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Six-Legged Walking Robot (Hexabot), Kinematics, Dynamics and Motion Optimization

S.Yu. Misyurin[a,b]*, G.V. Kreinin[a], N.Yu. Nosova[a]†,A.P. Nelubin[a,b]

[a]*Blagonravov Mechanical Engineering Research Institute of the Russian Academy of Sciences (MERI of RAN), 4 Mal. Kharitonyevskiy Pereulok, 101990, Moscow, Russia*

[b]*National Research Nuclear University MEPhI (Moscow Engineering Physics Institute) (MEPhI), 31 Kashirskoe shosse, 115409, Moscow, Russia*

Abstract

The movement of a walking six – legged robot hexabot (a "spider" robot) with the possibility of implementing various movements is considered. The equations of kinematics and dynamics of a separate robot leg with three degrees of freedom are written out, and the question of optimizing the robot movement is considered based on the study of dynamic equations. At the first stage for solving this problem, one leg is considered separately, as a kinematic system with open kinematics and with three degrees of freedom. The kinematics equations were presented in matrix form using the principle of rotation of the coordinate system. The dynamics equations are based on Lagrange equations of the second kind. The mass of the legs, reduced to the center of gravity, moments of inertia, moments developed by engines were taken into account, and ets. The conclusions were made about the optimal movement of the leg based on the obtained equation of kinetic energy of the robot's leg based on the obtained equation of the kinetic energy of the robot leg. This paper doesn't consider the movement of the entire platform (the spider's "body"), nor does it consider the influence of the friction force that occurs in kinematic pairs and when the robot's legs touch the surface during movement.

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* Corresponding author. Tel.: +7-926-530-9896
E-mail address: ssmmrr@mail.ru
* Corresponding author. Tel.: +7-915-122-2920
E-mail address: natahys@mail.ru

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1. Introduction

Walking robots have an indisputable advantage over other types of movement on the surface in such tasks as moving on sandy and swamp surfaces, moving off-road and in difficult terrain, moving under water, space purpose-interleaving on other planets and satellites of planets. The use of mechanisms (robots) on a wheeled or tracked basis in such conditions is impossible or ineffective. An analysis of the characteristics of walking propellers in comparison with wheeled and tracked ones is given in [1].

The development of mock-ups of walking robots has a long history, which began more than 60 years ago in countries such as the USSR, USA, Japan, Jugoslavije, etc. The following scientists have made a great contribution in this direction: D. E. Okhotsimsky [2] problems of control and stability of robots, V. V. Beletsky stability of bipedal walking [3], A. A. Artobolevsky, A. P. Bessonov, N. V. Umnov kinematics and dynamics of walking robots [4], M. Vukobratovich development of gaits and control of robots [5] and others. However, despite all the advantages of walking machines, they are not widely used. This is due to many reasons, among which the main ones can be noted, such as increased energy consumption during walking movement in relation to the traditional – wheeled, a complex robot control system that requires sufficiently large computing power, the lack of light and durable materials for the manufacture of the running gear (legs) of robots. Only recently, due to the rapid development of the digital industry, the appearance of new materials, including composite materials, the appearance of powerful and compact electric motors, the direction of walking machines (robots) has received a second wind. It should be noted that the greatest development has been received by insectomorphic robots [6, 7], which, due to the large number of legs, have increased stability when moving compared to anthropomorphic [8] or zoomorphic robots [9].

As mechanisms that make movement in multi-legged robots, it is advisable to use and, as a rule, use a mechanism with open kinematics.

Such mechanisms (with open kinematics) are found everywhere. Currently, a huge variety of industrial robots with open kinematics similar to the "Kuka" robots have found application in the industry [10]. The advantage of these robots is their relatively simple kinematic structure and good positioning accuracy. As a driving force, as a rule, electric motors are used, less often rotary pneumatic motors, for example [11]. Similar schemes of open kinematics are used in biorobots that copy the mode of movement of both humans [12] and insects [13, 14], in particular, spiders robotic (Fig. 1.). In these mechanisms, each leg has three degrees of freedom. Such insects are quite popular in the search for alternative movement mechanisms on difficult surfaces. Indeed, leg systems theoretically offer the potential for better rugged terrain than traditional wheeled or tracked designs, due to the low ground contact and lack of slippage. The use of robots with a large number of legs implies a better adaptation to uneven terrain, but at the same time a large number of legs inevitably lead to a more complex control system. Of all the legged systems, six-legged robots seem to be the logical trade-off between stability in motion and control complexity, and are therefore of great interest to research engineers. There are many developed gaits (kinematics of motion) spider-robot, but not always sufficiently investigated the dynamics of these "walks", insufficient attention has been paid to the issue of optimization of parameters of the legs, and optimizing movements [15-17].

2. Description of the mechanism

Let us consider in more detail the structure of the robot's leg (Fig. 2). Let us introduce a coordinate system in the center of the hinge for attaching the leg to the body O_1. This mount is a rotational pair in the plane of the "spider" body. The O_1z axis is directed vertically up along the rotation axis of the actuator. The O_1x axis is directed perpendicular to the O_1z axis, and is directed to the center of mass of the spider's body; the O_1y axis is perpendicular to the O_1zx plane and forms the right coordinate system.

Fig. 1. General view of the spider robot

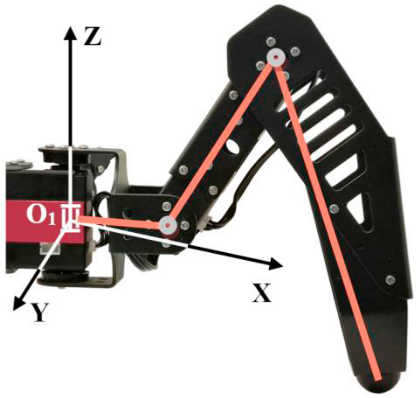

Fig. 2. Spider robot leg

Let's go to the kinematic description of the robot's leg (Fig. 3). O_1, O_2, O_3 are rotary kinematic pairs with angles of rotation. The O_1O_2 link rotates in the O_1x plane, α is the angle of the link deviation from the O_1x axis. The axis of rotation of the kinematic pairs O_2, O_3 are parallel to the O_1x plane. We introduce the following notation: $|O_1O_2| = l_1, |O_2O_3| = l_2, |O_3O_4| = l_3, |O_1A_1| = \rho_1, |O_2A_2| = \rho_2, |O_3A_3| = \rho_3$; J_{A1}, J_{A2}, J_{A3} are the moments of inertia of links 1, 2 and 3 relative to their centers of mass; $m_{1,2,3}$ are masses of these links; $\rho_{1,2}$ are the coordinates of their centers of mass relative to the kinematic pairs; J_{d1}, J_{d2}, J_{d3} are the moments of inertia of the engine rotors, installed in the joints of the links (if the movement from the actuator to the link is transmitted through the reducer, then the moment of inertia of the is substituted into the equation given to the output shaft of the gearbox); α, β and γ are generalized coordinates – the angles of rotation of the links, calculated according to the scheme in figure 3. M_{d1}, M_{d2}, M_{d3} are the moments of engines and M_{c1}, M_{c2}, M_{c3} are the moments of resistances. We introduce the notation for the lengths $|O_1A_2| = L_1, |O_1A_3| = L_2, |O_2A_3| = L_3$.

The leg has three degrees of freedom and moves with the help of kinematic pairs O_1, O_2, O_3.

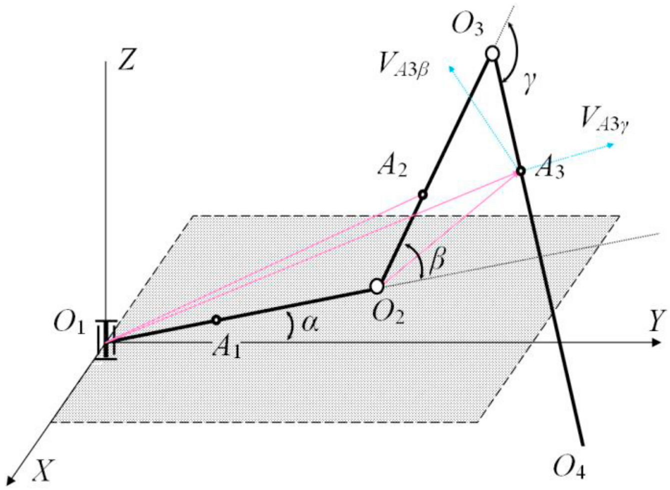

Fig. 3. A spider robot leg kinematic scheme.

3. Kinematics and dynamics of the mechanism

When solving problems of kinematics and dynamics of a robot with six legs, we rely on the fact that part of the legs moves in the air, while part of the legs are on the ground and supports the robot. It is necessary to find out how each leg moves separately, which movement will be the most economical or fast. In other words, at the first stage, we assume that the robot's body is stationary. According to this assumption, we consider each leg as an open kinematic chain. In accordance with this assumption, the equation of the direct kinematics problem has the form:

$O_1\ xyz$:

$$\overrightarrow{O_1O_4} = M_z(\alpha)\left[M_y(\beta)\left[M_y(-\gamma)\begin{pmatrix}0\\ l_3\\ 0\end{pmatrix}+\begin{pmatrix}0\\ l_2\\ 0\end{pmatrix}\right]+\begin{pmatrix}0\\ l_1\\ 0\end{pmatrix}\right] \tag{1}$$

where M_x, M_y, M_z are rotation matrices.

$$M_z(\alpha) = \begin{pmatrix}cos(\alpha) & -sin(\alpha) & 0\\ sin(\alpha) & cos(\alpha) & 0\\ 0 & 0 & 1\end{pmatrix},\ M_x(\alpha) = \begin{pmatrix}1 & 0 & 0\\ 0 & cos(\beta) & -sin(\beta)\\ 0 & sin(\beta) & cos(\beta)\end{pmatrix},$$

$$M_x(\gamma) = \begin{pmatrix}1 & 0 & 0\\ 0 & cos(\gamma) & -sin(\gamma)\\ 0 & sin(\gamma) & cos(\gamma)\end{pmatrix} \tag{2}$$

The resulting expression for the vector O_1O_4 determines the position of the output link of the robot's leg (i.e. O_4) in the O_1xyz coordinate system, given the generalized input coordinates α, β and γ.

Substituting expressions (2) in equation (1), we obtain the equations of motion of the robot's leg in an explicit form:

$$\overrightarrow{O_1O_4} = \begin{bmatrix}-\sin(\alpha)\left(\cos(\beta)\left(\cos(\gamma)l3+l2\right)-\sin(\beta)\sin(\gamma)\,l3+l1\right)\\ \cos(\alpha)\left(\cos(\beta)\left(\cos(\gamma)\,l3+l2\right)-\sin(\beta)\sin(\gamma)\,l3+l1\right)\\ \sin(\beta)\left(\cos(\gamma)\,l3+l2\right)+\cos(\beta)\sin(\gamma)\,l3\end{bmatrix} \tag{3}$$

Let us write out the equation of the mechanism dynamics based on the General Lagrange equation of the second kind:

$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{q}_i}\right)-\frac{\partial L}{\partial q_i} = R_i. \tag{4}$$

Where $L = T - U$ is the Lagrange function; T and U are the kinetic and potential energy of the system, respectively; q_i is the i-th generalized coordinate ($i = 1,2,3$). Each of the R_i terms on the right side represents the sum of non-potential generalized forces acting on the i-th coordinate, which also include the driving forces or moments of the drives. In our case, we can take $R_i = M_{di} - M_{ci}$, where $i = 1,2,3$.

Let's write out the kinetic energy.

$$\boldsymbol{T} = \boldsymbol{T}^{(1)} + \boldsymbol{T}^{(2)} + \boldsymbol{T}^{(3)}; \tag{5}$$

$$\boldsymbol{T}^{(1)} = \frac{m_1V_{A1}^2}{2}+\frac{J_{A1}\dot{\alpha}^2}{2}+\frac{J_{g1}\dot{\alpha}^2}{2} = (\rho_1\dot{\alpha})^2\frac{m_1}{2}+\frac{J_{A1}}{2}\dot{\alpha}^2+\frac{J_{g1}}{2}\dot{\alpha}^2 = \frac{\mathbf{1}}{\mathbf{2}}\left(\boldsymbol{\rho}_{\mathbf{1}}^{\mathbf{2}}\cdot\boldsymbol{m}_{\mathbf{1}}+\boldsymbol{J}_{\boldsymbol{A1}}+\boldsymbol{J}_{\boldsymbol{g1}}\right)\dot{\boldsymbol{\alpha}}^{\mathbf{2}}; \tag{6}$$

$$\boldsymbol{T}^{(2)} = \frac{V_{A2}^2\cdot m_2}{2}+\frac{J_{A2}}{2}\left(\dot{\alpha}^2+\dot{\beta}^2\right)+\frac{J_{g2}}{2}\dot{\beta}^2.$$

The speed of the point A_2 is a function of the generalized coordinates α and β, thus $V_{A2} = V_{A2}(\alpha,\beta)$, therefore:

$$V_{A2}^2 = \left(V_{A2\alpha}+V_{A2\beta}\right)^2 = \left(L_1\dot{\alpha}+\rho_2\dot{\beta}\right)^2 = L_1^2\dot{\alpha}^2+\rho_2^2\dot{\beta}^2+L_1\dot{\alpha}\cdot\rho_2\dot{\beta}\cdot cos(90) = L_1^2\dot{\alpha}^2+\rho_2^2\dot{\beta}^2$$

$$\boldsymbol{T}^{(2)} = \frac{(L_1^2\dot{\alpha}^2+\rho_2^2\dot{\beta}^2)m_2}{2} + \frac{J_{A2}}{2}\left(\dot{\boldsymbol{\alpha}}^2 + \dot{\boldsymbol{\beta}}^2\right) + \frac{J_{g2}}{2}\dot{\boldsymbol{\beta}}^2; \tag{7}$$

$$\boldsymbol{T}^{(3)} = \frac{V_{A3}^2 \cdot m_3}{2} + \frac{J_{A3}}{2}\left(\dot{\alpha}^2 + \left(\dot{\beta}+\dot{\gamma}\right)^2\right) + \frac{J_{g3}}{2}\dot{\gamma}^2; \tag{8}$$

The velocity of point A_3 is a function of the generalized coordinates α, β and γ, thus $V_{A3} = V_{A3}(\alpha,\beta,\gamma)$, therefore:

$$V_{A3}^2 = \left(V_{A3\alpha} + V_{A3\beta} + V_{A3\gamma}\right)^2 = V_{A3\alpha}^2 + V_{A3\beta}^2 + V_{A3\gamma}^2 + 2V_{A3\alpha}V_{A3\beta}cos(90) + 2V_{A3\alpha}V_{A3\gamma}cos(90) +$$
$$+2V_{A3\beta}V_{A3\gamma}cos(S) = L_2^2 \cdot \dot{\alpha}^2 + L_3^2 \cdot \dot{\beta}^2 + \rho_3^2 \cdot \dot{\gamma}^2 + 2L_3\rho_3\,cos(S) \cdot \dot{\beta};$$

Angle S is the angle between the velocity vectors $V_{A3\beta}$ and $V_{A3\gamma}$. In turn, these vectors are perpendicular to the O_2A_3 and O_2O_3 segments, respectively. Consequently, the angle S is equal to the angle $O_2A_3O_3$. From the triangle $O_2O_3A_3$ we have:

$$l_2^2 = L_3^2 + \rho_3^2 - 2L_3\rho_3 \cdot cos(S) => 2L_3\rho_3\,cos(S) = L_3^2 + \rho_3^2 - l_2^2;$$

Thus, we get:

$$V_{A3}^2 = L_2^2 \cdot \dot{\alpha}^2 + L_3^2 \cdot \dot{\beta}^2 + \rho_3^2 \cdot \dot{\gamma}^2 + (L_3^2 + \rho_3^2 - l_2^2) \cdot \dot{\beta}\dot{\gamma}$$

and therefore:

$$\boldsymbol{T}^{(3)} = \frac{(L_2^2\cdot\dot{\alpha}^2+L_3^2\cdot\dot{\beta}^2+\rho_3^2\cdot\dot{\gamma}^2+(L_3^2+\rho_3^2-l_2^2)\cdot\dot{\beta}\dot{\gamma})\cdot m_3}{2} + \frac{J_{A3}}{2}\left(\dot{\boldsymbol{\alpha}}^2 + \left(\dot{\boldsymbol{\beta}}+\dot{\boldsymbol{\gamma}}\right)^2\right) + \frac{J_{g3}}{2}\dot{\boldsymbol{\gamma}}^2$$

where

$$L_1^2 = l_1^2 + \rho_2^2 + 2l_1\rho_2 cos(\beta);$$

$$L_2^2 = \left(l_2 sin(\beta) - \rho_3 sin(\gamma-\beta)\right)^2 + (l_2 cos(\beta) + \rho_3 cos(\gamma-\beta) + l_1)^2 =$$
$$= l_2^2 + \rho_3^2 + 2l_2\rho_3\,cos(\gamma) + l_1^2 + 2l_1l_2\,cos(\beta) + 2l_1\rho_3\,cos(\gamma-\beta);$$

$$L_3^2 = l_2^2 + \rho_3^2 + 2l_2\rho_3 \cdot cos(\gamma).$$

The potential energy of the system is:

$$U_2 = m_2 g \cdot \rho_2 \cdot cos(\beta) + m_2 g \cdot l_2 \cdot cos(\beta);$$
$$U_3 = m_3 g \cdot \rho_3 \cdot cos(\beta-\gamma). \tag{9}$$

Let us write out the kinetic energy by substituting expressions 3-5 in 2 and grouping the terms by the derivatives of the generalized coordinates:

$$\boldsymbol{T} = \dot{\boldsymbol{\alpha}}^2 \cdot \boldsymbol{J}^{(1)} + \dot{\boldsymbol{\beta}}^2 \cdot \boldsymbol{J}^{(2)} + \dot{\boldsymbol{\gamma}}^2 \cdot \boldsymbol{J}^{(3)} + \dot{\boldsymbol{\beta}}\dot{\boldsymbol{\gamma}} \cdot \boldsymbol{J}^{(4)} \tag{10}$$

where

$$\boldsymbol{J}^{(1)} = \frac{1}{2}\left(\rho_1^2 \cdot m_1 + J_{A1} + J_{g1} + J_{A2} + L_1^2 \cdot m_2 + J_{A3} + L_2^2 \cdot m_3\right);$$

$$\boldsymbol{J}^{(2)} = \frac{1}{2}\left(\rho_2^2 \cdot m_2 + J_{A2} + J_{g2} + J_{A3} + L_3^2 \cdot m_3\right);$$

$$\boldsymbol{J}^{(3)} = \frac{1}{2}\left(\rho_3^2 \cdot m_3 + J_{A3} + J_{g3}\right);$$

$$\boldsymbol{J}^{(4)} = \frac{1}{2}\left(L_3^2 + \rho_3^2 - l_2^2 + J_{A3}\right)$$

Substituting expressions (9), (10) into (4), we get the equations for the dynamics of the robot's leg.

4. Conclusions

The use of mechanisms The obtained dynamic equations of the robot leg are quite difficult to analyze analytically. In general, they do not have an analytical solution. In general, they have no an analytical solution. For numerical solution and analysis, the system must be supplemented by adding the operation of three electric motors to the obtained equations.

The multiplier $J^{(1)}$, facing $\dot{\alpha}^2$, is the moment of inertia of links 1 and the system of the 2nd and 3rd links (considered at each given moment as a rigid structure) relative to the center O_1 of rotation of the first hinge. It is seen that the multiplier $J^{(1)}$ takes on its maximum value when L_1 and L_1 become maximum. This occurs when $\cos(\gamma) = \cos(\beta) = \cos(\gamma - \beta) = 1$. Therefore, the most difficult case for the engine (motor) of the first link will be at $\beta = \gamma = 0$, when three links are stretched into one line. It would seem that for fast movement, when it is easier for the first motor to turn with its foot (movement along the angle α) at angles $\gamma = 180$, $\beta = 90$, but the width of the robot's stroke will be minimal and the robot will make a narrow step. For a more detailed analysis of the choice of optimal movement, for example, for fast movement, it is necessary to conduct a numerical experiment based on a mathematical model of the dynamic process of movement. Based on a numerical experiment, it is necessary to perform multicriteria optimization using methods of visualizing solutions to the problem [13, 14, 16, 17].

It should be noted that this work did not consider the movement of the entire platform (the spider's "body"), nor does it consider the influence of the friction force that occurs in kinematic pairs and when the robot's legs touch the surface during movement. But when moving on a flat surface and there is no slippage at the points of contact of the legs with the surface on which the robot moves, these restrictions and assumptions are not significant.

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