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Investigation of the effect of algorithms of positioning robots on their power and energy consumption

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Abstract. The paper is devoted to the study of motion algorithms that determine the power and energy consumption of process equipment and positioning robots, which are important factors affecting the environment and environmental safety of the technosphere. Based on the study of mathematical models of the degrees of mobility of the gantry robot drives, it is found that under the traditional laws of motion, a fairly significant peak in power consumption occurs at the end of acceleration. The paper shows that by separating in time the moments of the end of acceleration of different drives, it is possible to significantly reduce the maximum power of the robot. A comprehensive approach to the choice of an algorithm and laws of motion that provide an acceptable combination of energy consumption and maximum power consumption has been developed. The authors have shown that there are such laws of motion that ensure the constancy of power for the duration of the acceleration stage and its minimization. The relationship between the minimum instantaneous power and power consumption for such robots has been established. The results obtained can be used to optimize the operation algorithms of both of existing and newly +-robots.

1 Current state of the problem

In the modern world, energy consumption in the technosphere is a key factor influence on the biosphere that determines the consumption of natural resources and the degree of environmental pollution. There are works in which the authors show that the law of motion determines the engine heating losses [4]. However, in the absence of recuperation heat losses on braking resistors are many times greater than heat losses in windings. There are known approaches to energy saving for transport robots, when the positive effect is determined by the choice of the motion path [1, 3]. Some authors [2] use a modified PSO method to optimize the trajectory of robots in the absence of resistance forces operating in zero gravity. However, all these works the problems only from one side: from the side of reducing energy consumption. energy consumption also determines the maximum power value. Reduction of energy consumption is often accompanied by an increase in the maximum power consumption, and vice versa [5]. In its turn, the maximum power consumption determines the size of the drive, its overall dimensions and weight [6], which is often a key factor in the design of robots and their power supply systems.

2 Problem statement

Considering the above, it is necessary to investigate the influence of motion laws and operating algorithms of the degrees of mobility of positioning robots at a given time of motion and movement on the energy costs and maximum power consumption, as well as to evaluate the effectiveness of optimization of motion algorithms for different motion laws and inertial load.

Let us construct a mathematical model of a gantry robot with two degrees of mobility having rectangular laws of acceleration variation. For example, we consider a gantry robot with mass m (Figure 1), when the motion vector of point A is equal to s and is implemented in time T.

The motion of the gantry along the X-axis can be considered as translational motion, and along the Y-axis as relative motion. To simplify the calculations and without violating the generality of the approach, a rectangular law of motion is considered for each degree of mobility. In this case, the dimensionless laws of change in acceleration, change in velocity and, and change in displacement variation have the following form:

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$$\rho''(\alpha,\zeta) := \begin{cases} \frac{1}{\zeta\cdot(1-\zeta)} & \text{if } 0 \le \alpha \le \zeta \\ 0 & \text{if } \zeta < \alpha < 1-\zeta \\ \frac{1}{\zeta\cdot(\zeta-1)} & \text{if } 1-\zeta \le \alpha \le 1 \end{cases} \quad (1)$$

$$\rho'(\alpha,\zeta) := \begin{cases} \frac{\alpha}{\zeta\cdot(1-\zeta)} & \text{if } 0 \le \alpha \le \zeta \\ \frac{1}{1-\zeta} & \text{if } \zeta < \alpha \le 1-\zeta \\ \frac{1-\alpha}{\zeta\cdot(1-\zeta)} & \text{if } 1-\zeta < \alpha \le 1 \end{cases} \quad (2)$$

$$\rho(\alpha,\zeta) := \begin{cases} \frac{\alpha^2}{2\zeta\cdot(1-\zeta)} & \text{if } 0 \le \alpha \le \zeta \\ \frac{(\zeta-2\alpha)}{2\cdot(\zeta-1)} & \text{if } \zeta < \alpha \le 1-\zeta \\ \frac{(1-\alpha)^2}{2\zeta\cdot(\zeta-1)} + 1 & \text{if } 1-\zeta < \alpha \le 1 \end{cases} \quad (3)$$

where $\alpha = t/T$ is the dimensionless time; $\zeta = \tau/T$ is the dimensionless acceleration time equal to the deceleration time. Figure 2 shows the corresponding dependence diagrams.

The absolute values of accelerations and velocities of motion are related to the relative values by the following equations:

where s is the stroke value for the corresponding degree of mobility.

$$\begin{aligned} a(t,\tau) &= k''\cdot\rho''(\alpha,\zeta) \\ v(t,\tau) &= k'\cdot\rho'(\alpha,\zeta) \\ x(t,\tau) &= k\cdot\rho(\alpha,\zeta) \end{aligned} \quad (4)$$

$$k'' = \frac{s}{T^2};\ k' = \frac{s}{T};\ k = s, \quad (5)$$

where s is the stroke value for the corresponding degree of mobility.

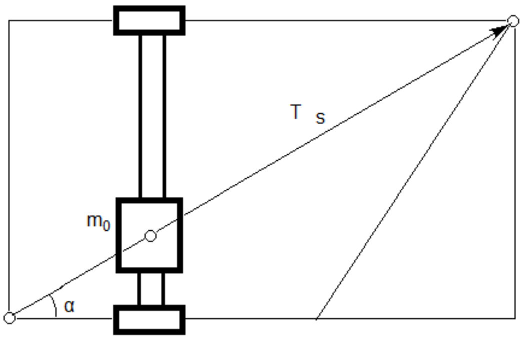

Fig. 1. Design pattern

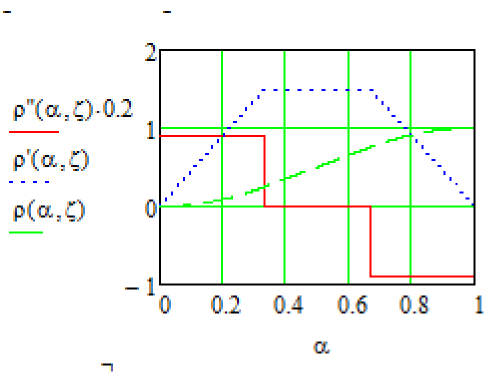

Fig. 2. Dependence diagrams for dimensionless acceleration, velocity and displacement on dimensionless time

The total instantaneous power is determined by the expression:

$$\eta_s(\alpha,\zeta_1,\zeta_2) = \rho'_1(\alpha,\zeta_1)\cdot\rho''_1(\alpha,\zeta_1) + \rho'_2(\alpha,\zeta_2)\cdot\rho''_2(\alpha,\zeta_2) \quad (6)$$

Hereafter, the digital index "1" means the ratio of the parameter to the translation degree of mobility of the manipulator, and "2" - to the relative degree of mobility.

The absolute and dimensionless values of the instantaneous power of the robot are related to each other by the following equation:

$$N_s(t,T,\tau_1,\tau_2) = N_1(t,T,\tau_1) + N_1(t,T,\tau_1) = k_{\eta 1}\cdot\eta_1(\alpha,\zeta_1) + k_{\eta 2}\cdot\eta_2(\alpha,\zeta_2) \quad (7)$$

The following designations for the coefficients of power conversion are introduced here:

$$k_{\eta 1} = \frac{m(S\cdot\cos(\varphi))^2}{T^3} \qquad k_{\eta 2} = \frac{m\cdot\mu\cdot(S\cdot\sin(\varphi))^2}{T^3} \quad (8)$$

where m is the mass of the moving parts of the robot, and μ is the coefficient that determines the fraction of the moving parts of the robot attributable to the relative degree of mobility.

In the absence of energy recovery, when the kinetic energy is dissipated on the braking resistor during deceleration, the energy cost for one cycle of motion (acceleration, uniform motion and deceleration) is determined by the time integral of the instantaneous power in the interval when the latter takes positive values:

$$p(\zeta_1,\zeta_2) = \int_0^1 \eta'_s(\alpha,\zeta_1,\zeta_2)\, d \quad , \quad (9)$$

where the following designation is introduced:

$$\eta'_s(\alpha,\zeta_1,\zeta_2) = \begin{cases} \eta_s(\alpha,\zeta_1,\zeta_2) & \text{if } \eta_s(\alpha,\zeta_1,\zeta_2) \ge 0 \\ 0 & \text{if } \eta_s(\alpha,\zeta_1,\zeta_2) < 0 \end{cases} \quad (10)$$

3 Study of a mathematical model of a robot with rectangular motion laws of degrees of mobility

It is obvious that duri synchronous operation of the drives according to the same types of motion laws selected above, the maximum instantaneous power will occur at the end of acceleration. The graph of the power changes is shown in Figure 3 (solid line). In this case, the minimum possible power will occur at each degree of mobility, but the total maximum power will be determined by the sum of the two minimum possible powers. The dotted line shows the law of variation of the robot power for the non-minimum possible powers of the degrees of mobility, the peaks of which are separated in time. Thus, in the considered example, the choice of rational laws of motion for each degree of mobility leads to an increase in the maximum power consumption by 41% as compared to the optimal value.

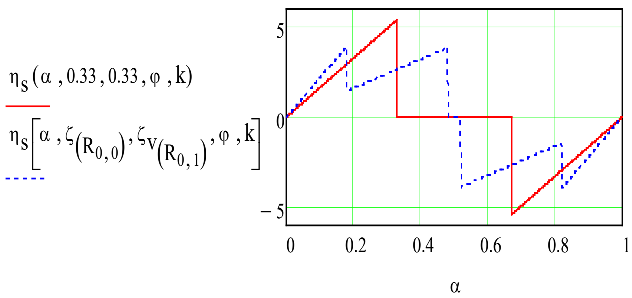

Fig. 3. Time dependences of the instantaneous power of the robot

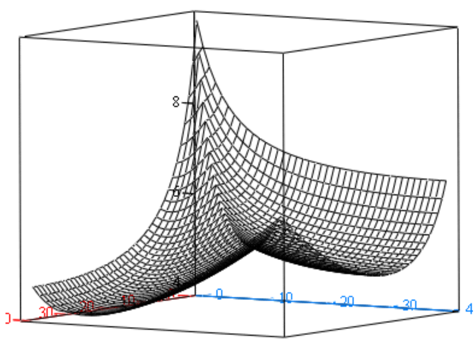

Fig. 4. Dependences of the maximum instantaneous power on the acceleration time of the degrees of mobility

To evaluate the efficiency of optimizing the acceleration time of translatory and relative degrees of mobility according to the criteria of minimum power the following formulas are obtained:

$$\delta_{\eta}(\varsigma_2) = \frac{\eta_m(\varsigma_1, \varsigma_2) - \eta_{min}}{\eta_{min}} \cdot 100\% \tag{11}$$

$$\delta_p(\varsigma_2) = \frac{p(\varsigma_1, \varsigma_2) - p_{min}}{p_{min}} 100\% \tag{12}$$

where $\eta_m(\zeta_1, \zeta_2)$ is the maximum value of the instantaneous power at the optimum value ζ_{10} and arbitrary value ζ_2; η_{min} is the minimum possible value of the maximum power per cycle; $p(\zeta_1, \zeta_2)$ is the energy consumption at optimum power value ζ_{10} and arbitrary value ζ_2; p_{min} is the minimum possible value of energy consumption.

Figure 5 and Figure 6 show the dependences of the efficiency of optimizing the acceleration time of the relative mobility degree at the optimal acceleration time of the translatory mobility degree according to the criteria of the minima of instantaneous power and energy consumption, respectively. The optimization efficiency shows by how many percent the instantaneous power and energy consumption will increase when the acceleration time of the relative degree of mobility changes compared to the optimal value. Similar graphs can be plotted for the translatory degree of mobility. It follows from the graphs that for the example under consideration, with an increase in acceleration time, power increases by 57% and power consumption increases by 40%.

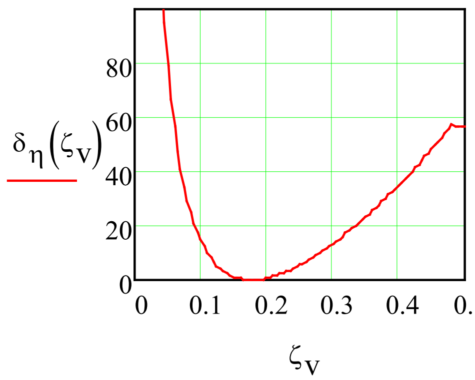

Fig. 5. Dependence of optimization efficiency ζ_{20} on the criterion of minimizing instantaneous power consumption

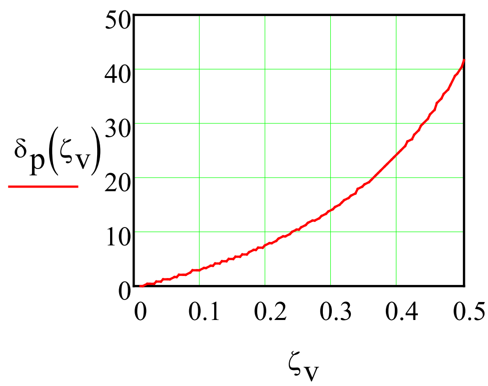

Fig. 6. Dependence of optimization efficiency ζ_{20} on the criterion of minimizing energy consumption

Figure 7 shows the parametric dependence of the optimization efficiency by the criterion of minimizing power on the optimization efficiency by the criterion of minimizing energy consumption. The following conclusions can be drawn from the graph. Firstly, if the acceleration time ζ_v lies in the interval [0.17; 0.5] a decrease in power leads to the decrease in energy consumption and, conversely, an increase in power leads to the increase in energy consumption. Secondly, in the interval [0; 0.17] a decrease in power is accompanied by an increase in energy consumption, and vice versa. Consequently, depending on the formulation of the problem it is possible to set weight coefficients for each criterion and determine the optimal acceleration time.

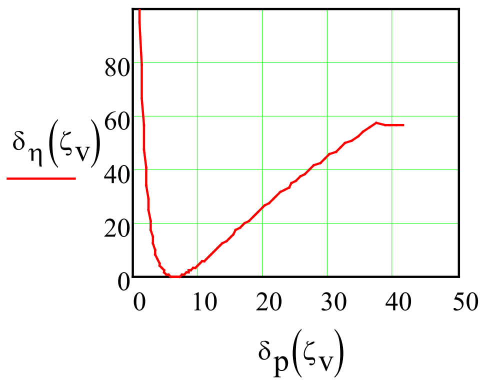

Fig. 7. Dependence of $\boldsymbol{\delta_n(\zeta_2)}$ on $\boldsymbol{\delta_p(\zeta_2)}$

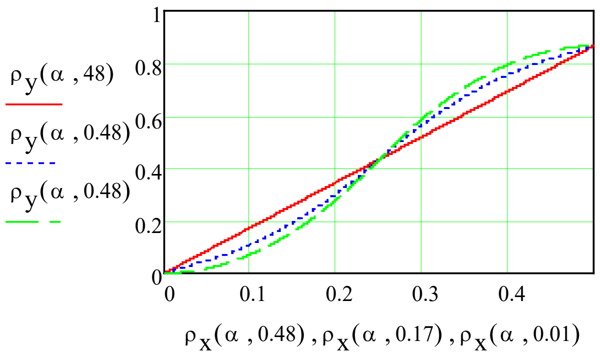

Fig. 8. Trajectories of the robot point A for different algorithms of movement of mobility degrees

Parametric equations of the trajectory of the robot output link in the plane have the following forms:

$$\rho_x(\alpha, \zeta_1) = \cos(\varphi)\cdot\rho(\alpha, \zeta_1) \quad (13)$$

$$\rho_y(\alpha, \zeta_2) = \sin(\varphi)\cdot\rho(\alpha, \zeta_2) \quad (14)$$

With the same laws of motion for each degree of mobility the trajectory of movement is a segment (Figure 8). Changing the dimensionless acceleration times for each degree of mobility leads to a curvature of the trajectory.

4 Mathematical model of a robot having mobility degrees moving according to the optimally synthesized law of motion

An optimally synthesized law is understood as a law of motion that ensures the constancy of power consumption in the acceleration stage under inertial load and, therefore, satisfies the equation:

$$m_0\cdot u'\cdot u'' = N \quad (15)$$

where u' and u'' are the velocity and acceleration of the moving mass m_0.

5 Investigation of the mathematical model of a robot having mobility degrees moving according to the optimally synthesized law of motion

The solution of equation (15) has the following form:

$$u = \frac{2}{3}\cdot\sqrt{\frac{2N\cdot t^3}{m_0}} \quad (16)$$

Differentiating equation (16) by time it is possible to obtain the following expressions for velocity and acceleration:

$$u' = \sqrt{\frac{2N}{m_0}t} \quad (17)$$

$$u'' = \sqrt{\frac{N}{2m_0\cdot t}} \quad (18)$$

Substituting the displacement value $s/2$, the acceleration time τ and half the motion cycle time $T/2$ into the solution of equation (16) we determine the power N required for such a displacement:

$$N = \frac{m_0\cdot s^2}{8\cdot\left[\frac{2}{3}\cdot\sqrt{\tau^3} + \sqrt{\tau}\cdot\left(\frac{T}{2} - \tau\right)\right]^2} \quad (19)$$

The time-constant powers that are necessary for the translatory and relative degrees of mobility are determined by the equations:

$$N_1 = \frac{m\cdot s^2\cdot\cos(\varphi)^2}{8\cdot\left[\frac{2}{3}\cdot\sqrt{\tau^3} + \sqrt{\tau}\cdot\left(\frac{T}{2} - \tau\right)\right]^2} \quad (20)$$

$$N_2 = \frac{m\cdot\mu\cdot s^2\cdot\sin(\varphi)^2}{8\cdot\left[\frac{2}{3}\cdot\sqrt{\tau^3} + \sqrt{\tau}\cdot\left(\frac{T}{2} - \tau\right)\right]^2} \quad (21)$$

The total, constant in magnitude, power consumed by the robot when moving on distance s during the time T is:

$$N_s = \frac{m \cdot s^2}{8 \cdot \left[\frac{2}{3} \cdot \sqrt{\tau^3} + \sqrt{\tau} \cdot \left(\frac{T}{2} - \tau\right)\right]^2} \cdot \left(\cos(\varphi)^2 + \mu \cdot \sin(\varphi)^2\right) \quad (22)$$

In dimensionless form the total power equals:

$$\eta_{s0}(\zeta) := \frac{1}{8 \cdot \left[\frac{2}{3} \cdot \sqrt{\zeta^3} + \sqrt{\zeta} \cdot \left(\frac{1}{2} - \zeta\right)\right]^2} \cdot \left(\cos(\varphi)^2 + \mu \cdot \sin(\varphi)^2\right) \quad (23)$$

Figures 9 and 10 show the dependences of power and energy consumption of the acceleration time. For the above example $\mu = \pi/4$ and $k = 0.6$ with the acceleration time for each degree of mobility equal to 0.5; the power and energy consumption are 1.8 and 0.9 in dimensionless units, respectively. In this case the minimum power consumption and maximum energy consumption are ensured. This corresponds to a reduction in power by 54% and in energy consumption by 18%.

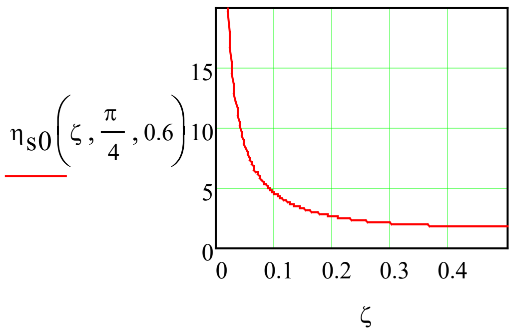

Fig. 9. Dependence of power on acceleration time for the synthesized law of motion

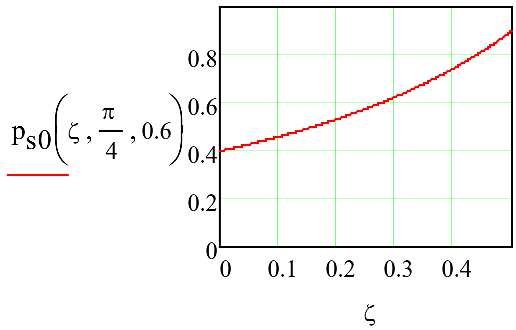

Fig. 10. Dependence of energy consumption on acceleration time for the synthesized law of motion

5 Conclusion

As a result of the analysis of the developed mathematical models of the two-axis gantry robot, it was found that the algorithm and the law of motion of its drives are able to change the power consumption and the energy consumption by tens of percent at the same travel distances and motion cycle duration. Under typical laws of motion, there are intervals of acceleration time, in which a decrease in power leads to a decrease in energy consumption, and intervals in which a decrease in power is accompanied by an increase in energy consumption.

Intentionally synthesized laws of motion make it possible to significantly reduce the power and energy consumption, however, a decrease in power is always accompanied by an increase in energy consumption and, conversely, an increase in power leads to a decrease in energy consumption throughout the whole interval of the acceleration time. In this case, the range of power variations is infinite, and the maximum possible change in energy consumption does not exceed 100% ... 150% and depends on the moving masses and degrees of mobility.

The results obtained can be used in the development of control algorithms for process equipment and gantry robots for various purposes. In addition, based on the results obtained, it can be argued that they are suitable for all types of robots with a large number of degrees of mobility. Ultimately, reducing energy consumption in the technosphere at a relatively low cost leads to the saving of natural resources and the reduction of environmental pollution. In the future, the results obtained analytically can be used in theoretical and experimental studies of energy consumption of specific types of motors and machines in general.

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