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MOBILE CLIMBING ROBOTS WITH ENERGY ACCUMULATORS

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ABSTRACT

The article proposes fundamentally new designs of mobile robots of arbitrary orientation in the technological space. The analysis of existing systems of mobile robots of arbitrary orientation is presented. An analysis is made of the methods of coupling robots to a surface of arbitrary orientation when performing technological operations. The difference between the proposed robot designs consists in the presence of energy accumulators that allow accumulating the potential energy at each previous step of the motion and transforming it into kinetic energy of motion at the next step of displacement. Two types of batteries are proposed: in the form of mechanical springs and compressed gas. Mathematical models of functioning of energy accumulators and calculation of their parameters are given. The results of modeling the operation of energy accumulators in the form of graphical and analytical dependences are given. Recommendations for improving the design of mobile robots are suggested.

1. INTRODUCTION

Mobile robots of arbitrary orientation in the technological space, also known as Climber Robot, are a new modification of mobile robots. Such robots are equipped with means of retaining the robot on the surface of arbitrary orientation relative to the horizon of the technological space. The creation of this type of robotics is at the initial stage and is dictated by the need to perform technological operations in such areas as monitoring of industrial facilities, installation and dismantling of building structures, repair and preventive maintenance of their components. Of particular relevance, the operation of these robots acquires in the extreme conditions of man-made disasters dangerous for human stay.

The presence of experimental samples of robots of this type [1, 2] does not eliminate the problem of reducing the gravitational load to ensure that the robot is held on an arbitrarily oriented displacement surface when performing technological operations. This problem can be solved by increasing the energy efficiency of mobile robots by periodically accumulating potential energy and converting it into kinetic energy of motion. As a result, this approach will save energy costs from autonomous power supplies of mobile robot drives.

2. PREREQUISITES AND MEANS FOR SOLVING THE PROBLEM

Studies on the creation of robots of arbitrary orientation began relatively recently - in the last decade of the twentieth century in countries of Western Europe, the United States, Japan, India, Korea, China and Russia. Mobile works [3, 4, 5, 6] are equipped with devices for retaining the robot on the surfaces in the form of vacuum devices. Vacuum grips of these robots do not depend on the physical and mechanical properties of the displacement surface, but in the case of airflow, they do not guarantee reliable retention of the robot. Here we can recommend a combined pneumonic-mechanical clutch system [6], which has the property of additional insurance of robots. The speed and simplicity of design are inherent in devices in the form of electromagnets [7, 8], but overcoming gravity due to the adhesion of magnets limits the use of this tool only for ferrimagnetic surfaces. Mobile robots with mechanical communication subsystems [9, 10] are distinguished by increased reliability, but their drive requires the use of reducers. This property increases the weight of the robot and, consequently, its gravitational load.

The development of systems for coupling the robot to the displacement surface is at technical solution that uses the technology of simple adhesion [11] and electrical adhesion [12]. These technologies are the most effective in terms of energy saving. But the experimental realization of this coupling with the displacement surface is characterized by a low speed of movement of the robot due to the sluggish adhesion effect, which so far prevents their industrial use.

The problem of synthesis of mobile robots of arbitrary orientation is not limited to the creation of coupling systems, but includes the creation of combined drives for

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the movement of robots [13]. The use of combined drives reduces the weight and total power of the robot and, as a result, reduces the gravitational load of the mobile robot. Another effective solution, aimed at reducing the weight of the robot, is the integration of drives of movement and orientation of the robot [14]. Thus, a free energy resource can be directed to the execution of technological operations.

At the same time, the above analysis of the studies shows the lack of technical solutions in which energy accumulators are used, so the problem of the energy efficiency of mobile robots remains relevant.

3. SOLUTION OF THE PROBLEM UNDER CONSIDERATION

Then we will offer two fundamentally new solutions for mobile robots with energy accumulators that will allow you to accumulate potential energy at each first step and convert it into kinetic energy of motion at each subsequent step of the robot's movement. A first embodiment of such a robot [15, 16] is shown in Fig.1. The body 1 is equipped with rotating pneumatic actuators 2 connected by means of gears 3 and 4 with stepping mechanisms made in the form of telescopic cylinders 5 and 6 and connected by a hinged parallelogram 7 with grippers 8 for engaging with the surface along which the robot moves.

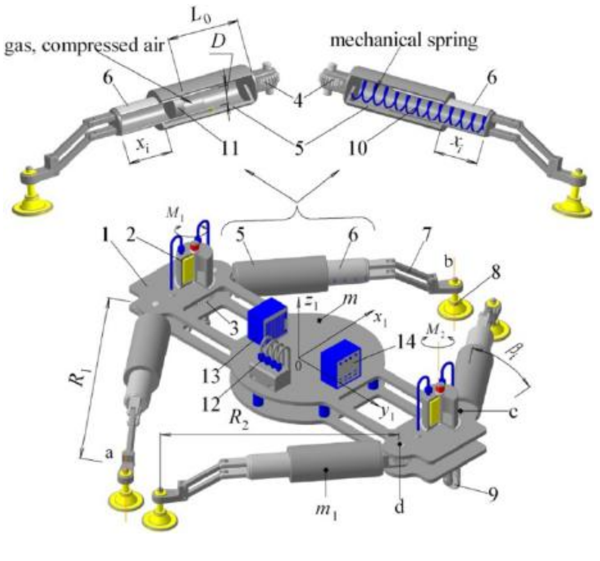


Fig.1. The robot model of arbitrary orientation with the accumulation and transformation of energy

To overcome obstacles on the surface along which the robot moves, it is additionally equipped with rolling bearings 9. Fig. 1 shows two versions of the walking mechanisms: with an energy storage module in the form of mechanical springs 10 and, alternatively, with a gas accumulator. In the latter embodiment, the energy storage device is a compressed air chamber. This chamber is formed by a cylinder 5 and a piston 11. In addition, the robot is equipped with pneumatic distributors 12, a power module 13 and a control unit 14.

When the grippers 8 are connected to the surface along which the robot moves, the motors 2 rotate the legs of the robot with the radius R_1 around the axes "a" and "b" under the action of the moving torque M_1, compressing the elastic element: either the mechanical springs 10 or the gas in the chamber 5, depending on the embodiment. Because of this compression, the accumulation of potential energy in the first stage occurs at the angle of rotation of the legs of the robot $0 \leq \beta \leq 45^0$, and in the second stage $45^0 \leq \beta \leq 90^0$ the elastic elements expand and transform the potential energy of compression into the kinetic energy of the robot's movement. At the same time, another pair of legs with radius R_2 rotates freely through the angle βi. Then, according to the commands of the control system, the first pair of clamps 8 is disconnected from the displacement surface, and the other pair of clamps in turn is turned on and the cycle of motion is repeated.

This mobile robot is designed to move small loads, about 25 ... 50 kg, and without any special effort performs technological operations. When a large load capacity of a mobile robot is required, the construction shown in Figure 2 is necessary. The walking mechanisms of this robot (pedals) are made in the form of hinged parallelograms with drives from hydraulic cylinders. As you can see in Figure 2, on the diagonal of the robot body are two legs with gas cylinders and two legs with rotary actuators [17]. When one pair of legs of the robot - with gas cylinders adhere to the surface of the motion with the help of vacuum grippers, and the other pair of legs with rotary drives is not connected with the surface of motion, then the motors move the robot in the direction of the Y axis. Simultaneously with this motion, movement of the piston of the gas cylinder. As a result, the gas is compressed in the cylinder and the potential energy of the compressed gas accumulates.

After disconnecting the first pair of vacuum grippers and switching on another pair of grippers, the compressed gas in the gas chambers expands and converts the potential energy into kinetic energy of the robot's motion, but with the electric motors switched off.

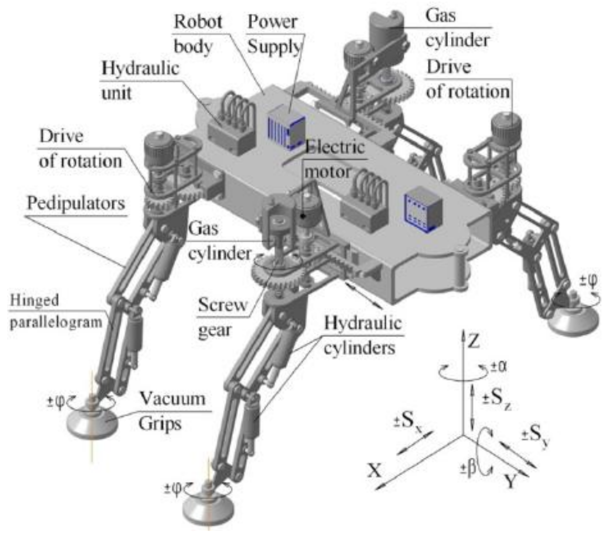


Fig.2. Walking mobile robot with energy accumulators

This way of moving the robot allows you to save the energy of an autonomous power source, which always has a limited resource. In Fig. 2 shows all possible movements of the robot in the XYZ coordinate system. These motions include three translational movements Sx, Sy, Sz and two rotational motions ±α and ±β. As a result, the robot has five degrees of freedom, which is enough to perform any technological operations on surfaces of arbitrary orientation.

The use of each of the variants of robots is determined by the goals of production. Thus, it is recommended to use the first of these design options for performing operations controlling the strength of industrial facilities or video shooting of various objects. It is recommended to use the second version of the mobile robot with hydraulic drives to perform work with large technological forces. But both versions of mobile robots make a move by converting the accumulated potential energy into kinetic energy of motion.

4. ANALYTICAL MODEL OF THE ROBOT

As an example of a dynamic model, consider the first of the above options for the construction of a mobile robot with energy accumulators. In Fig. 3 shows the design scheme of the robot's movement. As noted above, when moving in the first step $0 \le \beta_1 \le 45^0$, the robot moves to the value L_1 and the lower pedipulators move from position "A" to position "B", and the upper pedipulators make a turn from position "C" to position "D". When the robot moves to the distance L_1, gas or mechanical springs are compressed in telescopic cylinders (see Item 5, Fig. 1), depending on the version of the energy accumulator. A consequence of this compression of the gas is the creation of an elastic force J before reaching the angle of rotation of the value $\beta_1 = 45^0$. Further, to save power, drive M_1 is turned off, and the robot moves to L_2 at $45^0 \le \beta_1 \le 90^0$ already under the action of elastic force J, that is, due to the expansion force of the previously compressed gas or mechanical springs in said cylinders.

After turning the lower legs of the robot in Fig. 3 at an angle $\beta_1 = 90^0$, the control system disconnects the clamps "a" and "b" from adhesion to the surface, and vice versa, the two other grippers are engaged with the surface. Now the gas or mechanical springs are compressed in the upper legs of the robot, and the cycle of motion described above is repeated.

Thus, in the first stage of displacement L_1, when the legs of the robot rotate through the angle $0 \le \beta_1 \le 45^0$, gas compression occurs and the potential energy accumulates. In the second stage, when the legs of the robot rotate at an angle of $45^0 \le \beta_1 \le 90^0$, the stored energy is converted into the kinetic energy of the robot's motion under the action of the elastic force of compressed gas J, which expands.

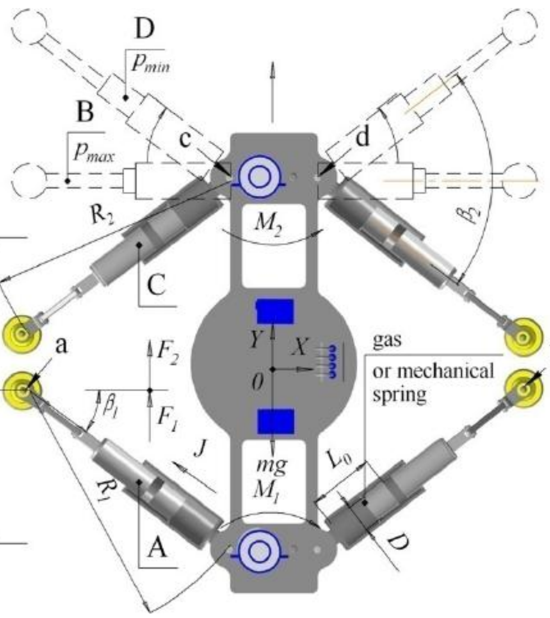


Fig.3. Scheme of the mobile robot (plan view)

The volumes of kinetic energy of the robot movement at different stages of displacement can be determined using the Lagrangian equations of the second kind. Since this method is classical, here for brevity we confine ourselves to the results of modeling. The expression of the kinetic energy of the robot body will have the form

$$T_k = \frac{mV^2}{2} = \frac{mR_2^2}{4\cos^4(45° - \beta_1)}(\dot{\beta}_1)^2 \tag{1}$$

where: m is the robot's body weight; V and $\dot{\beta}_1$ – respectively linear and angular velocities of the robot legs. For thelegs of the robot, in which there is no adhesion to the displacement surface, the kinetic energy T_1 will have a value:

$$T_1 = \frac{1}{2}\int\left(V_{x1}^2 + V_{y1}^2\right)dm \tag{2}$$

Substituting in expression (2) expressions for the projection of velocity and its value $V = \frac{ds}{dt} = \frac{R_2 \cos 45°}{\cos^2(45° - \beta_1)}\dot{\beta}_1$ and $dm = m_1 dy / R_2$, after integration, we obtain the final formula for finding the kinetic energy of the free leg of the robot:

$$T_1 = \frac{m_1 R_2^2}{2}\left(\begin{array}{l} \dfrac{(\dot{\beta}_1)^2}{2\cos^4(45° - \beta_1)} + \\ + \dfrac{\dot{\beta}_1\dot{\beta}_2\sqrt{2}\cos(45° - \beta_2)}{2\cos^2(45° - \beta_1)} + \dfrac{1}{3}(\dot{\beta}_2)^2 \end{array}\right), \tag{3}$$

where: m_1 is the mass of the pedipulator (legs) of the robot, and R_2 is the radius of its rotation.

The expression of the kinetic energy of the supporting leg (linked to the displacement surface) can be obtained from expression (2) after its integration, substituting the velocity of the translational motion of the robot $V = 0$ and the angular velocities $\dot{\beta}_2 = \dot{\beta}_1$ of the pedipulators:

$$T_2 = \frac{m_1 R_2^2}{6}(\dot{\beta}_1)^2 \tag{4}$$

Then the total kinetic energy T of each pedipulator on the two halves of the robot's travel cycle, i.e. at the stage of accumulation of potential energy when the elastic elements 4 are compressed and converted into kinetic energy of motion, will be:

$$T = \frac{R_2^2}{2}\left(\begin{array}{l} \dfrac{(2m_1 + m)(\dot{\beta}_1)^2}{2\cos^4(45° - \beta_1)} + \\ + \dfrac{m_1\dot{\beta}_1\dot{\beta}_2\sqrt{2}\cos(45° - \beta_2)}{\cos^2(45° - \beta_1)} + \\ \dfrac{2m_1}{3}\left((\dot{\beta}_2)^2 + (\dot{\beta}_1)^2\right) \end{array}\right). \tag{5}$$

Thus, the movement of the robot at each second half of the cycle occurs due to the energy accumulated at each first half of the travel step. This allows you to save 40% ... 45% of the energy volume on the movement of the robot and send the resulting energy reserve for the execution of technological operations. If a mechanical spring is used to accumulate potential energy (see item 10, figure 1), the force of the elastic element of the pedipulator will be

$$J = P_{min} + jR_2\left(1 - \frac{cos\,45°}{cos(45° - \beta_1)}\right);\; 0 \le \beta_1 \le 90°, \qquad (6)$$

where: P_{min} – preliminary compression and j – rigidity of the elastic element for accumulation of potential energy. In the case of accumulation of potential energy by compressing the gas in the cylinder 5 (Fig. 1), the force J of the elastic element (gas)

$$J = p\frac{\pi D^2}{4} - p_a\frac{\pi D^2}{4} = \frac{\pi D^2}{4}\left(p_o\frac{L_o}{L_o - x} - p_a\right)$$
$$0 \le \beta_1 \le 90° \qquad (7)$$
$$x = R_2\left(1 - \frac{cos\,45°}{cos(45° - \beta_1)}\right); L_o = \frac{p_{max}x_{max}}{p_{max} - p_o}$$

where: D – internal diameter of the gas chamber; p_o, p_a, p_{max} are the current, atmospheric and maximum chamber pressures, respectively; L_o - working length of the camera; x, x_{max} are the current and maximum compression of the elastic element, respectively.

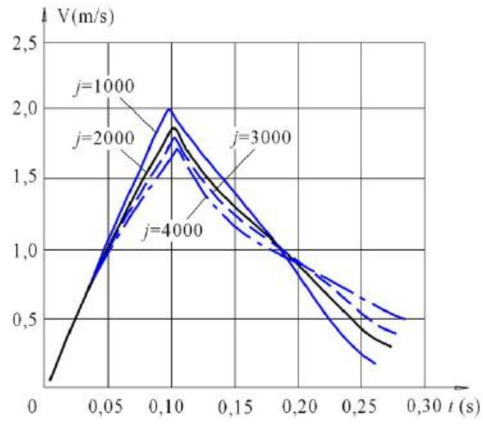
5. SIMULATION RESULTS

Elastic elements (spring or gas), as noted above, perform the function of accumulating potential energy during the first half of the displacement cycle, i.e. in the first half of the step, and their main characteristic is the rigidity j – parameter, which determines the amount of accumulated potential energy in the first half of the step of the pedipulator. As the simulation results show, the effect of rigidity j on the change in the speed of movement (Fig.4, a) is more pronounced in the second stage of the robot's movement, in terms of its decrease. However, this disadvantage is not so significant in comparison with the achieved energy saving when the robot moves with the engine switched off, that for mobile robots using autonomous power supplies with limited resources is of fundamental importance.

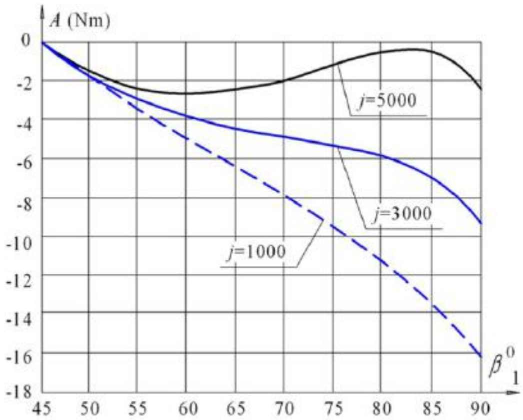
Fig. 4 (b) shows the dependence of the change in the work A on the rigidity of the elastic element j (N/m) and the robot's weighting forces in the second stage of $\beta_1 > 45°$ bias, that is, during the transformation of the potential energy into the kinetic energy of the robot's motion.

Since in the second stage of displacement $45° \le \beta_1 \le 90°$ the drive is shut off to save the energy of the robot's resources, and it moves only because of the kinetic energy, it is obvious that the rigidity value of the elastic drive element has a dominant effect on the dynamics of the motion. Analysis of these graphs shows that to increase the kinetic energy of the robot movement, it is advisable to increase the spring stiffness or initial pressure in the gas chamber, despite the fact that the counteraction to the drive in the first half of the step increases, that is, the efficiency of the drive decreases. However, this negative manifestation can be compensated by an increase in the transmission ratio (see Figures 3 and 4, Fig.1) of pedipulators.

Both versions of the synthesis of the mobile robot have objective advantages and disadvantages. Thus, the use of an energy storage device in the form of a spring increases the power of the robot, but because of the natural accumulation of the residual stresses of the spring, the service life decreases. Conversely, the use of compressed gas increases the service life by an order of magnitude, but is acceptable for robots with low payload.



a)



b)

Fig.4. The effect of the rigidity j (N / m) of the elastic element on the speed (a) and the work performed by this element (b) in the second stage β_1> 45°, when the robot moves under the action of kinetic energy.

6. CONCLUSIONS

6.1. The use of energy-saving mobile robots can significantly reduce energy costs in each subsequent stage of motion, which is of fundamental importance for robots using autonomous power supplies.

6.2. The developed technique of engineering calculations of the parameters of devices for accumulating gas energy allows us to perform not only their working design, but also to find the optimal or at least quasi-optimal ratio of the design and technological parameters of the robot.

6.3. The proposed approach to the synthesis of mobile robots can reduce their weight and total drive power and simultaneously increase the energy resource to improve the efficiency of both transport and technological operations performed by the robot in various areas of industry.

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