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Behavior of the six-legged robot in emergency situation

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The paper proposes a method of rocking the body of a six-legged robot, which provides a flipping of the body and the return of the robot to the operating position. It is shown that the autonomous rescue of the apparatus from an emergency position "upside down" is possible with the help of cyclic movement of the legs, if the body has an upper shell in the form of a truncated cylinder. The legs on the pre-chosen edge of the body through which the flip should occur, are passive, and straightened along the body so that they do not interfere with the flip. The legs on the opposite edge are active; they perform synchronous movement in a plane perpendicular to the longitudinal axis of the body, with a fixed angle in the knee. An analytical study and computer simulation of the full dynamics of the robot were fulfilled which confirmed the effectiveness of the developed technique for restore the functional capability of the robot. Computer simulation was carried out by means of the Universal Mechanism software package. The results of numerical experiments are presented.

Keywords: *six-legged robot, emergency, flipping of the robot's body, rocking*

Introduction

When the walking robot moves on the road [1, 2], various emergencies can occur. A problematic case is when the robot is in an upside down position with its legs oriented upwards. For a multi-legged robot with a body in the form of a polygon [3], reverse flipping of the body is difficult. A saving option is possible when due to the special design of the legs the robot can move both in the standard and inverted body positions [4]. Along with that, to facilitate the task of flipping the body, we can use the resonant effects that occur with a specific body shape due to special foot movements.

This article develops the results presented in [2, 5] regarding the construction of algorithms for controlling robot behavior in extreme situations using computer experimentation methods. The full dynamic model of the robot is automatically generated by the complex Universal Mechanism [6].

The problem to be solved is formulated as follows. As a result of unforeseen accident, the walking robot is lying on its back in the "upside down" position. Robot should, without assistance, at the expense of its management resources, turn over to its original working position when its legs are in support and the body is at the top. Such situations are often found in the animal world, and especially among insects and reptiles, which have a wide solid body. For example, beetles or turtles, and all of them learned how to overcome such difficulties in the process of evolution. The methods they use include pull-ups and push-ups from the support [7, 8].

Below, we propose another method of turning the robot from emergency to working position using dynamic effects that occur when the robot, being in an inverted position, begins to swing the body without supporting its feet on the ground due to a specially formed movement of the legs, providing an increase in the swing amplitude. As a result, the amplitude reaches such a value that the case inevitably turns over. Obviously, in this case, a simple periodic law of movement of the legs will not lead to success, since the period of swing of the body will depend on the amplitude. The article presents a constructively constructed algorithm for solving the formulated problem. This algorithm was worked out using the Universal Mechanism software package [6], taking into account the complete dynamics of the system as a whole, which has twenty four degrees of freedom. The results of computer simulation testify to the fundamental feasibility of the proposed robot control algorithm.

Formulation of the problem

To facilitate the process of revolution, the body of the walking robot in the working position can be in the form of a convex upward part of the cylinder cut off by a plane parallel to the axis of the cylinder. Consider the following model problem. Suppose that on a horizontal reference line lays a homogeneous segment of a circle having mass M. The segment is bounded by an arc of a circle of radius R and a chord, which is at a distance h from the center of the circle. The arc of the segment circle touches the reference line at a point A. A segment can roll without slippage along the reference line, rotating around the center of the mentioned circle by an angle φ counted from the vertical radius directed to the point of contact of the segment with the line. If $\varphi = 0$, then the segment lies so that its chord is parallel to the support line (Figure 1).

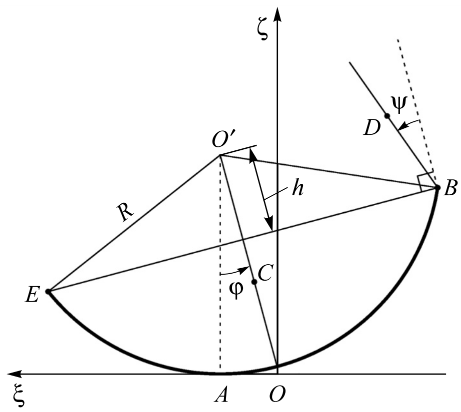


Figure 1. Emergency position of the robot.

A leg (rod) of mass m_1 is attached to the right end B of the chord of the segment by a flat hinge. The rod can rotate by angle ψ relative to the segment. The angle ψ is measured from the outer perpendicular to the chord of the segment. When $\psi = 0$, the leg is directed perpendicular to the chord away from the reference line. At the other end of the chord, a point mass m_2, is located at the point E that balances the leg. The center of mass D of the leg is located at a distance ρ from the point B. The center of mass C of the segment is located on the median perpendicular to the chord at a distance r from the center of the circumference of the segment. A segment has an inertia moment J relative to a straight line passing through the center of mass of the segment perpendicular to the plane of the segment. The moment of inertia of the leg relative to its center of mass is denoted by J_r. To describe the movement, we use the coordinate system $O\xi\zeta$. We place the beginning O at the point of tangency of the segment with the reference line at $\varphi = 0$. The axis $O\xi$ is directed along the reference line from right to left. The axis $O\zeta$ is directed vertically upwards. Note that, in accordance with the statement of the problem, the admissible value $\mathrm{tg}\varphi$ is limited by the limits

$$-\frac{\sqrt{R^2 - h^2}}{h} \le \mathrm{tg}\varphi \le \frac{\sqrt{R^2 - h^2}}{h}. \qquad (1)$$

For values $\mathrm{tg}\varphi$ outside the range (1), it should be assumed

$$\xi_A = R\,\mathrm{arctg}\frac{\sqrt{R^2 - h^2}}{h}\,\mathrm{sign}\,\varphi, \quad \dot{\xi}_A = 0. \qquad (2)$$

If the point A reaches the limit of the allowable range, then its speed should become equal to zero, while the speed of either the point E or B becomes equal to zero, and the system may experience an impact. For simplicity of research, bearing in mind the study of the possibility of the robot turning over from an uncomfortable upside-down position, we will not take into account condition (1), assuming that the entire circle, of which the arc of the segment in question is a part, is solid, but does not have mass.

Find the coordinates of the specified characteristic points of the system:

$$\xi_A = R\varphi, \quad \zeta_A = 0, \quad \xi_C = R\varphi - r\sin\varphi, \quad \zeta_C = R - r\cos\varphi,$$
$$\xi_B = R\varphi - h\sin\varphi - \sqrt{R^2 - h^2}\cos\varphi = R[\varphi - \sin(\varphi + \alpha)], \qquad (3)$$
$$\zeta_B = R - h\cos\varphi + \sqrt{R^2 - h^2}\sin\varphi = R[1 - \cos(\varphi + \alpha)],$$

$$\xi_D = \xi_B + \rho\sin(\varphi+\psi), \quad \zeta_D = \zeta_B + \rho\cos(\varphi+\psi),$$
$$\xi_E = R\varphi - h\sin\varphi + \sqrt{R^2-h^2}\cos\varphi = R[\varphi - \sin(\varphi-\alpha)], \tag{3}$$
$$\zeta_E = R - h\cos\varphi - \sqrt{R^2-h^2}\sin\varphi = R[1-\cos(\varphi-\alpha)],$$

where angle $\alpha = \angle EO'O$,

$$\sin\alpha = \frac{\sqrt{R^2-h^2}}{R}, \quad \cos\alpha = \frac{h}{R}.$$

The center of mass of the mechanical system has the coordinates

$$\xi_{cm} = R\varphi + \frac{m_1\rho\sin(\varphi+\psi) - S_1\sin\varphi - S_2\cos\varphi}{M+m_1+m_2},$$
$$\zeta_{cm} = R + \frac{m_1\rho\cos(\varphi+\psi) - S_1\cos\varphi + S_2\sin\varphi}{M+m_1+m_2},$$

here

$$S_1 = Mr + (m_1+m_2)h, \quad S_2 = (m_1-m_2)\sqrt{R^2-h^2}.$$

Let the Cartesian coordinate system $O'\xi'\eta'\zeta'$ be rigidly connected with the segment. Its beginning O' coincides with the center of the circle circumference, the axis $O'\xi'$ is aligned with the vector **BE**, the axis $O'\zeta'$ is perpendicular to the axis $O'\xi'$ and oriented upward, and the axis $O'\eta'$ complements the coordinate system to the right-oriented one. The absolute coordinates of the center of mass of the mechanical system under consideration can be represented as

$$\begin{gathered}\xi_{cm} = R\varphi + \xi'_{cm}\cos\varphi + \zeta'_{cm}\sin\varphi, \quad \eta_{cm} = 0,\\ \zeta_{cm} = R - \xi'_{cm}\sin\varphi + \zeta'_{cm}\cos\varphi,\end{gathered} \tag{4}$$

where

$$\xi'_{cm} = \frac{m_1\rho\sin\psi - S_2}{M+m_1+m_2}, \quad \eta'_{cm} = 0, \quad \zeta'_{cm} = \frac{m_1\rho\cos\psi - S_1}{M+m_1+m_2} \tag{5}$$

is the coordinates of the center of mass of the mechanical system in the axes $O'\xi'\eta'\zeta'$.

An analytical description of the swinging process is implemented using the theorem on the change in the kinetic moment of the system relative to the moving point A [9].

The mechanical model of the walking robot

The solid body of the robot has the shape of two truncated straight circular cylinders folded along a common rectangular plane intersection, a is the length of the plane intersection, b is its width. The radius of the base of the cylinder corresponding to the back of the robot is equal to R, the radius of the base of the cylinder corresponding to the belly of the robot is equal r. The body has a mass m. Six identical two-link legs are symmetrically attached to the sides of the flat intersection. The points of attachment of the legs on each side of the body are located at the same distance from each other. A separate leg consists of two solid links: thigh length l_1, mass m_1 and lower leg length l_2, mass m_2. In contrast to [2, 10], it is allowed to touch the surface of the support and surrounding objects with any part of the body and feet. The legs of the robot should not have mutual intersections during the whole movement.

Standardly, the trajectories of leg transfers are formed in the form of flat step cycles [2, 3], adaptable depending on the surfaces of obstacles, the speed of the robot, the prescribed trace points. Leg movements corresponding to step cycles are smoothed to maintain continuity of both the movement itself and its speed [2]. In emergency situations, the formation of leg movements directly using their angular coordinates is allowed.

It is assumed that the robot knows: its own position relative to obstacles and the supporting surface, the bearing capacity of the surface areas selected for the support, the articulated angles and the speed of movement of both the robot itself and the objects selected for the support. The programmed values of the articulated angles are generated by the control algorithm taking into account information about the current position of the surrounding objects and the realized configuration of the robot during its movement. The implementation of the programmed values of the articulated angles is carried out in the same way as in [2].

The presence of a force moment at the reference points is not assumed [3]. If the desired reaction extends beyond the friction cone, slippage occurs.

The actions of the walking robot in an emergency

The problem to be solved is formulated as follows. Suppose that as a result of an accident, the robot rolls over and finds itself in a position when it lies with its back upside down on an even horizontal supporting plane. It needs to choose the side edge of the body through which the flip will be carried out so that the back is up. Rescue activities take place in accordance with the steps below.

Step 1. The legs, the attachment points of which are located on the edge chosen for the flip, will be passive. They must be straightened and folded so that, if possible, they do not interfere with the flip. For example, the front foot can be directed forward along the body, the rear foot back along the body, and the middle foot can be put forward along the body so that it is pressed against the body and adjacent to the attachment point of the front foot.

Step 2. Legs that remain straight will be active. They begin to swing the body by directly controlling their articulated angles. Moreover, all three legs carry out synchronous movement in a plane perpendicular to the longitudinal axis of the body, with a fixed angle in the knee. For them, only the angles $\beta_i \equiv \psi$ between the hip of the leg and the body change. For more intense rocking, it is advisable to maximize the knee angle of all active legs, bringing its value to π as close as possible. The angle of deviation of the active legs from the body of the robot should not exceed values $\pi / 2$. If this restriction is violated, then at large swing amplitudes of the body, active legs, hitting the supporting plane, can interfere with the increase in the amplitude of rocking of the body. To achieve unlimited rocking of the body, it is impossible to accept a periodic function $\psi(t)$, since the period of oscillations of the body will depend on the amplitude. Let us denote by $\{t_j^+,\ j = 1, 2, ...\}$ a sequence of time instants for which the height of the suspension points of the passive legs above the supporting plane is minimal. Let there also $\{t_j^-,\ j = 1, 2, ...\}$ be a sequence of time instants for which the height of the suspension points of the active legs is minimal when swinging.

We assume that the index j corresponds to one half-cycle of oscillations and $t_j^- < t_j^+ < t_{j+1}^-$. Let ψ_M be the value of the angle at which the active legs are closest to the suspension points of the passive legs, and ψ_m is the value corresponding to the largest allowable distance of the active legs from the suspension points of the passive legs during the formed movement of the active legs. The prescribed dependence for the full cycle of oscillations has the form

$$\psi(t) = \begin{cases} \dfrac{\psi_M - \psi_j}{\Delta t}(t - t_j^-) + \psi_m, & t_j^- \le t < t_j^- + \Delta t, \\ \psi_M, & t_j^- + \Delta t \le t < t_j^+, \\ \dfrac{\psi_m - \psi_M}{\Delta t}(t - t_j^+) + \psi_M, & t_j^+ \le t < t_j^+ + \Delta t, \\ \psi_m, & t_j^+ + \Delta t \le t < t_{j+1}^-, \end{cases} \quad j = 0, 1, 2, ... \qquad (6)$$

Here ψ_j is the value of the angle ψ that was realized at the time t_j^-. Rocking starts with moving the active legs to the nearest position to the suspension points of the passive legs. In this case, the body leans towards the passive legs. Further, the angle ψ reaches a value $\psi = \psi_m$, and the body deviates towards the suspension points of the active legs (the reverse swing), etc. The value Δt sets the time interval of the transition process from one constant value ψ to another. This value should be less than the time of one half-cycle. The swinging occurs until the moment when the body turns over around the side edge of the body corresponding to the attachment points of the passive legs. The body cannot roll over the side containing suspension points of active legs, since the increase in amplitude occurs mainly on the half-cycle with $\psi = \psi_M$.

Step 3. After the body is turned over, the robot rests with its active legs in the supporting plane, and it will need to stand on its feet. In this position, it can rearrange the three legs, in which the front and rear legs are taken from the active side, and the middle leg — from the passive. Using the indicated three legs, the body is aligned to the correct position, and at the same time, the feet of the other three legs are transferred to the prescribed support points. After this, the final alignment of the body and legs to a standard position occurs.

Computer simulation

Management of a walking robot, the law of interaction of the body and feet with the supporting plane is implemented in the form of a DLL library connected to the Universal Mechanism software package [6]. The fixed supporting plane, the body and the legs of the robot interact with each other according to the model of friction based on the viscoelastic interaction of bodies at the contact points. Motion control is implemented through computer simulation of the operation of electromechanical drives of articulated angles. The execution of the required movement of the robot is carried out, as in reality, only as a result of supplying the value of the control electric voltage to the model of electromechanical drives. The ratio of the size of the body and the links of the legs is

$$a : b : R : r : l_1 : l_2 = 1 : 0.79 : 0.4 : 1.5 : 0.5 : 0.33.$$

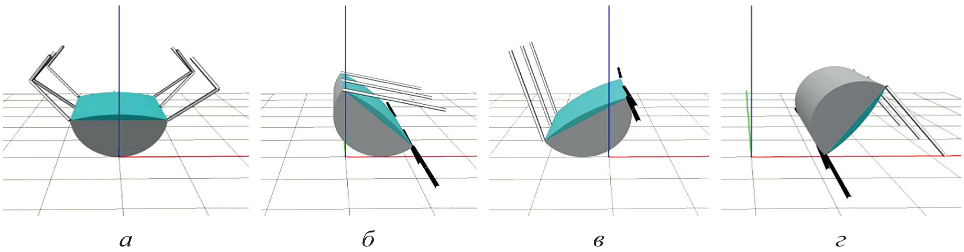
The masses of the robot body and the links of the legs are

$$m : m_1 : m_2 = 25.42 : 0.5 : 0.5.$$

The description of the movement of the robot body and its legs arises as a result of numerical integration of the differential equations of the full three-dimensional dynamics of the robot. Force interaction is assumed at the contact points of objects. The equations of dynamics are synthesized automatically [6]. The results of computer simulation are displayed on the monitor screen in the form of a movement of geometric images of the studied material objects.

Figure 2 shows the fragments of simulation of rocking.

Graphs of the time variation of the angles ϕ, ψ are presented on Figure 3 [9]. The angle between the construction vertical of the body and the vertical axis $O\zeta$ in the emergency position of the body is equal to π. The amplitude of the oscillations increases monotonously. In this case, the deviations of the angle ϕ are asymmetric with respect to the value π, since the equilibrium position of the walking robot body is shifted towards the passive legs. At the end of the swing, the robot body flips through the side with the suspension points of the passive legs. Passive legs, having finite dimensions, somewhat interfere with the flip. Therefore, irregularity is observed at the end of the flipping process.



(a) (b) (c) (d)

Figure 2. Initial position (a), one of the swings towards passive legs (b), reverse swing (c), position after robot’s turn over (d).

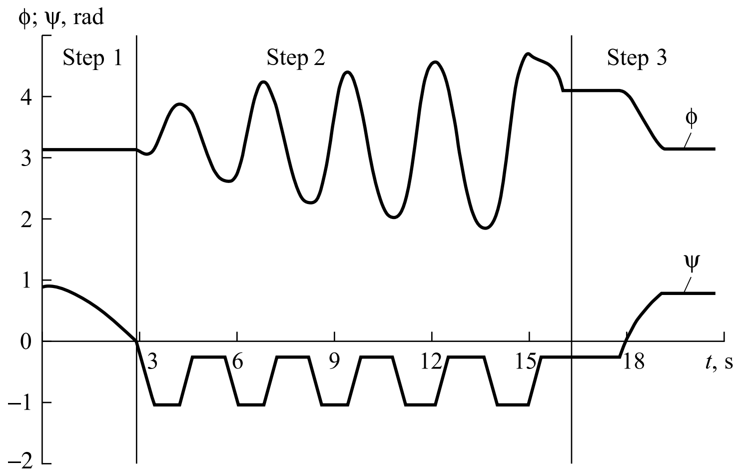


Figure 3. Dependence of the main angles on time.

Before the start of swinging, preparation is carried out: the active legs are brought into a straightened vertical position, and the passive legs are folded along the robot body. The graph shows the corresponding curves and the angle ψ corresponding to the middle active leg. After the end of the flip, the events of stage 3 occur [9].

Conclusions

The solution of the problem of rescuing an autonomous legged robot, emergency lying on a horizontal supporting plane on his back in the “upside down" position is presented. To save the robot, a special body shape is proposed in the form of two truncated straight circular cylinders folded in a flat section. A method of amplitude swinging of the system in the vicinity of the emergency equilibrium position has been developed and analytically justified [9], which allows using the kinematic and dynamic capabilities of the robot for self-rescue. A stable resonant motion of the system is synthesized, which ensures the turning of the body of the walking robot and its bringing to the normal working position.

The proposed algorithms for the formation of the movement of the robot during rescue from an emergency were worked out by computer simulation in a software environment that implements the calculation of the interaction of a three-dimensional full dynamic model of a mechanical system consisting of a robot interacting with a horizontal reference plane. As a result of an analytical study of a simplified dynamic model of the system, restrictions were established on the possibility of using the developed method associated with the geometric and mass characteristics of the design of a walking robot [9].

The stabilization of the walking robot's motion in the vicinity of the programmed motion is constructed on the basis of the feedback piecewise-formed with the discreteness of an integration step. Feedback is calculated by the mismatch between real and software articulated angles with the requirement of minimum angular velocities.

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Поведение шестиногого робота в аварийной ситуации

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Предложен метод раскачивания корпуса шестиногого робота, обеспечивающий переворот корпуса и возвращение робота в рабочее положение. Показано, что автономное спасение аппарата из аварийного положения «вверх ногами» возможно с помощью циклического движения ног, если корпус имеет верхнюю оболочку в виде усеченного цилиндра. Ноги на заранее выбранном краю корпуса, через который должен произойти переворот, являются пассивными и выпрямляются вдоль корпуса для того, чтобы не мешать раскачиванию. Ноги на противоположном краю являются активными, они осуществляют синхронное движение в плоскости, перпендикулярной продольной оси корпуса, при фиксированном угле в колене. Выполнены аналитическое исследование и компьютерное моделирование полной динамики робота, подтвердившие эффективность разработанной методики для восстановления функциональной состоятельности робота. Компьютерное моделирование проведено средствами программного комплекса «Универсальный механизм». Приведены результаты численных экспериментов.

Ключевые слова: *шестиногий робот, аварийная ситуация, переворот корпуса, раскачивание*

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