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Adaptive neural network control of hexapod for aerospace application

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Abstract. This research is a part of the work implemented by BSTU "Voenmeh" under the financial support of the Ministry of Education and Science of the Russian Federation for design and development of a precision mechanism with the parallel kinematics called "Hexapod". Based on the Stewart platform Hexapod as a positioning system with the parallel kinematics has many advantages in comparison with the serial kinematics mechanism. In engineering applications, very precise motion of parallel manipulators to track the desired trajectory has received a great deal of attention. The inverse kinematics problem of the hexapod is described, on the basis of which the desired trajectories are formed. The simulation model of hexapod dynamics implemented in the Matlab Simulink environment is shown. In this paper provides adaptive neural networks algorithm of the hexapods control with on-line tuning synaptic weights of network. Our results show an advantage of applying of the investigated algorithm in the problem of tracking control of the space applications hexapod.

1. Introduction.

In BSTU "Voenmeh" and JSC "ISS" named after M.F. Reshetnev is currently working to create a number of multi-step mechanisms with parallel kinematics (MIC) to ensure the precise positioning and orientation of spaceborne instruments and devices [1]. Most of the ultra-precise positioning and orientation systems based on the IPC created in modern times is a modification of the Guy-Stewart platform [2].

In this paper, the object of the study is an IPC ("Hexapod") of space based on six linear drives with stepping motors, depicted in Figure 1. The hexapod consists of a fixed base and a movable platform controlled by six identical linear actuators - legs (bars, posts). Each leg consists of two half-stems connected by hinges to the base and platform.

The main task of the hexapod control system is the development of the position of the mobile platform in the Cartesian coordinates relative to the base with an accuracy of ± 10 μm and orientation with an accuracy of ± 30 arc.sec. The working load of the hexapod is large-sized transformable objects with large mass-inertia characteristics and the center of mass remote from the moving platform.

Hexapod functions in the conditions of open space [3] - an extreme working environment, which determines the stringent requirements for the implementation of hardware. The control system is developed on the basis of a domestic radiation-resistant microcontroller [4]. Therefore, actual and important tasks are to assess the feasibility and improve the quality of the developed hexapod control algorithms. The presence of parametric and functional uncertainties of the hexapod under extreme operating conditions causes the application of adaptive approaches to control.

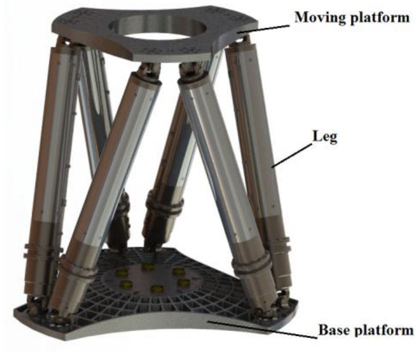

Figure 1. Hexapod sketch.

The exceptional approximating properties of artificial neural networks ensured the uninterrupted interest of the research engineers in their application in a variety of control tasks for mechatronic objects. Multilayer neural networks are used in identification problems, as nonlinear regulators or for forecasting the state of control objects. The main disadvantage of neural networks is the complexity of synthesis and learning in the problems of precise control of dynamic objects.

Nevertheless, in practice the methods of direct adaptive control based on trained on-line "light" neural networks have proved themselves well. In robotics, the approach [5, 6] of the application of an adaptive neural network with sigmoidal activation functions for controlling a manipulation robot with unknown dynamic parameters is known. Works [7-9] reflect the synthesis and implementation of the algorithm in the real-time operating system. In [10], a method of direct adaptive control based on a neural network with RBF - radially basic - activation functions is described. In [11], the RBF-based algorithm is applied in the problem of vibration isolation of the control object using the Stewart platform [2].

In the existing works, the questions of neural network control of the hexapode are not fully disclosed. Thus, the main goal of this work is to investigate the algorithms of direct adaptive neural network control and to evaluate its application in the problem of contour control of the hexapod of space purpose.

2. Hexapod Kinematic

The hexapod control is based on solving the inverse problem of the hexapod kinematics. A hexapod with a symmetrical arrangement of joints to the base and platform is considered, as shown in Figure 2. The pairs of hinges of the base and platform on the dividing circles form an angle of 120º with respect to the center. The hinges of the platform are shifted by an angle of 60º relative to the hinges of the base.

To solve kinematics problems, we introduce coordinate systems, as shown in Figure 2. The fixed coordinate system OXYZ is connected to the base, the mobile coordinate system O'X'Y'Z 'is connected to the platform. We define the initial "zero" position of the symmetrical hexapod, in which the legs have the same elongation. Thus, in this position, the coordinate system O'X'Y'Z 'relative to the OXYZ coordinate system is shifted along the OZ axis by the parameter h_0.

The numerical solution of kinematics problems will depend on the design parameters of the hexapod:

R_b, R_p — radii of dividing circles of the base and platform, respectively, on which the hinges are placed;

C_b, C_p — the distance between adjacent pairs (1-2, 3-4, 5-6) of the base joints and pairs (2-3, 4-5, 6-1) of the platform hinges, respectively.

The length of the legs in the "zero" position is defined as L_0 — "zero length of legs". Enter the leg numbers, as shown in Figure 2.

During the design of the hexapod design, the following parameters are selected:

$$R_b = 0.175 \text{ м}, R_p = 0.15 \text{ м}, \text{C}_b = 0.045 \text{ м}, C_p = 0.045 \text{ м}, h_0 = 0.4 \text{ м}.$$

The position of the center O 'of the platform with respect to the fixed coordinate system is specified by the Cartesian coordinates X, Y, Z. To determine the orientation of the platform, the Euler angles [3] $\varphi,\ \theta,\ \psi$. Thus, the linear position and the angular orientation of the platform are given by the vector $\mathbf{q} = [\,X,\ Y,\ Z,\ \varphi,\ \theta,\ \psi]^T$.

The set working range of the hexapod is: with respect to the X coordinate ± 100mm, the Y coordinate ± 100mm, the Z coordinate ± 25mm, the angular coordinates ± 7 deg.

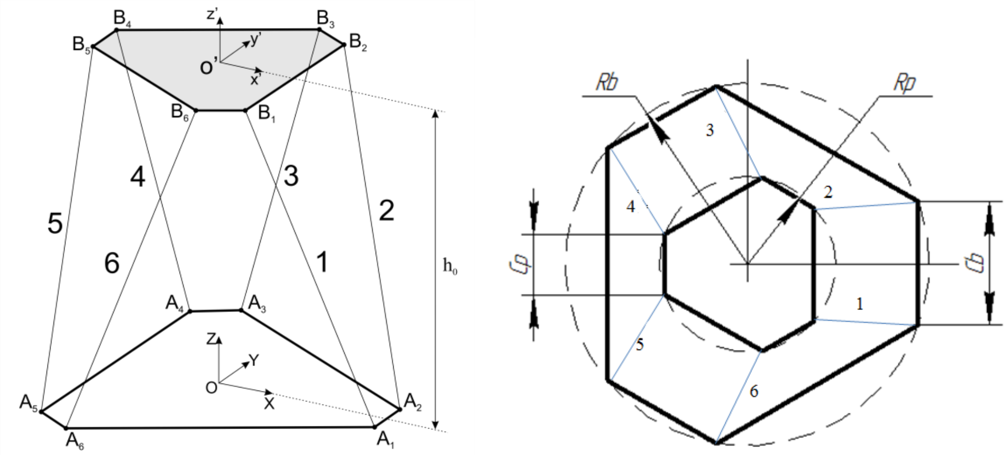

Figure 2. Kinematic scheme and design parameters of the hexapod.

For the connection between a fixed and a moving coordinate system, we use the matrix transformation in homogeneous coordinates [12]:

$$\mathbf{r} = \mathbf{T} \times \mathbf{r}', \tag{1}$$

where $\mathbf{r} = [\,X,\ Y,\ Z,\ 1]^T$ – vector of homogeneous coordinates of some point in the coordinate system OXYZ, T is the index denoting transposition of the vector, $\mathbf{r}'$ – is the vector of homogeneous coordinates of the same point relative to the moving coordinate system In the transformation (1), the extended matrix T is defined by $\mathbf{p} = [\,X',\ Y',\ Z']^T$ - the coordinates of the beginning of the mobile system relatively fixed - and the rotation matrix **R**

$$\mathbf{T} = \begin{vmatrix} & \mathbf{R} & & \mathbf{p} \\ 0 & 0 & 0 & 1 \end{vmatrix}, \tag{2}$$

Rotation matrix for choosing Euler angles – expression

$$\mathbf{R} = \begin{vmatrix} \cos\varphi\cos\psi + \sin\varphi\sin\theta\sin\psi & \sin\varphi\sin\theta\cos\psi - \cos\varphi\sin\psi & \sin\varphi\cos\theta \\ \cos\theta\sin\psi & \cos\theta\cos\psi & -\sin\theta \\ \cos\varphi\sin\theta\sin\psi - \sin\varphi\cos\psi & \sin\varphi\sin\psi + \cos\varphi\sin\theta\cos\psi & \cos\varphi\cos\theta \end{vmatrix}, \quad (3)$$

Calculating from (1-3) the transformation matrix T for a given vector $\mathbf{q}$ and knowing the coordinates of the points of attachment of the hinges of the legs to the base ($\mathbf{r}_{A_i}$ - vector of homogeneous coordinates of the point A_i в in the OXYZ system) and to the platform ($\mathbf{r}'_{B_i}$ -vector of homogeneous coordinates of a point B_i relatively O'X'Y'Z'), the solution of the inverse kinematics problem is easily found-the length of the *i*-th leg of the hexapod

$$L_i = \left\| \mathbf{r}_{A_i} - \mathbf{T} \times \mathbf{r}'_{B_i} \right\|, \quad (4)$$

As a rule, when the hexapode is contoured along a given trajectory $\mathbf{q}_r(t)$ in the Cartesian space of coordinates, on the basis of expression (4), the leg lengths defining in space $\mathbf{L}_r(t)$ are determined, and the hexapod control system must work out the trajectory.

3. Hexapod Neural Network Controller

In the structure of the adaptive neural network control algorithm for the hexapode shown in Figure 3, an artificial neural network (ANN) together with a nonlinear controller by error of control forms a force acting on linear drives - the legs of a hexapod.

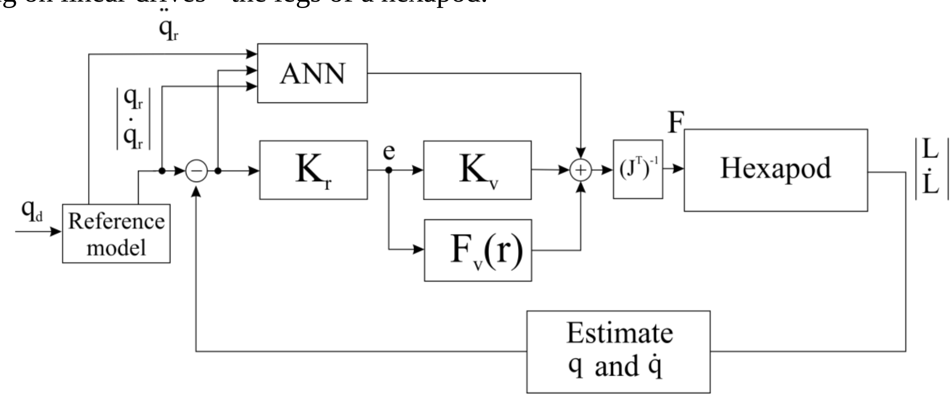

Figure 3. Block diagram of hexapod control controller.

The calculated forces of hexapode control are formed from the expression [5,6]

$$\mathbf{F} = (\mathbf{J}^T)^{-1} \cdot (\mathbf{W}^T \sigma(\mathbf{V}^T \mathbf{x}) + \mathbf{K}_v \mathbf{e} + \mathbf{F}_v(\mathbf{e})), \quad (5)$$

where $\mathbf{K}_v$ - diagonal positive definite coefficient matrix, $\mathbf{x} = \left| \mathbf{q}_\mathbf{r}^T \quad \dot{\mathbf{q}}_\mathbf{r}^T \quad \ddot{\mathbf{q}}_\mathbf{r}^T \quad (\mathbf{q}_\mathbf{r}^T - \mathbf{q}^T) \quad (\dot{\mathbf{q}}_\mathbf{r}^T - \dot{\mathbf{q}}^T) \right|^T$ - entrance of neural network, $\mathbf{W}^T$ и $\mathbf{V}^T$ - matrices of neural network weights, whose values are calculated in a parallel adaptation loop based on the integration of differential equations [5]

$$\begin{cases} \dot{\mathbf{W}} = \mathbf{\Gamma}\sigma(\mathbf{V}^T\mathbf{x})\mathbf{e}^T - \mathbf{\Gamma}\sigma'(\mathbf{V}^T\mathbf{x})\mathbf{V}^T\mathbf{x}\mathbf{e}^T - k\mathbf{G}\|\mathbf{e}\|\mathbf{W} \\ \dot{\mathbf{V}} = \mathbf{G}\mathbf{x}(\sigma'(\mathbf{V}^T\mathbf{x})\mathbf{W}\mathbf{e})^T\mathbf{e}^T - k\mathbf{G}\|\mathbf{e}\|\mathbf{V} \end{cases}, \quad (6)$$

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where $\mathbf{G}, \mathbf{\Gamma}$ - positive definite matrices of the algorithm adjustment coefficients, k is the scalar adjustment coefficient, $\mathbf{e}$ - filtered control error, σ - sigmoid activation function, σ' - derivative of the activation function, calculated from expressions

$$\mathbf{e} = \Lambda(\dot{\mathbf{q}}_\mathbf{r} - \dot{\mathbf{q}}) + (\mathbf{q}_\mathbf{r} - \mathbf{q}), \sigma(z) = (1 - e^{-z})^{-1}, \sigma'(z) = \sigma(z)(1 - \sigma(z)), \tag{7}$$

$\ddot{\mathbf{q}}_\mathbf{r}, \dot{\mathbf{q}}_\mathbf{r}, \mathbf{q}_\mathbf{r}$ - speed, and positions in Cartesian coordinates obtained from the reference model based on the signal $\mathbf{q}_\mathrm{d}$ - desired trajectory, $\dot{\mathbf{q}}, \mathbf{q}$ - real velocities and positions in Cartesian coordinates, calculated on the basis of the solution of the direct kinematics problem [14-16] by measurements of positions and velocities of lengths of legs, Λ - diagonal positive-definite matrix of filter coefficients, $\mathbf{J}$ - the Jacobi matrix, whose calculation algorithm is described in detail in [16], $\mathbf{F}_v(\mathbf{e})$ - the robustness rule ensures the stability of the algorithm with a variation in the weights of the neural network and is found from expression

$$\mathbf{F}_v(\mathbf{e}) = \mathbf{K}_z(\|Z\|_F + \mathbf{Z}_m)\mathbf{e}, Z = \begin{vmatrix} \mathbf{W} & 0 \\ 0 & \mathbf{V} \end{vmatrix}, \tag{8}$$

where $\|Z\|_F$ - Frobenius norm from the block matrix Z, $\mathbf{K}_z$ - positive definite matrix of adjustment factors, $\mathbf{Z}_m$ - the maximum value of the Frobenius norm of unknown target weights for the matrix Z.

The procedure for synthesizing the adaptive algorithm consists in choosing the adjustment coefficients $\mathbf{K}_v$, Λ, k, $\mathbf{G}, \mathbf{\Gamma}$, $\mathbf{K}_z$ and $\mathbf{Z}_m$. We note that the pair of coefficients $\mathbf{K}_v$ and Λ determine the proportional-differential (PD) algorithm for controlling the hexapode, so it is rational to sequentially synthesize the parameters of the PD controller, and then adjust the coefficients of the adaptive neural network controller.

4. Hexapod Control System Model

To assess the quality of hexapode control in the SimMechanics mathematical simulation package of the MatlabSimulink system, a hexapod control system model was created, shown in Figure 4.

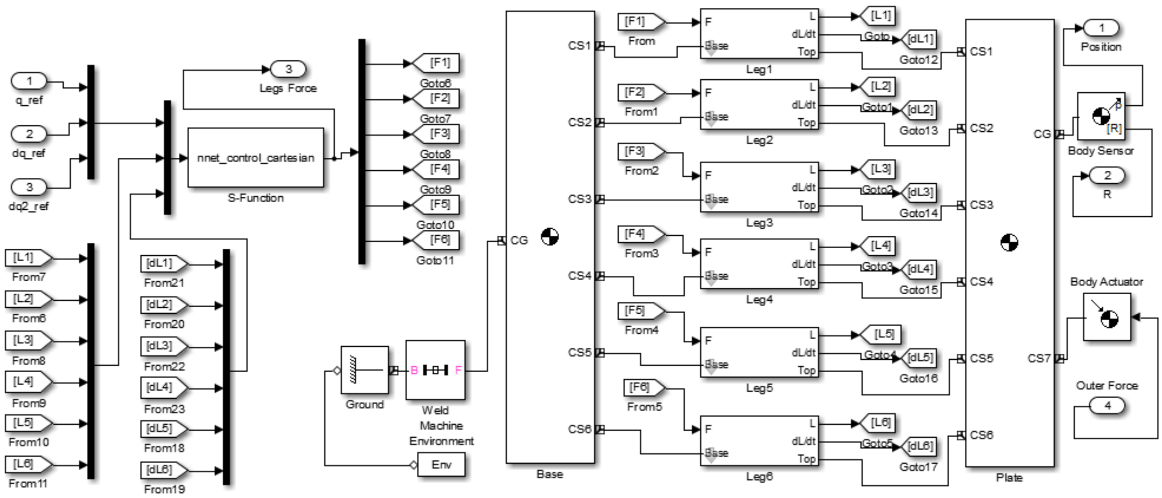

Figure 4. Hexapod control system model «Hexapod».

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The hexapod control is simulated under conditions of zero gravity. The hexapod control system generates leg efforts based on the regulator (5-8) implemented in the S-Function "nnet_control_cartesian". The input of the S-Function unit receives signals: set points, speeds, acceleration of leg lengths (q_ref, dq_ref, d2q_ref) and feedback signals - the position and speed of leg lengths. The reference signals in Cartesian coordinates are calculated from the desired desired position of the platform based on the solution of the task of planning the trajectories. The hexapod dynamics model consists of the following elements:

Base – a base, Plate – a platform, (Leg1-Leg6) – models of the dynamics of the hexapod legs, Machine Environment – general environment parameters of the simulation system (zero acceleration of free fall, accuracy of assembly of the mechanics model), Ground – the basis of the absolute frame of reference, Weld – base spike with an absolute coordinate system. The model allows you to calculate the positioning and orientation errors of the platform by the signal from the absolute position sensor BodySensor. On the input of the OuterForce, signals from external forces are applied to the center of mass of the platform. The hexapod's leg model, shown in figure figure5, corresponds to the kinematic structure [17] *RRPRR* - consists of two bodies of semi-stems BaseCylinder and PlateCylinder, connected by a cylindrical hinge of LegCylindrical, two-axis hinges of base and platform, represented by objects 2d jointbase и 2d jointplate respectively. Block JointSensor – element of the information system - generates in the model the signals of the linear position and speed of the drive, JointActuator transmits to the mechanics model the resulting force that determines the motion of the bodies in the linear actuator. The model takes into account the viscous frictional force, which depends linearly on the rate of change in leg length. The parameters of the mechanics of the hexapodshexapap for cosmic purposes are given: the mass of the platform with an inertia load of 100 kg, the main moments of inertia of the platform $J_{xx} = 4900\ \text{kg} \cdot m^2, J_{yy} = 4900\ \text{kg} \cdot m^2, J_{zz} = 6300\ \text{kg} \cdot m^2$.

The mass-inertial parameters of the legs are found from the solid hexapod model created in the SolidWorks environment [18].

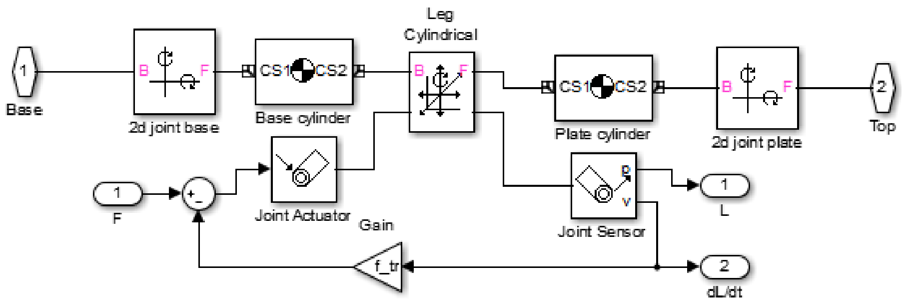

Figure5. The model of the hexapod leg «Leg».

5. Simulation of hexapod control

During the simulation of the hexapod control system, the parameters of the regulator PD were synthesized - the parameters of the matrices $\mathbf{K}_v$ and Λ. Synthesis was carried out in the mode of position control when input to the input of the planned trajectories generated in the reference model. After the synthesis procedure of the PD controller, the parameters of the artificial neural network are determined for the successful adaptation of the regulator. The influence of the number of neurons on the control error has been studied. On figure 6 a) the positional errors of working off the X coordinate in the test jump mode with constant dynamics parameters and the absence of external forces are shown.

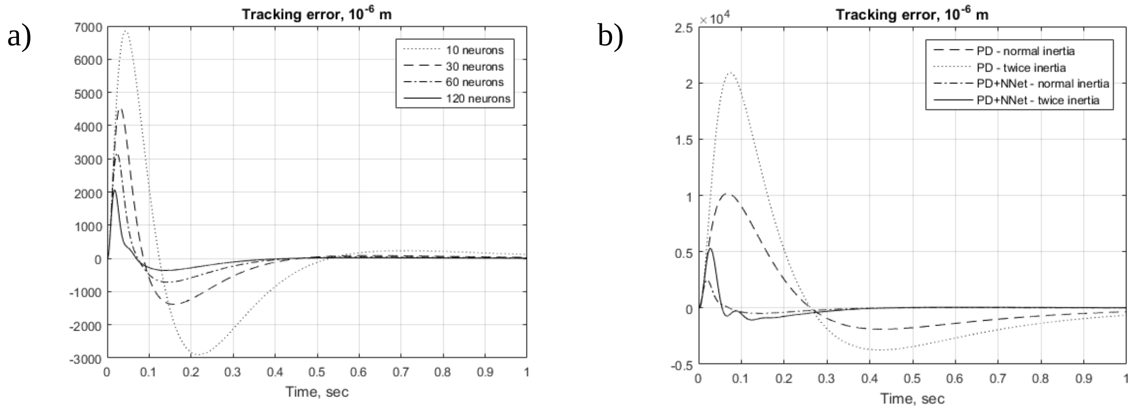

Figure 6. Control error: a) when neurons vary in the network, b) when the inertial parameters change.

The simulation results demonstrate a significant dependence of the quality of approximation on the number of neurons in the hidden layer: with an increase in the number of neurons, the error decreases. However, note that an excessive increase in the number of neurons leads to poor convergence of the adaptation contour, therefore, when evaluating the regulator under the conditions of parametric and functional uncertainties, we will take the number of neurons equal to 90. The influence of parametric uncertainty on the quality of control is also investigated. Figure 6 b) demonstrates the effect of a two-fold change in inertial parameters on the control error. Note that even with a two-fold change in parameters, the transient time for neural network control hardly changes.

To assess the quality of adaptation, comparative studies of synthesized PD and adaptive regulator with harmonic input action, double increase of mass inertial characteristics, as well as action of harmonic external forces on the platform

$$F_x(t) = F_0 \sin(\omega t), F_y(t) = F_0 \sin(2\omega t), F_z(t) = F_0 \sin(3\omega t), \quad (9)$$

where F_0 - amplitude, a ω - frequency of exposure. The simulation results are presented in Figure 7.

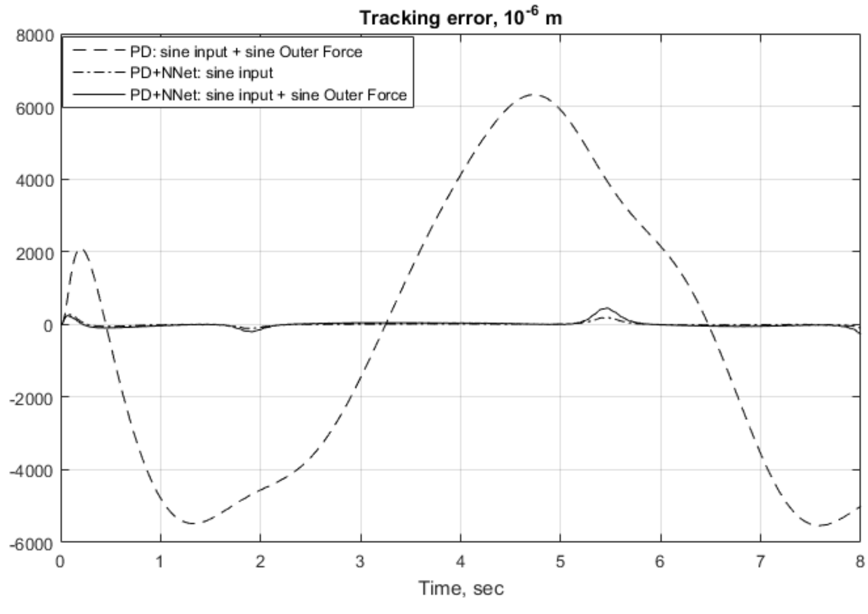

Figure7. Errors of positional control of a hexapode in a harmonic mode under the action of an external force.

Analysis of control errors shows that the adaptive neural network controller successfully copes with variations of the driving influences and external forces, improving the quality of hexapode control.

Conclusion

In the course of this work, Matlab-Simulink implements a hexapod control system model based on the adaptive neural network controller [5, 6]. Modeling of a hexapod control system with a workload under conditions of parametric and functional uncertainties is carried out. The performed investigations showed the efficiency of the regulator in the problem of contouring the hexapod. Adapting to the variable parameters and functional disturbances, the controller successfully parries the error, is easy to configure and robust. It does not require the calculation of the dynamics parameters of the control object. We note the simplicity of the structure of the artificial neural network of the regulator. The neural network has one layer, sigmoid activation functions, is adjusted during the control, allowing the initial state to use zero synaptic weights. To solve the problems of adaptation, there are 60 to 100 neurons. The errors of hexapod control are obtained, which demonstrate the advantages of the adaptive approach with respect to the proportional differential. The results of the research make it possible to give recommendations for the use of an adaptive neural network controller in control systems of mechanisms with parallel kinematics. In the future, it is planned to implement a regulator in the control system based on the domestic radiation-resistant microcontroller [3], as well as to solve the problems of automated tuning and synthesis of the parameters of the adaptive circuit.

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