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DYNAMIC MODEL OF A WALKING MOBILE ROBOT

Abstract: The difference between the provided dynamic model of mobile robot pedipulators is that the movement of the robot on the surface of arbitrary orientation is due to the conversion of accumulated potential energy into kinetic energy of motion. This approach to the management of step-by-step works allows you to save up to 30… 40% of the robot's energy resources and directs them to perform technological operations.

Key words: mobile works, walking mechanisms, pedipulators, vertical movement works

Introduction

One of the main tasks of designing walking robots of vertical movement is to create a transmission to move the robot on a vertical or any orientation of the moving surface. Engineering calculations of the design parameters of such robots should be carried out taking into account the dynamic loads when moving on the surface of arbitrary orientation. This is due to the fact that relative to traditional mobile robots, the gravitational force helps to stabilize their movement, and in the case of vertical movement robots – on the contrary, requires its overcoming in order to ensure the retention of the robot on the surface of arbitrary orientation in space.

Analysis of research and publications

In the works [1, 2, 3] the newest designs of vertical displacement robots without dynamic analysis of their displacement process are considered. In [4], a mathematical model of the movement of a walking robot is presented, which allows us to write the equation of motion of the robot in the form of equations of dynamics. However, since the force of inertia is proportional to the lifting force and the volume of the inert mass, the latter leads to an increase in the weight of the whole pedipulator, and therefore to an increase in the required power of horizontal drives, in energy costs. In [5], equations describing the dynamics of drives of robot mechanisms for moving on vertical surfaces, but without solving the problem of accumulation and conversion of potential energy into kinetic energy of motion of robots of this type. Thus, the task of building a dynamic model of a walking robot with an energy saving system is relevant.

The principle of operation of the walking robot

Given the fundamental difference between this robot and similar solutions, namely, its ability to accumulate potential energy in the first cycle of displacement and its transformation into kinetic energy of motion in the second cycle, we first consider the principle of operation of the robot.

In Fig. 1 shows a calculation scheme of a walking robot of vertical displacement, operating on the principle of recovery of displacement energy. The robot includes a housing 1, which houses a rotary actuator 2 connected via a transmission to the pedipulators 3 – stepping mechanisms. The latter are equipped with elastic elements 4, which perform the function of accumulating potential energy during the first half of the displacement cycle – in the first half of the step.

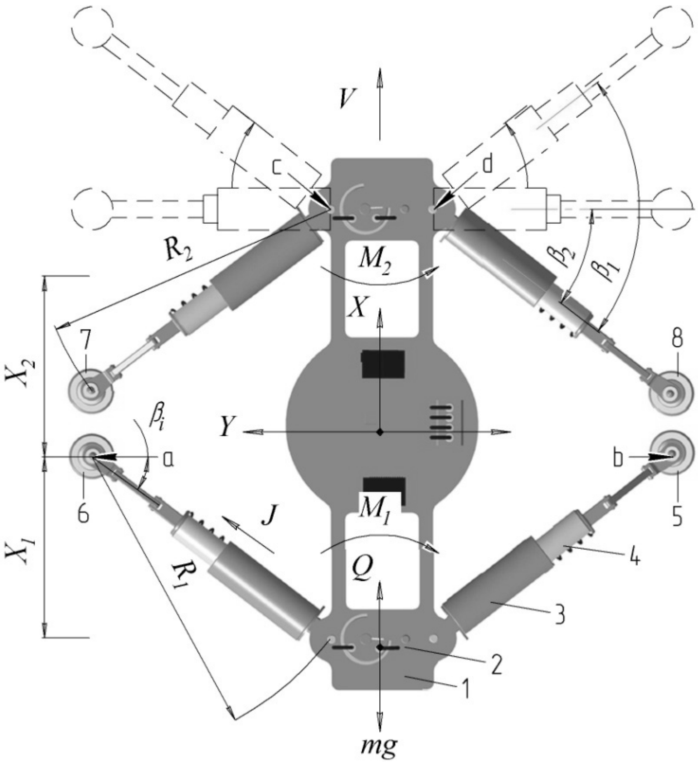

*Figure. 1.*Calculation scheme of vertical displacement

The grippers 5 y 8 hold the robot on a vertical or any arbitrary surface orientation and can have various designs, such as mechanical, vacuum, electromagnetic or other, depending on the type of moving surface and the technological functions of the robot. Captures 5, 6 and 7, 8 are switched on alternately for each half of the cycle (step) of moving the robot. Thus, when the grips 5 and 6 are on, the actuator 2 rotates each of the pedipulators 3 at a certain angle β_i around the respective points "a" and "b" on a variable radius $R_1 = Var$, because the grips 5 and 6 are coupled to the robot moving surface. Thus, the elastic elements 4 are compressed, accumulating potential energy $U = \frac{jx^2}{2}$, where: j – is the stiffness of the elastic element, N/m; x – is the magnitude of the spring deformation.

At the same time, when the grips 7 and 8 are off, a similar drive rotates another pair of pedipulators around the points "c" and "d" on the radius $R_2 = Const$, because these grips are not adhered to the moving surface. There is a movement of the housing 1 of the robot at a distance X_1 with a speed V, in the robot travels the distance of the first half of the cycle of its movement. This state corresponds to the maximum compression of the elastic elements 4, and hence the maximum of the accumulated potential energy. During the second half of the movement cycle in step X_2, the drive 2 is switched off and the robot moves due to the conversion of potential energy into kinetic energy of straightening of the elastic elements 4. At the end of the second half cycle of movement X_2, 5 and 6. Next, the cycle of longitudinal movement of the robot is repeated. Thus, due to the movement of the robot in the second half-cycle of movement due to the accumulated energy of deformation of the elastic elements in the first half-cycle, energy savings are achieved, which can be directed to technological needs.

Dynamic model of a walking robot

Initially, we will build dynamic model of the stepping robot. It will allow us to define objective functions and proceed with parametric optimization using a method that was improved by the authors. To describe the robot movement, we will use the Lagrange equations of the second kind:

$$\frac{d}{dt}\left(\frac{\partial T}{\partial \dot{q}_i}\right) - \left(\frac{\partial T}{\partial q_i}\right) = Q_{q_i}, \quad i = 1...k, \tag{1}$$

where: k – degree of freedom of a mechanical system; q_i – generalized coordinates; $\dot{q}_i$ – generalized velocities; $T(q_i, \dot{q}_i)$ – kinetic energy of mechanical system, which is a function of generalized coordinates and generalized velocities; Q_{q_i} – generalized force, which matches the generalized coordinate q_i. Let's determine potential and kinetic energy of robot movement in different stages, depending on the design parameters. Then we can get differential equations of a robot motion on the first and second parts of the movement cycle (step) and make dependencies between the parameters of the robot transmission.

In current model the system has two degrees of freedom. We choose rotation angle of the supporting leg $q_1 = \beta_1$ and the rotation angle of free leg $q_2 = \beta_2$ as generalized coordinates. Then $\dot{\beta}_1, \dot{\beta}_2$ are the generalized velocities. Let us name the leg attached to the surface of movement the 'supporting' leg. Then the 'free' leg is the one not attached to the surface. The robot body travels distance s that can be described with the following formula (see Fig. 1):

$$s = R_2 \cos 45^0 (1 - \mathrm{tg}(45^0 - \beta_1)), \quad 0 \le \beta_1 \le 90^0 . \tag{2}$$

Then velocity of the robot`s body is

$$V = \frac{ds}{dt} = \frac{R_2 \cos 45^0}{\cos^2(45^0 - \beta_1)} \dot{\beta}_1 ; \quad (\cos 45^0 = \sin 45^0 = \frac{\sqrt{2}}{2}) \tag{3}$$

And equation for the kinetic energy T_k of body will be

$$T_k = \frac{mV^2}{2} = \frac{mR_2^2}{4\cos^4(45^0 - \beta_1)} (\dot{\beta}_1)^2 , \tag{4}$$

where m – mass of robot body.

Let`s consider that the mass of each leg m_1 is evenly distributed along the robot. Free leg performs a plane parallel motion: it moves forward with the body with velocity V and rotates with angular velocity around the fixing point mounted to the body (points "c" and "d" in Figure 1). Speed projections of arbitrary point with coordinates x_1, y_1 can be represented as follows

$$V_{x_1} = \dot{\beta}_2 y \sin(45^0 - \beta_2) \ ; \quad V_{y_1} = V + \dot{\beta}_2 y co\mathrm{s}(45^0 - \beta_2) . \tag{5}$$

Kinetic energy of robot free leg is

$$T_1 = \frac{1}{2} \int (V_{x_1}^2 + V_{y_1}^2) dm . \tag{6}$$

We substitute the expressions for the velocity projections and $dm = m_1 dy / R_2$ in expression (6):

$$T_1 = \frac{m_1}{2R_2} \int_0^{R_2} (V^2 + 2V\dot{\beta}_2 y \cos(45^0 - \beta_2) + (\dot{\beta}_2)^2 y^2) dy$$

and perform integration

$$T_1 = \frac{m_1}{2} \left(V^2 + VR_2 \dot{\beta}_2 \cos(45^0 - \beta_2) + \frac{1}{3} (\dot{\beta}_2 R_2)^2 \right) \tag{7}$$

We then substitute expression (3) for the velocity V and get the final formula for finding kinetic energy of the free leg:

$$T_1 = \frac{m_1 R_2^2}{2}\left(\frac{(\dot{\beta}_1)^2}{2\cos^4(45^0 - \beta_1)} + \frac{\dot{\beta}_1 \dot{\beta}_2 \sqrt{2}\cos(45^0 - \beta_2)}{2\cos^2(45^0 - \beta_1)} + \frac{1}{3}(\dot{\beta}_2)^2 \right). \qquad (8)$$

Supporting leg, having its grips attached to the surface, performs rotational movement with angular velocity $\dot{\beta}_1$. At the same time, the mutual displacement of the leg parts due to the spring deformation may be neglected. We can get the expression for kinetic energy of supporting leg from the formula (7) by substituting robot linear velocity *V = 0* and angular velocities of the pedipulators $\dot{\beta}_2 = \dot{\beta}_1$:

$$T_2 = \frac{m_1 R_2^2}{6}(\dot{\beta}_1)^2 \ . \qquad (9)$$

Then the total kinetic energy *T* during the two halves of the robot movement cycle will be:

$$T = T_k + 2T_1 + 2T_2 = \frac{R_2^2}{2}\left(\begin{array}{l} \dfrac{(2m_1 + m)(\dot{\beta}_1)^2}{2\cos^4(45^0 - \beta_1)} + \dfrac{m_1 \dot{\beta}_1 \dot{\beta}_2 \sqrt{2}\cos(45^0 - \beta_2)}{\cos^2(45^0 - \beta_1)} + \\ + \dfrac{2m_1}{3}((\dot{\beta}_2)^2 + (\dot{\beta}_1)^2) \end{array} \right). \qquad (10)$$

To get the differential equations of robot movement during both parts of the cycle, we first construct an equation for the generalized forces. In order to do this, we find the partial derivatives of the kinetic energy that are contained in equations (1):

$$\frac{\partial T}{\partial \dot{\beta}_1} = \frac{R_2^2}{2}\left(\frac{(2m_1 + m)\dot{\beta}_1}{\cos^4(45^0 - \beta_1)} + \frac{m_1 \dot{\beta}_2 \sqrt{2}\cos(45^0 - \beta_2)}{\cos^2(45^0 - \beta_1)} + \frac{4m_1}{3}\dot{\beta}_1 \right);$$

$$\frac{\partial T}{\partial \beta_1} = -\frac{R_2^2 \sin(45^o - \beta_1)}{2}\left(\frac{2(2m_1 + m)(\dot{\beta}_1)^2}{\cos^5(45^o - \beta_1)} + \frac{2m_1 \dot{\beta}_1 \dot{\beta}_2 \sqrt{2}\cos(45^o - \beta_2)}{\cos^3(45^o - \beta_1)} \right); \qquad (11)$$

$$\frac{\partial T}{\partial \dot{\beta}_2} = \frac{R_2^2}{2}\left(\frac{m_1 \dot{\beta}_1 \sqrt{2}\cos(45^o - \beta_2)}{\cos^2(45^o - \beta_1)} + \frac{4m_1}{3}\dot{\beta}_2 \right);$$

$$\frac{\partial T}{\partial \beta_2} = \frac{R_2^2}{2}\left(\frac{m_1 \dot{\beta}_1 \dot{\beta}_2 \sqrt{2}\sin(45^o - \beta_2)}{\cos^2(45^o - \beta_1)} \right).$$

Additionally it is recommended to calculate total derivatives with respect to time. After that generalized forces Q_{q_i} can be found using

$$Q_{q_i} = \frac{\delta A_{q_i}}{\delta_{q_i}} \qquad (12)$$

where: δ_{q_i} – possible increment of the generalized coordinate; δA_{q_i} – possible work of forces that influence the mechanical system during the corresponding movement.

In our case, we use possible increment δ_{β_1} of rotation angle β_1 of mobile robot leg and resulting possible increment δ_s of displacement *s*. This is the distance on which drive forces perform possible work

$$\delta A_{\beta_1} = \left(\frac{2M_1 i}{nz} - 2J\sin(45^o - \beta_1) - (m + 2m_1)\,\mathrm{g}\sin(\gamma) \right)\delta s - \\ -m_1 g\sin(\gamma) R_2 \cos(45^o - \beta_1)\delta\beta_1 \quad , \tag{13}$$

where: M_1 – pedipulator(leg) drive torque, *N/m*; *i* – transmission ratio *n*, *z* – gear module and teeth number respectively; *m*, m_1 – mass of robot body and single leg mass respectively. The force of pedipulator elastic element is equal to:

$$J = P_{\min} + jR_2\left(1 - \frac{\cos 45^0}{\cos(45^0 - \beta_1)}\right); \quad 0 \le \beta_1 \le 90^0 \ .$$

Taking into account equation (2), we will get the increment of the distance *s*:

$$\delta_S = \frac{R_2 \sin 45^o}{\cos^2(45^o - \beta_1)}\delta_{\beta_1} \ . \tag{14}$$

Therefore, generalized force is equal to

$$Q_{\beta_1} = Q_2 + Q_1 , \tag{15}$$

Where driving force on the second half of robot movement:

$$Q_2 = \left(\frac{2M_1 i}{nz}\right)\frac{R_2 \sin 45^o}{\cos^2(45^o - \beta_1)}; \tag{16}$$

and on the first half:

$$Q_1 = -\left(2J\sin(45^o - \beta_1) + (m + 2m_1)g\sin(\gamma)\right)\frac{R_2 \sin 45^o}{\cos^2(45^o - \beta_1)} - \\ -m_1 g\sin(\gamma) R_2\cos(45^o - \beta_1). \tag{17}$$

Similarly, the differential equations of motion of the robot on the second part of the cycle, substituting the value of $M_1 = 0$ in the expression for the generalized force when changing the angle of rotation of the pedipulator β_1 within (Fig. 1).

Simulation results

The system of differential equations was solved using numerical fourth order Runge-Kutta method and simulated in the MATLAB environment. The results are shown below. As it was mentioned above, pedipulators use elastic elements (Fig. 1, item 4) for accumulation of potential energy in the first half of the step. The main characteristic of elastic elements is their stiffness *j* – parameter that defines the compression force of these elements and the accumulated potential energy in the first half of the pedipulator step. Fig. 2 shows that this parameter has more significant effect on the robot displacement *s(t)* in the second half of the step than in the first half when the drive is disabled and accumulated potential energy is converted into the kinetic energy of motion. Similarly, the stiffness of elastic elements affects the angular movement of pedipulators (Fig. 3).

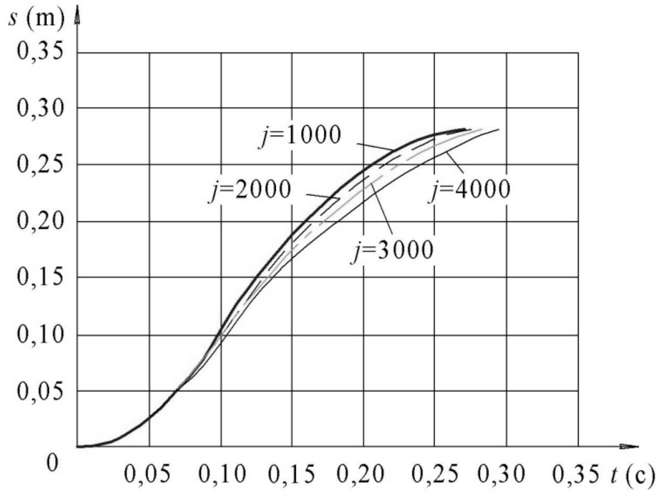

Figure 2. Distance-time graphs for different stiffness ***j*** (*N/m*) of the elastic elements

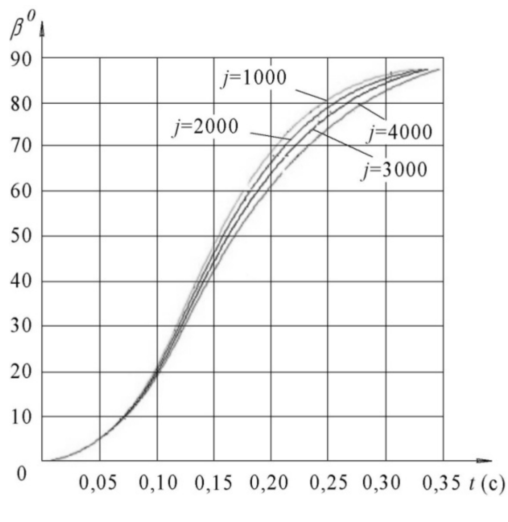

Figure. 3. Angular movement graphs for pedipulator depending on the stiffness *j* (*N/m*) of the elastic elements

The work in the second half of the step is different than in the first, ie when the engine is off during the conversion of the accumulated potential energy into the kinetic energy of the robot. The same applies to the influence of the stiffness of the elastic elements on the magnitude of the angular displacement of the pedipulators (Fig. 3). From which we can conclude that to increase the kinetic energy of the work, it is advisable to increase the stiffness, despite the fact that this increases the resistance of the drive in the first half of the step, ie decreases the efficiency of the drive. The last negative manifestation can be compensated by increase in a gear ratio of a drive of pedipulators of the robot.

The next step of the above research is to create an engineering methodology for designing walking robots of arbitrary orientation, containing devices for storing potential energy and converting it into kinetic energy of the robot.

Conclusions

As a result of modeling the process of moving a walking robot, it is established:

1. To increase the kinetic energy of the work, it is advisable to increase the stiffness of the potential energy storage, despite the fact that the resistance of the drive increases in the first half of the step, ie decreases the efficiency of the drive. The latter negative manifestation can be compensated by increasing the gear ratio of the robot pedipulator.

2. The maximum value of the stiffness of the elastic elements in the process of converting potential energy into kinetic energy of motion of the robot changes from less to greater impact at the end of this process.

3. In the differential equations of motion of the work on the first part of the cycle, a restriction of the extreme value of the angle is introduced, at which the torque of the pedipulator drive is still active. Since the value of the specified angle depends on the torque and stiffness of the elastic element, to prevent excessive energy consumption and significant impact on the leg movement limiter, the angle value is selected by simulation so that the linear speed at the end of the support leg rotation is close to zero.

4. In practice, the requirements of paragraph 3 of these conclusions, ie the reduction of dynamic load during transients, can be satisfied by the use of dampers devices for converting impact energy into liquid friction energy.

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