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# Walking Mobile Robot of Arbitrary Orientation

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## Abstract

The article describes the device and the mathematical model of a walking mobile robot of a fundamentally new construction. The difference between this technical solution is the ability to move the robot on surfaces of arbitrary orientation in different coordinate systems: rectangular Cartesian, cylindrical and spherical. In the proposed design, the walking robot mechanism is made in the form of flexible pedipulators and allows the mobile to perform transitions on surfaces that have an arbitrary orientation at different angles to the horizon. The technique for calculating the construction parameters of the walking robot mechanism and the trajectories of the robot legs bending is given. This walking robot is designed to perform technological operations in extreme conditions.

**Index Terms:** Mobile robots, walking machines, pedipulator, robots of vertical movement.

## 1. Introduction

The difference between mobile robots that move on surfaces of arbitrary orientation, including vertical surfaces, is that they are equipped with a system of holding the robot on the displacement surface to overcome the gravitational component of dynamic loads. Therefore, the most important task of designing such robots is the problem of matching the parameters of the robot's transmission with the modes of technological and transport loads. Engineering calculations of construction parameters of such robots should be carried out taking into account dynamic forces when moving along the surface of arbitrary orientation. If relative to traditional mobile robots the gravitational force helps to stabilize their movement, in the case of vertical moving robots - on the contrary, it needs to overcome it in order to ensure that the robot is kept on the surface of displacement of arbitrary orientation in space.

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## 2. Related Work

Traditional industrial works [1] are stationary or transport and are not capable of performing technological operations on surfaces such as a vertical wall, ceiling or surfaces at different angles to the horizon. Mobile works [2, 3, 4, 5] are equipped with devices for retaining the robot on surfaces of arbitrary orientation, and works [6, 7] are additionally equipped with a subsystem of energy recovery of displacement drives, which allows reducing the drive power, and hence the total mass of the robot. Technical solutions [8, 9, 10, 11] allow the robot to move over surfaces that are oriented at different angles to the horizon, but only in 2D space, that is, in a plane. In the general case, variations in the performance of the transmission of the above-mentioned robots limit their movement only in the Cartesian coordinate system. Unlike the above technical solutions, the robot model [12] allows servicing objects in a cylindrical coordinate system, in particular, objects such as trees, but in the presence of a soft porous moving surface of the robot. This property limits the technological capabilities of the specified robot. At a time when there are maintenance facilities that are also close to the cylindrical coordinate system, for example, electric grid posts, columns, pipes of thermal power plants and the like. In addition, the mobile robot must also work in a spherical coordinate system peculiar to man. The development of devices for coupling the robot to the displacement surface is the technical solution [13], in which the adhesion mechanism of rock climbing is used. From the point of view of mobile robot navigation and visual inspection of the positions of the robot, interesting works are [14, 15], which can be used to program mobile robots. Thus, the task of creating pedipulators, that is, walking mechanisms for mobile robots capable of performing technological operations in a space of arbitrary orientation, is topical.

## 3. Problem Statement

1. It is necessary to create a stepping mechanism that will allow the mobile robot to perform technological operations in a space of arbitrary orientation, that is, regardless of the type of the coordinate system of the production space.
2. To carry out the synthesis of analytical dependencies for the engineering calculations of the structural and technological parameters of the mobile walking robot.

## 4. Problem Solving

The first task is constructive. The authors carried out the solution of this problem as follows. The mobile walking robot is equipped with a body 1 (Fig.1), which consists of the upper and lower platforms, on the axes of these platforms pedipulators 2 are installed. Each pair of pedipulators through the transmissions 3 has electric drives 4. The pedipulators are equipped with grippers 5 for engaging with the displacement surface and turning actuators 6 for matching the position of the grippers relative to the displacement surface. The type of grips can be different, for example, vacuum, mechanical, electromagnetic or use the properties of adhesion depending on the material and the topology of the surface over which the robot moves.

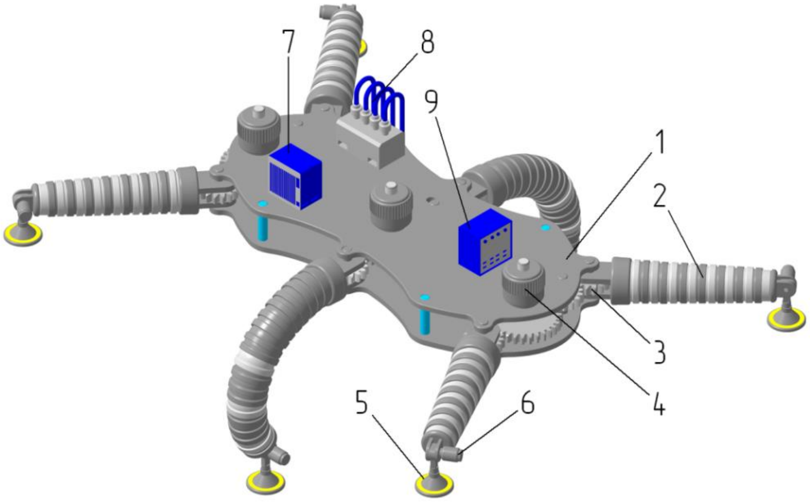


Fig.1. 3D Model of the Walking Robot

On the upper platform of the housing, there is a module 7 of power supply for the mobile robot, a block 8 of hydraulic or pneumatic valves and a gas or liquid pressure generator, and a controller 9 for controlling the robot.

The main difference of the robot is that each of its legs (Fig.2) is made in the form of a set of rings from the 1st to the last "n".

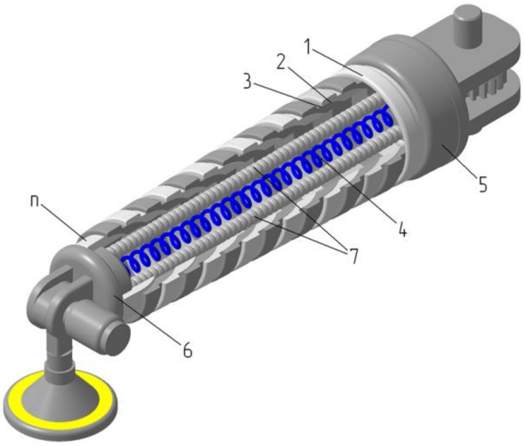
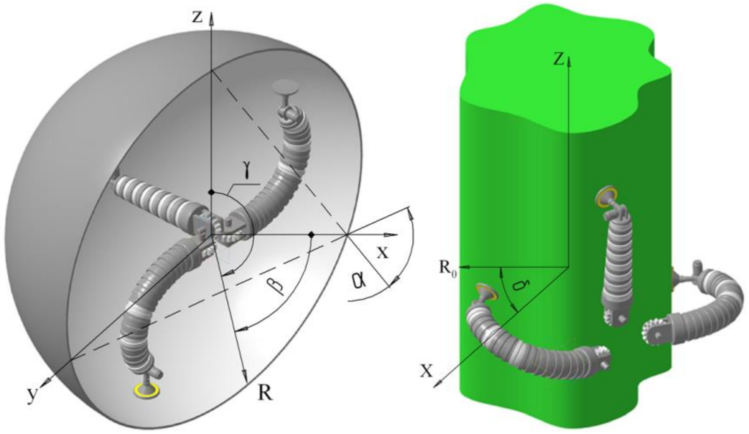


Fig.2. Model of one Robot's Leg in 1/4 Volume Section

The number of rings 1 is determined by the appointment of the robot: the more rings, the higher the accuracy of the orientation of his legs, and with a decrease in their number, the carrying capacity of the robot increases. Each of the rings from the initial 1 to the final "n" comes into contact with each other along the spherical internal surfaces 2 and the outer 3. All the rings are connected by an elastic element 4 (for example, a coil spring or flexible rod) that is pivotally attached to the bodies 5 and 6 These corps have corrugated pipes 7 inside the rings, which are under different pressure of gas or liquid. The minimum number of corrugated pipelines should be four - two in the vertical and horizontal planes of the longitudinal section of each leg of the robot. The use of gas or liquid under pressure in said pipelines is determined by the carrying capacity and the technological function of the walking robot.

According to the given control program, different combinations of pressures are created in corrugated pipelines. As a result, the consequence is the bending of the legs of the robot in the planes of any coordinate system. Such a technical solution provides the possibility of arbitrary orientation of the mobile robot's actuators when performing any technological functions and moving on the surface of an arbitrary topology.

Fig.3 (a) shows the orientation of the legs of the robot in Cartesian X, Y, Z, spherical $R, \beta, \gamma;$ coordinate systems; where: R is the radius of the foot; $\beta$, $\gamma$ – angles of the robot's leg bending due to the difference in pressure in the corrugated pipelines. For clarity of perception, the robot body is not shown conditionally. The corner $\alpha$ defines the service zone of the robot in a spherical $R, \beta, \gamma$ coordinate system.



(a) (b)

Fig.3. The Orientation of the Robot Pedipulators: in Cartesian and Spherical (a) and Cylindrical (b) Coordinate Systems (The Robot Body is not Shown Conditionally)

Similarly, Fig.3 (b) illustrates the possibility of pedipulators working in a cylindrical coordinate system $R_0, \delta, Z$ (where: $R_0$ – is the current radius of the service object; $\delta$ – is the polar angle, and $Z$ – is the coordinate of the cylindrical coordinate system). As indicated above, the need for a mobile robot to operate in a cylindrical coordinate system is dictated by the presence of such maintenance facilities as, for example, trees, power transmission poles, columns and pipes of various industrial uses.

## 5. Determining the Parameters of Pedipulators

To program the orientation of the robot in space, it is necessary to obtain the axial position equations for each pedipulator, and for its reliable operation, formulas for calculating the structural strength are needed.

Corrugated pipes, which are under different pressure of gas or liquid: for example $p_1, p_2$ – the pressure in the lower and upper pipelines (see item 7, Fig.2), that are in the same plane and are installed inside the rings, due to the difference in pressure $\Delta = p_1 - p_2$ they allow bending (i.e., the orientation drive) in an arbitrary direction, respectively, of the selected coordinate system.

In Fig. 4 shows three possible positions A, B, C of the robot leg bending, for example, in the XZ plane.

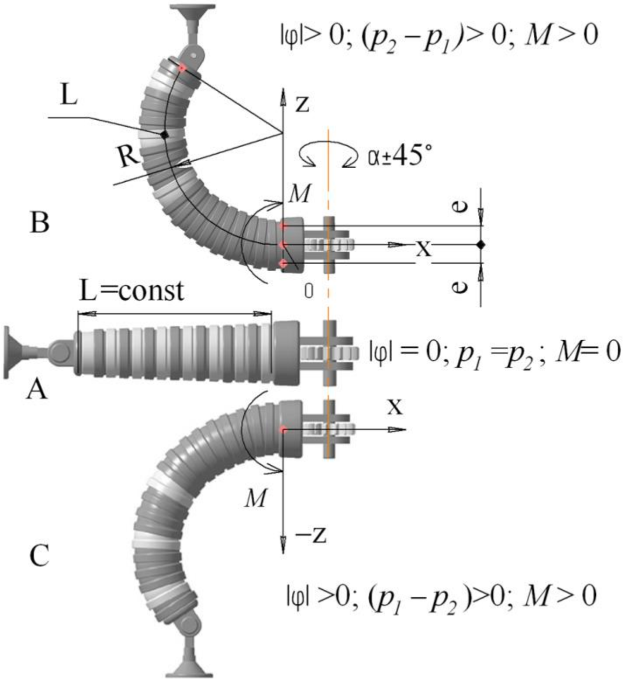


Fig.4. The position of the robot's leg, depending on the difference in pressure $\Delta = p_1 - p_2$ in the corrugated pipes; $M$, $\varphi$ – bending moment and bending angle; $\alpha = \pm 45^0$ – the angle of rotation of the transmission (see item 3, Fig.1); *e* – eccentricity of the location of corrugated pipelines

We choose the origin of the Cartesian coordinate system 0xyz at the place where the foot is attached to the robot body. We consider that there are four pipelines, two of which are located in a vertical plane (in the upper one there is pressure $p_1$, and in the lower one $p_2$) and two other pipelines in the horizontal plane (in the right pressure is $p_3$, and in left pressure is $p_4$). Due to the action of these pressures, forces arise that, while bending the robot's leg, orient it in space:

$$F_1 = p_1 \frac{\pi d^2}{4};\ \ F_2 = p_2 \frac{\pi d^2}{4};\ \ F_3 = p_3 \frac{\pi d^2}{4};\ \ F_4 = p_4 \frac{\pi d^2}{4}, \tag{1}$$

where $d$ – is the internal diameter of the corrugated pipes.

Since the axes of the pipelines are offset by an amount $e$ with respect to the axis of the pedipulator, there are moments that bend the robot's leg:

$$M_1 = \frac{\pi d^2}{4}(p_1 - p_2)e;\quad M_2 = \frac{\pi d^2}{4}(p_3 - p_4)e \tag{2}$$

These moments are in different planes, and therefore it is advisable to consider them as vectors. The vector $\vec{M}_1$ is directed along the $0y$ axis, and the vector $\vec{M}_2$ has a direction opposite to the $0z$ axis. Since the vectors $\vec{M}_1$ and $\vec{M}_2$ are mutually perpendicular, the modulus of the total vector is equal to:

$$M = |\vec{M}| = \sqrt{(\vec{M}_1)^2 + (\vec{M}_2)^2} = \frac{\pi d^2}{4} e\sqrt{(p_1 - p_2)^2 + (p_3 - p_4)^2} \qquad (3)$$

and its direction forms an angle $\beta$ with the *0z* axis, and

$$\cos\beta = \frac{M_2}{M} = \frac{p_3 - p_4}{\sqrt{(p_1 - p_2)^2 + (p_3 - p_4)^2}} \qquad (4)$$

From this we find the angle $\beta$ of the inclination of the plane of the bend of the robot's leg relative to the plane 0xz:

$$\beta = \arccos\left(\frac{p_3 - p_4}{\sqrt{(p_1 - p_2)^2 + (p_3 - p_4)^2}}\right); \quad 0^o \le \beta \le 180^o; \quad 0 \le \beta \le \pi . \qquad (5)$$

The pedipulator is bent in a plane perpendicular to the total angular momentum vector $\vec{M}$ . The dihedral angle between this plane and the coordinate plane *0xy* equals *β*. The equation of the plane in which the pedipulator is bent has the form:

$$\frac{M_1}{M} y - \frac{M_2}{M} z = 0$$

After substituting the expressions for the moments, we obtain a connection with the effect of various pressures in corrugated pipelines:

$$z = \frac{p_1 - p_2}{p_3 - p_4} y \qquad (6)$$

From this we obtain the dependence of the angle $\beta$ on the different pressure values in the pipelines:

$$tg\beta = \frac{p_1 - p_2}{p_3 - p_4} \qquad (7)$$

The formulas for determining the angle $\beta$ between the modulus of the total angular momentum vector $|\vec{M}|$ and the *0z* axis are:

$$\begin{aligned} \beta &= arctg\left(\frac{p_1 - p_2}{p_3 - p_4}\right); \text{at } p_3 > p_4 \\ \beta &= \pi + arctg\left(\frac{p_1 - p_2}{p_3 - p_4}\right); \text{at } p_3 < p_4 \end{aligned} \qquad (8)$$

Then we see that when $p_1 > p_2$ the pedipulator is bent by the convexity upwards, and when $p_1 < p_2$ it is bent by the convexity downwards. These conditions are represented by the following formula:

$$p_3 = p_4 + \frac{p_1 - p_2}{tg\beta} \tag{9}$$

To program the movement of the mobile robot, it is necessary to use the equation of the pedipulator axis. If, for example, a pedipulator of length $L$ is bent along an arc of a circle of radius $R$ in a given plane, then the equation of the pedipulator axis in the fixed coordinate system will have the form:

$$\begin{cases} x = R\sin\varphi; \\ y = \left(R\cos\varphi - R\right)\cos\beta;\ 0 \le \varphi \le \dfrac{L}{R} \\ z = \left(R\cos\varphi - R\right)\sin\beta \end{cases} \tag{10}$$

The relationships (10) are illustrated by the graphs of the position of the pedipulator axis work on Fig. 5.

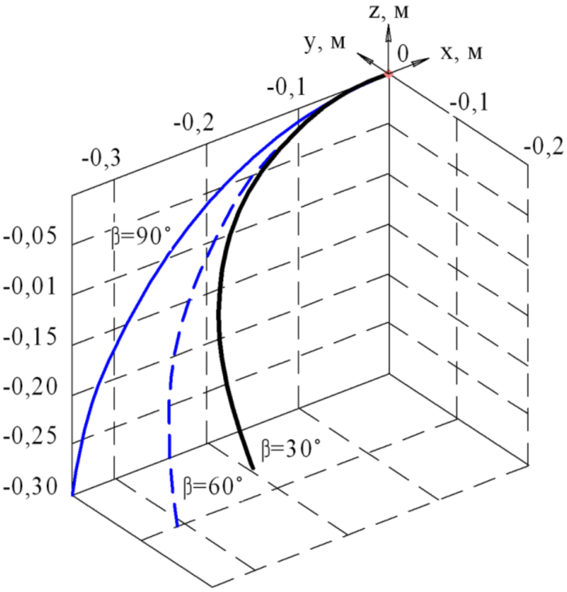


Fig.5. Bending of Pedipulator Axis for Different Values of Angle $\beta$

Further, we will find analytical dependencies of design parameters that will ensure reliable operation of the work. As indicated above, each pedipulator is made in the form of hemispherical rings connected by an elastic element. If this flexible member is a flexible rod, then the force $Q$ of the tension of such a rod must ensure a constant contact of the rings, i.e., the condition:

$$Q \ge F = (p_1 + p_2)\frac{\pi d^2}{4} \tag{11}$$

where: $F$ is the force that develops under pressures $p_1$ and $p_2$ in corrugated pipelines with an internal diameter $d$.

In addition, the rod should be quite flexible so that the angle $\varphi$ of the robot's leg bending is significant (for example, $\varphi = \pi / 2$). From the theory of the resistance of materials it is known that the curvature of such a rod depends on the bending moment and stiffness of the rod, that is:

$$\frac{1}{\rho} = \frac{M_1}{E_1 J_1} \tag{12}$$

where: $\rho = L / \varphi$ – the ratio of the length $L$ of the robot's leg to the angle $\varphi$ of its bending when the rod is bent along the arc of the circle; $M_1$ is the bending moment; $E_1$ – modulus of elasticity; $J_1$ is the moment of inertia.

Then the bending moment will be equal to:

$$M_1 = E_1 J_1 \varphi / L \tag{13}$$

Since the rod, which pulls together the rings of the robot's leg, works simultaneously on stretching and bending, the strength condition will have the form:

$$\frac{Q}{S} + \frac{M_1}{W_1} \le [\sigma] \tag{14}$$

where: $S$ – the area of the rod; $W_1$ – the moment of resistance; $[\sigma]$ – allowable normal voltage. In the case of a rod of the circular cross-section with diameter $d_1$, condition (14) takes the form:

$$\frac{(p_1 + p_2) d^2}{d_1^2} + \frac{E_1 d_1 \varphi}{2L} \le [\sigma] \tag{15}$$

and in the case of a rectangular section, when $S=bh$, $b=2h$ (where: $b$ is the width and $h$ is the section height), the expression:

$$\frac{(p_1 + p_2) \pi d^2}{8h^2} + \frac{E_1 h \varphi}{2L} \le [\sigma] \tag{16}$$

For compact notation of relations of constructive parameters, we introduce the notation: $k = \frac{E_1 \varphi}{2L}$; $a_1 = [\sigma] / k$; $a_2 = \frac{(p_1 + p_2) d^2}{k}$; $a_3 = \frac{(p_1 + p_2) \pi d^2}{8k}$ and multiply expressions (15) and (16) by $d_1^2$ and $h^2$, as a result, we obtain the conditions that must be observed when designing pedipulators to work reliably:

$$\begin{aligned} & d_1^3 - a_1 d_1^2 + a_2 \le 0 \\ & h^3 - a_1 h^2 + a_3 \le 0 \end{aligned} \tag{17}$$

Fig.6 shows the graphs of the change in the parameters of the left parts of expressions (17), which is convenient for calculating the design characteristics of the robot pedipulators.

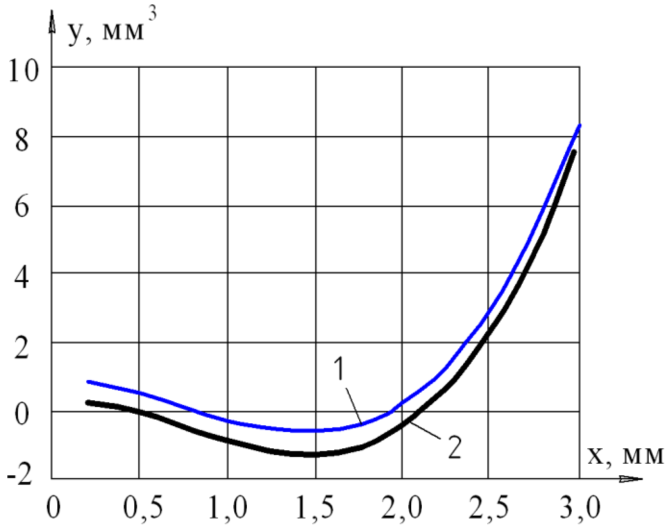


Fig.6. Calculation of the Strength of the Pedal Leg rod (graph 1 – Corresponds to a rod of Circular Cross-Section; 2 – Rectangular Section *b=2h*)

The implementation of the model was carried out in the Matlab environment under the constraints of the initial parameters:

$$\begin{aligned} 5\times10^3 &\le (p_1 - p_2) \le 15\times10^3 \\ 5\times10^3 &\le (p_3 - p_4) \le 15\times10^3 \end{aligned} \tag{18}$$

$$0,02 \le d \le 0,04$$

$$0,025 \le e \le 0,045$$

where: $(p_1 - p_2)$ and $(p_3 - p_4)$ – the pressure differences in the corrugated pipelines, Pa; *d* – internal diameter of these pipelines, m; *e* – eccentricity, i.e. displacement of the axis of the pipeline relative to the axis of the robot's leg, m; and also the modulus of elasticity *E* = 200·103(MPa); the shear modulus G = 78,5·103 (MPa) for the steel grade 65G. The above limitations are determined by the industrial expediency of operating a mobile robot.

## 6. Conclusion

A fundamentally new implementation of mobile robot pedipulators in the form of a set of hemispherical rings and corrugated pipelines under different gas or liquid pressures provides an opportunity to achieve an arbitrary orientation of the walking mobile robot in different working spaces: rectangular Cartesian, spherical and cylindrical coordinate systems. This effect provides an expansion of the technological capabilities of the robot.

The obtained functional dependencies provide the possibility to program the orientation of the robot's motion in arbitrary coordinate systems, as well as carry out calculations of the constructive parameters of pedipulators of the walking robot.

The next step of the research is the construction of a research sample of the walking robot and the experimental approbation of the obtained results of mathematical modeling.

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