on the wall.

However, normal reactions N_i cannot be determined uniquely from (6) if $n > 3$. The robot is a statically indeterminate structure if $n > 3$ and some additional analysis is needed.

There are two possibilities described briefly below.

A. The conventional approach takes into acoount elastic flexibility of the structure. In this case stiffness of different parts and joints of the robot must be measured or estimated. The longitudinal flexibility of legs (grippers) and/or the torsional flexibility of joints may be essential. Equations of equilibrium (3) and additional relationships between forces and elastic deformations form a system of equations from which normal reactions N_i can be determined.

B. The second (guaranteed) approach does not need additional and often inaccurate information about elastic properties of the structure. We require that the conditions (7) are satisfied for any admissible N_i satisfying (3). Thus we come to the condition

$$\sup_{x,y,N_i} Q \le f \tag{8}$$

where sup is taken with respect to all x, y and all $N_i \ge 0$ satisfying (3).

Finally, we have the following algorithm for verifying conditions of equilibrium.

1) For a given position of the robot calculate components of all external active forces (R_x, R_y, R_z) and of their moment (M_x, M_x, M_z) with respect to the point 0.

2) Calculate Φ_i according to (2).

3) Calculate coordinates of the point K according to (5).

4) Check conditions (6) where D is convex hull of all gripper in the plane Oxy. Instead of D one can take the convex polygon $D' \subset D$ whose vertices are centres of grippers. Then some margin for conditions (6) is secured. If these conditions are violated the robot may fall; if they are satisfied the next check must be performed.

5) If we take into account elastic flexibility of the robot then normal reactions N_i are determined according to the approach A. Then the condition (7) must be checked. For the guaranteed approach B the condition (8) must be checked. If conditions (7), (8) for the cases A, B respectively are violoted, the robot may slide alond the surface. If they are satisfied (together with conditions (6)), the robot will be in equilibrium.

Note that such parameters of the robot as stiffness of its structure, coefficient of friction, pressure p_i under the gripper, are known only approximately. Therefore in order to be on the safe side one should satisfy all conditions of equilibrium with a big margin.

6. Numerical calculations

Numerical calculations were performed for different versions of the climbing robot according to the algorithm described above. One of these versions has a platform with the length equal to 0.344 m and the width equal to 0.151 m. Its grippers (legs) have the length equal to 0.044 m and the radius 0.034 m. The pressure p_i under the grippers was taken as 0.1 p, see (2). Coefficient of friction was assumed equal to 0.5. Calculations were carried out for different positions and configurations of the robot on a vertical wall according to both approaches A, B. In approach A longitudinal and torsional stiffness were taken into account. The calculations made it possible to evaluate the carrying capacity of the climbing robot, i.e. the admissible total mass of the robot. This mass was found to be between 48 kg and 67 kg (for different approaches and values of stifness). To be on the safe side, we should not make the total mass greater than 40 kg. The payload of this robot is about 20 kg.

Advanced and bigger versions of a climbing robot were developed recently. They can carry reliably a payload more than 40 - 50 kg.

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