

Effect of gait on the energy consumption of walking robots

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Abstract. The energy consumption of walking robots has been considered on the base of solution of variational problem. It is fixed that the gait is affected on the energy efficiency and must vary with speed.

Keywords: walking robot, walking mechanism, energy efficiency, energy consumption, heat losses, variational problem, gait of walking robot.

1. Introduction

One of the problems of walking robots is their low energy efficiency. It is known [1] that energy consumptions grow in proportion to the cube of speed when walking robot moves with constant velocity of its body. This is due with the periodic acceleration and deceleration of unbalanced walking mechanisms in the transfer phase from one position to another. The use of energy recovery allowing to accumulate energy in the braking phase of the walking mechanism in the transfer and then to give it in the phase of accelerating, allows to increase the energy efficiency [2].

It is known methods to improve energy efficiency at the expense of motion comfort as bipedal [3] and multilegged robots [4]. For multilegged robots with dual walking mechanisms resulting equation gives you the opportunity to choose such law of motion, which ensures low energy consumption [5]. This equation for walking movers operating from a common motor has a form:

$$\dot{T} + QV = Q_a V_a, \tag{1}$$

where T is kinetic energy of robots body and its movers; Q, V, Q_a, V_a - according resistance force and the velocity of the body translational motion in the current time and their average values in the one cycle.

In the general case the Eq. (1) is nonlinear differential equation of the second order with respect to the coordinates.

2. Statement of the problem

As we know there is a fairly complete classification of possible gaits of multilegged walking robots during their translational motion with rectilinear and uniform motion of body center of mass. The ratio mode γ is the important element of classification:

$$\gamma = \frac{\tau - t_i}{\tau}, \tag{2}$$

where t_i is the time spent of walking mechanism in the phase of interacting with supported surface, τ is total cycle time.

The another important feature is the time τ_j of the start transfer of j mover to a new position. The countdown is since the beginning of shifting phase of one of the walking mechanism.

This mechanism is considered as baseline $\tau_j = 0$.

Given that of the beginning and end of the transfer, j mover it absolute speed:

$$\dot{x}_j = 0, \tag{3}$$

the motion of the body is performed without sliding of its pads on the ground.
 The possible dependence $\dot{x}_j = \dot{x}_j(t)$ are shown in the Fig. 1.

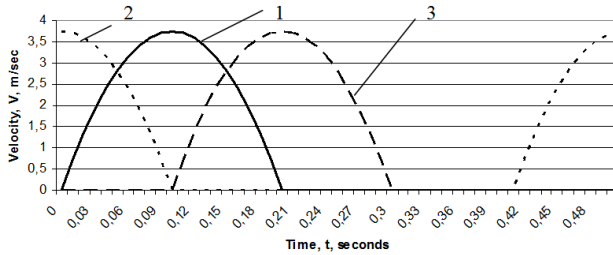


Fig. 1. Velocities of movers for example gait ($\tau = 0.5$ second):
 1 – The baseline walking mechanism $\tau_j = 0$, 2 – j walking mechanism in case $\tau_j > 0$,
 3 – j walking mechanism in case $\tau_j < 0$.

The simplest analytical dependence of the absolute speed \dot{x}_j with time and satisfying the set conditions in Eq. (3) has the form:

$$\dot{x}_j = \begin{cases} -\frac{6S}{t_i^3}(t - \tau_j)^2 + \frac{6S}{t_i^2}(t - \tau_j), & \tau_j < t < \tau_j + t_i, \\ 0, & t < \tau_j, \quad t > \tau_j + t_i, \end{cases} \tag{4}$$

$$\dot{x}_j = \begin{cases} -\frac{6S}{t_i^3}(t - \tau_j)^2 + \frac{6S}{t_i^2}(t - \tau_j), & \tau + \tau_j < t, \quad t < \tau_j + t_i, \\ 0, & \tau_j + t_i < t < \tau_j + \tau, \end{cases} \tag{5}$$

where S is the distance at which the walking mechanism pad is transferred over time $\tau - t_i$.

The main goal of submitted paper is to define such a low of rectilinear motion of the robot center of mass during its forward motion which provides the minimum of total heat losses all engines that control motion of all movers at various gaits and speeds.

3. Design scheme and mathematical model of walking robot

The translational motion of walking robot body of mass M and N its movers of mass m each are studied. These motions are described by absolute coordinates x_c, x_j (Fig. 2) at that a_j – coordinate of j mover installation, z_j – coordinate j mover with respect to the point of its installation.

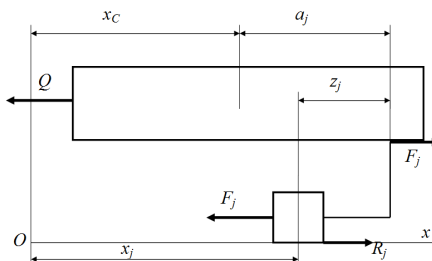


Fig. 2. Design scheme of walking robot

The resistance force Q and forces of interactions between the body of walking robot and their movers F_j are generated by drives of the course motion. The interaction of j mover with supported

surface is taken into account by tangent forces R_j . The supported surface is modeled by homogeneous elastic medium and the body of the robot is modeled by absolutely solid. For this reason, all reactions R_j for movers interacted with a ground are equal each other:

$$R_j = R. \tag{6}$$

Then the differential equations, described the motion of considered mechanical system have a form:

$$\begin{aligned} M\ddot{x}_c &= \sum F_j - Q, & j &= 1, 2, \dots, N, \\ 0 &= R - F_j, & j &= 1, 2, \dots, k, \\ m\ddot{x}_j &= -F_j, & j &= k + 1, k + 2, \dots, N, \end{aligned} \tag{7}$$

where N is the total number of movers, k is the number of movers interacted with the support surface in a given moment of time and dependent on the gait. It follows from Eq. (7) that the force, generated by actuator is determined from second equation for movers interactive with the support surface and for movers which are in phase of transfer the force is determined from third. The constant force R is determined from the first Eq. (7):

$$R = \frac{M\ddot{x}_c + Q + \sum_{j=k+1}^N m\ddot{x}_j}{k}. \tag{8}$$

The feature of the Eq. (8) is the fact that in the process of motion a number of movers k interact with the supporting surface may change. Hence considered mechanical system is system of variable structure.

4. Method of solution

In accordance with the task the method of solution is based on the requirement of the minimum of integral.

$$I_* = \int_0^\tau \sum_{j=1}^N F_j^2 dt. \tag{9}$$

It is taken into account the isoperimetric condition:

$$\int_0^\tau \dot{x}_c dt = S, \tag{10}$$

where S is the distance, traversed by the body of robot during the time of interacting of walking mechanism with a supported surface.

Then we can obtain a new functional I by combining Eq. (9) and Eq. (10):

$$I = \int_0^\tau \left(\sum_{j=1}^N F_j^2 + \mu \dot{x}_c \right) dt = \int_0^\tau \Phi dt. \tag{11}$$

$$\Phi = \sum_{j=1}^k \left(\frac{M\ddot{x}_c + Q + \sum_{j=k+1}^N m\ddot{x}_j}{k} \right)^2 + \sum_{j=k+1}^N (m\ddot{x}_j)^2 + \mu \dot{x}_c, \tag{12}$$

where μ is undetermined Lagrange multiplier.

Since \ddot{x}_j are defined as time function Eq. (4) and Eq. (5) and parameters S , t_i , τ_j , the Euler-Poisson equations [6], providing the minimum of functional has a form:

$$\frac{d}{dt} \left(\frac{\partial \Phi}{\partial \dot{x}_c} \right) - \frac{\partial \Phi}{\partial x_c} = C, \quad (13)$$

or in expended form:

$$2 \frac{M^2}{k} \ddot{x}_c + 2 \frac{M}{k} \sum_{j=k+1}^N m \ddot{x}_j = \mu + C, \quad (14)$$

where C is arbitrary constant.

The Eq. (14) must satisfy the initial and final conditions:

$$x_c(0) = 0, \quad x_c(\tau) = S, \quad \dot{x}_c(0) = \dot{x}_c(\tau) = V_0, \quad (15)$$

which allow to determine three arbitrary constants of differential equation and the amount $\mu + C$, V_0 – initial and final velocity of robot’s body in each cycle.

One more peculiarity of Eq. (14) is dependence of the amount k of movers interacting with a support surface from the gait.

5. Examples of the influence of gait on energy efficiency

The real walking robot “Ortonog” [7] (Fig. 3) have been considered as example of walking robot.



Fig. 3. Walking robot “Ortonog”

For this robot four mechanisms of walking always are interacted with the support surface. It is considered a such gait when the interacting with a support surface is carried out in pairs of two mechanisms of walking with ratio mode $\gamma > 0.5$. It is presented on chart in Fig. 4 the dimensionless parameter ε :

$$\varepsilon = \frac{I}{m^2 g^2 \tau}, \quad (16)$$

where ε is parameter proportional energy losses, depending on ratio mode and average speed of robot, g is acceleration of gravity.

The results show us that in order to minimize the energy consumption it is necessary to change the gait. This is confirmed by theory of synchronization [8], behavior of animals and investigation of multilegged walking machines and robots motion [9].

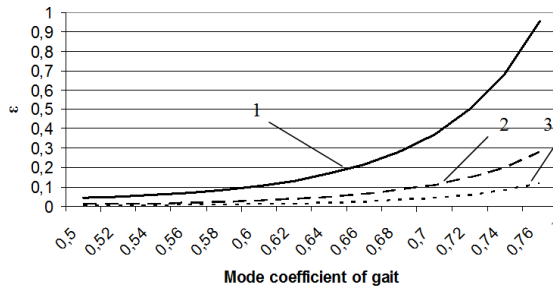


Fig. 4. Dependencies of the rate of energy loss of walking robot's speed and gait
1 – V_0 is 0.5 m/s, 2 – V_0 is 0.33 m/s, 3 – V_0 is 0.25 m/s

6. Conclusion

The gait of walking robot significant effects on the energy consumption. For each speed you should choose energy optimal gait, but the most effective use of such actuator together with control system which could independently change the gait.

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