Foot of Leg of a Walking Robot: Design and Calculation of Parameters

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In the field of modern robotics, anthropomorphic designs of walking robots are becoming increasingly popular. This trend is due to the versatility of the functions that mobile robots of this type can perform. One of the problems of operating walking robots is to ensure their stability when moving on surfaces of various topologies. It is known that the stability of a walking robot depends on the speed and acceleration of its movement, the mass of the robot and its payload, the position of the center of gravity of the robot's body, and also on the specific pressure on the ground along which the robot moves. The present research is devoted to the last problem. In the article, the authors proposed a fundamentally new design of the foot of a walking robot, which allows you to adjust the specific pressure on the ground by changing the area of the robot's supporting surface. When a walking robot moves from a hard surface to loose soils, such as sand, snow, soft marshy soils, and others, the new foot design allows you to increase the area of support thereby reducing the specific pressure on the ground, and, therefore, increases the stability of the robot.

The article also provides analytical formulas for calculating the parameters of a new foot of a walking robot, namely the magnitude of the movements of the toes, their speed, the variable bearing area of the foot, the specific pressure on the ground, and the strength of the elastic elements of the robot foot. Graphical dependences of these parameters are also presented in the form of diagrams that will help researchers and engineers create similar structures with variable ground pressure. The main motivation for these studies was to increase the stability of the walking robot by regulating the specific pressure on various soils on which the mobile robot can move.

***Keywords**: foot construction, walking robot, ground pressure, pedipulator*

1. INTRODUCTION

The tasks of ensuring the stability of walking robots are diverse, they involve improving the design of the legs of robots, the so-called pedipulators or walking mecha–nisms. Typically, the leg of a walking robot consists of a thigh, lower leg, and foot. Each of these links can have a different degree of freedom. However, to ensure the stability of the robot, it is necessary to take into account such parameters as the speed and acceleration of its movement, body weight, and the payload of the robot. The limit values of these parameters, in turn, depend on the area of the supporting surface of the robot's legs, the value of which determines the specific pressure on the ground along which the mobile robot moves.

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It is known that the value of the specific pressure on the ground of any machine, including a robot, is defined as the ratio of the total mass of the machine to the value of the contact area of the soil (kg/m^2) on which any machine moves. In the general case, the specific pre–ssure on the ground depends on the mass of the robot and the total area of support on the ground. We assume that the robot has two legs and, accordingly, two feet. The resistance of a two-walking robot depends on many factors (balance, speed, acceleration, and mass), inclu–ding the specific pressure on the ground on which the robot moves. When the density of the ground decreases, such as when the walking robot moves to loose ground such as sand, snow, and the like, it is desirable to increase the foot support area to reduce the specific pressure. Reducing the value of the specific pressure on the ground by increasing the foot support area prevents the robot's legs from sinking into loose soil. The consequence of this effect is to increase the stability of the robot or any other walking mechanism, that is, the pedipulator. Conversely, when a walking robot moves from a loose ground surface to a hard surface, it is desirable to reduce the footprint of the robot foot in order to increase the movement speed. But in this case, the magnitude of the indicated decrease in the area of contact of the foot with the ground will be determined by the dynamic parameters of the walking robot, for example, the limiting values of acceleration and inertial forces of motion.

Thus, in both of these cases, it is advisable to control the area of the robot's support on soils with different densities. To solve this problem, a new design of the foot of a walking robot is proposed below and the results of modeling the functioning of the foot are given.

2. PREREQUISITES AND MEANS FOR SOLVING THE PROBLEM

Theoretical and experimental research in the field of synthesis of walking robots is due to their greater versatility of functions in comparison with robots on a wheeled or tracked transmission. In [1], the design of the legs of the robot based on the intelligent control of servos is proposed. However, in this work, the feet of the robot's legs do not have the ability to transform their shape or size. In [2], it is indicated that the design of the foot has a great influence on the quality of contact with the ground, and in the article [3], the design of a flexible robotic foot is proposed to absorb the shock loads of the foot. However, these studies do not provide for changes in the size of the robot's foot during walking. The results of studies [4] indicate the need to take into account the influence of the physical and mechanical properties of various soils on the dynamics of walking of the robot, including loose soils. The work [5] provides information about the contact forces between the foot and the ground based on the measurement of the force by a triaxial sensor device.

Studies [6] illustrate the walking of a humanoid robot that has 6 degrees of freedom in each leg and 1 degree of freedom in each foot. However, these works do not provide for the possibility of changing the shape of the robot's foot. The original designs of the foot of a walking robot are given in [7, 8], but a common feature of the above technical solutions is the absence of a change in the specific pressure of the robot's feet on the ground. The flexible mechanisms of the robot foot [9] and the humanoid foot of the robot with muscle drives [10], as well as the humanoid robot [11] and the miniature robot [12], make it possible to adapt the robot's legs to different topologies of soils, on which the walking robot moves, but without changes in the specific pressure on the ground.

Sufficiently effective designs of the robot foot for gait stabilization are proposed in [13, 14], as well as a biotechnological robotic foot [15] with conical gearing allows compensating the yaw moment during bipedal walking, which also solves the problem of robot motion stabilization. In [16], flat springs with torsion suspension are used in the design of the robot foot, which reduces the sensitivity of the foot to dynamic disturbances. However, as in previous works, the robot's feet have a constant footprint on the ground, which does not allow changing the specific pressure on the ground when moving over loose soils. The paper [17] proposes the design of a robot foot in the form of a flexible plate with variable stiffness. This technical solution ensures the adaptation of the foot to the surface of movement and ensures reliable contact of the foot with the surface. Anthropomorphic designs of the robot's legs also make it possible to adapt the movement of the robot to surfaces with different topologies [18]. However, in both of these cases, the total area of the foot remains constant and does not change when the robot's foot moves from solid ground to loose ground, which does not allow for changing the specific pressure on the surface when the robot moves. In studies [19, 20, 21], to improve the stability of walking robots, improved algorithms for controlling the walking of a robot are proposed, but without changing the design of the robot's feet. It is advisable to use an analog of the information polygon to study the stability of a walking robot [22].

Thus, the analysis of the above studies shows that the problem of increasing the stability of walking robots based on the regulation of the specific pressure on the ground by changing the foot support area remains relevant.

3. FORMULATION OF THE PROBLEM

Various original designs of the legs and feet of mobile robots do not have the ability to adjust the footprint of the robot's leg to reduce the specific pressure on the ground on which the robot moves. This property is necessary to increase the stability of walking robots when they move on loose soils. It is also necessary to perform a kinematic analysis of the foot with a variable footprint on the ground and develop analytical expressions for calculating the parameters of the foot. This technique will allow researchers and engineers to create similar designs for robot legs. Therefore, it is necessary to create a mobile robot foot structure with a variable support area during the movement of the walking robot. This problem can be solved by making the foot of the robot in the form of several fingers, which are equipped with a drive and connected by elastic membranes between the fingers, as shown below.

4. SOLUTION OF THE PROBLEM UNDER CONSIDERATION

The engineering novelty of the proposed technical solutions lies in a fundamentally new design of the foot of a mobile robot [23], and the scientific novelty is displayed by the kinematic analysis of the foot with an illustration of graphical and analytical dependencies for calculating the parameters and modeling the functioning of the foot. The main motivation of this study is to create a foot with a variable area of support for the legs of a mobile robot. This will increase the stability of the robot when moving on soils with arbitrary topology and soil density. For a better understanding of the new foot model, we first consider its design and principle of operation.

4.1 Design the foot of leg of a robot

Figure 1 shows a 3D model of a walking robot's foot that has the ability to change its footprint on the ground. For a better understanding of the principle of operation of the foot, Figure 2 is a kinematic diagram of the foot. The foot of the mobile robot contains a central toe, which is conventionally shown in Figure 1 in a ½ sec–tion for a better understanding of its drive. The central toe forms the body of the foot and contains a self-braking screw gear. This screw gear consists of a screw and a nut, which is installed in the guides of the central finger and forms a kinematic pair of translational motion with it. The screw is mounted on rolling bearings and is connected to an electric motor through a coupling. An encoder is installed on the electric motor shaft, that is, a device that converts the angle of rotation of the motor shaft into an electrical signal for controlling the motor.

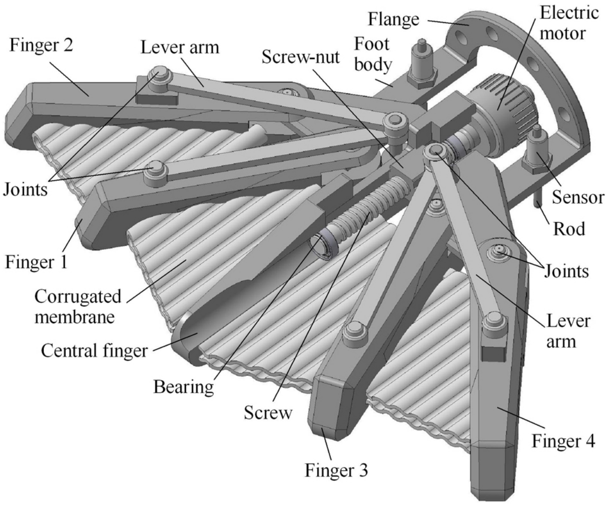

Figure 1. The Foot of Leg of a Walking Robot

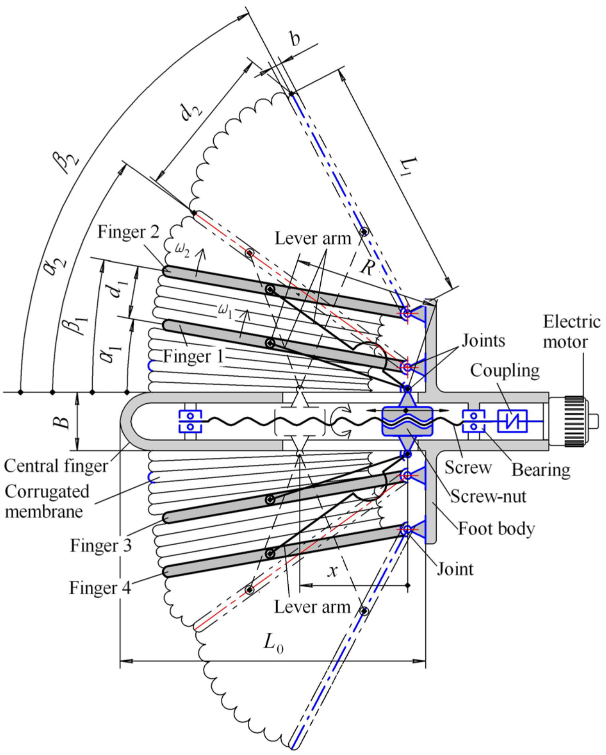

Figure 2. Kinematic diagram of a foot with a variable area of support on the ground

On both sides of the central fixed finger, movable fingers 1, 2, and fingers 3, and 4 are symmetrically placed. The movable fingers are installed in the foot body on hinged supports and connected to the screw transmission nut by levers, which are also mounted on the hinge joints of the nut and each movable toe of the foot.

Thus, the movable fingers form rotational kinematic pairs with the body of the foot and the nut. Elastic corrugated membranes are fixed between the movable toes, which have the ability to stretch with an increase in the area of foot support on the ground. On the body of the foot, which forms the central toe, sensors with rods are installed to control the amount of immersion of the foot in loose or soft soil along which the walking robot moves. The flange with holes is intended for fastening the foot to the lower leg of the walking robot.

4.2 Functioning of the foot

The foot works as follows. In the initial state, that is, when moving the robot's legs on hard ground, fingers 1 and 2 (also fingers 3 and 4) are at the minimum angles α_1 and β_1 (see Figure 2) relative to the central toe and thus form the minimum possible foot support area. In the event of a change in the topology of the surface on which the walking robot moves, that is, when the robot's legs move to loose or soft soils (for example, sand, snow, or wetlands), there is a threat of deepening the robot's legs into the ground and, as a result, loss of robot stability. To prevent this phenomenon, after contact with soft ground, the rods enter inductive sensors (see Figure 1), and thus a proportional signal is generated to turn on the electric motor. The latter transfers rotation to the screw, which imparts a linear movement to the nut by a certain amount of "X" (see Figure 2). After the nut has passed this distance, the levers turn the movable fingers 1 and 2 (as well as the fingers 3 and 4) through the corresponding rotation angles α_2 β_2. The new position of the fingers is shown in Figure 2 with dashed lines. Movable fingers, when rotated around the hinge joints, stretch the corrugated membranes that are installed between the fingers. As a result of the rotation of the fingers and the deformation of the corrugated membranes, the area of \u200b\u200bsupport of the foot on the ground increases. Due to the increase in the area of foot support on the ground, the specific pressure of the robot's legs on the ground along which they move decreases. As a result, the foot is prevented from sin–king into soft or loose ground. Ultimately, these actions contribute to increasing the stability of the walking robot.

5. CALCULATION OF FOOT PARAMETERS

For the possibility of designing similar feet with a vari–able footprint on the ground, a method for calculating the parameters is further proposed, which includes kine–matic analysis and calculation of the variable foot area to determine the specific pressure on the ground. Ana–lytical and graphical dependences of foot parameters are also presented, which can be used by researchers and engineers to model similar foot structures.

5.1 Kinematic analysis of the foot

Figure 3 shows the kinematic diagram of finger 1 (see also Figure 2). The symmetrical finger 3 has a similar design. Finger 1 has a length of AA_1, is pivotally mounted in the joint and, when the electric motor is turned on, rotates around the joint point A. Lever CB, which transmits movement to the finger AA1, is pivotally fixed at point C on the finger and at point B on the drive a nut that moves forward by the amount “x”. The initial angle of inclination of finger 1 (also symmetrical finger 3) is equal to α_1. In the process of turning the finger, the distance AC remains constant, that is, AC = AC_1 = Const.

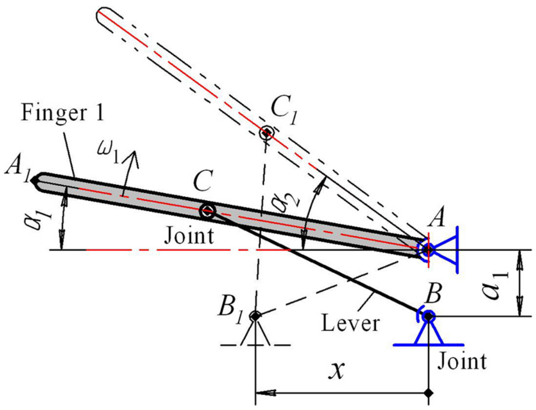

Figure 3. Kinematic diagram mechanism of the finger 1 with *AC*=Const. (see also Figure 2)

From the triangle ΔABC, according to the cosine theorem, we have the relation

$$BC^2 = AC^2 + AB^2 - 2ACAB\cos(\angle CAB), \qquad (1)$$

where AB=a_1, $AB = a_1$, $\angle CAB = 90^o + \alpha_1$.

From equation (1) we find:

$$AC = \sqrt{R^2 - (a_1\cos(\alpha_1))^2} - a_1\sin(\alpha_1) \qquad (2)$$

After moving the nut by the value BB_1=x from the triangle ΔABB_1, we determine:

$$AB_1 = \sqrt{x^2 + a_1^2}, \qquad (3)$$

and from the triangle ΔAB_1C_1 we find the angle $\angle C_1AB_1$:

$$\angle C_1AB_1 = \arccos\left(\frac{AC^2 + a_1^2 + x^2 - R^2}{2AC\sqrt{x^2 + a_1^2}}\right) \qquad (4)$$

Then, at an arbitrary point in time, the angle of inclination of finger 1 (AA_1, see also Figure 3) in the direction of movement is calculated by the formula:

$$\alpha_2 = \angle C_1AB_1 + \angle B_1AB - \frac{\pi}{2} = arctg\left(\frac{x}{a_1}\right) + \\ + \arccos\left(\frac{AC^2 + a_1^2 + x^2 - R^2}{2AC\sqrt{x^2 + a_1^2}}\right) - \frac{\pi}{2}. \qquad (5)$$

If the screw makes N rp/m, then its angular speed $\omega = \frac{\pi N}{30}$ rad/s and the movement “x” of the nut in time t seconds and its linear speed “V” will be equal to

$$x = \frac{Ns}{60}t; \quad V = \frac{dx}{dt} = \frac{Ns}{60}\, m/s, \qquad (6)$$

where s – is the pitch of the drive screw.

Find the angular speed of rotation of finger 1 (also symmetrical finger 3, see Figure 2)

$$\omega_1 = \frac{d\alpha_2}{dt} = \frac{Ns}{60}\left(\frac{a_1}{a_1^2 + x^2} - \frac{x\left(1 + \frac{R^2 - AC^2}{a_1^2 + x^2}\right)}{2AC\sin(\angle C_1AB_1)\sqrt{x^2 + a_1^2}}\right) \qquad (7)$$

Figure 4 shows the kinematics of finger 2 (see also Figure 2). The symmetrical finger 4 has a similar design. The initial angle of inclination of the finger 2 (as well as the symmetrical finger 4) is equal to β_1. In the process of turning the finger, the distance A_2C_2 remains constant, that is, $A_2C_1 = A_2C_2$ = Const.

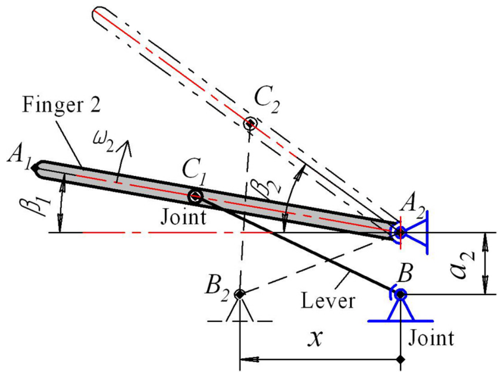

Figure 4. Kinematic diagram mechanism of the finger 2 with *A*2*C*2 =Const. (see also Figure 2)

Analogous formulas are obtained for finger 2 (as well as for symmetrical finger 4). According to the theorem of cosines, for the segment A_2C_2 we have a relation

$$A_2C_2 = \sqrt{R_1{}^2 - (a_2\cos(\beta_1))^2} - a_2\sin(\beta_1), \qquad (8)$$

where a_2 – is the distance from the hinge of finger 2 to the hinge of the nut in the initial position; β_1 is the angle formed by finger 2 with the direction of movement in the initial position. Accordingly, the distance A_2B_2 and angles $\angle B_2A_2B$, $\angle C_2A_2B_2$ are calculated using the for–mulas:

$$A_2B_2 = \sqrt{x^2 + a_2^2}; \quad \angle B_2A_2B = arctg\left(\frac{x}{a_2}\right); \\ \angle C_2A_2B_2 = \arccos\left(\frac{(A_2C_2)^2 + a_2^2 + x^2 - R_1{}^2}{2A_2C_2\sqrt{x^2 + a_2^2}}\right). \qquad (9)$$

The angle between finger 2 and the direction of movement at an arbitrary moment in time

$$\beta_2 = arctg\left(\frac{x}{a_2}\right) + \\ + \arccos\left(\frac{(A_2C_2)^2 + a_2^2 + x^2 - R_1{}^2}{2A_2C_2\sqrt{x^2 + a_2^2}}\right) - \frac{\pi}{2}. \qquad (10)$$

Let's find the angular speed of rotation of finger 2

$$\omega_2 = \frac{d\beta_2}{dt} = \frac{Ns}{60}\left(\frac{a_2}{a_2^2 + x^2} - \frac{x\left(1 + \frac{R_1^2 - (A_2C_2)^2}{a_2^2 + x^2}\right)}{2A_2C_2 \sin(\angle C_2 A_2 B_2)\sqrt{x^2 + a_2^2}} \right) \qquad (11)$$

5.2 Determination of the specific ground pressure

The area of contact of the foot with the ground, on which the robot moves, consists of the area of the central toe $S_0 = BL_0$ (see Figure 2), the area of the fin–gers, and the area of corrugated membranes. We define the areas of the extreme fingers 2 and 4 as $S_{2,4} = 2bL_1$. If the line of the extreme toe 2 is extended to the intersection with the central toe, then two circular sectors will be formed: one of radius $r_1 = L_1 + \frac{a_2}{\sin\beta}$ and the other of radius $r_2 = 0.2L_1 + \frac{a_2}{\sin\beta}$, and the total distance of contact of the foot with the ground can be determined as follows:

$$S = S_o + S_{2,4} + 2\left(\frac{1}{2}\beta r_1^2 - \frac{1}{2}\beta r_2^2\right), \qquad (12)$$

where coefficient 2 also takes into account the plane of the sector between the central finger and finger 4; β (rad) – is the central angle of a circular sector. In the unfolded form, the contact area of the foot with the ground is defined as

$$S = BL_o + 2bL_1 + \beta\left(L_1 + \frac{a_2}{\sin\beta}\right)^2 - \beta\left(0.2L_1 + \frac{a_2}{\sin\beta}\right)^2. \qquad (13)$$

The specific pressure of the robot on the surface of contact with the ground is found by the formula

$$p = \frac{\frac{1}{2}(m + 2m_1)g}{S} = \frac{\frac{1}{2}(m + 2m_1)g}{BL_o + 2bL_1 + \beta\left(L_1 + \frac{a_2}{\sin\beta}\right)^2 - \beta\left(0.2L_1 + \frac{a_2}{\sin\beta}\right)^2}, \qquad (14)$$

where m – is the mass of the robot; m_1 – mass of one leg of the robot; g is the acceleration of free fall, g = 9.82 m/s^2.

5.3 Calculation of parameters of corrugated membranes

As mentioned above, between the toes of the robot's feet are corrugated webs (see Figure 1 and Figure 2), which are made of an elastic material, such as polyvinyl chloride. When turning the toes of the foot, these membranes are stretched to increase the area of foot support in order to reduce the specific pressure on the ground and increase the stability of the walking robot. Figure 5 shows the cross-sectional dimensions of the corrugated webs. For foot design, formulas are needed to calculate the dimensions of the webs and calculate the stress that occurs in the corrugated webs when they are stretched.

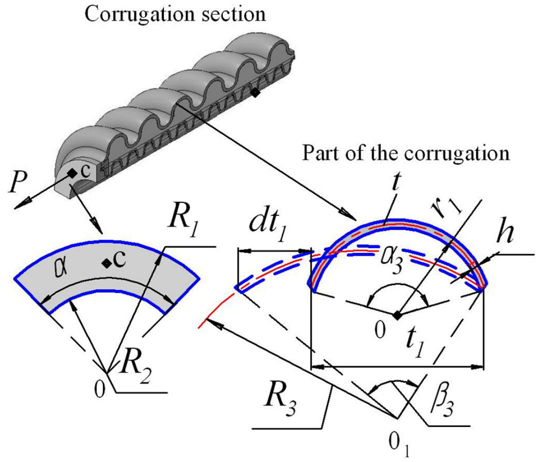

Figure 5. Cross-section dimensions of corrugated membranes

First, find the distance between the ends of fingers 1 and 2 in the initial position (that is, before moving the nut, (see Figure 2):

$$d_1 = \sqrt{(L_1\cos\beta_1 - L_1\cos\alpha_1)^2 + (L_1\sin\beta_1 + a_2 - a_1 - L_1 sin\alpha_1)^2} \qquad (15)$$

and the distance between the fingers in the final position (i.e. after moving the nut):

$$d_2 = \sqrt{(L_1\cos\beta_2 - L_1\cos\alpha_2)^2 + (L_1\sin\beta_2 + a_2 - a_1 - L_1 sin\alpha_2)^2}. \qquad (16)$$

We assume that in the initial position the corrugated membranes are not loaded, then it is possible to deter–mine the required number of corrugation elements of the elastic membrane

$$n = \frac{d_1}{t}, \qquad (17)$$

where t – is the length of one corrugation element. The total elongation of the membrane is equal to $\Delta d = d_2 - d_1$, and the elongation of one element of the corrugated membrane is

$$\Delta t = \frac{\Delta d}{n} = \frac{(d_2 - d_1)}{d_1} t. \qquad (18)$$

The value of the angles α_3, β_3 in Figure 5 is found from the equation of the elongation of the corrugation:

$$\Delta t_1 = 2\frac{r_1\alpha_1}{\beta_1}\sin(\beta_1 / 2) - t_1 \qquad (19)$$

namely:

$$\alpha_3 = 2\arcsin\left(\frac{t}{2r_1}\right); \quad \frac{s\,\mathrm{in}(\beta_3 / 2)}{\beta_3} = \frac{\Delta t + t}{2r_1\alpha_3} \qquad (20)$$

Then we find the driving force acting on the corru–gations

$$q = \frac{P}{\alpha R_1}, \ \text{N/m}, \tag{21}$$

where P – is the force that stretches the corrugations (Figure 5). The linear force formula can be represented as follows

$$q = \frac{E\Delta t}{k_1}, \tag{22}$$

where E – is the modulus of elasticity of the corrugation material; dimensionless coefficient:

$$k_1 = \left(\begin{array}{l} \frac{1}{J}\left(\frac{\alpha_1 r_1}{\beta_3}\right)^3 \left(\frac{1}{2} + \cos^2\left(\frac{\beta_3}{2}\right) - \frac{3\sin\beta_3}{2\beta_3}\right) + \\ + \frac{\alpha_1 r_1}{2h}\left(1 + \frac{\sin\beta_3}{\beta_3}\right) \end{array} \right) \tag{23}$$

where h – is the thickness of the corrugation film; a moment of inertia: $J = h^3/12$ (other designations see Figure 5).

The normal stresses that arise in the corrugated membrane during its deformation can be found using the formula

$$\sigma = \frac{q}{h} < [\sigma]. \tag{24}$$

where [σ] – is the allowable normal stress for the material from which the corrugated membrane between the toes is made. Thus, formula (24) is a condition for the strength of the corrugated membrane.

5.4 Analysis of simulation results

Based on the formulas (5) and (10) created above, graphs of changes in the angles of rotation of the toes (Figure 6) relative to the central toe were constructed.

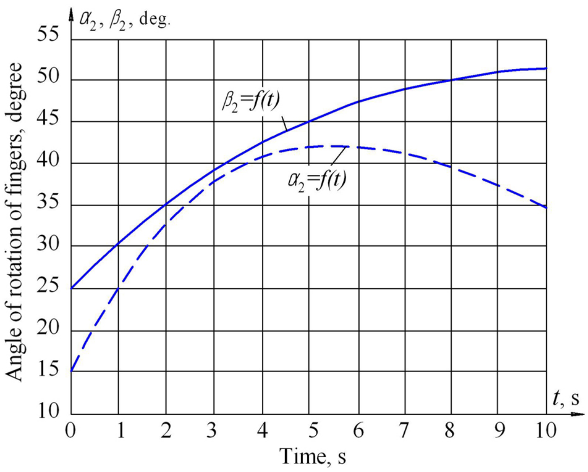

Figure 6. Graphs of changes in the angles of rotation of the fingers relative to the central finger: at a_1=0.02 m; a_2=0.04 m; lever length *CB*=0.04 m (see Figure 3): lever length C_1B =0.1 m (see Figure 4)

As can be seen from these graphs, the speed of tur–ning the fingers is sufficient for the efficient operation of the foot, and these graphs are non-linear, which should be taken into account when programming the foot drive of a walking robot.

Figure 7 shows the change in the angular velocities of the toes as a function of time. It is known that the change in speed characterizes the acceleration of the actuators, in this case, this is the acceleration of the toes of the robot. An increase in acceleration is undesirable since it can lead to an increase in inertial loads. There–fore, it is recommended not to exceed the accelerations indicated in the graphs of Figure 7.

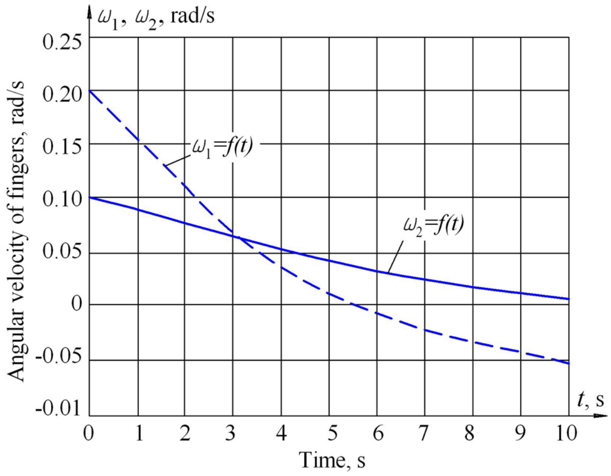

Figure 7. Change in the angular velocities of the fingers depending on time: at a_1=0.02 m; a_2=0.04 m; lever length CB=0.04 m (see Figure 3): lever length C_1B =0.1 m (see Figure 4)

Based on formulas (12) and (13), the graphs in Fi–gure 8 of the change in the area of the robot's foot sup–port during the movement of the fingers were obtained. It is from the area of the support of the foot that its spe–cific pressure on the ground depends. The foot support area and its pressure on the ground are inversely pro–portional, namely: the larger the foot support area, the less will be the specific pressure on the ground on which the robot moves.

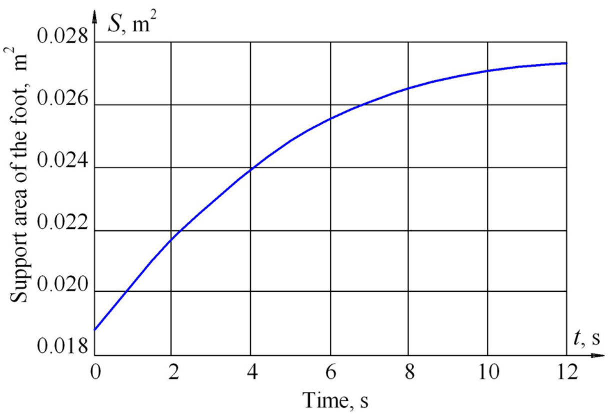

Figure 8. Graphs of changes in the area of the robot's foot support

Figure 9 shows graphs of changes in the specific pressure on the ground, which were obtained on the basis of dependence (14) for various robot masses: m = 30 kg and m = 40 kg. In cases of changing the mass of the walking robot, similar graphs can also be obtained based on the functional dependence (14) given above.

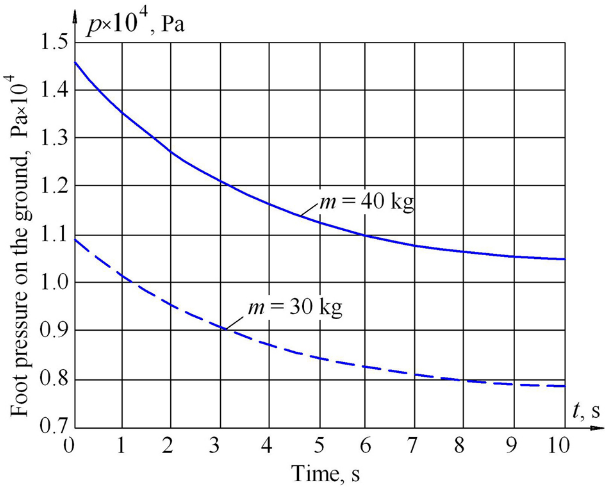

Figure 9. Graphs of changes in the specific pressure of the robot foot on the ground

From these graphs, it becomes apparent that the ground pressure decreases over time due to the increase in the footprint of the robot foot. This proves the expe–diency of regulating the foot support area when the walking robot moves to loose soils. Ultimately, a decre–ase in the specific pressure on the ground contributes to an increase in the stability of the walking robot, which was to be proved.

6. DISCUSSION

Thus, in contrast to the above studies [3, 5, 6], this paper presents a new design of the foot of a walking robot, which allows, as a result of an increase in the area of the robot's support, to reduce its specific pressure on the ground along which the robot moves. Despite the fact that in [9-11] the pliable mechanisms of the robot foot and muscle actuators make it possible to adapt the robot's legs to various soil topologies, these actuators do not take into account the density of soils and the degree of immersion of the legs of walking robots during their transition from solid soil to soft soils. Therefore, in this article, the foot of a walking robot is equipped with sensors for immersion (see Figure 1) of the robot's foot into soft ground. This new difference in the design of the foot makes it possible to turn on the drive of the fingers in a timely manner based on the signals of these sensors in order to increase the area of contact of the robot's foot with soils of various topologies. Moreover, due to the installation of the encoder on the motor shaft, it is possible to proportionally control the area of contact of the robot's legs with the ground.

As evidenced by the simulation results in the form of graphs of changes in the area of the robot foot support (see Figure 8), as well as graphs of changes in the specific pressure of the robot foot on the ground (see Figure 9), these parameters are inversely proportional. Therefore, in contrast to the studies [17, 18], where original designs were used to adapt the robot legs, in this article, the authors propose to use an alternative approach, namely, automatic control of the value of the robot leg support area and, as a result, an inversely proportional change in the specific pressure on the ground on which the robot moves.

In the proposed design of the robot foot, corrugated polyvinyl chloride membranes are installed between the toes of the foot. This material is not the only one, it is possible to use other elastic materials for webbing between the toes. It is important that the new webbing material membranes the strength condition of the above formula (24) in order to exclude the possibility of destruction of the elastic membranes between the toes. At the same time, it is desirable that the tensile strength of the material of elastic membranes be not less than $4 \cdot 10^7 \ldots 7 \cdot 10^7$ Pa, and Young's modulus of elasticity should be within $E = (2.6 \cdot 10^9 \ldots 4.0 \cdot 10^9)$ Pa. In this article, the thickness of the membrane material and the dimensions of the corrugations are taken for robots weighing up to 50 kg; for larger robots, it is recom–mended to increase these parameters. At the same time, the above formulas (14) – (24) remain valid for calcu–lating the parameters of the foot.

7. CONCLUSION

In this article, the authors propose a fundamentally new design of the foot of a walking robot, the main difference of which is the ability to change the foot support area with a change in the density of the soil along which the robot moves. This property is achieved due to the execution of the robot's foot in the form of fingers with a drive for their movements and the pre–sence of corrugated elastic membranes between the toes of the foot. The positive effect is that by increasing the contact area of the foot with the ground, the specific pressure of the robot on soft ground or loose ground, such as sand, snow, and similar soft ground, decreases. Also, for the first time, sensors for immersing the foot in soft ground were used in the foot. Based on the signals from these sensors, it is possible to increase the contact area of the foot in a timely manner to prevent the loss of stability of the walking robot.

The proposed method for calculating the parameters of the foot includes calculations of the dimensions, kinematic characteristics, and strength conditions of the foot. This new foot synthesis technique will allow rese–archers and engineers who work in the field of robotics to create similar leg designs for walking robots. Diag–rams of changes in kinematic characteristics, as well as changes in the area of contact of the foot with the ground and the specific pressure on the ground, provide an opportunity to model new similar designs of robot legs.

Ultimately, the results of the research contribute to the stabilization of the movement of mobile robots on surfaces of arbitrary topology. The main result of these studies is to increase the stability of the walking robot due to the timely increase in the area of contact of the foot with the ground and, as a result, to reduce the specific pressure of the robot on loose or soft soils along which the walking robot moves.

DECLARATION OF CONFLICTING INTERESTS

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

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СТОПАЛО НОГЕ ХОДАЈУЋЕГ РОБОТА: ДИЗАЈН И ПРОРАЧУН ПАРАМЕТАРА

М. Полишчук, М. Ткач

У области модерне роботике, антропоморфни дизајни ходајућих робота постају све популарнији. Овај тренд је због разноврсности функција које мобилни роботи овог типа могу да обављају. Један од проблема руковања ходајућим роботима је да се обезбеди њихова стабилност при кретању по повр–шинама различите топологије. Познато је да стабил–ност ходајућег робота зависи од брзине и убрзања његовог кретања, масе робота и његовог корисног терета, положаја тежишта тела робота, а такође и од специфичног притиска на тло по коме се робот креће. Ово истраживање је посвећено последњем проблему. У чланку су аутори предложили фунда–ментално нови дизајн стопала робота који хода, који вам омогућава да прилагодите специфични притисак на тло променом површине потпорне површине робота. Када се робот за ходање креће са тврде површине на растресито тло, као што су песак, снег, мека мочварна тла и друго, нови дизајн стопала вам омогућава да повећате површину ослонца и на тај начин смањујете специфични притисак на тло, а самим тим и повећава стабилност робота.

У чланку су дате и аналитичке формуле за израчунавање параметара новог стопала робота који хода, а то су величина покрета прстију, њихова брзина, променљива носива површина стопала, спе–цифични притисак на тло и чврстоћа еластичних елемената стопала робота. Графичке зависности ових параметара су такође представљене у облику дијаграма који ће помоћи истраживачима и инже–њерима да створе сличне структуре са променљивим притиском на тло. Главна мотивација за ове студије била је повећање стабилности ходајућег робота регулисањем специфичног притиска на различита тла по којима мобилни робот може да се креће.