Mobile Robot for Monitoring Park Trees: Design and Modeling

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One of the modern problems in the field of ecology is the creation of environmentally friendly equipment for monitoring and maintaining trees in parks and forests. The traditional use of forest machines and self-propelled tractors with internal combustion engines has a negative impact on the environment as a result of pollutant emissions, i.e., combustion products and fuel residues. An alternative to this tradition can be the use of mobile robots with remote control of their electric drives when performing such technological operations as pruning bacterial growths of trees and diagnosing the state of tree massifs. The article proposes a fundamentally new mobile robot design for monitoring park trees. The main differences between the robot are the new designs of the body and the walking mechanisms of the mobile robot. These design differences provide the robot with high maneuverability when choosing the path of movement along the tree trunk and reliable holding of the robot body on the tree at a sufficient movement speed to perform diagnostics of the state of tree massifs. The article also describes the dynamic models of the movement of a mobile robot along a tree trunk. It presents the simulation results in the form of graph-analytical dependencies of the robot parameters, which constitutes the scientific aspect of the problem. The main motivation of the conducted research is the creation of environmentally friendly equipment in the form of a mobile robot with a reliable system of retention on the surface moving and sufficient performance to perform park tree monitoring operations.

Keywords: *mobile robots, stepping mechanisms, climber robot, tree diagnostics*

1. INTRODUCTION

The use of mobile robots of arbitrary orientation in the technological space, also known under the term Climber Robot, is becoming more and more relevant. A distinctive feature of this type of mobile robot is its ability to overcome the gravitational load when moving on surfaces of arbitrary orientation relative to the horizon, including vertical surfaces. In particular, such surfaces include tree trunks and their branches moving along, which is necessary to perform various technological operations due to the need for periodic monitoring and maintenance of park and forest tracts of trees. Mobile robots with an electromechanical drive and autonomous power sources are a good alternative to using automotive and tractor equipment with internal combustion engines, which do not contribute to environmental cleanliness. In addition, mobile robots of arbitrary orientation in the technological space increase the safety of servicing high-rise objects because they exclude the direct participation of a person in the performance of these operations, leaving the person (operator) only with remote control functions. However, this type of mobile robot is at the initial stage of development in the form of prototypes. Therefore, the results of the studies presented below should be relevant.

The article proposes a fundamentally new design (Patent UA 126262) of a mobile robot for monitoring park trees. The proposed method for calculating the dynamic parameters of a mobile robot allow the transition to the direct design of prototypes of these robots. The general scientific significance of the article lies in the fact that, for the first time, a complete dynamic model of the functioning of a mobile robot for monitoring and diagnosing the condition of trees is provided, regardless of their species and topology.

2. PREREQUISITES AND MEANS FOR SOLVING THE PROBLEM

Initially, we will consider the most promising technical solutions for mobile robot prototypes that can move through trees and other high-altitude objects. A mobile robot [1] of the Boston Dynamics laboratory is known, which has the ability to move not only through trees but also along the walls of tall buildings. However, this robot does not have a device for turning it to change the route of movement, which significantly limits its maneuverability. This shortcoming is compensated in

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the mobile robot [2] by using spring grips for coupling with a tree trunk and a linear drive for opening the grips. However, the deformation of the elastic elements of the grips leads to an increase in the load of electric drives and, as a result, to an increase in their power, which does not contribute to a decrease in the gravitational load of the mobile robot. To securely hold the robot on a tree, it is preferable to use self-braking mechanisms, as is done in a mobile robot [3]. Mobile robots for picking nuts [4], robots for spraying pesticides [5], as well as mobile robots [6] for moving through trees and trimming their branches have an original design. But these robots move only along smooth tree trunks, which limits their maneuverability when moving between tree branches. A known vehicle [7] is called a "caterpillar", the body of which is made in the form of bellows with gas. This robot has sufficient maneuverability but very low load capacity and strength since the bellows is a thin corrugated chamber. Of course, these publications are of interest to engineers who create various designs of mobile robots of arbitrary orientation to perform special technological operations. However, in these publications, there are no methods for calculating the dynamic parameters of robots, which hinders their optimal design.

In [8], a dynamic model for a robot with flat and parallel pedipulators is proposed, which does not meet the requirements for a mobile robot that operates in a cylindrical coordinate system, which is typical of a tree trunk. The study of the dynamics of the movement of a mobile device along vertical ferrimagnetic surfaces is described in [9]. Still, in this case, electromagnetic gripping devices are used, which is unacceptable for wooden surfaces. Noteworthy are the dynamic models of anthropomorphic robots, the designs of which are distinguished by the versatility of functions. So in [10], a dynamic model of a walking robot is proposed, and in [11], a hand control system for an anthropomorphic robot is given. However, it is known that anthropo–morphic structures, as a rule, are distinguished by the complexity of devices and very high cost. Studies of the Climbing Robot dynamics for moving along vertical flat walls of houses are presented in [12]. Still, the topology of tree surfaces radically differs from the surface of the walls of house panels. Various designs of mobile robots for vertical movement are proposed in [13]. However, the designs of the gripping devices of these robots do not satisfy the topology of tree trunks and branches. The results of experimental studies [14] indicate the possibility of using the reactive thrust of a pneumatic generator to keep the robot on an arbitrary movement surface. But the use of jet thrust in the crowns of branches of park and forest trees is very problematic.

Original technical solutions are systems of adhesion to the surface on which the robot moves, based on hybrid statistical glue [15], as well as vacuum grippers [16]. But these bonding systems are difficult to apply to porous tree bark surfaces. This problem is partially solved in [17, 18] based on the wheelbase of the transmission of a mobile robot, as well as in [19] based on a servo drive for moving along smooth tree trunks, that is, without such obstacles as tree branches. An original device for the maintenance of trees and shrubs was proposed in [20] but without a drive and trans–mission for moving this device along vertical surfaces or surfaces of arbitrary orientation. To move a similar device for pruning shrubs, it was proposed to use a special helicopter [21], which certainly increases the economic costs of maintaining park arrays of trees. This drawback can be compensated for by a technical solution [22], which has manipulators to hold the robot on a tree during its maintenance, but without automatic control. A mobile robot [23] has the ability to move between tree branches and collect seeds and leaves of wild trees in the jungle, but this robot cannot perform forceful operations, such as drilling a tree trunk to take wood samples for laboratory analysis. A mobile robot [24], due to the combination of a linear drive and a current sensor, has the ability to adapt to the surface of a tree trunk. Also, the original solutions of mobile robots [25–27] for the maintenance of palm trees can be used to monitor park trees, but without the technological load when taking wood samples. In addition, in these publications, there is no information about the dynamic parameters of the transmission of robots. Dynamic models of robots are presented in [28–30] but without relatively mobile robots for servicing trees in parks and forests. Studies [31] are of interest from the point of view of optimal control of anthropomorphic devices. The article [32] proposes the walking mechanisms of a miniature robot based on biological systems with two principles of movement with the help of legs. It is shown that with the help of modern software engi–neering, bionics can become an effective tool. These technical solutions could be adapted to the monitoring conditions of various objects.

Based on the above analysis of publications, it can be argued that the tasks of studying the dynamics of the movement of a mobile robot for monitoring the condi–tion of trees and ensuring its reliable movement along tree trunks remain relevant.

3. FORMULATION OF THE PROBLEM

Despite the many original designs of mobile robots of arbitrary orientation, there are still no dynamic models of robots for monitoring parks and forest trees. The absence of a method for dynamic analysis of this type of robot prevents the design of their functional devices in terms of systems for reliable adhesion to the surface of trees and devices that provide maneuverability of the robot when changing its orientation. Therefore, it is necessary to create a mobile robot design that can hold onto an arbitrary surface of movement in case of an emergency shutdown of the autonomous power sources of its drives. This problem can be solved by using a self-braking transmission of the robot and calculating the allowable dynamic loads, which are proposed below.

4. SOLUTION OF THE PROBLEM UNDER CONSIDERATION

The technical novelty of the proposed technical solu–tions lies in a fundamentally new design of a mobile robot [33], and the scientific novelty is displayed by the presented dynamic models with an illustration of graphical and analytical dependencies for calculating the parameters and modeling the specified robot. The main motivation of this study is the creation of a mobile robot that has a higher reliability of keeping on a tree trunk and maneuverability when performing tree moni–toring operations of arbitrary topology. For a better understanding of the dynamic models of the robot, we first consider its design and principle of operation.

4.1 Walking robot design

Figure 1 shows the construction of a mobile robot. The robot body is assembled from separate rings that contact each other along spherical surfaces with a radius R. The robot body rings are pulled into a package by a mechanical spring, the ends of which are fixed on cover 1 and cover 2. Thus, the robot body is a flexible package of spherical rings. A cable is provided to bend the robot body in a vertical plane, which is wound on a pulley mounted on cover 2 and driven by an electric motor. The ends of the specified cable are fixed in clamps that are installed on cover 1. The cable has two branches, "G" and "H". Depending on the reversal of the electric motor. Hence, in the direction of the pulley's rotation, the robot's body bends up or down according to a given control program. The robot's body bending in the horizontal plane is determined by the combinations of adhesion to the surface of the tree trunk of mechanical grippers C, D, F, and E, as shown below in the text of the article.

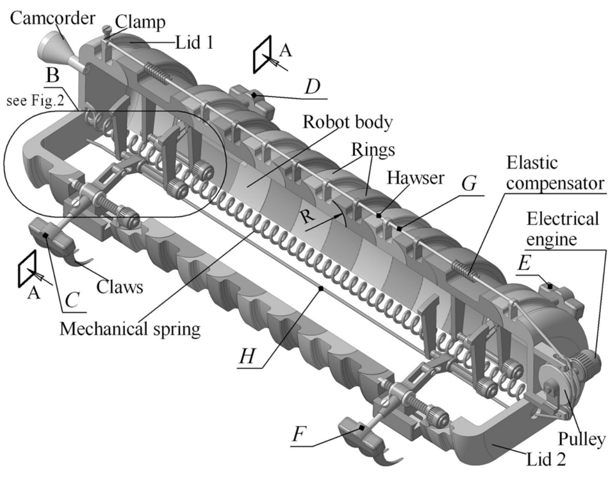


Figure 1. Mobile robot in section ¼

These mechanical grippers have claws for gripping the surface of a tree trunk. Cover 1 has a video camera for video filming of the tree crown and a drill bit (see Figure 4) for taking laboratory samples of the state of the tree trunk or branch.

Figure 2 shows the design of the mechanical gripper drive to move the robot and hold it on the tree trunk. The telescopic arm, on which, for example, grip "C" is fixed, has a screw gear driven by engine 1 and moves in the guide mechanism by the amount of travel step x2 of grip "C" (or x1 for grip "D"). In addition, a splined shaft driven by engine 2 is installed on fixed consoles.

This splined shaft, when engine 2 is turned on, informs the lever that is mounted on it of angular move–ment. This reversible angular movement is transmitted via an axle in the lever slot to a telescopic lever with a mechanical grip "C". Thus, the claws of mechanical grippers enter the tree trunk and exit the surface of the trunk. All other drives of mechanical grippers D, F, and E are arranged similarly.

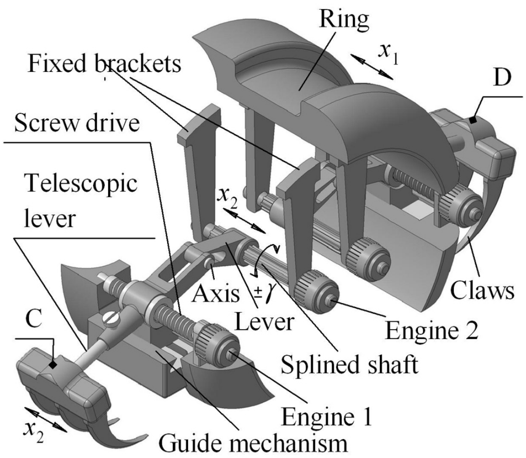


Figure 2. Drive design of mechanical grippers C, D, F, and E with claws for gripping the robot with a tree trunk or branches (Fragment "B" see Figure 1)

Figure 3 shows a cross-section of the robot body in plane A–A (see Figure 1). As noted above, the lever, which is mounted on the splined shaft, depending on the direction of the engine 2 reverse (see also Figure 2) performs an angular movement and through the axis in the groove of this lever transmits the angular movement to the telescopic lever with a mechanical grip "C" (similarly for other grips D, F and E). The ratio of these angular movements depends on the ratio of the dimen–sions L and l of the telescopic lever. So, for example, if L/l >1, then there is a force multiplication for softwood species, and with a ratio L/l < 1, there is a reduction in the entry force of the gripper claws for hardwood species.

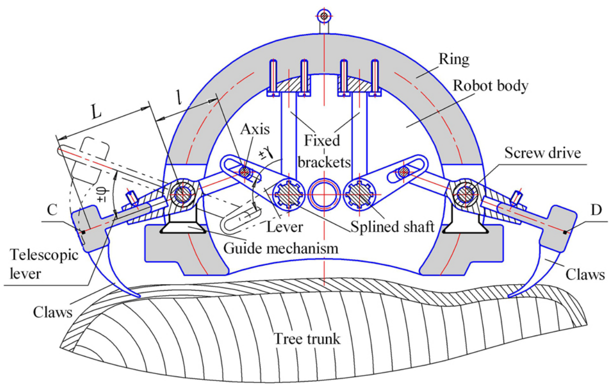
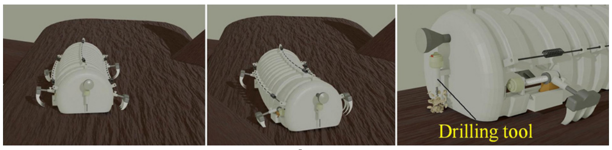


Figure 3. Cross section of the robot body in plane A–A (see Figure 1)

Figure 4 shows examples of scenes of the movement of a mobile robot along a tree trunk or its large branch. Figures 4(a) and 4(b) show that the robot can move in a straight line or turn left or right by bending its body. The combinatorics of these movements is determined either by remote radio control commands or by a pre-compiled automatic control program. In the latter case, it is necessary to install optical or tactile sensors on the robot's body to detect obstacles to its movement.



a b c

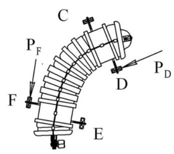
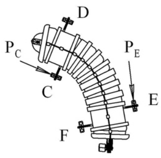
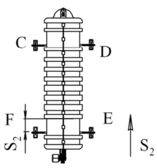
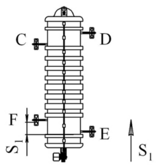
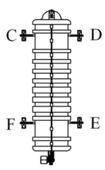
Figure 4. Scenes of the movement of a mobile robot along a tree trunk: a – the rectilinear movement of the robot; b – rotation of the robot when changing the movement route; c – taking laboratory samples of wood with a drill tool.

4.2 Algorithm of robot movement

The movement program algorithm depends on the peri–odic activation of engines 1 and 2 (see also Figure 2) and the state of engagement of the claws of mechanical grippers C, D, F, and E. This algorithm is detailed (at each movement step) in Table 1 below. As can be seen from Table 1, rectilinear vertical movement (see steps 1, 2, 3), as well as left and right turns of the robot (see steps 4 and 5) in the horizontal plane of motion, are determined by the combination of switching on the gripper drives C, D, F, and E.

Bending the robot body up or down in the vertical plane of movement is performed by reversing the tether drive motor, shown in Figure 1 (see above).

Table 1. Algorithm of robot movement and combinatorics of grips C, D, F, and E

No	Moving stage	Position of the robot (plan view)	State of capture
5	Bending of the body of robot on the right		Mechanical grip D and F are engaged with a displacement surface. Mechanical grip C and E are free from clutch (see Fig. 1). The robot body is back to the right due to the action of forces P_F and P_D respectively, after engine 1 reverse (Fig. 2) and of Screw drive of grippers D and F.
4	Bending of the body of robot on the left		Mechanical grip C and E are engaged with a displacement surface. Mechanical grip D and F are free. The robot body is turn left due to action forces P_c and P_e, respectively, when turning on of Engine 1 (see Fig. 2) and of Screw drive of grippers C and E.
3	Completion the second step S_2		Mechanical grip C and E are engaged with a displacement surface. Mechanical grip D and F are free from clutch. The body of the robot moved at a distance S as a result inclusion of Engine 1 (see Fig. 2) and of Screw drive of grippers D and F.
2	Completion the first step S_1		Mechanical grip D and F attached to the surface with a displacement surface. Mechanical grip C and E are free from clutch due to revers engine 2 . The body of the robot moved at a distance S_1 as a result inclusion of Engine 1 (see Fig. 2) and of Screw drive of grippers C and E.
1	Starting position		Mechanical grip C and E attached to the surface displacement due to turning on Engine 2 and return of Splined shaft (see Fig. 2). Mechanical grip D and F are free from coupling

The combination of bends in the body of the mobile robot in various directions ensures the high maneuve–rability of the robot when bypassing various obstacles. The presence of self-braking screw gears in drives C, D, F, and E (see Figure 2) ensures that the robot is kept on the tree surface in the event of an emergency shutdown of power supply sources for electric motors. The latter property increases the reliability of the functioning of a mobile robot of arbitrary orientation in emergencies.

5. SIMULATION OF THE FUNCTIONING OF A WALKING ROBOT

To be able to study a walking mobile robot for moni–toring park trees, it is necessary to develop its dynamic model. Below is the dynamic model of the robot's movement, as well as graphs of changes in kinematic characteristics and the first created analytical formulas for calculating the grip force of the robot with the tree surface and ensuring the state of stability of the mobile robot on the tree.

Dynamic model of robot movement

To describe the movement of the robot, we will use the Lagrange equation of the second kind

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

where k – is the number of degrees of freedom of the mechanical system; q_i – generalized coordinates; $\dot{q}_i$ – generalized speeds; $T(q_i,\dot{q}_i)$ – kinetic energy of the mechanical system, which is a function of generalized coordinates and generalized velocities; Q_{q_i} is the generalized force corresponding to the generalized coordinate q_i. In this case, the system has two degrees of freedom (we assume that the legs free from coupling with the tree move synchronously). For the generalized coordinates, we will choose the translational movement of the robot body $q_1 = x_1$ and the translational movement of each free leg relative to the body $q_2 = x_2$. Accordingly $\dot{x}_1, \dot{x}_2$ – generalized speeds. Then the expression for the kinetic energy T_k of the body will have the form

$$T_k=\frac{m_k V^2}{2}=\frac{m_k(\dot{x}_1)^2}{2}, \tag{2}$$

and the kinetic energy T1 of one free leg can be found using the formula

$$T_1=\frac{m_1(\dot{x}_1+\dot{x}_2)^2}{2}, \tag{3}$$

where m_k is the mass of the robot body, m_1 is the mass of the leg. The total kinetic energy T of the mechanism is equal to

$$T=T_k+2T_1=\frac{m_k(\dot{x}_1)^2}{2}+m_1(\dot{x}_1+\dot{x}_2)^2. \tag{4}$$

Let's find the partial derivatives of the kinetic energy included in equation (1)

$$\frac{\partial T}{\dot{x}_1}=m_k\dot{x}_1+2m_1(\dot{x}_1+\dot{x}_2);\ \frac{\partial T}{\partial \dot{x}_2}=2m_1(\dot{x}_1+\dot{x}_2);$$
$$\frac{\partial T}{\partial x_1}=\frac{\partial T}{\partial x_2}=0. \tag{5}$$

Let's calculate more complete time derivatives:

$$\frac{d}{dt}\left(\frac{\partial T}{\partial \dot{x}_1}\right)=m_k\ddot{x}_1+2m_1(\ddot{x}_1+\ddot{x}_2);$$
$$\frac{d}{dt}\left(\frac{\partial T}{\partial \dot{x}_2}\right)=2m_1(\ddot{x}_1+\ddot{x}_2). \tag{6}$$

Generalized forces Q_{q_i} can be found using the general formula

$$Q_{q_i}=\frac{\delta A_{q_i}}{\delta_{q_i}}, \tag{7}$$

where δ_{q_i} – is the possible increase of th ≤≤e generalized coordinate; δA_{q_i} – the possible work of the forces acting on the mechanical system on the corresponding possible displacement.

In this case, we will provide a possible increase δ_{x1} in the movement of the robot body x_1. As a result, we obtain a possible increase in the angle of rotation of the screw $\delta_\varphi=2\pi\delta_{x_1}/s$, at which moment M_1 of the screw gear drive performs work. Also, perform the possible work of the force of the weight of the robot:

$$\delta A_{x_1}=\left(\frac{2M_1 i}{s}2\pi-(m_k+2m_1)g\right)\delta_{x_1} \tag{8}$$

where s – is the thread pitch of the screw, acceleration of free fall g=9.81 m/s^2. Therefore, the generalized force will be equal to

$$Q_{x_1}=\left(\frac{4\pi M_1 i}{s}-\left(m_k+2m_1\right)g\right) \tag{9}$$

Let's give a possible increase to the movement of the leg by x_2. As a result, the possible gain $\delta_\varphi=2\pi\delta_{x_2}/s$ (i – the transmission ratio of the screw gear) and the angle during the reverse rotation of the screw, to which the moment M_3 is applied, will be obtained. It is at this increment that the moment M_3 will perform the possible work $\delta A_{x_2}=2\pi M_2 i\delta x_2/s$, and the generalized force will be equal to

$$Q_{x_2}=4\pi M_3 i/s-2m_1 g \tag{10}$$

Substitute the found expressions of derivative and generalized forces into expression (1) and, after some simplifications, obtain the differential equations of mo–tion of the robot on the first part of the cycle of the robot's movement

$$m_k\dot{x}_1+2m_1(\dot{x}_1+\dot{x}_2)=$$
$$=\left(\frac{4\pi M_1 i}{s}-(m_k+2m_1)g\right); \tag{11}$$
$$2m_1(\ddot{x}_1+\ddot{x}_2)=4\pi M_3 i/s-2m_1 g.$$

The differential equations of the robot's motion on the second part of the cycle of the robot's movement will be similar to (11). The system of differential equations was solved under the initial conditions: $t=0$, $x_1=x_2=0$, $\dot{x}_1=V_1$, $\dot{x}_2=V_2$:

$$x_1(t)=V_1t+At^2;\ x_2(t)=V_2(t)+Bt^2$$
$$\dot{x}_1(t)=V_1+2At;\ \dot{x}_2(t)=V_2+2Bt \tag{12}$$

where indicated:

$$b=\frac{4\pi M_3 i/s-2m_1 g}{2}$$
$$a=\frac{4\pi M_1 i/s-\left(m_k+2m_1\right)g}{2}$$
$$A=\frac{a-b}{m_k};B=\frac{b}{2m_1}-A$$

The results of the calculations are given below in the Results section.

Determining the force of adhesion of the robot to the surface tree

Figure 5 shows the diagram of the interaction of the drive lever with the gripping device with claws, on which the driving torque M_2 acts. We assume that the lengths L and l of the arms of the telescopic lever, the distance H between the axes of the levers, as well as the angle of inclination of the driving lever $-\pi/8\le\gamma\le\pi/8$, are known; (-22,5° ≤ γ ≤ 22,5°). Based on the theorem of cosines, we find the length of the segment BC (Figure 5) if:

$$l^2=H^2+BC^2-2H\times BC\cos\gamma$$

then from here, we get the formula for calculating the segment BC:

$$BC=H\cos\gamma-\sqrt{l^2-\left(H\sin\gamma\right)^2} \tag{13}$$

Using the theorem of sines, we find the angle of inclination of the robot's leg

$$\varphi=\arcsin\left(\frac{BC\sin\gamma}{l}\right) \tag{14}$$

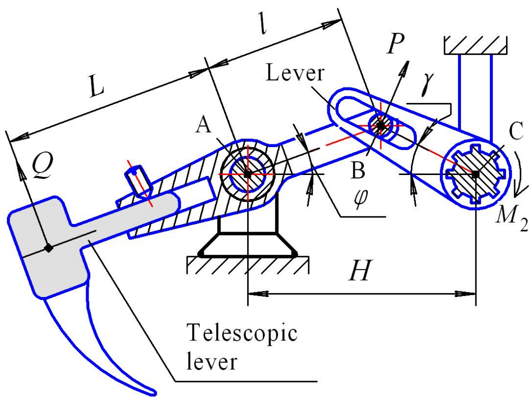


Figure 5. Diagram of the legs of a mobile robot

The force P depends on the value of the driving tor–que M_2:

$$P=\frac{M_2 i}{BC} \tag{15}$$

and the force Q, which sinks the claws of the gripping device into the tree, is found from the condition of equilibrium of the robot's legs $Pl\cos(\varphi+\gamma) - QL = 0$.

Hence, taking into account (15), we obtain the force of adhesion of one leg of the robot to the surface tree

$$Q = \frac{M_2 il}{L \times BC}\cos(\varphi+\gamma) \tag{16}$$

where the cosine value is calculated using the formula

$$\cos(\varphi+\gamma) = \frac{H^2 - l^2 - BC^2}{2lBC}$$

Stability condition of a mobile robot.

This condition ensures the reliability of holding the mobile robot on the tree trunk. When performing a technological operation, the robot is attached to the tree trunk with the claws of all four legs of the robot, each of which is pressed by the force Q. In addition, an additional technological force T_3 will act on the robot, which tries to tear the robot away from the tree, for example, the force of a drill bit or the force of cutting branch trees, and the like. Therefore, the stability condition of a mobile robot on a tree can be written as follows:

$$\frac{2QL_2}{T_3(L_1+L_2)} > k_c \tag{17}$$

where k_c is the stability margin factor; T_3 – is technological force; L_1 is the distance from the point of force application T_3 to the nearest gripping device; L_2 is the center-to-center distance between the gripping devices of the robot. Thus, to ensure reliable maintenance of the mobile robot on the tree, the following condition must be met:

$$T_3 < \frac{2QL_2}{(L_1+L_2)k_c}. \tag{18}$$

5.4. Analysis of simulation results

On the basis of the dynamic model of the robot, the simulation results are obtained in the form of graphical-analytical dependencies. The calculations were made with the following values of the parameters of the mobile robot: the mass of the robot body m_k=8 kg; the mass of one leg of the robot m_1=m_k/4; robot movement step S = 0.025 m; thread pitch of the screw mechanism (see Figure 2) s = 0.002 m; the gear ratio of the screw mechanism i = 2. Figure 6 shows the dependencies of the magnitude of the movements of the body and legs of the mobile robot in time.

As can be seen from the presented graphs, with a decrease in the torques of the direct-acting screw drive motors M_1 and reverse M_3, the robot travels the same path for a longer period of time, which is natural, because with a decrease in torque, the work performed by the torque also decreases. In the general case, if in one revolution of the screw gear, the moment performs work

$$A_1 = 2\pi M_1 ik_c \tag{19}$$

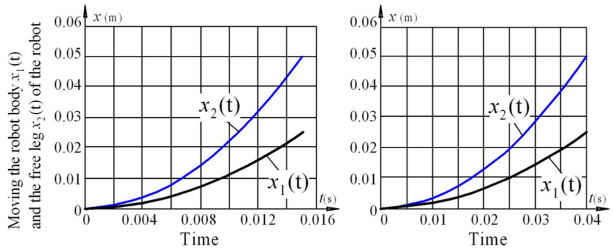


Figure 6. Graphs of movements of the body x1(t) and free legs x2(t) of the mobile robot: a – when M1=0,363 Nm, M3=0,215 Nm; b – when M1=0,059 Nm, M3=0,033 Nm

where i – is the gear ratio of the screw gear; k_c – is the efficiency factor; 2π – is the angle of rotation of the screw, then, accordingly, the weight force G_{max} of the robot also performs work, namely:

$$A_2 = -G_{max}s \tag{20}$$

where s – is the screw pitch. According to the classical principle of possible movements, the sum of works should be equal to zero, that is:

$$2\pi M_1 ik_c = G_{max}s. \tag{21}$$

From relation (21), it seems possible to determine the load force of a mobile robot for any weight

$$G_{max} = \frac{2\pi M_1 ik_c}{s} \tag{22}$$

and also get the formula for determining the minimum torque of the screw drive:

$$M_1^{min} = \frac{G_{max}s}{2\pi ik_c} \tag{23}$$

Figure 7 shows graphs of changes in the robot's speed over time. As can be seen from the graphs, these dependencies are linear, which is important for building a motion control system for a mobile robot.

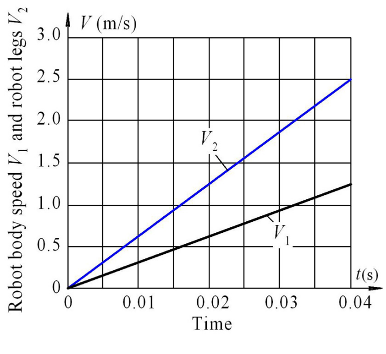


Figure 7. Graphs of changes in the speed of the body robot V_1 and the clutch-free legs V_2 of the robot for the values of the motor torques M_1=0,059 Nm, M_3=0,033 Nm

Figure 8 and Figure 9 shows the dependence of the force of the claws of the robot's grippers on the angle of inclination of the drive arm with (Figure 8) and without (Figure 9) reduction of the telescopic arm (see also Figure 5). As can be seen from the graphs, for the ratio $l > L$, i.e., in the presence of reduction in the mechanism of gripping devices, the adhesion force of the robot claws is much greater than in the absence of reduction, when l = L. This condition is important for the operation of a mobile robot when servicing hard or soft trees.

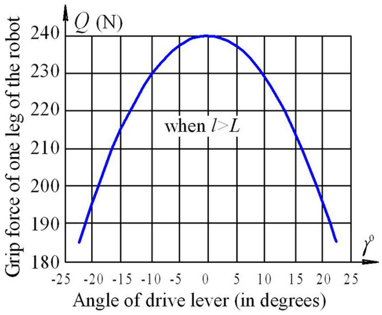


Figure 8. Changing the strength of the robot's claws from the angle of the drive arm with parameter values (when *l* > *L*): *L*=0,1 m, *l*=0,15 m, *H*=0,2 m, M_3=4 Nm

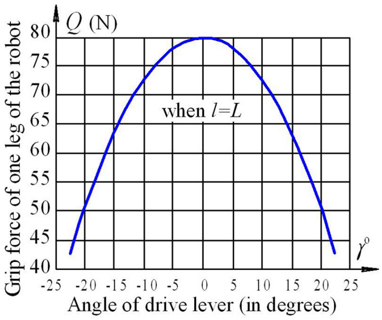


Figure 9. Changing the strength of the robot's claws from the angle of the drive arm with parameter values (when *l* = *L*): *L*= 0,1 m, *l* = 0,1 m, *H*=0,2 m, M_3=4 Nm

When monitoring hardwood trees, the ratio of lever arms l > L is recommended to increase the strength of the claws of the grippers, and when servicing softwood trees, the gripping force can be less, i.e., at l = L, but this will increase the speed of movement of the gripping devices of the robot.

6. DISCUSSION

Thus, in contrast to studies [1, 2], this article developed a dynamic robot model for monitoring the state of park trees and analyzed the dynamic parameters of a mobile robot. In relation to mobile robots [4–7], the new design of the mobile robot allows servicing trees with any topology. It has much greater maneuverability due to the flexible body of spherical rings. Unlike mobile robots [17, 18], which use a wheeled transmission, this robot uses a walking mechanism, which is better suited to the topology of trees. The presence of self-braking screw gears in the new robot's drives guarantees the mobile robot's retention on the surface tree in the event of an emergency shutdown of the autonomous power sources of the robot. The design of the mobile robot does not impose restrictions on the type of electric motors, but preference should be given to a digital drive for higher control accuracy.

As can be seen from the graph in Figure 6, the mobile robot has a high movement speed. The legs of the robot work in pairs and diagonally of the robot body, so the movement speed of the legs, which are free from adhesion to the surface, is higher. However, such speed values are acceptable when the robot moves along a smooth tree trunk. When the robot moves between tree branches, its speed must be limited to 0.1…0.3 m/s. However, in any case, condition (18) must be observed to ensure the stability of the mobile robot. It should also be remembered that the values of accelerations of movement (see also Figure 7), combined with the mass of moving parts, determine the inertial forces and therefore affect the degree of stability of the robot. Therefore, when changing the direction of movement of the robot, preference should be given to lower values of the acceleration of movement to reduce the forces of inertia and ensure the robot's stability.

A comparison of the graphs in Figure 8 and Figure 9 shows that the clutch force of the robot's claws increases significantly when the ratio of the arms of the telescopic lever l > L (see also Figure 5). This condition is recommended for hardwoods.

7. CONCLUSION

In this article, the authors proposed a fundamentally new design of a walking mobile robot for monitoring park trees, the main difference of which is increased maneuverability of movements. This property is achieved through the execution of the robot body in the form of a package of spherical rings, which allow the robot to bend in any direction depending on the route of movement along the tree.

The presence of a self-braking screw gear in each drive of the legs of the mobile robot increases the reliability of holding the robot on a tree trunk in the event of an emergency power failure of the electric motors of its drives. The proposed analytical and graphical dependences of the dynamic parameters of a walking mobile robot allow researchers and engineers in the field of robotics to carry out the multivariate design of such devices. The simulation results of this robot's functioning illustrate its industrial applicability as a walking Climbing robot for the maintenance of park trees.

Ultimately, the proposed mobile robot has not only the ability to move along the surfaces of trees of arbitrary topology but also to change the trajectory of movement due to the combinatorics of turning on the drives and bending the robot body. The main result of these studies is to reduce the cost of a walking mobile robot and eliminate human labor at high altitude service objects such as park trees.

DECLARATION OF CONFLICTING INTERESTS

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

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МОБИЛНИ РОБОТ ЗА ПРАЋЕЊЕ ДРВЕЋА ПАРКА: ПРОЈЕКТОВАЊЕ И МОДЕЛИРАЊЕ

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Један од савремених проблема у области екологије је стварање еколошки прихватљиве опреме за праћење и одржавање дрвећа у парковима и шумама. Традиционална употреба шумских машина и самоходних трактора са моторима са унутрашњим сагоревањем негативно утиче на животну средину као резултат емисије загађујућих материја, односно продуката сагоревања и остатака горива. Алтернатива овој традицији може бити употреба мобилних робота са даљинском контролом њихових електричних погона приликом извођења таквих технолошких операција као што су обрезивање бактеријских израслина дрвећа и дијагностицирање стања дрвећа. У чланку се предлаже фундаментално нови дизајн мобилног робота за праћење дрвећа у парку. Главне разлике између робота су нови дизајн тела и механизама за ходање мобилног робота. Ове дизајнерске разлике обезбеђују роботу високу управљивост при избору путање кретања дуж стабла и поуздано држање тела робота на дрвету при довољној брзини кретања за обављање дијагностике стања масива дрвећа. У чланку су описани и динамички модели кретања мобилног робота дуж стабла. Резултате симулације представља у виду графско-аналитичких зависности параметара робота, што чини научни аспект проблема. Основна мотивација спроведеног истраживања је стварање еколошки прихватљиве опреме у виду мобилног робота са поузданим системом задржавања на површини кретања и довољним перформансама за обављање операција праћења парковског дрвећа.