DOI: 10.14529/ctcr190202

# TO THE PROBLEM OF IMPROVE POSITIONING PRECISION OF ROBOTIC MANIPULATOR UNDER CONDITIONS OF INCOMPLETE INFORMATION

***V.I. Shiryaev***, *shiriaevvi@susu.ru,*
***V.P. Shcherbakov***, *shcherbakovvp@susu.ru,*
***A.A. Bragina***, *braginaaa@susu.ru*
*South Ural State University, Chelyabinsk, Russian Federation*

The control algorithm of robotic manipulator (RM) movement along the program trajectory by the method of Lyapunov function is obtained. The method uses the decomposition of original multiply-connected nonlinear system into subsystems and realizes the possibility of decentralized control of each of moving RM links. The control signal is formed taking into account the dynamics of RM mechanical system and electric drives. When constructing the control system, the coefficients of nonlinear system dynamics equations a constructed in the form of the Lagrange – Maxwell equations are calculated. The control for the initial nonlinear system is obtained explicitly. The stability of dynamical system in entire phase space and its dissipativity in region of phase space are investigated with a significant influence of disturbing moments in operating conditions. To compensate for them, an adaptive signal-type additive has been introduced into the control law, which ensures system performance at significant rates of change in power moments on the output shafts of drives. The influence of measurement errors of RM state vector on the formation of control is taken into account.

In the Acsocad software according to the mathematical model of RM link, a block diagram is made up with subsystems of gradient tuning and signal adjustment. The movement of one link along the program trajectory is considered. To take into account the influence of measurement noise on the values of current, speed and position, blocks with adding a random signal having a normal distribution are added to system. Simulation was performed in the absence and influence of noise on measurements both at constant values of adjustable coefficients, and using the coefficient gradient tuning method. Constructed curves of coefficients optimal values to obtain the minimum deviation value from the program trajectory. The efficiency of using the gradient tuning and signal adjustment methods when RM is moving in conditions of incomplete information is shown.

*Keywords: control, nonlinear systems, Lyapunov functions, bounded disturbances, uncertainty, dissipativity, limiting set estimation, stability.*

**Introduction**

A manipulation robot is a mechanical system whose dynamics is described by Lagrange's differential equations. The main difficulties encountered in solving problems of controlling such a mechanical system are due to its high order, non-linearity and the presence of dynamic interaction between various degrees of freedom. In the study of nonlinear continuous and discrete control systems, the main method of analysis with the use of complete models of dynamics is the method of Lyapunov function. It is also used to study the dissipativity of systems when the values of the constant parameters of the system are uncertain. At the same time the main objective is to choose a Lyapunov function that would allow to conduct the analysis effectively enough [1–3]. When solving the problem of synthesis of the control moments of robot manipulator (RM) by this method, a function that reflects the change in the total energy of the dynamic system can be chosen as a Lyapunov function that allows to study the behavior of the phase trajectories of the system in the entire phase space. With this approach, the Lyapunov function is selected from the first integrals of the motion of the system. Along with the task of constructing a model when managing a dynamic system, the task of measuring the state vector of a system with limited noise, which considered in [4–20], is important.

**1. Formulation of the problem**

The object of the study is a three-link robot manipulator with electric drives, the full model of which dynamics is constructed in the form of Lagrange – Maxwell equations [16, 17] and according to the well-known rules [21] is reduced to a non-linear model by the form of the relationship between its input and output parameters, defined by the vector differential

$$\dot{\bar{x}} = F\left(\bar{x}, \bar{U}, \bar{v}\right), \tag{1}$$

where $U = \left(u_1, u_2, ..., u_n\right)^T$ are the input signals, and $x = \left(x_1, x_2, ..., x_n\right)^T$ are the output signals, which are determined ambiguously and depend on random factors $v = \left(v_1, v_2, ..., v_s\right)^T$, $s = 1, \ldots, 3n$.

The dynamic system (1) operates under uncertainty. Along with external disturbances, the quality of the control is also affected by the disturbances caused by errors in measuring the components of the state vector of the system.

The problem of tracking the points of a program trajectory with control actions constrained in magnitude is considered. The state vector of the RM $x_\lambda = \left(\eta_\lambda, \dot{\eta}_\lambda, I_{a\lambda}\right)^T$ is determined by manipulator generalized coordinates, given rotation angles $\eta^\lambda$, $\lambda = 1,2,3$ and angular velocities $\dot{\eta}_\lambda$ of the links of the RM, as well as generalized velocities of electric drives, that is the currents of motor armature windings $I_{a\lambda}$. Generalized coordinates and velocities are assumed to be measurable at any specific time. The points of the program trajectory are given by the generalized coordinates $\eta_\lambda^\circ$ and velocities $\dot{\eta}_\lambda^\circ$, $I_{a\lambda}^\circ$. The problem of the motion control of the RM at the point of the program trajectory $x^\circ = \left(\eta_\lambda^\circ, \dot{\eta}_\lambda^\circ, I_{a\lambda}^\circ\right)^T$ is set as the problem of return of a certain region from an arbitrary point due to deviation from the trajectory under the action of disturbances.

Perturbations $\Delta\eta^\lambda$, $\Delta\dot{\eta}^\lambda$, $\Delta I_a^\lambda$ are introduced as the difference between the current and program values of the phase vector coordinates. It is assumed that the generalized coordinates and velocities of the system are accessible to measurement, and the control forces are subject to restrictions on the norm.

The control is synthesized using the Lyapunov function method in the tensor form of the record, which removes the cumbersomeness of the given expressions.

The Lyapunov function $V$ is constructed as a bundle of first integrals of the perturbed motion of the system.

$$V = J + \rho J_\lambda J_\lambda, \quad \lambda = 1,2,3,$$

where $\rho$ is the positive constant,

$$J = \frac{1}{2} c_{\lambda\mu} \dot{\eta}^\lambda \dot{\eta}^\mu + \frac{1}{2}\left(L_{a\lambda\mu} - L_b^{\nu\gamma} M_{\lambda\gamma} M_{\nu\mu}\right) \Delta I_a^\lambda \Delta I_a^\mu + W_p(\Delta\eta), \quad \lambda, \mu, \gamma, \nu = 1,2,3, \tag{2}$$

$$J_\lambda = \left(L_{a\lambda\mu} - L_b^{\nu\gamma} M_{\gamma\mu} M_{\nu\lambda}\right) I_{a\mu} - \left(L_{a\lambda\mu} - L_b^{\nu\gamma} M_{\gamma\mu}^\circ M_{\nu\lambda}^\circ\right) I_{a\mu}^\circ + L_b^{\nu\gamma} n_\gamma \frac{\partial M_{\nu\lambda}}{\partial \eta_\beta} \Delta\eta_\beta, \quad \lambda, \mu, \gamma, \nu = 1,2,3, \tag{3}$$

$c_{\lambda\mu}$ is the manipulator metric tensor, $L_{a\lambda\mu}$, $L_{b\lambda\mu}$ are inductance tensors, $M_{\lambda\mu}$ is the tensor of mutual inductance of armature winding and stimulation of electric motors, $L_b^{\lambda\gamma}$ is calculated using the formula $L_{b\nu\lambda} L_b^{\lambda\gamma} = \delta_\nu^\gamma$, where $\delta_\nu^\gamma$ denotes Kronecker symbol; $R_{\lambda\mu}$, $B_{\lambda\mu}$ are tensors, defining the dissipation of electromagnetic and mechanical energy of the system, accordingly, $W_p(\eta)$ is the manipulator potential energy.

Total derivative $\dot{V}$ of the function $V$ in the force of the system (1), taking into account (2), (3), has the form

$$\dot{V} = -B_{\lambda\mu} \dot{\eta}^\lambda \dot{\eta}^\mu + \left(U_\lambda - R_{\lambda\mu} I_a^\mu\right)\left(\rho J_\lambda + \delta_{\lambda\mu} \Delta I_a^\mu\right),$$

operating on the degree of freedom $\lambda$, $U_\lambda$ is the control restrained by limitation $U_\lambda \in R^S$, $R^S$ is the restricted closed set given from the control resources.

Choosing the controls in the form of

$$U_\lambda = R_{\lambda\mu} I_a^\mu - \alpha\left( J_\lambda + \frac{1}{\rho}\delta_{\lambda\mu}\Delta I_a^\mu \right), \qquad (4)$$

with positive constant $\alpha$, we will obtain

$$\dot{V} = -B_{\lambda\mu}\dot{\eta}^\lambda\dot{\eta}^\mu - \rho\alpha\left( J_\lambda + \frac{1}{\rho}\delta_{\lambda\mu}\Delta I_a^\mu \right)^2 .$$

The derivative $\dot{V}$ of the Lyapunov function is negative definite, and, consequently, the equilibrium position of the system is stable.

**2. Parametrization of control law**

The constructed control (4) contains two arbitrary parameters $\alpha$ and $\rho$. For their choice, we submit the control law in the form

$$U_\lambda = R_\lambda I_{a\lambda} + K_{\lambda\mu}^1\Delta I_a^\lambda + K_{\lambda\mu}^2\Delta\eta^\lambda, \quad \lambda,\mu = 1,2,3, \qquad (5)$$

where the tensors $K_{\lambda\mu}^1$ and $K_{\lambda\mu}^2$, whose elements contain unknown parameters, are to be calculated and realized in the controller. Let us take the following objective function as a parameter choice criterion

$$Q = \frac{1}{2}(\Delta x_\lambda)^2,$$

where the vector of deviations $\Delta x_\lambda \in R^{n_\lambda} : \Delta x_\lambda = \left(\Delta I_a^\lambda, \Delta\eta^\lambda, \Delta\dot{\eta}^\lambda\right)^T$, $\lambda = 1,2,3.$

When minimizing the objective function with respect to the required parameters, we shall take the differential equations of the object as constraints in a simplified form: we assume that the RM is in a potential-free field, the mutual inductance factors are negligible, and its dynamics is described by a system of differential equations obtained from the system (1) by linearizing it in the position of the robotic arm with orthogonal arrangement of links. These constrains have the form

$$\dot{\bar{x}} = A\bar{x} + B\bar{U} + C\bar{v} .$$

In this equation $A$ is a block matrix whose structure is determined by the metric tensor of the manipulator and the tensors of inductance and mutual inductance of the armature windings and excitation of drive electric motors, $\bar{U} = (u_1, u_2, u_3)^T$, $\bar{v} = (v_1, v_2, v_3)^T$ – disturbances, $B$, $C$ – matrixes of the system.

Decentralized control (4) makes it easier to solve the problems of control by representing the initial nonlinear system in the form of three subsystems, each of which is subject to mutually uncorrelated disturbances. Given the small dimension of the subsystems, we obtain their equations linearized in the neighborhood of the points of the program trajectory

$$\dot{x} = A_\lambda x + B_\lambda u + C_\lambda \nu ,$$

$$A_\lambda = \begin{pmatrix} 0 & 1 & 0 \\ 0 & -D_\lambda / J_\lambda & C_M / J_\lambda \\ 0 & -C_E / L_\lambda & -R_\lambda / L_\lambda \end{pmatrix}, \quad B_\lambda = \begin{pmatrix} 0 \\ 0 \\ 1/L_\lambda \end{pmatrix}, \quad \lambda = 1,2,3,$$

where $x, u, \nu$ – are the vectors of the state, control, and disturbances, $A_\lambda, B_\lambda$ are the matrices; $C_M, C_E$ are the coefficients of proportionality of the torque and EMF resulting from the rotation of the motor armature; $L_\lambda$ is the inductance of the armature winding; $D_\lambda$ and $R_\lambda$ are the coefficients of the viscous friction and the resistance of armature winding, respectively, which determine the dissipation of mechanical and electromagnetic energies, respectively; $J_\lambda$ is the moment of inertia of the subsystem brought to the shaft of the electric motor.

When setting ratios the task of the subsystem is to find the minimum of the scalar function $Q = \frac{1}{2}(\Delta x_\lambda)^2, \lambda = 1,...,N,$ by the gain coefficient vectors $k_\lambda$. Rate of change of the objective function

$$\dot{Q}_\lambda = \left(\frac{\partial Q}{\partial k}\dot{k}\right)_\lambda \qquad (6)$$

in the tuning process should be less than zero and as less as possible, thus ensuring the quickest descent in the direction of the minimum $Q_\lambda$. It follows from the (6) that a gradient tuning algorithm can be used to solve the minimization problem, which has the following form of the function under consideration

$$\dot{k}_\lambda = -\left(\Gamma\varphi^T\left(\Delta x\right)^T\right)_\lambda,$$

where $\Gamma_\lambda$ is the diagonal matrix of the coefficients of regulating loops.

**3. Control under significant influence of disturbance torques**

Among the main reasons for the deterioration of the quality of robot control are unpredictable changes in load moments at the output actuator shafts, the effect of viscous and dry friction forces, the elimination methods of which are difficult to implement, and the intensification of the destabilizing interference of subsystems. These phenomena are difficult to overcome using actuators with only linear feedback on the output variables of the subsystems, especially since the controller gains have design constrains. One of the means of compensation for disturbing factors are signal-type control algorithms that ensure the system's operability at significant rates of change in disturbing factors. The advantages of algorithms include the high speed of adaptive processes and ease of implementation, however, due to the limitation of input signals of electromechanical systems, the adaptability of algorithms is also limited. Accordingly, it is advisable to use them to control the object, when there are disturbing factors with a limited range of their variation and high speed.

Let us construct an algorithm for RM control under a significant influence of disturbance torques using the Lyapunov. We take into account the effect of the dry friction force moments $M_\lambda^{st} = k_{\lambda\mu}^{st} sign\left\{\dot{\eta}_\mu\right\}$ in the elements of the mechanical transmissions of RM and the moment of forces opposing the movement of the operating element, caused by the work performed $M_\lambda^r = -k_{\lambda\mu}^r\dot{\eta}_\mu$, where $k_{\lambda\mu}^{st}$ and $k_{\lambda\mu}^r$ are the diagonal matrices of the coefficients of friction and resistance, respectively. We shall call a disturbance random torque caused by the impact of external factors, the emergence of which is inevitable in the operating process of manipulating equipment, as $M_\lambda^{sl}$. In the control synthesis, we shall assume that $M_\lambda^{sl}$ is limited in value.

We shall add a relay component to the equation (5)

$$U_\lambda^\circ = U_\lambda + U_\lambda^{sp}, \qquad (7)$$

where $U_\lambda^{sp} = -k_{\lambda\mu}^{sp}\left|\dot{\eta}_\mu\right| sign\left\{J_\lambda + \frac{1}{\rho}\delta_\lambda^\mu \Delta I_{a\mu}\right\}$, $k_{\lambda\mu}^{sp}$ is a diagonal matrix, the positive elements of which are chosen based on the requirements imposed on the quality of control, control resources and magnitudes of the disturbance torques.

Evaluation of the stability of the movement of the RM in the management (7) gives inequality, which should be guided by the choice of coefficients, based on the condition $\dot{V} \le 0$:

$$\left|M_\mu^{sl}\dot{\eta}_\mu\right| \le \rho k_{\lambda\mu}^{sp}\left|\left(L_{a\lambda\mu} + \frac{1}{\rho}\delta_\lambda^\mu\right)\Delta I_{a\mu} + I_{b\nu}\frac{\partial M_{\nu\beta}}{\partial\eta_\lambda}\Delta\eta_\beta\right|\left|\dot{\eta}_\mu\right|.$$

**4. Simulation of control law**

The structural diagram of the second subsystem of RM is shown in Fig. 1. The presented model realizes the movement along the program trajectory, which determined by the expressions $\eta_\circ^1 = \eta_\circ^3 = 0$, $\eta_\circ^2 = 0.5\sin 2t$. To obtain the measured values of current $I_a^2$, velocity $\dot{\eta}^2$ and position $\eta^2$, the Noise blocks that allow generating Gaussian noise, as well as FK units that perform signal filtering, are added to the diagram.

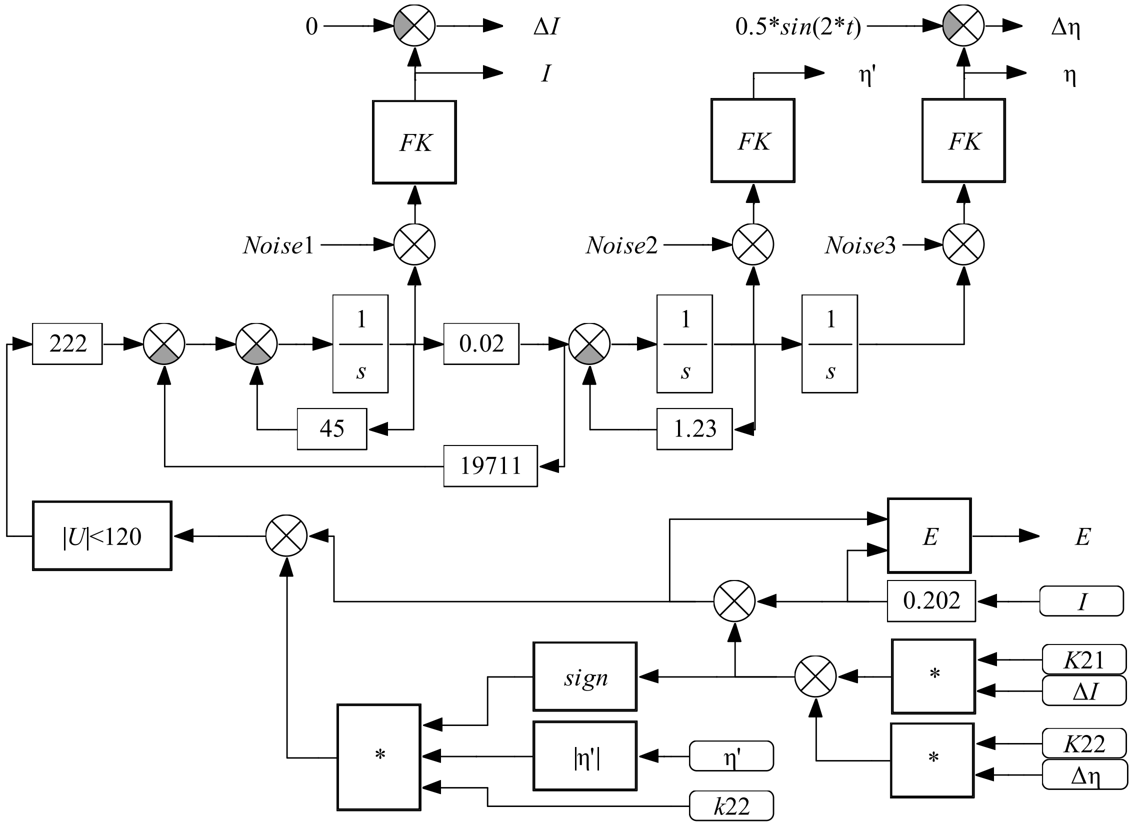


**Fig. 1. Structural diagram of the second subsystem of RM**

The control law of the second subsystem is simulated in the form (5). The value of the signal adjustment coefficient $k_2^2$ (k22 in diagrams) has a constant value, and the values of the parameters $K_{22}^1$ and $K_{22}^2$ (K21 and K22 in diagrams, respectively) are determined during the motion of subsystem using a gradient adjustment with the values of the specified coefficients $\gamma_1$ and $\gamma_2$. The structural diagrams of the gradient adjustment subsystems for coefficients $K_{22}^1$ и $K_{22}^2$ are shown in Figs. 2, 3.

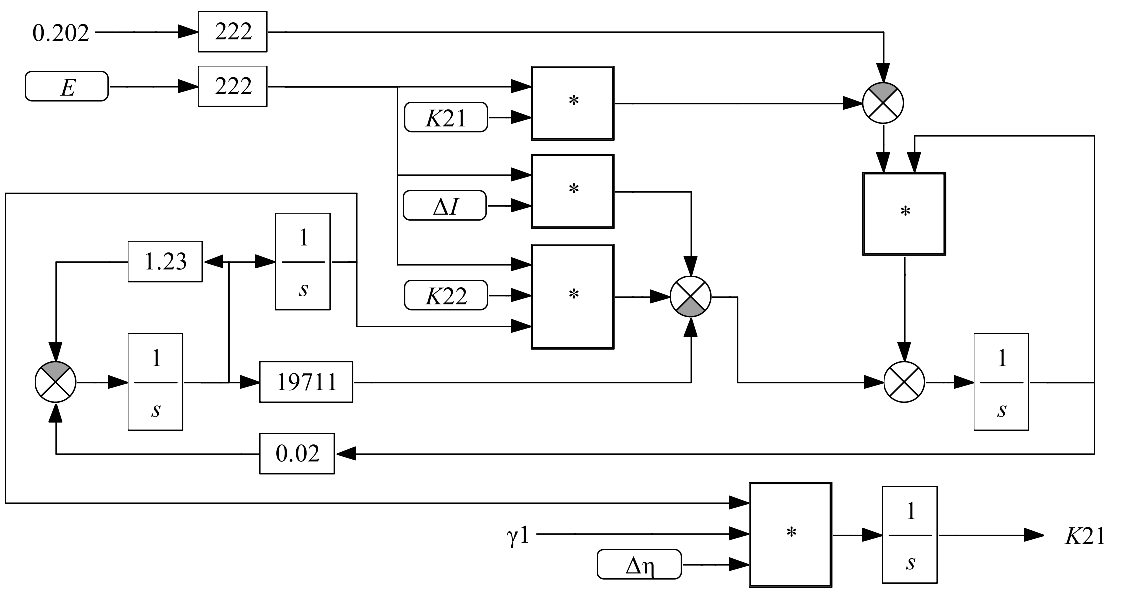


**Fig. 2. Structural diagram for adjusting the coefficient K21**

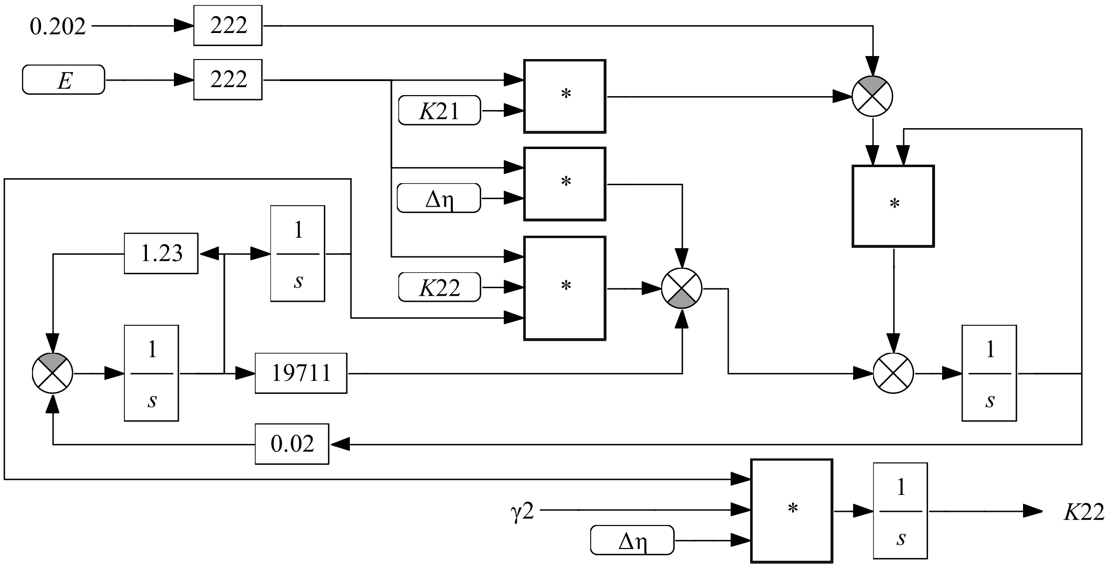


**Fig. 3. Structural diagram for adjusting the coefficient K22**

The initial values of the adjustable coefficients $K_{22}^1$, $K_{22}^2$ and $k_2^2$ are choosen to be equal to –5 V/A, –13305 V/rad and 80 Vs/rad, respectively, and values of coefficients $\gamma_1$ and $\gamma_2$ are assumed to be equal to $-4000$ and $-10{,}9^{11}$, respectively. The results of simulation of the second subsystem without regard to the influence of noise are shown in Figs. 4–6. The values of coefficients $K_{22}^1$ (Fig. 4) and $K_{22}^2$ (Fig. 5) are determined during the motion of subsystem in real-time mode for the purpose of decrease deviation of position $\Delta\eta^2$ from the program value (Fig. 6).

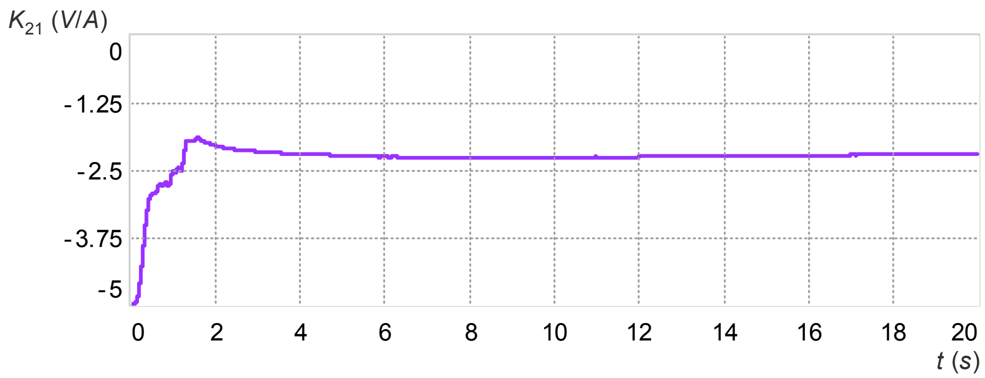


**Fig. 4. Curve of changes in the adjustable coefficient K21**

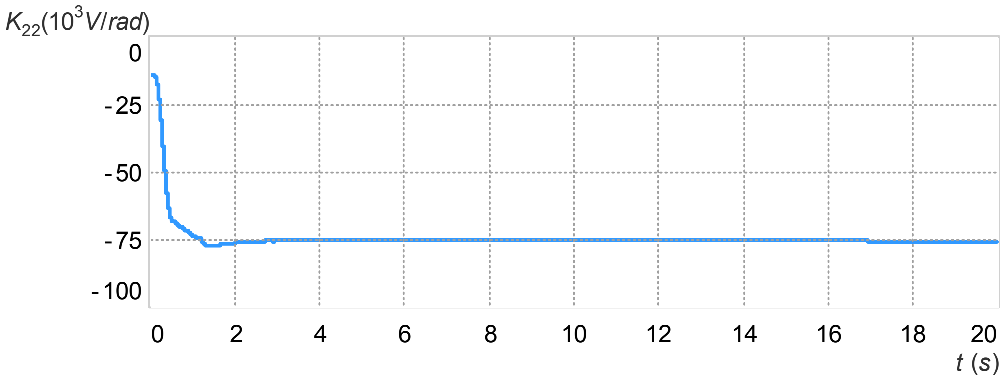


**Fig. 5. Curve of changes in the adjustable coefficient K22**

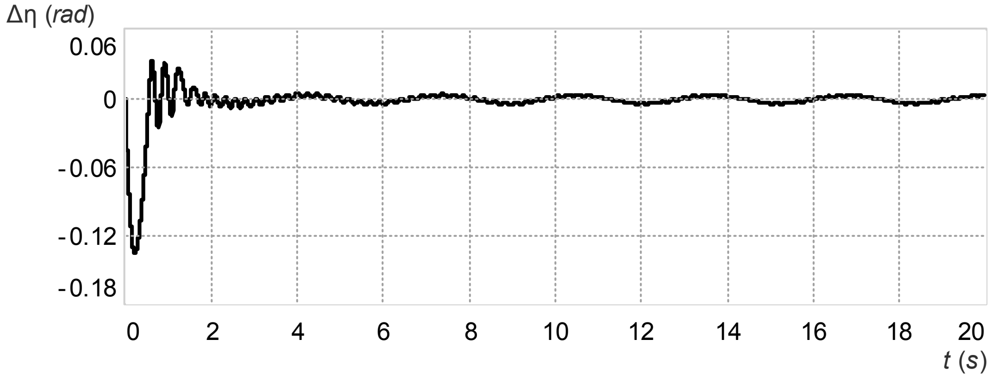


**Fig. 6. Curve of deviation of position from the program value**

It should be noted that the observed transient processes are conventionally divided into two areas. In the first area, the duration of which is up to 4 seconds, there is a significant change in current due to the start of the engine. The maximum absolute error value (MAO) in this area is 0.14 rad, however, the main program of RM is constructed so that during this period of time there is no interaction with the object.

During this time, the primary gradient adjustment of the parameters $K_{22}^{1}$ and $K_{22}^{2}$ is carried out, the values of which by the end of the first section are –2.186 V/A and –75363 V/rad, respectively. Further, during the processing of the object, the values of the adjustable parameters change by no more than 10% relative to the values determined at the end of the first section, and MAO value in this area does not exceed 0,004 rad.

If the gradient tuning and the signal adjustment are not used, and the values of –2,186 V/A and –75363 V/rad are chosen as constant values of parameters $K_{22}^{1}$ and $K_{22}^{2}$, then MAO value will be 0,075 rad in the first area, and 0,0056 rad in the second area. If the signal adjustment is used, then the MAO value in the second area is equal to 0,0065 rad. Thus, the use of constant coefficients with the included signal adjustment allows to control the link in the absence of noise and disturbances more accurately than without the use of signal adjustment.

To determine the optimal combination of parameter values $K_{22}^{1}$ and $K_{22}^{2}$, allowing to achieve maximum accuracy of movement along the program trajectory, a function $S\left(K_{22}^{1}, K_{22}^{2}\right)$ is built, the value of which at each point corresponds to the MAO value of the second trajectory area from 4 to 20 seconds with corresponding values of coefficients $K_{22}^{1}$ and $K_{22}^{2}$. Fig. 7 shows the dependence $K_{22}^{2}$ on $K_{22}^{1}$, which makes it possible to reach the minimum of the MAO value, and in Fig. 8, the curve of the MAO value at the corresponding points.

Thus, with an increase in the value of the coefficients $K_{22}^{1}$ and $K_{22}^{2}$, a decrease in the MAO value of the second area of the trajectory to a value of 0.0025 rad is observed.

This allows to increase in the specific case under consideration by 60% accuracy relative to the results of applying the gradient tuning method.

When the noise channels Noise1, Noise2, Noise3 are affected, having a deviation of the normal distribution of 1, 0.001 and 0.001, respectively, the MAO value increases. So, when using constant values of coefficients $K_{22}^{1}$ and $K_{22}^{2}$, improving accuracy by 60% without the influence of noise, the MAO value of the second area of the trajectory will be 0.0286 rad.

However, when using a gradient tuning with signal adjustment, the MAO value of the second trajectory area (Fig. 9) will be only 0.0106 rad.

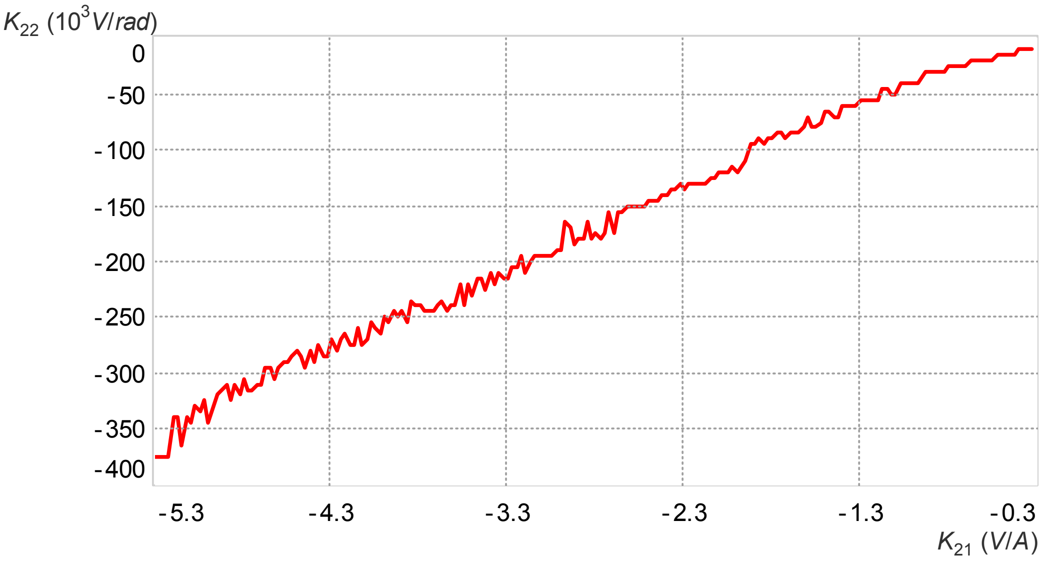


**Fig. 7. Curve of optimal values of coefficients K21 and K22**

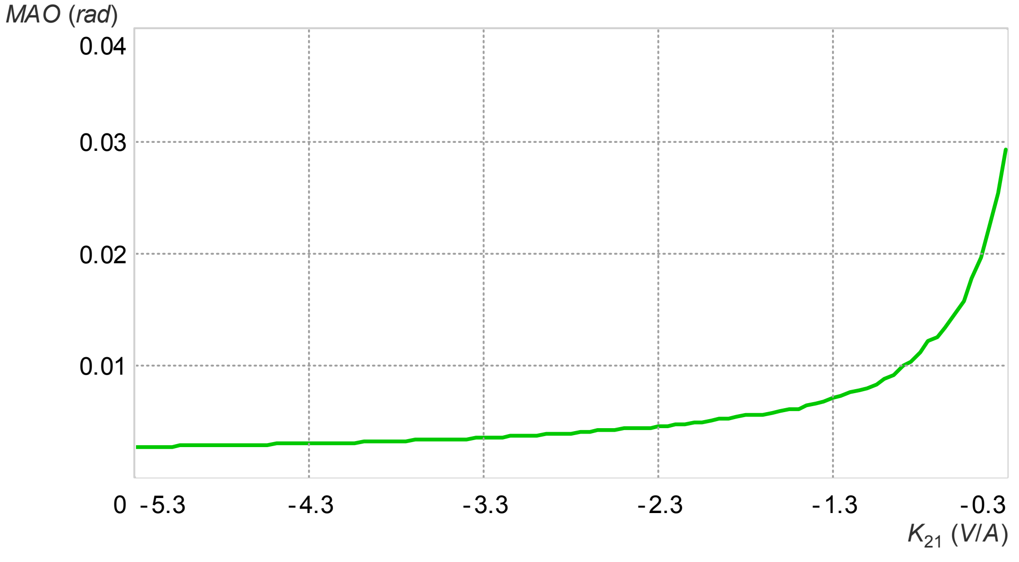


**Fig. 8. MAO value of the second trajectory area**

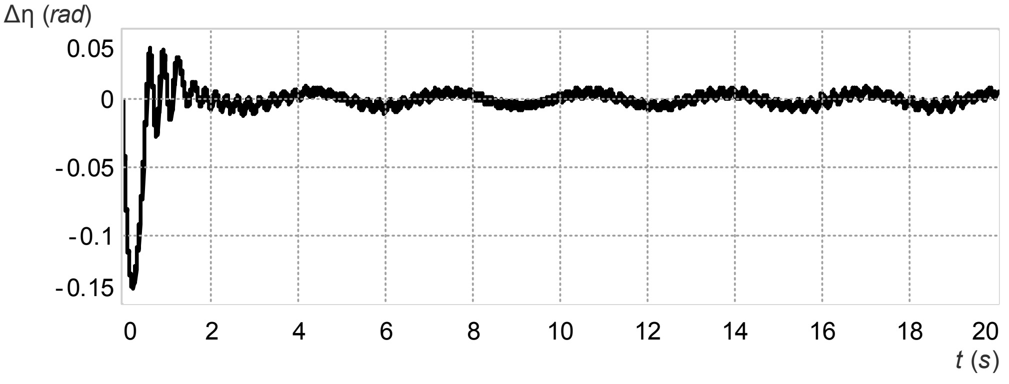


**Fig. 9. Curve of deviation of position from the program value**

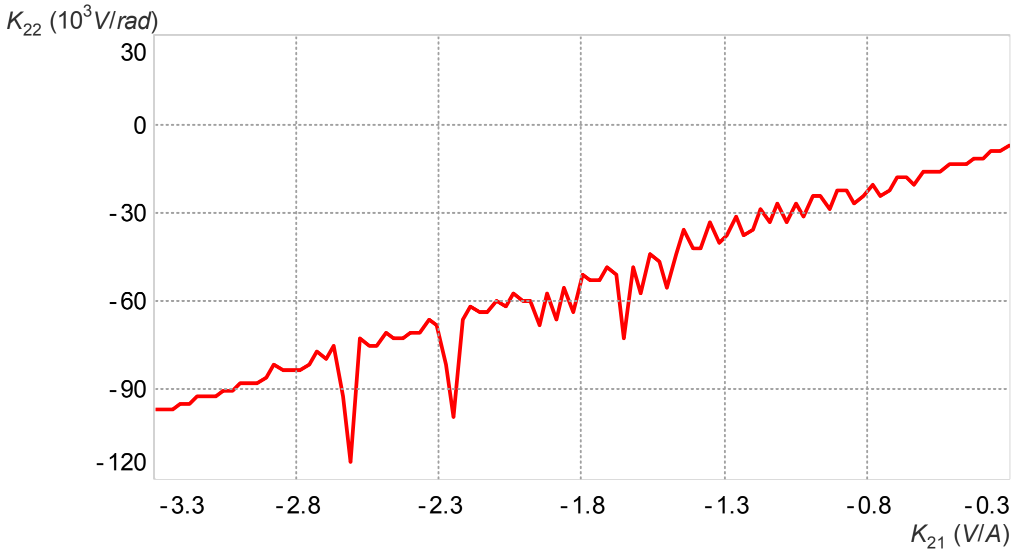


**Fig. 10. Curve of optimal values of coefficients K21 and K22**

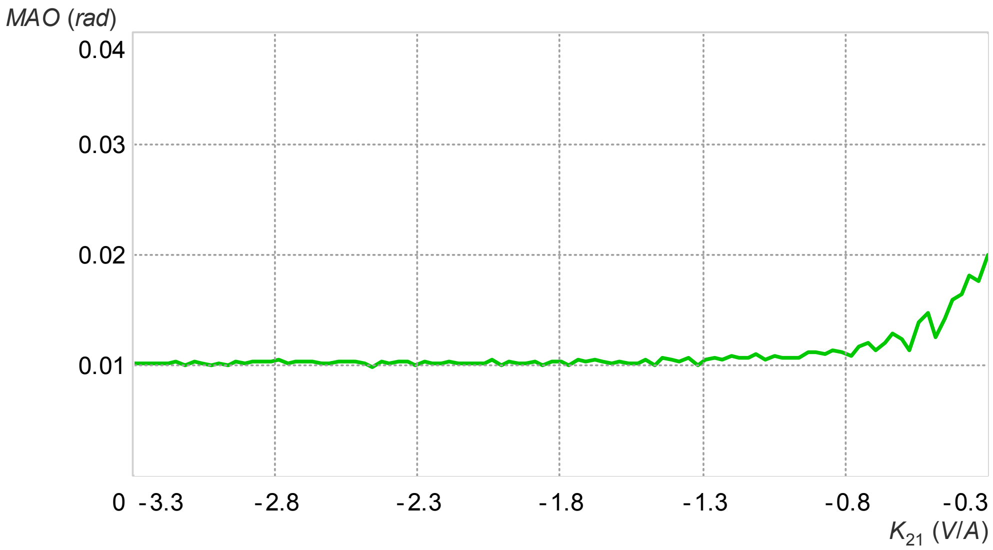


**Fig. 11. MAO value of the second trajectory area**

Fig. 10 shows the dependence $K_{22}^2$ on $K_{22}^1$, which makes it possible to reach the minimum of the MAO value, and in Fig. 11, the curve of the MAO value at the corresponding points. The smallest MAO value in this case is 0,01 rad that it is less than 6% higher than the result of the gradient tuning method.

**Conclusion**

This allows to conclude that, despite the less accurate indicators of the gradient tuning method using signal adjustment without regard to the influence of noise compared with the method of selecting and using constant optimal coefficient values, this method works effectively in the conditions of incomplete information and does not require additional calculations of values of the coefficients $K_{22}^1$ and $K_{22}^2$.

The decentralized control algorithm of the RM by the direct Lyapunov method is constructed using the complete nonlinear model of the dynamics of the control object, ensuring a stable movement to the point of the program trajectory. With the destabilizing influence of the interconnections of RM subsystems, the significant influence of disturbances in the operating mode and the availability of typical

nonlinearities, the expediency of using the control algorithm of the signal type is substantiated. The property of the system dissipativity and the stability resulting from it under certain conditions are considered. The results of simulation are presented.

**The work was supported by Act 211 Government of the Russian Federation, contract No. 02.A03.21.0011.**

## References

1. Lychak M.M. [Robust Dissipativity of Discrete Systems and Its Study by Means of a Sequence of Sets of Lyapunov Function]. *Cybernetics and Systems Analysis*, 2008, no. 2, pp. 13–23. (in Russ.) DOI: 10.1007/s10559-008-0016-7

2. Kuntsevich V.M., Lychak M.M. [Elements of the Theory of Evolution of Sets and the Stability of These Processes]. *Cybernetics*, 1983, no. 1, pp. 105–111. (in Russ.)

3. Kuntsevich V.M., Lychak M.M. *Sintez sistem avtomaticheskogo upravleniya s pomoshch'yu funktsiy Lyapunova* [Synthesis of the System of Automatic Control by Lyapunov Functions]. Moscow, Nauka, 1977. 399 p.

4. Bortsov Yu.A., Polyakhov N.D. *Elektromekhanicheskie sistemy s adaptivnym i modal'nym upravleniem* [Electromechanical Systems with Adaptive and Modal Control]. Leningrad, Energoatomizdat, 1984. 214 p.

5. Korenev, G.V. *Tselenapravlennaya mekhanika upravlyaemykh manipulyatorov* [Object Oriented Mechanics of Controlled Manipulators]. Moscow, Nauka, 1979. 447 p.

6. Kuntsevich V.M., Lychak M.M. *Sintez optimal'nykh i adaptivnykh sistem upravleniya: Igrovoy podkhod* [The Synthesis of Optimal and Adaptive Control Systems: Game Approach]. Kiev, Nauk. dumka, 1985. 247 p.

7. Kuntsevich V.M. Set-valued Estimation of State and Parameter Vectors within Adaptive Control Systems. *Bounding Approaches to System Identification*, 1996, pp. 239–259. DOI: 10.1007/978-1-4757-9545-5_15

8. Kuntsevich V.M. [Guaranteed Results in the Problems of Parametric Identification and Estimations of State Vector (Filtration) under Slowly Changeable Restricted Obstacles of Changes]. *Problems of Control and Information Science*, 2006, no. 4, pp. 50–57. (in Russ.)

9. Kuntsevich V.M., Kurzhanskii A.B. [Fields of Achievement of Linear and Some Classes of Nonlinear Systems of Discrete Systems and Their Control]. *Problems of Control and Information Science*, 2010, no. 1, pp. 5–21. (in Russ.)

10. Kuntsevich V.M., Kuntsevich A.V. [Invariant Sets of the Set of Linear and Nonlinear Discrete Systems with Restricted Disturbances]. *Automatics and Telemechanics*, 2012, no. 1, pp. 92–106. (in Russ.)

11. Kuntsevich V.M. [Control of the Set of Linear and Nonlinear Dynamic Systems at the Measurements with Restricted Obstacles]. *Trudy instituta matematiki i mekhaniki UrO RAN* [The Research Papers of the Institute of Mathematics and Mechanics of the Ural Branch of the Russian Academy of Sciences]. Ekaterinburg, UB RAS, 2014, vol. 20, no. 4, pp. 178–186.

12. Shiryaev V.I. Synthesis of Control of Linear Systems in Incomplete Information. *Journal of Computer and Systems Sciences International*, 1994, no. 3, pp. 229–237.

13. Shiryaev V.I. [Problems of Control by Dynamic Systems with Incomplete Information]. *Mechatronics*, 2001, no. 8, pp. 2–5. (in Russ.)

14. Shiryaev V.I., Dolbenkov V.I., Il'in E.D., Podivilova E.O. [Estimation of the State of Dynamic System in the Conditions of Indeterminacy]. *Ekstremal'naya robototekhnika: sb. dokl. Mezhdunar. nauch.-tekhn. konf.* [Extreme Robotic Technology: International Conference Abstracts]. St. Petersburg, Politekhnika-servis, 2011, pp. 234–243.

15. Fokin L.A., Shiryaev V.I. Preliminary Comparison of Kalman and Minimax Approaches to Error Estimation of Integrated Navigation System. *IEEE International Siberian Conference on Control and Communications (SIBCON-2013) Proceedings*, 2013, pp. 212–214. DOI: 10.1109/SIBCON.2013.6693599

16. Shiryaev V.I., Bragina A.A. [On Control of Robotic Manipulator in the Conditions of Indeterminacy]. *Robotics and Engineering Cybernetics*, 2014, no. 1 (2), pp. 18–21. (in Russ.)

17. Bragina A.A., Shcherbakov V.P., Shiryaev V.I. Synthesis of Adaptive Control of Robotic Manipulator by the Method of Lyapunov Functions. *IFAC-PapersOnLine*, 2018, vol. 51, no. 32, pp. 298–303. DOI: 10.1016/j.ifacol.2018.11.399

18. Shiryaev V.I., Podivilova E.O. Set-Valued Estimation of Linear Dynamical System State when Disturbance is Decomposed as a System of Functions. *Procedia Engineering*, 2015, vol. 129, pp. 252–258. DOI: 10.1016/j.proeng.2015.12.045

19. Chernousko F.L. Minimax Control for a Class of Linear Systems Subject to Disturbances. *Journal of Optimization Theory and Applications*, 2005, vol. 127, no. 3, pp. 535–548. DOI: 10.1007/s10957-005-7501-1

20. Bo Zhou, Kun Qian, Xu-Dong Ma, Xian-Zhong Dai A New Nonlinear Set Membership Filter Based on Guaranteed Bounding Ellipsoid Algorithm. *Acta Automatica Sinica*, 2013, vol. 39, no. 2, pp. 146–154. DOI: 10.1016/s1874-1029(13)60017-8

21. Erugin N.P., Shtokalo I.Z. *Kurs obyknovennykh differentsial'nykh uravneniy* [The Course of Ordinary Differential Equations]. Kiev, Vishcha shkola, 1974. 472 p.

***Received 10 March 2019***

**УДК 621.865.8** **DOI: 10.14529/ctcr190202**

# К ЗАДАЧЕ УЛУЧШЕНИЯ ТОЧНОСТИ ПОЗИЦИОНИРОВАНИЯ РОБОТА-МАНИПУЛЯТОРА В УСЛОВИЯХ НЕПОЛНОТЫ ИНФОРМАЦИИ

***В.И. Ширяев, В.П. Щербаков, А.А. Брагина***

*Южно-Уральский государственный университет, г. Челябинск, Россия*

Получен алгоритм управления движением манипуляционного робота (МР) по программной траектории методом функций Ляпунова. Метод использует декомпозицию исходной многосвязной нелинейной системы на подсистемы и реализует возможность децентрализованного управления каждым из подвижных звеньев МР. Управляющий сигнал формируется с учетом динамики механической системы МР и электроприводов. При построении системы управления вычисляются коэффициенты уравнений динамики нелинейной системы, построенных в форме уравнений Лагранжа – Максвелла. Управление для исходной нелинейной системы получено в явном виде. Исследована устойчивость динамической системы во всем фазовом пространстве и ее диссипативность в области фазового пространства при существенном влиянии возмущающих моментов в рабочих режимах. Для их компенсации в закон управления введена адаптивная добавка сигнального типа, обеспечивающая работоспособность системы при значительных скоростях изменения силовых моментов на выходных валах приводов. Учтено влияние ошибок измерения вектора состояния МР на формирование управления.

В программном продукте Acsocad по математической модели звена МР составлена структурная схема с подсистемами градиентной настройки и сигнальной подстройки. Рассматривается движение одного звена по программной траектории. Для учета влияния шума измерений на значения тока, скорости и положения в систему введены блоки, добавляющие случайный сигнал, имеющий нормальное распределение. Выполнено моделирование в условиях отсутствия и влияния шума на измерения как при постоянных значениях настраиваемых коэффициентов, так и с использованием метода градиентной настройки коэффициентов. Построены кривые оптимальных значений коэффициентов для получения минимального значения отклонения от программной траектории. Показана эффективность использования методов градиентной настройки и сигнальной подстройки при движении МР в условиях неполноты информации.

*Ключевые слова: управление, нелинейные системы, метод функций Ляпунова, ограниченные возмущения, неопределенность, свойство диссипативности, предельное множество, стабилизация.*

### *Литература*

*1. Лычак, М.М. Робастная диссипативность дискретных систем и ее исследование с помощью последовательности множеств функций Ляпунова / М.М. Лычак // Кибернетика и системный анализ. – 2008. – № 2. – С. 13–23. DOI: 10.1007/s10559-008-0016-7*

*2. Кунцевич, В.М. Элементы теории эволюции множеств и устойчивость этих процессов / В.М. Кунцевич, М.М. Лычак // Кибернетика. – 1983. – № 1. – С. 105–111.*

*3. Кунцевич, В.М. Синтез систем автоматического управления с помощью функций Ляпунова / В.М. Кунцевич, М.М. Лычак. – М.: Наука, 1977. – 399 с.*

*4. Борцов, Ю.А. Электромеханические системы с адаптивным и модальным управлением / Ю.А. Борцов, Н.Д. Поляхов. – Л.: Энергоатомиздат, 1984. – 214 с.*

*5. Коренев, Г.В. Целенаправленная механика управляемых манипуляторов / Г.В. Коренев. – М.: Наука, 1979. – 447 с.*

*6. Кунцевич, В.М. Синтез оптимальных и адаптивных систем управления: Игровой подход / В.М. Кунцевич, М.М. Лычак. – Киев: Наук. думка, 1985. – 247 с.*

*7. Kuntsevich, V.M. Set-valued estimation of state and parameter vectors within adaptive control systems / V.M. Kuntsevich // Bounding Approaches to System Identification. – 1996. – Vol. 15. – P. 239–259. DOI: 10.1007/978-1-4757-9545-5_15*

*8. Кунцевич, В.М. Гарантированные результаты в задачах параметрической идентификации и оценивания вектора состояния (фильтрации) при медленно изменяющихся ограниченных помехах измерений / В.М. Кунцевич // Проблемы управления и информатики. – 2006. – № 4. – С. 50–57.*

*9. Кунцевич, В.М. Области достижимости линейных и некоторых классов нелинейных систем дискретных систем и управления ими / В.М. Кунцевич, А.Б. Куржанский // Проблемы управления и информатики. – 2010. – № 1. – С. 5–21.*

*10. Кунцевич, В.М. Инвариантные множества семейств линейных и нелинейных дискретных систем с ограниченными возмущениями / В.М. Кунцевич, А.В. Кунцевич // Автоматика и телемеханика. – 2012. – № 1. – С. 92–106.*

*11. Кунцевич, В.М. Управление семейством нелинейных динамических систем при измерениях с ограниченными помехами / В.М. Кунцевич // Труды института математики и механики УрО РАН. – Екатеринбург: УРО РАН, 2014. – Т. 20, № 4. – С. 178–186.*

*12. Shiryaev, V.I. Synthesis of control of linear systems in incomplete information / V.I. Shiryaev // Journal of Computer and Systems Sciences International. – 1994. – no. 3. – P. 229–237.*

*13. Ширяев, В.И. Алгоритмы управления динамическими системами в условиях неопределенности / В.И. Ширяев // Мехатроника. – 2001. – № 8. – С. 2–5.*

*14. Оценивание состояния динамической системы в условиях неопределенности / В.И. Ширяев, В.И. Долбенков, Е.Д. Ильин, Е.О. Подивилова // Экстремальная робототехника: сб. докл. Междунар. науч.-техн. конф. – 2011. – С. 234–243.*

*15. Fokin, L.A. Preliminary comparison of Kalman and Minimax approaches to error estimation of integrated navigation system / L.A. Fokin, V.I. Shiryaev // IEEE International Siberian Conference on Control and Communications (SIBCON-2013) Proceedings. – 2013. – P. 212–214. DOI: 10.1109/SIBCON.2013.6693599*

*16. Ширяев, В.И. Об управлении манипуляционным роботом в условиях неопределенности / В.И. Ширяев, А.А. Брагина // Робототехника и техническая кибернетика. – 2014. – №1(2). – С. 18–21.*

*17. Bragina A.A., Shcherbakov V.P., Shiryaev V.I. Synthesis of adaptive control of robotic manipulator by the method of Lyapunov functions / A.A. Bragina, V.P. Shcherbakov, V.I. Shiryaev // IFAC-PapersOnLine. – 2018. – Vol. 51, no. 32. – P. 298–303. DOI: 10.1016/j.ifacol.2018.11.399*

*18. Shiryaev, V.I. Set-valued estimation of linear dynamical system state when disturbance is decomposed as a system of functions / V.I. Shiryaev, E.O. Podivilova // Procedia Engineering. – 2015. – Vol. 129. – P. 252–258. DOI: 10.1016/j.proeng.2015.12.045*

*19. Chernousko, F.L. Minimax control for a class of linear systems subject to disturbances / F.L. Chernousko // Journal of Optimization Theory and Applications. – 2005. – Vol. 127, no. 3. – P. 535–548. DOI: 10.1007/s10957-005-7501-1*

*20. A New Nonlinear Set Membership Filter Based on Guaranteed Bounding Ellipsoid Algorithm / Bo Zhou, Kun Qian, Xu-Dong Ma, Xian-Zhong Dai // Acta Automatica Sinica. – 2013. – Vol. 39, no. 2. – P. 146–154. DOI: 10.1016/s1874-1029(13)60017-8*

*21. Еругин, Н.П. Курс обыкновенных дифференциальных уравнений / Н.П. Еругин, И.З. Штокало. – Киев: Вища школа. – 1974. – 472 с.*

**Ширяев Владимир Иванович**, д-р техн. наук, профессор, заведующий кафедрой систем автоматического управления, Южно-Уральский государственный университет, г. Челябинск; shiriaevvi@susu.ru.

**Щербаков Василий Петрович**, старший преподаватель кафедры систем автоматического управления, Южно-Уральский государственный университет, г. Челябинск; shcherbakovvp@susu.ru.

**Брагина Асия Ахмедовна**, канд. техн. наук, доцент кафедры систем автоматического управления, Южно-Уральский государственный университет, г. Челябинск; braginaaa@susu.ru.

***Поступила в редакцию 10 марта 2019 г.***

**ОБРАЗЕЦ ЦИТИРОВАНИЯ**

Shiryaev, V.I. To the Problem of Improve Positioning Precision of Robotic Manipulator under Conditions of Incomplete Information / V.I. Shiryaev, V.P. Shcherbakov, A.A. Bragina // Вестник ЮУрГУ. Серия «Компьютерные технологии, управление, радиоэлектроника». – 2019. – Т. 19, № 2. – С. 16–28. DOI: 10.14529/ctcr190202

**FOR CITATION**

Shiryaev V.I., Shcherbakov V.P., Bragina A.A. To the Problem of Improve Positioning Precision of Robotic Manipulator under Conditions of Incomplete Information. *Bulletin of the South Ural State University. Ser. Computer Technologies, Automatic Control, Radio Electronics*, 2019, vol. 19, no. 2, pp. 16–28. DOI: 10.14529/ctcr190202