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FORECASTING OF THE DISTRIBUTED CYBER-PHYSICAL SYSTEMS STATE

The important component for the solution of the problem of decentralized coordination of the distributed cyber-physical systems (DCPS) control is obtaining of the primary information, needed for searching the optimal control. Such information may be divided into conditional constant – the parameters of the controlled object, and variable – state of the controlled object. Determination of the object parameters is carried out by means of identification problem solution. Object persistence and correspondingly, the possibility of changing its elements state during the coordination cycle stipulates the need to forecast the processes in DCPS. In greater part of the research, dealing with the forecasting problem methods are considered where in this or that way expert assessments and conclusions are used. This concerns mainly social-economic processes, forecasts in the sphere of medicine, education, etc.

In the given study the forecasts for the cyber-physical systems are considered, although, in this case models of physical processes and formal methods of the forecasting play far more important role , however, at certain stages expert assessments are also used, in particular, regarding the ranges of possible change of the parameters, list of influencing factors, etc. The prediction method of the state of the distributed cyber-physical systems with the continuous objects on the base of space-time spectral approach to the prediction of DCPS state with continuous and discrete object states has been improved, study of the characteristic of DCPS state prediction has been performed. The possibility of the realization of the prediction method, using the machine learning and simulation modelling has been considered. The expediency of the prediction depth as with the increasing of the depth (interval) of the prediction the fuzziness of the prediction results increases. At the same time, computational resources and time are spent for the prediction. Gradually the situation arises, when the positive effect of the prediction becomes less than the expenses for its realization, this determines the expedient maximum depth of the prediction.

***Key words:** prediction, distributed systems**,** coordination.*

Introduction

Problem of the prediction of various processes has long history, numerous methods and examples of the solution of different problems. Greater part of these examples are devoted to the problems of nontechnical character, mainly social-economic and political.

The paper [1] contains the classification and characteristics of the prediction problems, shown in Table 1.

Table 1

Classification of the prediction objects

Nature	Scalability	Complexity	Determination	Trend	Information provision
Technical	Sublocal	Ultrasimple	Determined	Discrete	Total amount
Technical-economic	Local	Simple	Stochastic	Aperiodic	Incomplete amount
Social-economic	Subglobal	Complex	Mixed	Cyclic	Qualitative
Military-political	Global	Supercomplex	Fuzzy	Complex, close to helical	Lack of information
Natural	Superglobal	Complex	Stochastic	Cyclic	Incomplete amount

This classification represents rather simplified approach to technical prediction. In particular, from the point of view of scalability the tasks of processes prediction in the distributed technical systems of different scales up to such global as the Internet are not taken into account.

Considering the objects of prediction from the point of view of the complexity, it should be taken into consideration the definition of the complex system according to L. A. Rastrygin [2]: complex system is a system where the synergetic effects are observed, i. e., the system, consisting of a set of the interacting components (subsystems), as a result, the system obtains new properties, not available at the subsystem level. There exist numerous similar technical systems, namely neural networks.

Determinacy of the processes is not a characteristic feature of technical systems. Availability of various random disturbing impacts on the system as well as nondeterministic behavior of people, interacting with technical facilities of the automated systems lead to nondeterministic and sometimes chaotic processes. In its turn, non-determinacy combined with non- linearity of numerous technical objects results in synergetic effects and complex trends.

Information provision very seldom is complete. To a large extent this concerns the distributed dynamic systems, their complete control requires huge expenses and is practically impossible.

As far back as at the beginning of the last century the outstanding economist A. Bazarov-Rudnev [3] distinguished three methods of prediction: extrapolation, analytical model, expert evaluation. Nowadays in the sphere of technical systems control more than 200 modifications and combinations of these methods of prediction are used in various branches of human activity.

The correct approach to the prediction comprises several stages:

- detailed study of the natured of the investigated object or process in order to select the adequate prediction method;
- allocation of two groups among the available data – for the development of the forecasts and for the verification of the obtained results;
- updating of the output data to reveal the mistakes;
- elaboration of the predictions and assessment the validity of the obtained results;
- usage (interpretation) of the obtained results and execution, if necessary, the updating and supplementing the predictions.

Numerous methods of prediction are based either on the usage of the expert assessments or on the modeling or on the combination of these methods [4, 5, 6].

In greater part of studies, devoted to the problems of prediction, methods where the expert assessments are used in one way or another, are considered. This concerns mainly social-economic processes and predictions in the sphere of medicine, education.

Problem set up

Separate type of the prediction problems, requiring additional studies is the prediction of the state of the distributed cyber-physical systems with continuous technological objects. In such systems, several types of the communication between the components of DCPS, influencing the result of the prediction are observed: physical interaction of the separate zones of the continuous distributed technological object (DTO), energy and information interaction between local control systems (LCS) and controlled elements in DTO zones, information interaction between LCS coordinators [7].

Technique of the distributed object state prediction and the algorithm of the proactive coordination depends on spatial-time characteristics of the impacts on the object. Proceeding from the spatial distribution of the impact three main types will be distinguished:

– Point impact;
– Zonal impact;
– Spatial-continuous impact.

Greater part of the objects simultaneously are subjected to several impacts with different spatial distributions. These impacts change dynamic processes in the distributed object. Generalized structure of the proactive coordination control over the distributed cyber-physical object is shown in

Fig. 1. Local control system (LCS) controls the state v of the distributed object element, providing it with the stream of the resource p_0. Task v_0 arrives from the coordinator, which searches the optimal control according to the set criterion. Predictor forecasts the element state change at certain control, i. e., the system coordinator-predictor function as the reference model of the system.

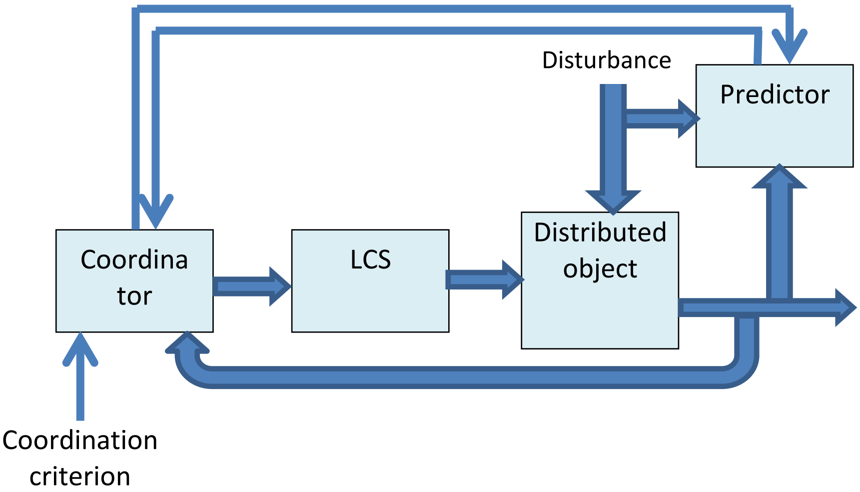

Fig. 1. Scheme of the coordination with the predictor

However, not only LCS influences the state of the object element but also the neighboring elements, external environment and the resource expenditures, accumulated in the controlled zone of the object, on the production, which depend on the volume of production, determined by the amount of the raw material x and state v.

Hence, dynamic processes in the distributed object with the resource control are considered as the interaction of three fields:

– Field of the object parameters $\mathbf{V}(\mathbf{Z},t)$, where $\mathbf{V}=\{v_i\}$ – is the vector of states; v_i – is the state of the i th element of the object; $\mathbf{Z}_i=\{z_{ik}\}$ – is the vector of coordinates of the i th element of the object;

– Field of the controlling impacts $\mathbf{p_0}(\mathbf{Z},t)$;

– Field of disturbances $\mathbf{u}(\mathbf{Z},t)$;

– Stream of the raw material $\mathbf{X}(\mathbf{Z},t)$.

Aim of the research is the elaboration of the approach to the prediction of the states field change under the impact of the disturbance field and the stream of the raw materials. The source of LCS resource remains unlimited.

Results obtained

In [8] the model of the distributed continuous object element was elaborated. Fig. 2 shows the impacts on the object element.

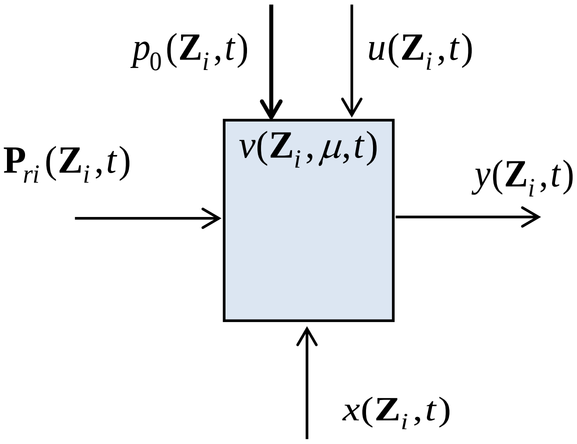

Fig. 2. Element of the object of cyber-physical system

Models of the dependence of resource expenditures for the production on the state of the element (reverse production function of the element) and the system of the element state equations in differential form are presented in [8]:

$$\begin{cases} dv_i = \left(K \left(p_{0i} + \sum_{j=1}^{n_\varepsilon} p_{ji} \right) - \Delta v_i \right) dt, \\ \mathbf{P}_{ri}(\mathbf{Z}_i,t) = \sum_{j=1}^{n_\varepsilon} p_{ji} \\ y_i = w(v_i,\Delta v_i) \\ \Delta v_i = \dfrac{\mu(v_i)x_i}{\eta} \end{cases} \tag{1}$$

where μ – are the specific expenditures of the resource per unit of the raw material x; $\mathbf{P}_r = \{p_{ji}\}$ – is the matrix of the streams of the resources between the elements of DTO; K – is the coefficient of the resource capacity(characterizes the value of the object state change per unit of the arrived resource); η – is the efficiency factor; n_ε – is the number of DTO elements in ε-region of the i th element, impact of which on its state is substantial [8].

The simplest case $\mu(v) = const$ will be considered. Then, with (1), integrating on the surface of the ε- region with the center in $\mathbf{Z}_i$, we obtain

$$v(\mathbf{Z}_i,t) = v(\mathbf{Z}_i,0) + \eta \int_0^t \left[p_0(\mathbf{Z}_i,t) + u(\mathbf{Z}_i,t) + \iint_{S/\varepsilon(\mathbf{Z}_i)} \{\mathbf{P}_r(\mathbf{Z}_i,t) \times \mathbf{1}\} d[s(\mathbf{Z})] - \mu x \right] dt \, . \tag{2}$$

Integral on the surface gives the averaged value of the stream of the resource exchange between the considered element and other elements of the distributed object.

For infinitely small element of the continuous object it can be written

$$v(\mathbf{Z}_i,t)=v(\mathbf{Z}_i,0)+\eta\int_0^t\left[p_0(\mathbf{Z}_i,t)+u(\mathbf{Z}_i,t)+\operatorname{div}\left[\mathbf{p}_r(\mathbf{Z}_i,t)\right]-\mu x\right]dt .$$

Value of the resource stream between two elements with the coordinates $(\mathbf{Z}_i,\mathbf{Z}_\mathbf{j})$ [8]

$$p_j(\mathbf{Z}_i,\mathbf{Z}_\mathbf{j},\tau_{0j})=\gamma\left(\mathbf{Z}_i-\mathbf{Z}_\mathbf{j}\right)\left[v(\mathbf{Z}_i)-v(\mathbf{Z}_\mathbf{j})\right]. \tag{3}$$

where

$$\gamma\left(\mathbf{Z}_i-\mathbf{Z}_\mathbf{j}\right)=\frac{1}{8\left(\pi\lambda\tau_{0j}\right)^{3/2}}e^{-\frac{\left|\mathbf{Z}_i-\mathbf{Z}_\mathbf{j}\right|^2}{4\lambda\tau_{0j}}}$$

At each point of the distributed object the flow of the overstreaming

$$\operatorname{div}p_r(\mathbf{Z}_i)=\iint\limits_{S/\varepsilon(\mathbf{Z}_i)}\gamma\left(\mathbf{Z}_i-\mathbf{Z}_\mathbf{j}\right)\left[v(\mathbf{Z}_i)-v(\mathbf{Z}_\mathbf{j})\right]dz_1dz_2 . \tag{4}$$

As the prediction is carried out on the base of the data, obtained from the discrete sensors, discrete form of the equation is more convenient (4). In linear objects the flows are additive, thus

$$P_r(\mathbf{Z}_i)=\sum_{j:\mathbf{Z}_\mathbf{j}\in\varepsilon(\mathbf{Z}_i)}\gamma\left(\mathbf{Z}_i-\mathbf{Z}_\mathbf{j}\right)\left[v(\mathbf{Z}_i)-v(\mathbf{Z}_\mathbf{j})\right]. \tag{5}$$

Equivalent structural diagram of the element is shown in Fig. 3.

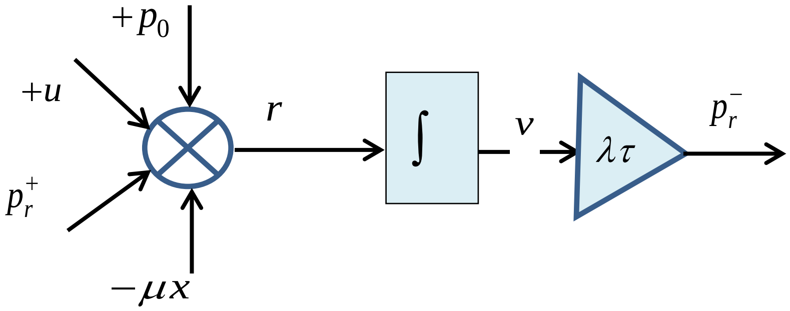

Fig. 3. Equivalent structural diagram of the element

Prediction of DTO elements state is performed in fuzzy conditions. Fuzziness of the element state is stipulated by the following factors:

– Fuzziness of the external environment impact;
– Fuzziness of the surrounding elements state, which influence the considered element;
– Fuzziness of the parameters of the impact distribution environment;
– Fuzziness of the vectors of the production program $\mathbf{X}$ and specific expenditures $\mathbf{M}$.

Impact of the external environment and surrounding elements is performed by means of the resource flow. Dispersion of the object element state will be evaluated

$$\sigma_v^2(\mathbf{Z}_i,t)=\sigma_{v(\mathbf{Z}_i,0)}^2+\int_0^\infty\int_0^\infty G_{rr}\left(\omega,\mathbf{\Psi}\right)e^{i\mathbf{\Psi}Z_i}d\mathbf{\Psi}d\omega , \tag{6}$$

where G_{rr} – is a autospectral density of the resource arriving/spent by the elements.

Taking into account the fact that in linear objects spectral densities of power are adaptive with the account of mutual correlation the balance of spectral densities of the element resource will be written

$$\left\{\begin{aligned}
&G_{p_0 v_0}(\omega,\mathbf{\Psi}) = G_{v_0 v_0}(\omega,\mathbf{\Psi})\cdot W_{v_0 p_0}(\omega)\\
&G_{rr}(\omega,\mathbf{\Psi}) = G_{p_0 v_0}(\omega,\mathbf{\Psi}) + G_{uu}(\omega,\mathbf{\Psi}) + G_{xx}(\omega,\mathbf{\Psi}) + \sum_{r\in\varepsilon} G_{p_r p_r} +\\
&\qquad + 2G_{p_0 u}(\omega,\mathbf{\Psi}) + 2G_{p_0 x}(\omega,\mathbf{\Psi}) + 2\sum_{r\in\varepsilon} G_{p_0 p_r}(\omega,\mathbf{\Psi}) -\\
&\qquad - 2G_{ux}(\omega,\mathbf{\Psi}) + 2\sum_{r\in\varepsilon} G_{up_r}(\omega,\mathbf{\Psi}) - 2\sum_{r\in\varepsilon} G_{p_r x}(\omega,\mathbf{\Psi})\\
&G_{vv}(\omega,\mathbf{\Psi}) = G_{rr}(\omega,\mathbf{\Psi})\cdot\left(\frac{1}{T\omega}\right)^2\\
&G_{p_r p_r}(\omega,\mathbf{\Psi}) = \int_0^\infty \left\{ \iiint_\Omega \left[R_{p_r p_r}(\tau,\mathbf{Z}) e^{-j\mathbf{\Psi}\mathbf{Z}} \right] e^{-j\omega\tau} d\mathbf{Z} \right\} d\tau
\end{aligned}\right. \tag{7}$$

where ω – is temporal circular frequency; $\mathbf{\Psi}$ – is the vector of spatial circular frequences; G_{rr} – is autospectral density of the power of the general input resource; $G_{p_0 p_0}$ – is autospectral density of the control impact (external resource) power; G_{uu} – is autospectral density of the disturbances power; G_{vv} – is the autospectral density of the state power(accumulated resource); G_{xx} --is the autospectral density of the resource usage and/or resource dissipation ; $G_{p_{r_0} p_{r_0}}$ – is autospectral density of the input resource with the account of the propagation; G_{ux} – is mutual spectral density of the disturbance power and raw material.

Impact of the external environment and the raw material expenditures for the production may be considered as independent, thus $G_{ux} = 0$.

Mutual spectral density of the control impact power and input resource, arriving from the neighbouring elements $G_{p_0 p_r}$ is determined by the algorithm and parameters of the coordinator and LCS. In the simplest case the coordinator calculates the impact by the formula:

$$v_0 = \left(\mu x - \sum_{r\in\varepsilon(\mathbf{Z}_i)} p_r - ku \right)\cdot\left| W_{v_0 p_0}^{-1} \right|, \tag{8}$$

where $p_r = p_r^+ - p_r^-$; in brackets – the balance of the resource flows at the input of the element; $W_{v_0 p_0}$ – is transfer function of the element state regulator (v_0 – its input, p_0 – output), $k = \dfrac{W_0 W_{ЛСУ}}{1 + W_0 W_{ЛСУ}}$ – is the coefficient of the external environment impact weakening by the impact of LCS, after that the optimization problem is solved. The coordinator calculates p_r on the base of (5). As the algorithm contains a great number of factors, influencing the result, this leads to the decrease of the mutual pair correlation, thus we can assume that $G_{v_0p_r}\approx 0$. Similarly $G_{p_rx}\approx 0$ and $G_{up_r}\approx 0$.

As the optimal value of the input resource is set by the coordinator, which takes into account the impact of the external environment and LCS, to find G_{v_0u}, we multiply (8) by v_0, average and perform Fourrier transform. We obtain:

$$G_{v_0v_0}(\omega,\mathbf{Z}_i)=\left[\mu G_{v_0x}(\omega,\mathbf{Z}_i)-kG_{v_0u}(\omega,\mathbf{Z}_i)\right]\cdot W^{-1}_{v_0p_0}(\omega), \qquad (9)$$

where

$$G_{v_0u}(\omega,\mathbf{Z}_i)=\frac{\mu}{k}G_{v_0x}(\omega,\mathbf{Z}_i)-\frac{W_{v_0p_0}(\omega)}{k}G_{v_0v_0}(\omega,\mathbf{Z}_i). \qquad (10)$$

For the determination G_{p_0x} we will proceed from the assumption that the greater the disturbing impact of the neighbouring elementss and the surrounding environment , the greater is the deviation of the p_0 value from the nominal v_0. It is obvious that at $\underset{\mathbf{Z}}{\forall}v(\mathbf{Z})=v_0=u$ the flows of the resource streaming will miss. For obtaining the temporal dependence $R_{p_0x}\left(\tau,Z_i\right)$ the structural diagram at the local coordination will be considered (Fig. 4).

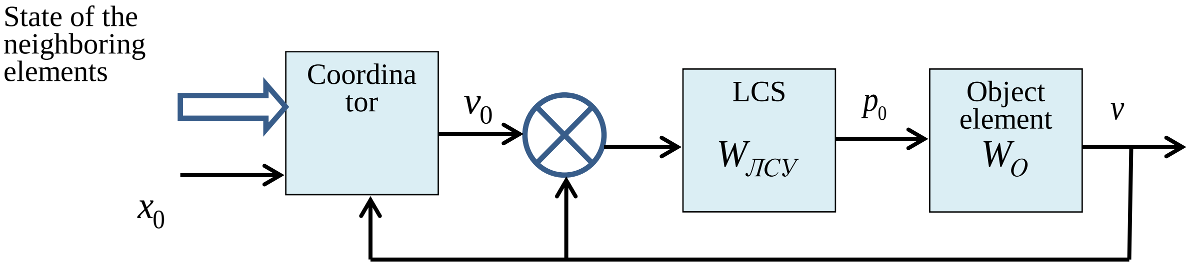

Fig. 4. Diagram of local coordination

Transfer function $x_0\overset{W}{\rightarrow}v_0$

$$W_{x_0\to v_0}(p)=\frac{W_K}{1+W_K\dfrac{W_{ЛСУ}W_0}{1+W_{ЛСУ}W_0}}=\frac{W_K\left(1+W_{ЛСУ}W_0\right)}{1+W_{ЛСУ}W_0+W_KW_{ЛСУ}W_0}.$$

It is assumed that the coordinator and LCS are the aperiodic elements with time constants T_K and $T_{ЛСУ}$, correspondingly. We obtain:

$$W_{x_0\to v_0}(p)=\frac{\dfrac{1}{1+T_Kp}\left(1+\dfrac{1}{1+T_{ЛСУ}p}\cdot\dfrac{1}{T_0p}\right)}{1+\dfrac{1}{1+T_{ЛСУ}p}\cdot\dfrac{1}{T_0p}+\dfrac{1}{1+T_Kp}\cdot\dfrac{1}{1+T_{ЛСУ}p}\cdot\dfrac{1}{T_0p}}=$$

$$=\frac{T_{ЛСУ}pT_0p+T_0p+1}{(1+T_Kp)(1+T_{ЛСУ}p)T_0p+(1+T_Kp)+1},$$

frequency transfer function is

$$W_{x_0\to v_0}(j\omega)=\frac{1-T_{ЛСУ}T_0\omega^2+T_0 j\omega}{(1+T_K j\omega)(1+T_{ЛСУ} j\omega)T_0 j\omega+(1+T_K j\omega)+1}. \tag{11}$$

Spectral densities of power are connected by the relation

$$G_{p_0x}(\omega,Z_0)=G_{xx}(\omega,Z_0)\cdot W_{x_0\to p_0}(j\omega)=$$
$$=G_{xx}(\omega,Z_0)\cdot\frac{1-T_{ЛСУ}T_0\omega^2+T_0 j\omega}{(1+T_K j\omega)(1+T_{ЛСУ} j\omega)T_0 j\omega+(1+T_K j\omega)+1} \tag{12}$$

Spatial component of the spectral densities is determined by geometrical characteristics of the distributed object and location of the points of the control impact application. Impact of the external disturbance can be considered to be the white noise in time, its amplitude is maximal at the boundaries of the object and exponentially falls at the distance from the boundary.

The results of modeling the coordination process presented in Fig. 5, show that the spatial disturbance of the resource is the sum of exponentially falling functions with the modes in the points of the impact application. That is:

$$G_{uu}(\omega,\Psi)=G_{uu}(\omega,\Psi\notin S)\cdot e^{-\frac{1}{4\lambda\tau}\left[\min\limits_{\forall\Psi_\Omega}(\Psi_\Omega-\Psi)\right]}=g_u e^{-\frac{1}{4\lambda\tau}\left[\min\limits_{\forall\Psi_\Omega}(\Psi_\Omega-\Psi)\right]}, \tag{13}$$

where Ω – is the boundary of the distributed object (region S); g_u – is the amplitude of the external noise;

$$G_{v_0v_0}(\omega,\Psi)=\sum_i G_{v_0v_0}(\omega,\Psi_{0i})\cdot e^{-\frac{1}{4\lambda\tau}(\Psi_{0i}-\Psi)}, \tag{14}$$

where Ψ_{0i} – is the vector of the coordinates of the i th point of the control impact application.

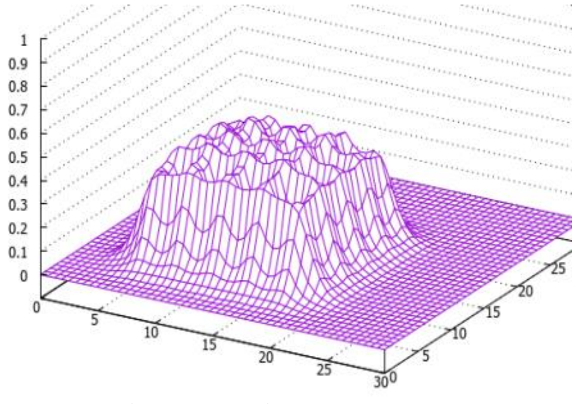

Fig. 5. Result of modeling of DCPS coordination process

In stationary mode of the distributed object usage the production task does not change in time, thus $G_{xx}(\omega,\Psi)=G_{xx}(\omega=0,\Psi)$.

Spatial-temporal correlation function of the state is found. Proceeding from Wiener-Khinchin theorem we will write:

$$K_{vv}(\tau,\mathbf{Z})=2\int_0^\infty\int_0^\infty G_{vv}(\omega,\Psi)\cdot e^{i\omega\tau}\cdot e^{i\mathbf{\Psi Z}}d\omega d\Psi. \tag{15}$$

Similarly, other spectral densities of the model power are transformed into correlation functions

(7).

Diagram of the regression prediction can be presented in the form of the tree in Fig. 6. Taking into account the linearity of the elements state dependence on the influencing factors in the model (1), as well as correlation dependence between the amount of the raw material x and control impact p_0 (12), the predicted value of the i^{th} element state in time interval τ will be written in the form of the equation of the multifactoral regression on the independent factors.

$$
\begin{aligned}
v(\tau,\mathbf{Z}_i) = {} & v(0,\mathbf{Z}_i) + K_{vu}(\tau,\mathbf{Z}_i)\sqrt{\frac{K_{vv}(0,\mathbf{Z}_i)}{K_{uu}(0,\mathbf{Z}_i)}}\left[u(0,\mathbf{Z}_i) - m_u(\mathbf{Z}_i)\right] + \\
& + K_{vx}(\tau,\mathbf{Z}_i)\sqrt{\frac{K_{vv}(0,\mathbf{Z}_i)}{K_{xx}(0,\mathbf{Z}_i)}}\left[x(0,\mathbf{Z}_i) - m_x(\mathbf{Z}_i)\right] + \\
& + \sum_{j\in\varepsilon(\mathbf{Z}_i)} \gamma(\mathbf{Z}_i - \mathbf{Z}_{\mathbf{j}}) K_{vu}(\tau+\tau_{0j},\mathbf{Z}_j)\sqrt{\frac{K_{vv}(0,\mathbf{Z}_j)}{K_{uu}(0,\mathbf{Z}_j)}}\left[u(\tau-\tau_{0j},\mathbf{Z}_j) - m_u(\mathbf{Z}_j)\right] + \\
& + \sum_{j\in\varepsilon(\mathbf{Z}_i)} \gamma(\mathbf{Z}_i - \mathbf{Z}_{\mathbf{j}}) K_{vx}(\tau+\tau_{0j},\mathbf{Z}_j)\sqrt{\frac{K_{vv}(0,\mathbf{Z}_j)}{K_{xx}(0,\mathbf{Z}_j)}}\left[x(\tau-\tau_{0j},\mathbf{Z}_j) - m_x(\mathbf{Z}_j)\right]
\end{aligned}
$$

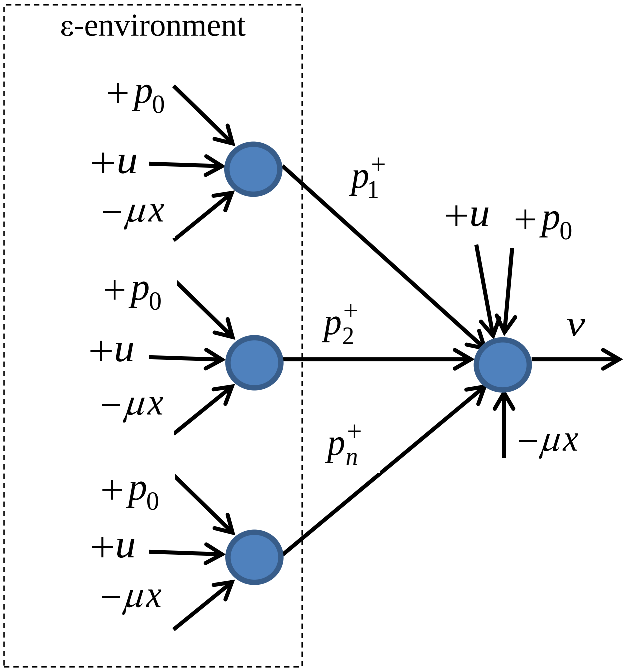

Fig. 6. Structural-logic diagram of DCPS element state prediction

Prediction of DPCS state by the suggested spatial-temporal method was studied at the model in the environment Scilab. DCPS with four lineally located controlled elements was modeled. The prediction was performed for the element $i = 2$, in the environment of which elements $i = 1$ and $i = 3$ are present. Also there is a remote element $i = 4$. External impact $u(t)$ – is common for all the elements. Graphs of the model processes are shown in Fig. 7: 1 – is the change of the external environment state $u(t)$; 2 – change of the raw material input, for its recycling the resource is spent, for the element $i=1$; 3 – change of the raw material input for the element $i=3$; 4 – change of the raw material input for element $i=4$; 5 – change of the raw material input for the element $i=2$; 6 – state of the element $i=2$; 7 – prediction of the element $i=2$ state; 8 – error of the prediction.

Modeling showed that for DCPS of the given structure RMSE=14 %, it is accepted for the usage of the prediction results for the purposes of the coordination control.

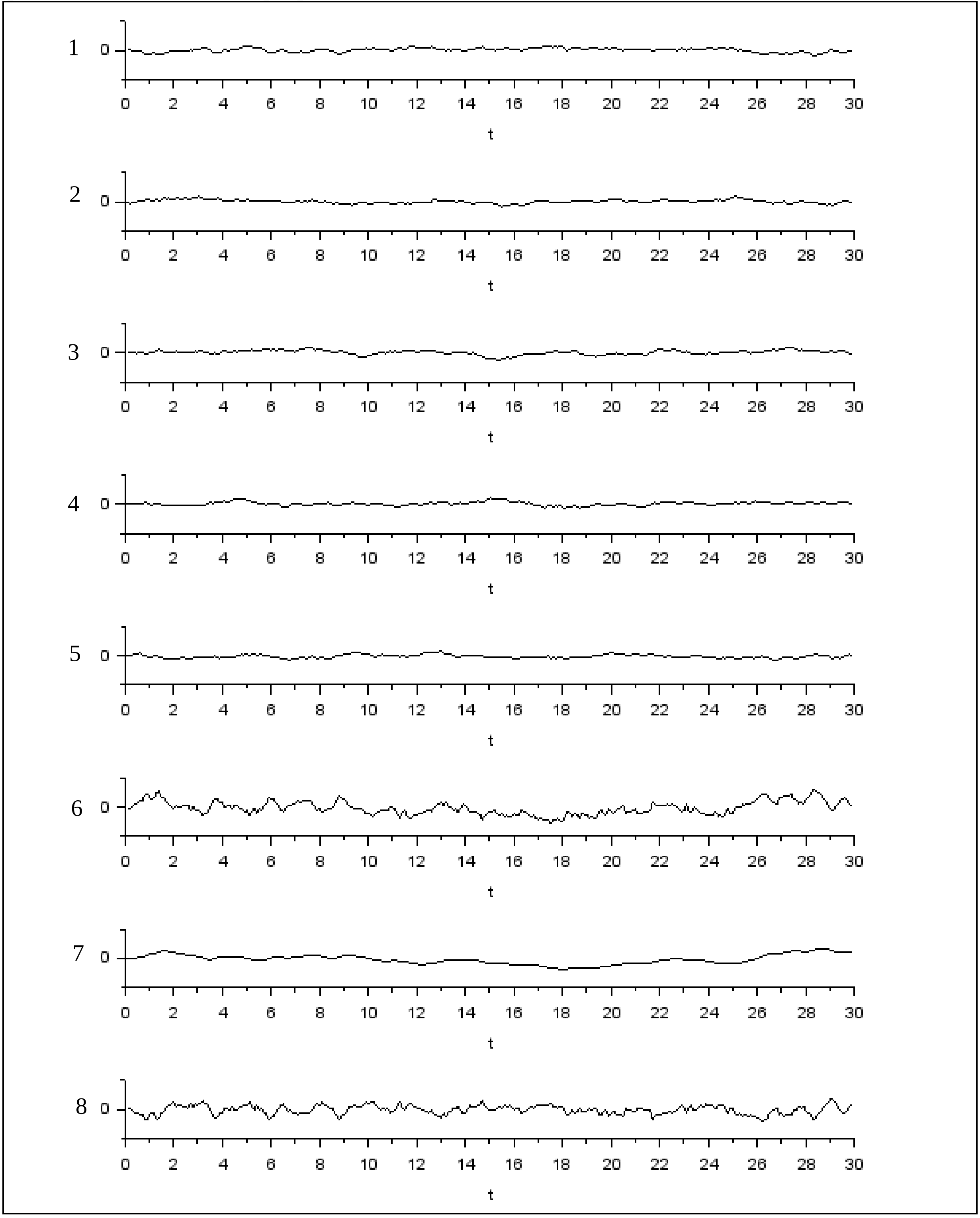

Fig. 7. Results of the predictor operation modeling

Conclusions

Method of the prediction of the distributed cyber-physical systems with the continuous objects state has been improved in the research, the given method is based on the model of DCPS with the continuous production object and resource control of the state in spacial-time spectrum of states and disturbances, which enables to optimize the control coordination at the interval of the impacts correlation. Characteristic feature of the method is the account of not only the temporal but also spacial spectral density of the object states power and impacts. The method has been realized in Scilab environment. Modeling of the system of four controlled elements showed that the prediction provides RMSE=14 %, that is acceptable for using the results of the prediction for the purposes of the coordination control.

REFERENCES

1. Timofeeva N. M. Recommendations on the technological predictions / N. M. Timofeeva. – M. : Academy of the predictions, 2003. – 257 p. (Rus).
2. Rastrigin L. A. Adaptation of the complex systems / L. A. Rastrigin. – Riga : Zinatne, 1981. – 375 p. (Rus).
3. Bazarov V. A. Capitalist cycles and reconstruction process of the economy in the USSR / V. A. Bazarov. – Planning economy, 1927. – 189 p. (Rus).
4. Analysis of the peculiarities of the application and classification of the prediction methods in the sphere of the networks development and telecommunication technologies / D. O. Peregudov, O. V. Selukov, V. V. Krukhta [et al.] // Bulletin of State University of Information and Communication Technologies (SUICT). – 2009. – № 7 (1). – P. 27 – 40. (Ukr).
5. Ivakhnenko A. G. Long-term forecasting and complex systems control / A. G. Ivakhnenko. – Kyiv : Telhnika, 1975. – 312 p. (Rus).
6. Theoretical-methodological aspects of social-political prediction studies [Electronic resource] / S. I. Vyrovyi, N. P. Diachenko // Actual problems of state management. – 2013. – № 2. – P. 138 – 143. – Access mode : http://nbuv.gov.ua/UJRN/apdy_2013_2_20. (Ukr).
7. Dubovoyi V. M. Study of the durability and convergence of the decentralized coordination of local control systems of the distributed cyber-physical systems / V. M. Dubovoyi, M. S. Yukhymchuk // Bulletin of Vinnytsia Polytechnic Institute. – 2021. – Issue 4, Series 2021. – P. 62 – 69. doi: 10.31649/1997-9266-2021-157-4-62-69. (Ukr).
8. Dubovoyi V. M. Decentralized coordinative control of the distributed cyber-physical systems with continuous objects : [monograph] / V. M. Dubovoyi, M. S. Yukhymchuk. – Vinnytsia : VNTU, 2022. – 230 p. (Ukr).

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