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Improving the Niryo One robotic platform by the optimizing of the drive operating modes. Part II

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Abstract. The paper considers the issue of improving the Niryo One robotic platform by optimizing the operating modes of the manipulator drive. The relevance of the research is due to the need to increase the efficiency and accuracy of robotic systems in industrial and research applications. The second part of the study presents the development of a mathematical model of manipulator dynamics, which takes into account the design features and parameters of the Niryo One platform. Based on the constructed manipulator model, the manipulator motion trajectories were optimized using the sequential quadratic programming method (SLSQP — Sequential Least Squares Programming). Optimization was aim at minimizing energy consumption and task execution time while adhering to constraints on the dynamic characteristics of the system.

The proposed approach to determining optimal driving modes based on numerical methods of nonlinear programming. As optimization result of trajectories were obtain that provide a reduction in the load on the drives and an increase in the smoothness of movement compared to typical modes, that can be implemented in standard platform software. A comparative analysis of optimal and typical driving modes was conduct based on the criteria of energy efficiency and work dynamics.

The results obtained can be used to modernize existing and develop new control algorithms for two-mass robotic systems, as well as to increase reliability and service life. Prospects for further research been related to the adaptation of the developed method for manipulators with other kinematic schemes and under conditions of variable external loads.

Keywords: Niryo One, manipulator, optimization, power minimization, improvement, SLSQP method, mathematical model, two-link manipulator.

INTRODUCTION

Today's robotics have a key role in educational processes, providing students and researchers with tools for hands-on learning about automation, programming, and engineering. One of the popular educational platforms is Niryo One it’s a flexible and affordable robotic arm that is used in educational institutions to demonstrate the principles of industrial manipulators. However, like any technical system, Niryo One is not a perfect robotic system. In particular, the energy efficiency of such a system is not optimal. The significant power consumption of the drive of this manipulator directly affects the duration of autonomous operation, productivity and overall efficiency of its use.

The previous part of the article examined general methods for improving the boom drive mechanism of the Niryo One educational robotic platform. This part of the article is devoted to a more in-depth analysis of power optimization issues - a relevant topic that allows not only to increase the efficiency of the platform, but also to expand the possibilities of its application in educational and research projects. Power optimization includes a set of measures aimed at reducing energy consumption, improving power management, and implementing modern control algorithms that balance performance and energy efficiency.

ANALYSIS OF WORK ON OPTIMIZATION OF DRIVE POWER OF ROBOTIC PLATFORMS

One of the main areas of power optimization is reducing the energy consumption of robotic systems. Several key classical approaches been identified in the scientific literature and practical developments:

- hardware optimization involves the use of energy-efficient components, such as low-voltage motors, modern low-power microcontrollers, and optimized power supply circuits. For example, replacing standard servos with models featuring lower current consumption can significantly reduce the overall load on the power source [1-3];
- optimal operation mode management achieved by implementing algorithms that allow individual platform nodes to be switched to standby mode when not in use. This approach is particularly relevant for systems operating in cyclic modes with pauses. However, a drawback of this method is an increase in cycle time [2, 4];
- mechanical design optimization accomplished by reducing the mass of moving parts, using lightweight materials, and improving the mechanical efficiency of transmissions. This helps to reduce the load on motors and, consequently, energy consumption [5-7].

Modern methods for optimizing drive power actively employ algorithmic approaches, including:

- adaptive control, which uses algorithms to dynamically adjust operating parameters of the drive (e.g., speed, acceleration) depending on the current load and task requirements. This avoids excessive energy consumption in modes where high performance is not necessary [8-10];
- trajectory optimization, which involves developing algorithms to determine the most efficient motion trajectories for manipulators, minimizing energy costs for movement. This is especially important for tasks where precision is not critical, and energy efficiency is a priority [11];
- machine learning is applied to predict load and optimize operating modes in real time. For example, neural networks can analyze energy consumption data and suggest optimal parameters for specific tasks [12-14].

An important aspect of power optimization is improving the power system, in particular:

- the use of modern batteries, for example, lithium-polymer or lithium-iron-phosphate batteries with higher energy density and lower internal resistance, allows you to increase the time of autonomous operation of the electrical system;
- the introduction of energy recovery mechanisms, for example, during engine braking, allows returning part of the energy back to the power system, which is especially effective for platforms with cyclic loads;
- optimization of the power distribution scheme through the use of intelligent power controllers that dynamically distribute energy between platform nodes depending on their current needs.

Analysis of existing work shows that optimizing the power of robotic platforms is a complex task that requires consideration of both hardware and software aspects. This research focuses on optimizing the energy consumption of a two-link manipulator when moving a payload between two points.

PRESENTATION OF THE MAIN MATERIAL

The Niryo One robot's boom system consists of six series-connected links that form a serial kinematic structure with six degrees of freedom (6 DOF). Each link connected to the adjacent one using rotational joints, which allows for the implementation of complex trajectories of the end effector movement in three-dimensional space. This configuration provides high flexibility and maneuverability, but requires precise control of each joint to prevent positioning errors under dynamic loads. Thus, the main components of such a boom system are rigid links connecting the rotary joints – joints equipped with stepper motors. An end effector is a tool (usually a gripper) that performs the main functions.

In this work, it proposed to investigate the motion of two serially connected links of a manipulator - a boom with a length of l_1 and forearm length l_2.

To the effectively optimize the operating modes of the manipulator drive, it is necessary to create an adequate mathematical model that describes the dynamics and kinematics of the manipulator. To simplify calculations and modeling, we will consider a two-mass model in the future, where the mass m_1 – the mass of the link l_1 and m_2 – the mass of the link l_2.

The center of mass of the first link is at a distance $1/2l_1$ rom the axis of its rotation, and the center of mass of the second link is at a distance $l_1+1/2l_2$ from the axis of rotation of the first link. The load is located at the end of the second link. The generalized coordinates for the considered manipulator system taken to be the rotation angles α and β. The dynamic model of the considered case shown on Fig. 1.

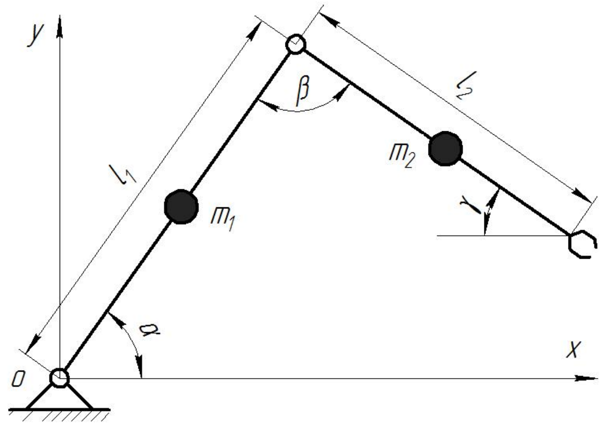

Fig. 1. Dynamic model of the manipulator

For the case where the drive mechanisms are located in the joints of the boom system, and the movement of the links is implemented by direct transmission of torque from the drive mechanism to the moving frame, therefore, the optimization objective function can be represented as the minimization of the root-mean-square integral powers of the drive:

$$I = \int_0^T \sqrt{(P_1(t)^2 + P_2(t)^2)}dt \to \min , \qquad (1)$$

where: $P_1(t) = \frac{M_1(t)\omega_1(t)}{\eta_1}$ and $P_2(t) = \frac{M_2(t)\omega_2(t)}{\eta_2}$ – the power of the component drive mechanisms; M_1(t), M_2(t) – driving torques; ω_1(t), ω_2(t) – an angular velocities of moving parts.

The objective function (1) in this form will take into account the case when the system can move in the opposite direction in the recovery mode, where energy will be generate. This case requires additional study and is not consider in this work. This is due to the fact that the implementation of the physical model for the manipulator under consideration does not contain special means capable of accumulating the energy produced by such a system.

The moments in the hinges of the links are determined from the Lagrange equations of the 2nd kind:

$$\begin{aligned} &\frac{d}{dt}\left(\frac{\partial T}{\partial \dot{\alpha}}\right) - \frac{\partial T}{\partial \alpha} + \frac{\partial \Pi}{\partial \alpha} = M_1; \\ &\frac{d}{dt}\left(\frac{\partial T}{\partial \dot{\beta}}\right) - \frac{\partial T}{\partial \beta} + \frac{\partial \Pi}{\partial \beta} = M_2, \end{aligned} \qquad (2)$$

where: T and Π respectively, the kinetic and potential energy of the mechanical system.

Kinetic energy of the mechanical two-mass boom system of the manipulator:

$$T = \frac{J_{01}\dot{\alpha}^2}{2} + \frac{J_{c2}\dot{\gamma}^2}{2} + \frac{m_2\upsilon_{c2}^2}{2}, \qquad (3)$$

where $J_{01} = \frac{1}{3}m_1 l_1^2$ – the moment of inertia of the first link relative to the axis of rotation; m_2 – mass of the second link; υ_2 – a linear velocity of the center of mass of the second link; $J_{c2} = \frac{1}{12}m_2 l_2^2$ – the moment of inertia of the second link relative to its own center of mass; $\gamma = \pi-(\alpha+\beta)$.

The linear velocity of the center of mass of the second link is determined through the components of the velocities in Cartesian coordinates:

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$$\upsilon_{c2}^2 = \dot{x}_{c2}^2 + \dot{y}_{c2}^2, \qquad (4)$$

where: $x_{c2} = l_1 \cos\alpha + \frac{1}{2} l_2 \cos\gamma$;

$y_{c2} = l_1 \sin\alpha - \frac{1}{2} l_2 \sin\gamma$,

then

$$\upsilon_{c2}^2 = (l_1\dot{\alpha}\sin\alpha - \tfrac{1}{2} l_2 \sin(\alpha+\beta)(\dot{\alpha}+\dot{\beta}))^2 + \\ + (l_1\dot{\alpha}\cos\alpha - \tfrac{1}{2} l_2 \cos(\alpha+\beta)(\dot{\alpha}+\dot{\beta}))^2. \qquad (5)$$

Potential energy of a mechanical system:

$$\Pi = m_1 g \frac{l_1}{2}\sin\alpha + m_2 g (l_1 \sin\alpha - \frac{l_2}{2}\sin\gamma). \qquad (6)$$

Finally, it was have the following equations of motion of the manipulator boom system:

$$M_1 = \frac{1}{4}(2g(m_1 l_1 \cos\alpha + \\ + m_2 l_2 \cos(\alpha+\beta)) + \\ + m_2(4 l_1 l_2 g \sin(\beta)\dot{\alpha}\dot{\beta} + 2 l_1 l_2 \sin\beta\dot{\beta}^2) + \\ + (4(J_{01} + J_{c2}) + (4l_1^2 + l_2^2)m_2 - \\ - 4 l_1 l_2 m_2 \cos\beta)\ddot{\alpha} + (4J_{c2} + l_2^2 m_2 - \\ - 2 l_1 l_2 m_2 \cos\beta)\ddot{\beta}; \qquad (7)$$

$$M_2 = \frac{1}{4} m_2 l_2 (2g\cos(\alpha+\beta) - \\ - 2 l_1 \sin\beta\dot{\alpha}^2 + (l_2 - 2 l_1 \cos\beta)\ddot{\alpha} + l_2\ddot{\beta}). \qquad (8)$$

Note that in the obtained equations, the first derivatives with respect to the angles of rotation α and β are angular velocities, then:

$$\omega_1(t) = \frac{d\alpha}{dt} = \dot{\alpha}, \qquad (9)$$

$$\omega_2(t) = \frac{d\beta}{dt} = \dot{\beta}. \qquad (10)$$

From the analysis of the equations, it is obvious that the moments on the drive mechanisms will depend not only on the external load, but also on the angular velocities of the links. From equation (1) we also see that for the optimal value of the drive power, it is necessary to simultaneously optimize both the angular velocity and the drive torque.

In the control problems of the movement of the robot arm, the motion trajectories must be smooth differentiable functions without discontinuities. This condition imposes a restriction on control, which cannot be relay-based. The general form of the solution of the displacement function in generalized coordinates will be described by polynomials of the 5th class:

$$\alpha(t) = a_0 + a_1 t + a_2 t^2 + a_3 t^3 + \\ + a_4 t^4 + a_5 t^5; \qquad (11)$$

$$\beta(t) = b_0 + b_1 t + b_2 t^2 + b_3 t^3 + \\ + b_4 t^4 + b_5 t^5, \qquad (12)$$

where: a_0, a_1, a_2, a_3, a_4, a_5 та b_0, b_1, b_2, b_3, b_4, b_5 – some coefficients that need to be determined.

The physical system of the manipulator has the following limitations:

$$|\omega_1(t)| \le \omega_{1\max},\ |\omega_2(t)| \le \omega_{2\max};$$
$$|M_1(t)| \le M_{1\max},\ |M_2(t)| \le M_{2\max};$$
$$\alpha(0) = \alpha_0, \alpha(T) = \alpha_1,\ \beta(0) = \beta_0, \beta(T) = \beta_1;$$
$$\omega_1(0) = \omega_1(T) = 0,\ \omega_2(0) = \omega_2(T) = 0.$$

Such restrictions allow us to determine some coefficients. To do this, we define the derivatives:

$$\dot{\alpha}(t) = a_1 + 2a_2 t + 3a_3 t^2 + 4a_4 t^3 + 5a_5 t^4; \qquad (13)$$

$$\ddot{\alpha}(t) = 2a_2 + 6a_3 t + 12 a_4 t^2 + 20 a_5 t^3; \qquad (14)$$

$$\dot{\beta}(t) = b_1 + 2b_2 t + 3b_3 t^2 + 4b_4 t^3 + 5b_5 t^4, \qquad (15)$$

$$\ddot{\beta}(t) = 2b_2 + 6b_3 t + 12 b_4 t^2 + 20 b_5 t^3, \qquad (16)$$

Taking into account the boundary conditions of motion, we find the corresponding coefficients of polynomials (11) and (12):

$$\alpha(0) = a_0 = \alpha_0,\ \beta(0) = b_0 = \beta_0,$$
$$\omega_1(0) = a_1 = 0,\ \omega_2(0) = b_1 = 0;$$

$$\alpha(T) = \alpha_0 + a_2T^2 + a_3T^3 + a_4T^4 + a_5T^5 = \alpha_1;$$

$$\omega_1(T) = 2a_2T + 3a_3T^2 + 4a_4T^3 + 5a_5T^4 = 0;$$

$$\beta(T) = \beta_0 + b_2T^2 + b_3T^3 + b_4T^4 + b_5T^5 = \beta_1;$$

$$\omega_2(T) = 2b_2T + 3b_3T^2 + 4b_4T^3 + 5b_5T^4 = 0.$$

Then:

$$a_4 = \frac{-2a_2 - 3a_3T - 5a_5T^3}{4T^2};$$

$$a_5 = \frac{2a_2T^2 + a_3T^3 - 4(\alpha_1 - \alpha_0)}{T^5};$$

$$b_4 = \frac{-2b_2 - 3b_3T - 5b_5T^3}{4T^2};$$

$$b_5 = \frac{2b_2T^2 + b_3T^3 - 4(\beta_1 - \beta_0)}{T^5};$$

Let's consider the gradient optimization method SLSQP (Sequential Least Squares Programming) - this is a method of sequential approximation using the least squares method and is an extension of the SQP method. Since the goal of this problem is to find the minimum integral, then in essence this method can be apply as an iterative method of constrained nonlinear minimization of the functional. For this problem, it is necessary to find a displacement function along generalized coordinates, which must be a smooth function and differentiable, therefore this method can be used to solve the given problem.

The essence of this method is to apply a quadratic approximation of the next objective function at each iteration step:

$$Q(x) = f(x_k) + \nabla f(x_k)^T (x - x_k) + \\ + \frac{1}{2}(x - x_k)^T H_k (x - x_k) \quad (17)$$

where: $f(x_k) = I(x_k)$ – the value of the objective function at the point x_k; $\nabla f(x_k)$ – gradient of the objective function at the point x_k; $H_k = \frac{\partial^2 f(x)}{\partial x_i \partial x_j}$ – Hessian matrix or Hessian approximation; x_k – vector of coefficients of polynomials of displacement functions.

At each step, the method solves a constrained quadratic programming subproblem using this approximation as the objective function. The constraints are linearize around the current point. The refined value of the coefficients is determined as follows:

$$x_{k+1} = x_k + \delta_k p^*, \quad (18)$$

where: x_k – vector of coefficients at the current iteration step k; x_{k+1} – vector of new coefficients at the next iteration $k+1$; p^* – optimal search direction vector; $\delta_к$ – step length (scalar).

The vector p has the same dimension as the coefficient vector x_k. The elements of this vector are the increments of the coefficients Δa_i and Δb_i which show how much each coefficient needs to be changed a_i or b_i, to minimize the quadratic approximation of the objective function and satisfy the linearized constraints.

The vector p^* is found from the solution of QP sub problems:

$$p^* = \arg\min(\nabla f(x_k)^T p + \frac{1}{2} p^T H_k p). \quad (19)$$

Scalar $\delta_к \in [0, 1]$ ensures that moving in the direction $p*$ then the objective function will decrease and the constraints are not violated too much.

Using linear search, minimizing the merit function Φ, determine $\delta_к$:

$$\delta_k = \arg\min I(x_k) + \mu \sum_{i=1}^{m} \max(0, g(x_k)), \quad (20)$$

where $\mu > 0$ – a positive number that determines how strongly the algorithm "punishes" constraint violations; $g(x_k)$ – a function that returns the amount by which a limit exceeds zero, then:

$(g(x_k) = \max(|M_{i,k}(t,x)|) - [M_{i\_\max,k}]);$

$M_{i\_\max,k}$ - the maximum actual torque of the drive; $M_{i,k}(t,x)$ – maximum permissible torque that the drive is capable of realizing.

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For the next mechanical system parameters: l_1 = 0,25 m; l_2 = 0,2 m; m_1 = 0,912 kg; m_2 = 0,5 m and a move time of 6 s at the initial specified turning angles $\alpha_0 = 10^{\circ}$, $\beta_0 = 30^{\circ}$ and final values $\alpha_1 = 80^{\circ}$, $\beta_1 = 180^{\circ}$ the values of the coefficients of the polynomials were determined. This should ensure optimal power consumption: a_2 = 0,405; a_3 = -0,232; b_2 = = -0,011; b_3 = -0,0088.

Fig. 2 shows graphs showing the dependence of the changes in kinematic and force parameters for this manipulator. The graphs of the power changes are show in Fig. 3. From the Fig. 2 *a* and *b* it is clear that the kinematic characteristics of the obtained motion mode fully satisfy the adopted boundary conditions.

The graphs of angular velocity changes for this motion mode show that such a mode will have dynamic loads at the boundaries of motion, i.e. at the beginning of acceleration and the end of braking. From the graphs of moment changes, we see that at the beginning of the movement for the given initial conditions, the static moment of resistance for the second link of the manipulator will have a negative value. This is explained by the fact that for the second link, at the beginning of the motion, gravitational forces will create a driving moment, not a moment of resistance. The power change graphs show that the dominant part of the power change falls on the first drive link, which will also have a greater load (on Fig. 3).

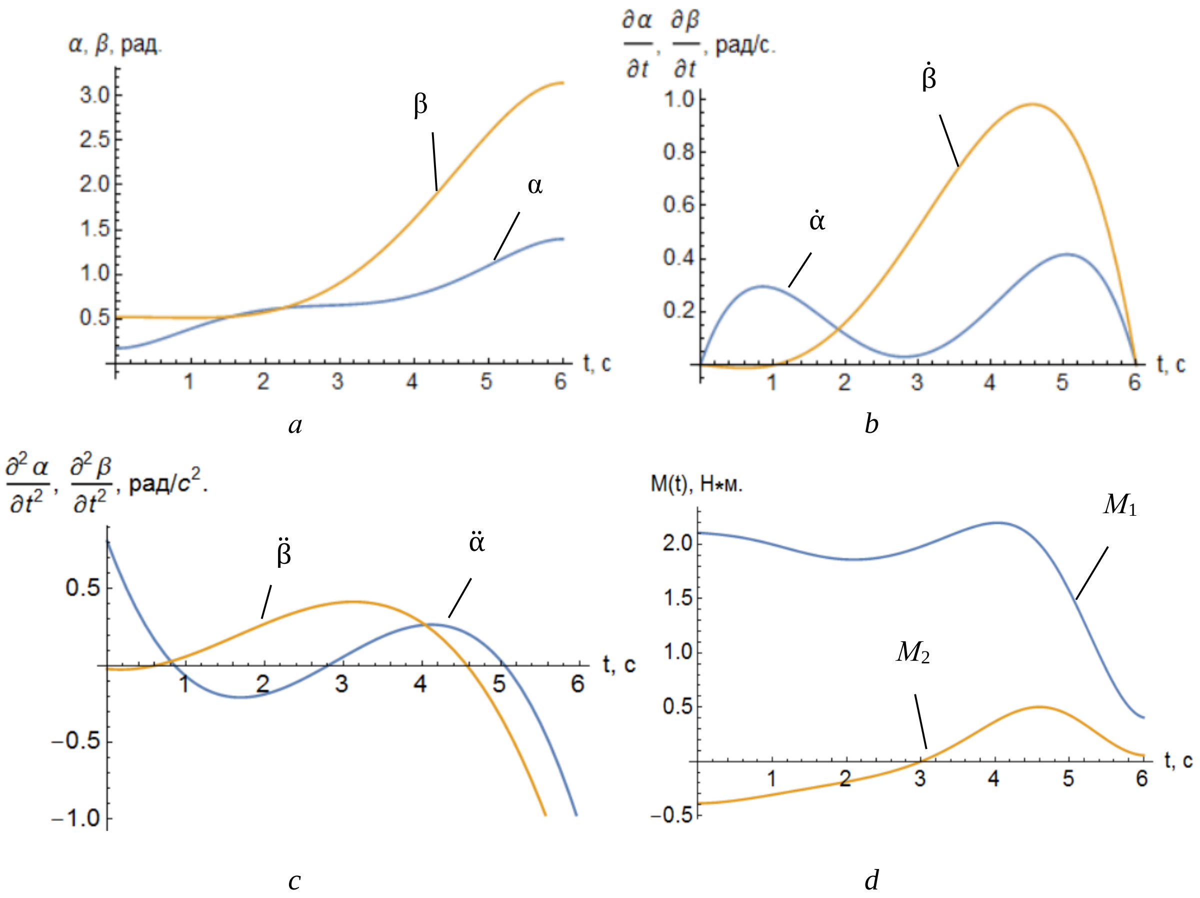


Fig. 2. Results of theoretical modeling of drive power optimization for a two-link manipulator:
a – angles of rotation of links; *b* – angular velocities of rotation of links; *c* – angular accelerations of links; *d* – drive torques

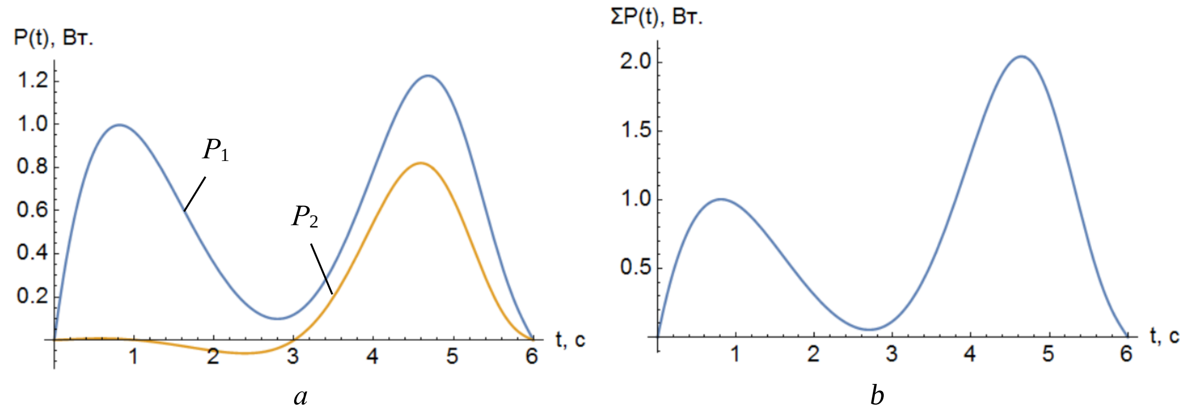


Fig. 3. The graphs of power changes on individual moving links of the boom system (*a*) and total power consumption (*b*)

The change in static torque in drive mechanisms is analyzed and compared with the total drive torque. Static moments of resistance will be determined by the following formulas:

$$M_{cm1} = m_1 g \frac{l_1}{2}\cos(\alpha) + + m_2 g (l_1 \cos(\alpha) + \frac{l_2}{2}\cos(\gamma)); \quad (20)$$

$$M_{cm2} = m_2 g \frac{l_2}{2}\cos(\gamma)\,. \quad (21)$$

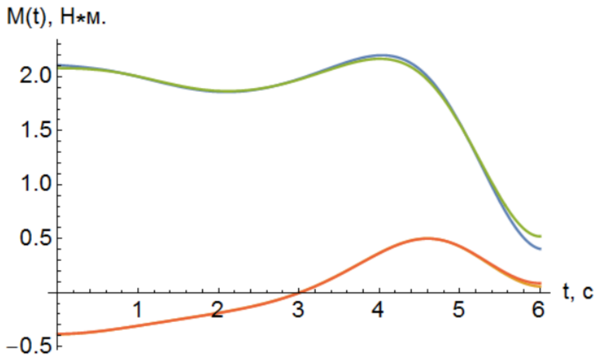


Fig. 4. Graphs of changes in static and total drive torques in the boom joints for driving each of the manipulator links

From the graphs in Fig. 4 it is clear that the total drive torque on each of the drives for this mode of motion is practically equal to the static load torque.

The dynamics of the system motion does not significantly affect the drive load and will most likely be crucial for positioning accuracy.

To assess the effectiveness of the resulting motion mode, a comparison was make with typical motion modes (see Fig. 5 and Fig. 6):

- angle displacement

$$\alpha(t) = \begin{cases} \alpha_0 + \dfrac{at^2}{2}, 0 \le t \le \dfrac{T}{2} \\ \alpha_0 + \dfrac{aT^2}{8} + \upsilon_{max}(t - \dfrac{T}{2}) - \\ -\dfrac{a(t-\dfrac{T}{2})^2}{2}, \dfrac{T}{2} < t \le T \end{cases} \quad (22)$$

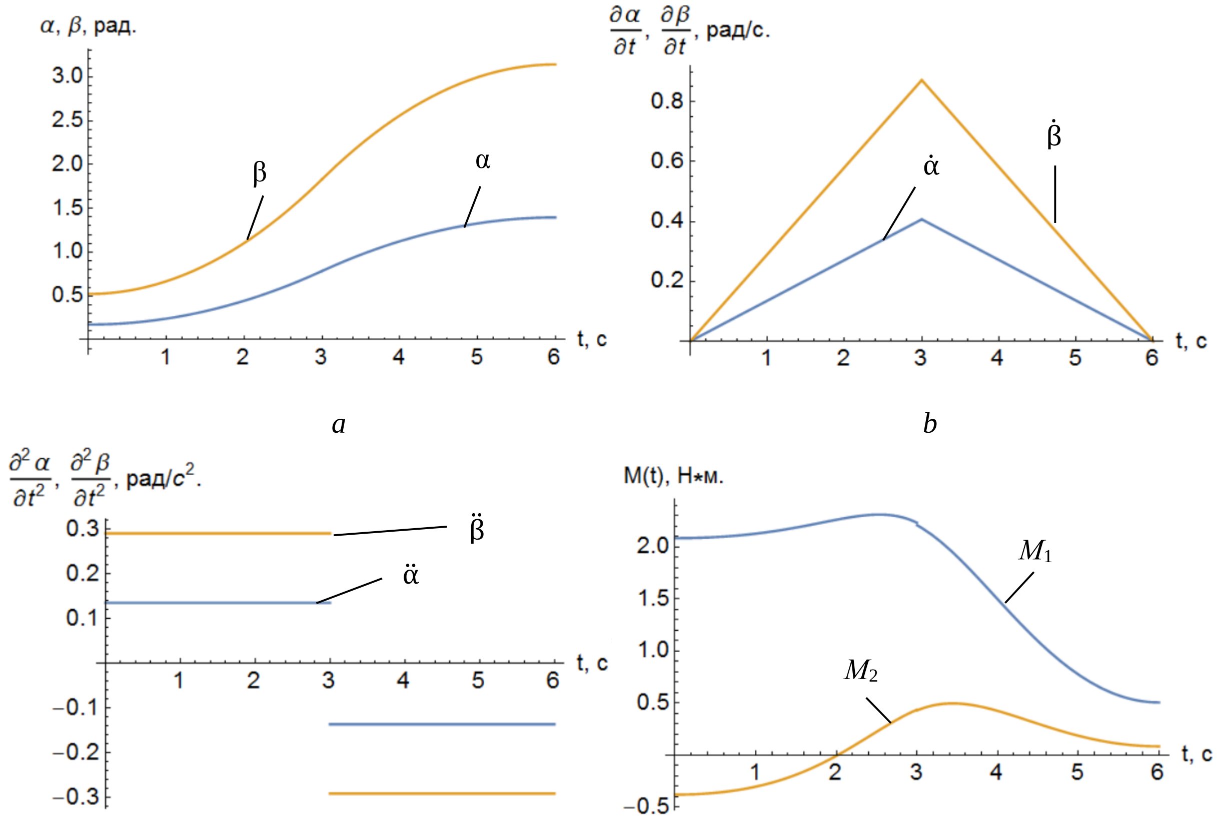
- velocity

$$\omega(t) = \begin{cases} at, 0 \le t \le \dfrac{T}{2} \\ \upsilon_{max} - a(t - \dfrac{T}{2}), \dfrac{T}{2} < t \le T \end{cases} \quad (23)$$

- acceleration

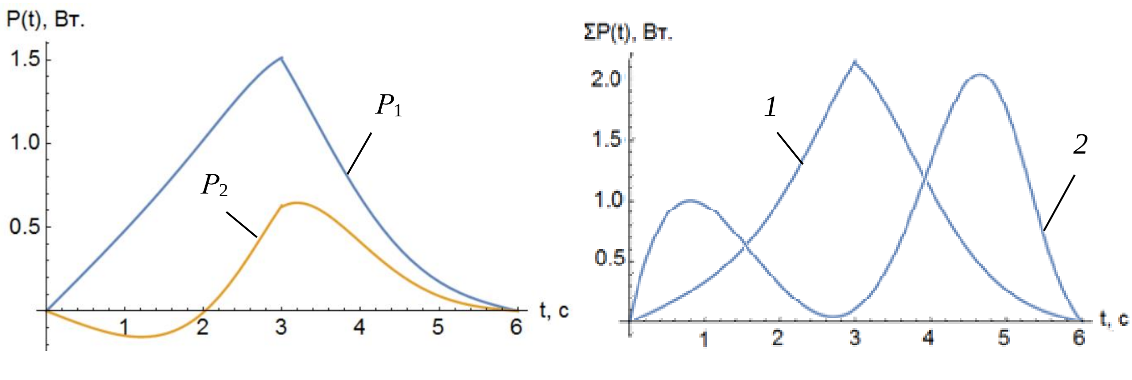
$$\varepsilon(t) = \begin{cases} a, 0 \le t \le \dfrac{T}{2} \\ -a, \dfrac{T}{2} < t \le T \end{cases} \quad (24)$$

where: $a = 4(\alpha_1\text{-}\alpha_0)\,/T^2$.



c *d*

Fig. 5. Theoretical modeling results for a typical triangular motion mode of a two-link manipulator: *a* – angles of rotation of links*; b* – angular velocities of rotation of links; *c* – angular accelerations of links; *d* – driving moments



a *b*

Fig. 6. Graphs of power changes on individual moving links of the boom system (*a*) and total power consumption (*b*): *1* – for typical triangular mode; 2 – for optimized polynomial mode

CONCLUSIONS

The optimization of the drive power of the two-link manipulator performed in this work allowed us to establish the next facts:

- optimization by the integral criterion with the pi-integral function of the square root of the sum of the squares of the component capacities allows taking into account the full capacity without recuperation;
- for the optimal power value, you need to know the optimal change in the driving torque and angular velocity, but in this case, the driving torque will depend on the law of displacement and therefore will depend on the nature of the change in the angular velocity;

- if the masses and dimensions of the links of the mechanical system are not significant, then the influence of the dynamic component on the change in power will be small, and therefore it is possible to implement movement according to typical laws of motion;
- when the manipulator is operating in a gravitational field, reverse effects will occur, which allows energy recovery;
- from the graph in Fig. 6 it is clearly seen that the total work spent on performing the movement for the optimal mode of movement and for the typical triangular one will be practically the same;
- to optimize the drive power, it is further desirable to develop a general optimization methodology using numerical methods and genetic algorithms.

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Вдосконалення роботизованої платформи Niryo One за рахунок оптимізації режимів роботи приводу. Частина II

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Анотація. В роботі розглянуто питання вдосконалення роботизованої платформи Niryo One шляхом оптимізації режимів роботи приводу маніпулятора. Актуальність дослідження зумовлена необхідністю підвищення ефективності та точності роботи робототехнічних систем у промислових і дослідницьких застосуваннях. У другій частині дослідження представлено розробку математичної моделі динаміки маніпулятора, яка враховує особливості конструкції та параметри платформи Niryo One. На основі побудованої моделі проведено оптимізацію траєкторій руху маніпулятора з використанням методу послідовного квадратичного програмування (SLSQP – Sequential Least

Squares Programming). Оптимізація спрямована на мінімізацію енергоспоживання та часу виконання завдань при дотриманні обмежень на динамічні характеристики системи.

Запропонований підхід до визначення оптимальних режимів руху базується на чисельних методах нелінійного програмування. В результаті оптимізації отримано траєкторії, що забезпечують зниження навантаження на приводи та підвищення плавності руху порівняно з типовими режимами, реалізованими в стандартному програмному забезпеченні платформи. Проведено порівняльний аналіз оптимальних і типових режимів руху за критеріями енергоефективності та динаміки роботи.

Отримані результати можуть бути використані для модернізації існуючих та розробки нових алгоритмів керування двомасовими робототехнічними системами, а також для підвищення надійності та ресурсу роботи. Перспективи подальших досліджень пов’язані з адаптацією розробленого методу для маніпуляторів з іншими кінематичними схемами та в умовах змінних зовнішніх навантажень.

Ключові слова: Niryo One, маніпулятор, оптимізації, мінімізація потужності, вдосконалення, метод SLSQP, математична модель, дволанковий маніпулятор.