ПРОБЛЕМИ ПРИЙНЯТТЯ РІШЕНЬ ТА УПРАВЛІННЯ В ЕКОНОМІЧНИХ, ТЕХНІЧНИХ, ЕКОЛОГІЧНИХ І СОЦІАЛЬНИХ СИСТЕМАХ

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COMBINED CONTROL OF MULTIRATE IMPULSE PROCESSES IN A COGNITIVE MAP OF COVID-19 MORBIDITY

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Abstract. In this article, a cognitive map (CM) of COVID-19 morbidity in a given region was built. A general linear impulse process (IP) model in the CM was developed and measured, and unmeasured CM node coordinates were defined. The general IP model was decomposed into interrelated subsystems with measurable and unmeasurable node coordinates. For the subsystem with measurable node coordinates, multirate sampling of coordinates was conducted, resulting in the development of discrete dynamics models for quickly and slowly measured node coordinates. External controls were selected in IP models based on the possible variation of resources of node coordinates and CM weighting coefficients. IP control laws based on the variation of CM nodes and weight were designed. As a result, recurrent procedures for control generation in closed-loop control subsystems with multirate sampling were formulated. Experimental research on the control subsystems was carried out. It confirmed high efficiency for decreasing COVID-19 morbidity.

Keywords: cognitive map, impulse processes, control law, optimality criterion, COVID-19.

INTRODUCTION

In the given article, cognitive modeling is applied to the research of dynamic processes of coronavirus morbidity. Cognitive modeling is based on the notion of a cognitive map (CM) which is defined as a weighted oriented graph with nodes representing coordinates (concepts, factors, characteristics) of a complex system and weighted edges (arcs) describing cause and effect interrelations between CM nodes. CM is built by experts. It allows qualitative description of interrelations between complex system's components and quantitative assessment of the effect of each CM node on all others, using edges of the oriented graph.

During evolution of a complex system with impulse-type behavior CM coordinates evolve with time under the effect of different disturbances. Each coordinate takes value $z_i(k)$ at discrete time moments $k = 0,1,2,...$ At the next sampling period the value $z_i(k+1)$ is determined by the value $z_i(k)$ and information about increase or decrease of values of other nodes adjacent to given i-th node, at time moment k. Change of any j-th node at time moment k is called "impulse" and according to [1] is denoted by $P_j(k)$ and is given as a difference

$P_j(k) = z_j(k) - z_j(k-1),\ \ k > 0$. Impulse $P_j(k)$ incoming to the j-th node will propagate over the paths of the CM to other nodes while increasing or decreasing. Propagation process of disturbances in the CM is defined by the difference equation [1]

$$z_i(k+1) = z_i(k) + \sum_{j=1}^{n} a_{ij} P_j(k), \quad i = 1,...,n, \tag{1}$$

where a_{ij} is a weight of an oriented graph's edge connecting the j-th node with the i-th one. If an edge connecting i-th and j-th nodes is absent, respective coefficient $a_{ij} = 0$.

CM nodes coordinates propagation rule (1) is often written as a first-order difference euqatin in variables increments

$$\Delta z_i(k+1) = \sum_{j=1}^{n} a_{ij} \Delta z_j(k), \tag{2}$$

which describes CM IP. Here $\Delta z_i(k) = z_i(k) - z_i(k-1),\ i = 1,2,...,n.$ In a vector form equation (2) is written as follows

$$\Delta\overline{Z}(k+1) = A\Delta\overline{Z}(k), \tag{3}$$

where A is a transposed adjacency matrix of the CM, $\Delta\overline{Z}(k)$ is a vector of increments of coordinates z_i of CM nodes, $i = 1,2,...,n$. From the control theory perspective the model (3) describes dynamics of linear multivariate system in discrete time under free motion of CM nodes.

Not all CM nodes are measurable in different complex systems. E.g., it is impossible to accurately measure level of a population health, level of democracy in a society, level of corruption and shadow economy, level of political activity etc. To solve this problem, [2] suggests to decompose the initial CM model (2), (3) into two interrelated CM. So, n CM nodes coordinates z_i are broken down into p measurable nodes x_i $(i = 1,...,p)$ and $(n-p)$ unmeasurable nodes y_l, $l = p+1,...,n$. Then IP model (3) can be presented as two interrelated subsystems of IP:

$$\Delta\overline{X}(k+1) = A_{11}\Delta\overline{X}(k) + A_{12}\Delta\overline{Y}(k)\,; \tag{4}$$

$$\Delta\overline{Y}(k+1) = A_{21}\Delta\overline{Y}(k) + A_{22}\Delta\overline{X}(k)\,, \tag{5}$$

where $\overline{X}$ is a vector of measurable CM nodes, $\overline{Y}$ is a vector of unmeasurable nodes. Here matrices of weights A_{12}, A_{22} represent interrelations between the first (4) and the second (5) parts of the initial CM (3).

In [3] the problem of control automation for CM IP is solved by means of varying CM nodes coordinates and weights with unirate sampling, where controls are designed in a closed-loop control system. For this purpose equation (4) with measurable coordinates is used, augmented by controls as follows:

$$\Delta\overline{X}(k+1) = A_{11}\Delta\overline{X}(k) + A_{12}\Delta\overline{Y}(k) + B\Delta\overline{u}(k) + L(k)\Delta\overline{a}(k),$$

where $\Delta\overline{u}(k) = \overline{u}(k) - \overline{u}(k-1)$ is the first difference of an external control vector formed by means of varying resources of CM nodes coordinates,

$\Delta\overline{a}(k)=\overline{a}(k)-\overline{a}(k-1)$ is the first difference of a control vector based on varying the degree of influence $a_{ij}(k)$ of the coordinate $\Delta x_j(k)$ on the coordinate $\Delta x_i(k)$. The rules for writing matrices B and $L(k)$ are described in [3, 4]. Applying variations $\Delta\overline{u}(k)$ and $\Delta\overline{a}(k)$ as control inputs is necessary when dimensions $\dim\Delta\overline{u}(k)$ or $\dim\Delta\overline{a}(k)$ are much less than number of nodes $\dim\Delta\overline{X}(k)$. In such a case using only one group of controls significantly decreases accuracy and speed of control systems for CM IP.

Among the coordinates of the vector $\overline{X}$ in the model (4) there can be some coordinates $\overline{X}_f$ measured (fixed) with a small sampling period T_0 and some coordinates $\overline{X}_s$ measured with a big sampling period $h=mT_0$ where m is integer greater than 1. To describe dynamics of such a system a model of an IP with multirate sampling was developed in [5].

CONSTRUCTION OF A COVID-19 MORBIDITY CM

Fig. 1 shows a CM of cause-and-effect relations in the process of spread of COVID-19 morbidity in a given region. The following nodes are included into the CM: 1 – number of daily revealed infected patients; 2 – number of daily vaccinated people; 3 – number of patients dying daily of COVID-19; 4 – number of

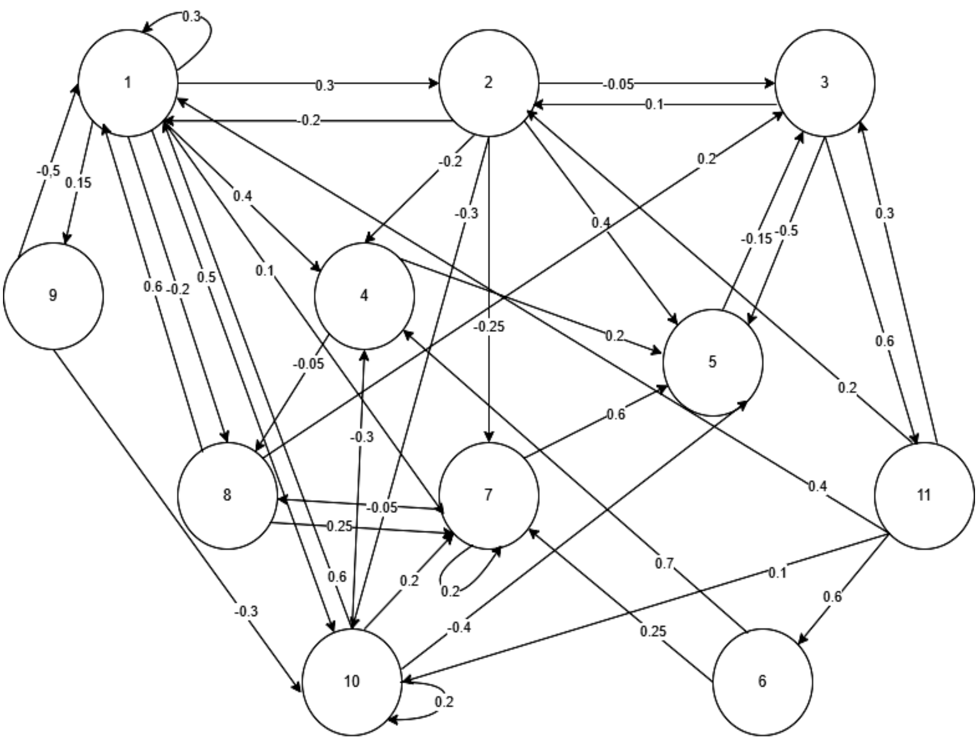

Fig. 1. COVID-19 morbidity CM

patients in isolation in the given region; 5 – number of patients recovered from COVID-19 in the given region; 6 – number of infected passengers revealed during arriving from other regions; 7 – number of patients in hospitals in the given region; 8 – degree of contacts intensity set for the population of the given region when being in industrial, educational, public spaces; 9 – level of contact protection against infection (wearing masks); 10 – number of not isolated sick people who move freely (including those who arrived from other regions and ere not revealed at arrival); 11 – level of danger of the virus strain.

Each CM node affects other nodes. Degree of the effect is estimated by the weights which can be positive or negative. E.g., the effect of the node 2 on the node 10 is reflected by the coefficient -0.3 because increase of number of daily vaccinated people leads to decrease of number of infected not isolated people who freely move; increase of level of danger of the virus strain (node 11) leads to increase of number of daily revealed infected patients with coefficient 0.4.

For cognitive modeling all CM nodes coordinates which represent factors of different physical nature are usually kept in a single scale. That's because when building the weighted oriented graph experts cannot correctly set the weighting coefficients of edges between CM nodes if they are measured in different units (like level of wearing masks, number of patients, danger of the virus strain). Here we suggest using 100 points scale for all CM nodes coordinates where 0 points means absence of a given factor and 100 points means maximal possible level of this factor at the given time interval. Obviously, when defining these factors values some subjectivity is possible, but it does not interfere with modeling or control of the whole system behavior.

MODELS DEVELOPMENT FOR CM IP SUBSYSTEMS WITH MULTIRATE SAMPLING FOR QUICKLY AND SLOWLY MEASURED COORDINATES

We develop models with multirate coordinates sampling based on the model (3), (5) of the subsystem with measurable coordinates. We assume that some coordinates $\overline{X}_f$ of the vector $\overline{X}$ belong to the quickly measured CM nodes with a small sampling period T_0 and some coordinates $\overline{X}_s$ are measured in discrete time moments with a big sampling period $h = mT_0$. Then the IP model (5) can be generally written in an intermediate form with unirate sampling as follows:

$$\begin{pmatrix} \Delta\overline{X}_f(k+1) \\ \Delta\overline{X}_s(k+1) \end{pmatrix} = \begin{pmatrix} A_{11f} & A_{11fs} \\ A_{11sf} & A_{11s} \end{pmatrix} \begin{pmatrix} \Delta\overline{X}_f(k) \\ \Delta\overline{X}_s(k) \end{pmatrix} + \begin{pmatrix} B_f & 0 \\ 0 & B_s \end{pmatrix} \begin{pmatrix} \Delta\overline{u}_f(k) \\ \Delta\overline{u}_s(k) \end{pmatrix} +$$

$$+ \begin{pmatrix} L_f(k) & 0 \\ 0 & L_s(k) \end{pmatrix} \begin{pmatrix} \Delta\overline{a}_f(k) \\ \Delta\overline{a}_s(k) \end{pmatrix} + \begin{pmatrix} A_{12f} \\ A_{12s} \end{pmatrix} \Delta\overline{Y}(k). \quad (6)$$

Quickly measured coordinates $\overline{X}_f$ are nodes 1, 2, 3, 4, 5, 6, 7 of the CM (Fig. 1). Slowly measured node x_s is the CM node 8 – degree of contacts intensity for the population of the given region. Unmeasured coordinates are nodes 9, 10, 11. To create controls $\Delta u_2(k)$, $\Delta u_4(k)$, $\Delta u_8(k)$ we can use varying the resources of the nodes 2, 4, 8 respectively. Varying the weight coefficient a_{67} (how number of infected passengers revealed during arriving from other regions affects number of patients in hospitals) can be used to create a control $\Delta a_{67}(k)$. Then sizes of the vectors in the model (6) will be $\dim \overline{X}_f = 7$, $\dim \overline{X}_s = 1$, $\dim \overline{u}_f = 2$, $\dim \overline{u}_s = 1$, $\dim \overline{Y} = 3$, $\dim \Delta\overline{a}_f = 1$, $\dim \Delta\overline{a}_s = 0$.

According to CM on Fig. 1, matrices in the model (6) will be the following:

$$A_{11f} = \begin{pmatrix} 0.3 & -0.2 & 0 & 0 & 0 & 0 & 0 \\ 0.3 & 0 & 0.1 & 0 & 0 & 0 & 0 \\ 0 & -0.05 & 0 & 0 & -0.15 & 0 & 0 \\ 0.4 & -0.2 & 0 & 0 & 0 & 0.7 & 0 \\ 0 & 0.4 & -0.5 & 0.2 & 0 & 0 & 0.6 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0.1 & -0.25 & 0 & 0 & 0 & 0.25 & 0.2 \end{pmatrix},$$

$$A_{11fs} = \begin{pmatrix} 0.6 & 0 & 0.2 & 0 & 0 & 0 & 0.25 \end{pmatrix}^{\mathrm{T}},$$

$$A_{11sf} = \begin{pmatrix} -0.2 & 0 & 0 & -0.05 & 0 & 0 & -0.05 \end{pmatrix}, \; A_{11s} = 0.$$

Matrix B_f is created by the CM IP control system designer. It has to ensure scaling and switching designed controls $\Delta\overline{u}_f(k)$. Elements of the matrix B_f are zeros and ones. Element $b_{i\mu} = 1$ when the i-th CM node is affected by the μ-th component of the control vector. Thus in each row of the matrix B_f only one element can be equal to one and all others will be zero. Size of the matrix B_f for the given CM (6) is 7×2 where 7 and 2 are sizes of vectors $\overline{X}_f$ and $\overline{u}_f(k)$ respectively. Then

$$B_f = \begin{pmatrix} 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 \end{pmatrix}^{\mathrm{T}}.$$

The rules for writing the matrix $L_f(k)$ can be found in [3]. For the model (6) $L_f(k) = \begin{pmatrix} 0 & 0 & 0 & 0 & 0 & \Delta x_6(k) & 0 \end{pmatrix}^{\mathrm{T}}$.

Unmeasurable CM nodes coordinates y_9, y_{10}, y_{11} in the model (6) are included into the vector $\Delta\overline{Y}(k)$ as unmeasurable disturbances. Then matrix A_{12f} in the CM (Fig. 1) will be

$$A_{12f} = \begin{pmatrix} -0.5 & 0.6 & 0.4 \\ 0 & 0 & 0.2 \\ 0 & 0 & 0.3 \\ 0 & -0.3 & 0 \\ 0 & -0.4 & 0 \\ 0 & 0 & 0.6 \\ 0 & 0.2 & 0 \end{pmatrix}.$$

There is only one slowly measurable coordinate 8 in the CM which can be affected by the control u_s with a sampling period $h = mT_0$ via varying resources of the node 8. So in model (6) $B_s = 1$, $L_s(k) = 0$. Unmeasurable nodes 9, 10, 11 don't affect the node 8, so $A_{12s} = 0$.

Thus IP model (5) is split into two parts. The first part describing dynamics of the quickly measured CM nodes with sampling period T_0 can be written based on (6) as follows:

$$\Delta\overline{X}_f\left[\left[\frac{k}{m}\right]h + (l+1)T_0\right] = A_{11f}\Delta\overline{X}_f\left[\left[\frac{k}{m}\right]h + lT_0\right] + A_{11fs}\Delta\tilde{x}_s\left[\left[\frac{k}{m}\right]h\right] +$$

$$+\begin{pmatrix} B_f & L_f\left[\left[\frac{k}{m}\right]h + lT_0\right]\end{pmatrix}\begin{pmatrix}\Delta\overline{u}_f\left[\left[\frac{k}{m}\right]h + lT_0\right] \\ \Delta a_f\left[\left[\frac{k}{m}\right]h + lT_0\right]\end{pmatrix} + \Delta\overline{\xi}_f\left[\left[\frac{k}{m}\right]h + lT_0\right], \quad (7)$$

where $\left[\frac{k}{m}\right]$ is integer part of dividing k by m, $l = 0,1,...,m-1$. The first difference

$$\Delta\overline{X}_f\left[\left[\frac{k}{m}\right]h + lT_0\right] = \overline{X}_f\left[\left[\frac{k}{m}\right]h + lT_0\right] - \overline{X}_f\left[\left[\frac{k}{m}\right]h + (l-1)T_0\right],$$

$$\Delta\tilde{x}_s\left[\left[\frac{k}{m}\right]h\right] = x_s\left[\left[\frac{k}{m}\right]h\right] - x_s\left[\left(\left[\frac{k}{m}\right] - 1\right)h\right] \text{ if } l = 0$$

and zero otherwise. Disturbances vector

$$\Delta\overline{\xi}_f\left[\left[\frac{k}{m}\right]h + lT_0\right] = A_{12f}\Delta\overline{Y}\left[\left[\frac{k}{m}\right]h + lT_0\right]$$

is generated by the unmeasurable nodes $\Delta\overline{Y}$ of the CM.

The second part of the model described the dynamics of the slowly measured CM node 8 can be written in the intermediate form based on (6) as

$$\Delta x_s\left[\left[\frac{k}{m}\right]h + (l+1)T_0\right] = A_{11sf}\Delta\overline{X}_f\left[\left[\frac{k}{m}\right]h + lT_0\right] + B_s\Delta u_s\left[\left[\frac{k}{m}\right]h + lT_0\right]. \quad (8)$$

Based on the iterative procedure described in [5] the model (8) can be transitioned to the form where the coordinate x_s and the control u_s have the big sampling period $h = mT_0$, considering that $A_{11s} = 0$ and there are no external disturbances and weights-varying based controls:

$$\Delta x_s\left[\left(\left[\frac{k}{m}\right] + 1\right)h\right] = A_{11sf}\Delta\tilde{\tilde{\overline{X}}}_f\left[\left[\frac{k}{m}\right]h + (m-1)T_0\right] + B_s\Delta u_s\left[\left[\frac{k}{m}\right]h\right], \quad (9)$$

where $$\Delta x_s\left[\left(\left[\frac{k}{m}\right] + 1\right)h\right] = x_s\left[\left(\left[\frac{k}{m}\right] + 1\right)h\right] - x_s\left[\left[\frac{k}{m}\right]h\right];$$

$$\Delta\tilde{\tilde{X}}_f\left[\left[\frac{k}{m}\right]h+(m-1)T_0\right]=\overline{X}_f\left[\left[\frac{k}{m}\right]h+(m-1)T_0\right]-\overline{X}_f\left[\left(\left[\frac{k}{m}\right]-1\right)h+(m-1)T_0\right].$$

CONTROL AUTOMATION OF CM IP WITH MULTIRATE SAMPLING

For designing algorithms of CM IP automated control dynamics (7), (9) of the vectors $\overline{X}_f$, x_s should be written in full CM nodes coordinates (not in increments):

$$\overline{X}_f\left[\left[\frac{k}{m}\right]h+(l+1)T_0\right]=$$
$$=(I_{11f}+A_{11f}-A_{11f}q^{-1})\overline{X}_f\left[\left[\frac{k}{m}\right]h+lT_0\right]+A_{11fs}\Delta\tilde{x}_s\left[\left[\frac{k}{m}\right]h\right]+$$
$$+\begin{pmatrix}B_f & L_f\left[\left[\frac{k}{m}\right]h+lT_0\right]\end{pmatrix}\begin{pmatrix}\Delta\overline{u}_f\left[\left[\frac{k}{m}\right]h+lT_0\right]\\ \Delta a_f\left[\left[\frac{k}{m}\right]h+lT_0\right]\end{pmatrix}+\Delta\overline{\xi}_f\left[\left[\frac{k}{m}\right]h+lT_0\right];\quad (10)$$

$$x_s\left[\left(\left[\frac{k}{m}\right]+1\right)h\right]=$$
$$=x_s\left[\left[\frac{k}{m}\right]h\right]+A_{11sf}\Delta\tilde{\tilde{X}}_f\left[\left[\frac{k}{m}\right]h+(m-1)T_0\right]+B_s\Delta u_s\left[\left[\frac{k}{m}\right]h\right],\quad (11)$$

where q^{-1} is a reverse shift operator with sampling period T_0.

To design quickly changes controls $\Delta\overline{u}_f,\Delta a_f$ the following quadratic criterion is suggested:

$$J_f\left[\left[\frac{k}{m}\right]h+(l+1)T_0\right]=E\left\{\left[\overline{X}_f\left[\left[\frac{k}{m}\right]h+(l+1)T_0\right]-\overline{G}_f\right]^{\mathrm{T}}\times\right.$$
$$\times\left[\overline{X}_f\left[\left[\frac{k}{m}\right]h+(l+1)T_0\right]-\overline{G}_f\right]+\begin{pmatrix}\Delta\overline{u}_f^{\mathrm{T}}\left[\left[\frac{k}{m}\right]h+lT_0\right] & \Delta a_f\left[\left[\frac{k}{m}\right]h+lT_0\right]\end{pmatrix}\times$$
$$\left.\times\begin{pmatrix}R_{f1} & 0\\ 0 & r_{f2}\end{pmatrix}\begin{pmatrix}\Delta\overline{u}_f\left[\left[\frac{k}{m}\right]h+lT_0\right]\\ \Delta a_f\left[\left[\frac{k}{m}\right]h+lT_0\right]\end{pmatrix}\right\},\quad (12)$$

where E is expectation (mean), $\overline{G}_f$ is set-point vector for stabilization of CM nodes coordinates $\overline{X}_f$.

Based on minimization of criterion (12) with respect to vector $\begin{pmatrix} \Delta \overline{u}_f \\ \Delta a_f \end{pmatrix}$, having used model (10), we find quick combined control vector that affects nodes $\overline{X}_f$ according to (10):

$$\begin{pmatrix} \Delta \overline{u}_f \left[\left[\frac{k}{m} \right] h + lT_0 \right] \\ \Delta a_f \left[\left[\frac{k}{m} \right] h + lT_0 \right] \end{pmatrix} =$$

$$= -\left\{ \begin{pmatrix} B_f^{\mathrm{T}} \\ L_f^{\mathrm{T}} \left[\left[\frac{k}{m} \right] h + lT_0 \right] \end{pmatrix} \begin{pmatrix} B_f & L_f \left[\left[\frac{k}{m} \right] h + lT_0 \right] \end{pmatrix} + \begin{pmatrix} R_{f1} & 0 \\ 0 & r_{f2} \end{pmatrix} \right\}^{-1} \begin{pmatrix} B_f^{\mathrm{T}} \\ L_f^{\mathrm{T}} \left[\left[\frac{k}{m} \right] h + lT_0 \right] \end{pmatrix} \times$$

$$\times \left\{ (I_{11f} + A_{11f} - A_{11f} q^{-1}) \overline{X}_f \left[\left[\frac{k}{m} \right] h + lT_0 \right] + A_{11fs} \Delta \tilde{x}_s \left[\left[\frac{k}{m} \right] h \right] + \right.$$

$$\left. + \Delta \overline{\xi}_f \left[\left[\frac{k}{m} \right] h + lT_0 \right] - \overline{G}_f \right\}. \quad (13)$$

To design the slow control Δu_s, the second optimality criterion is suggested:

$$J_s \left[\left(\left[\frac{k}{m} \right] + 1 \right) h \right] = E \left\{ \left[x_s \left[\left(\left[\frac{k}{m} \right] + 1 \right) h \right] - G_s \right]^2 + r_s \Delta u_s^2 \left[\left[\frac{k}{m} \right] h \right] \right\}, \quad (14)$$

where G_s is set-point vector for x_s stabilization. Based on minimization of criterion (14) with respect to Δu_s, having used model (11), we find slow combined control that affects node 8:

$$\Delta u_s \left[\left[\frac{k}{m} \right] h \right] = -\frac{B_s}{B_s^2 + r_s} \left(x_s \left[\left[\frac{k}{m} \right] h \right] + A_{11sf} \Delta \tilde{\tilde{X}}_f \left[\left[\frac{k}{m} \right] h + (m-1) T_0 \right] - G_s \right). \quad (15)$$

EXPERIMENTAL RESEARCH OF THE IP CONTROL SYSTEM IN THE COVID-19 MORBIDITY CM

For a computational simulation initial values of CM nodes coordinates were set at the medium levels $x_i = 50,\ i = 1,...,11$. Problem statement of the experiments is to move CM nodes coordinates x_2, x_4, x_7, x_8 to the new levels $G_2 = 60,\ G_4 = 40,\ G_7 = 40,\ G_8 = 40$. It means that we need to increase number of daily vaccinated people (x_2), decrease number of patients in isolation in the given region (x_4), decrease of patients in hospitals in the given region (x_7), decrease degree of contacts intensity set for the population of the given region when being in industrial, educational, public spaces (x_8). In the fast control subsystem (13) control vector consists of the controls $\Delta\overline{u}_f = (\Delta u_2 \quad \Delta u_4)^{\mathrm{T}}$ and $\Delta a_f = \Delta a_{67}$, and in the slow subsystem (15) there is only one control $\Delta u_s(rh) = \Delta u_8(rh)$, where $r = \left[\frac{k}{m}\right]$. Ratio between sampling periods of fast and slow subsystems $h = mT_0$ is selected with the coefficient $m = 6$.

Fig. 2 shows the charts for the results of simulation of CM nodes $x_i, i = 1,...,11$, and Fig. 3 demonstrates charts of the generated increments of controls $\Delta u_2(kT_0), \Delta u_4(kT_0), \Delta a_{67}(kT_0), \Delta u_8(rh)$ based on control laws (13) and (15).

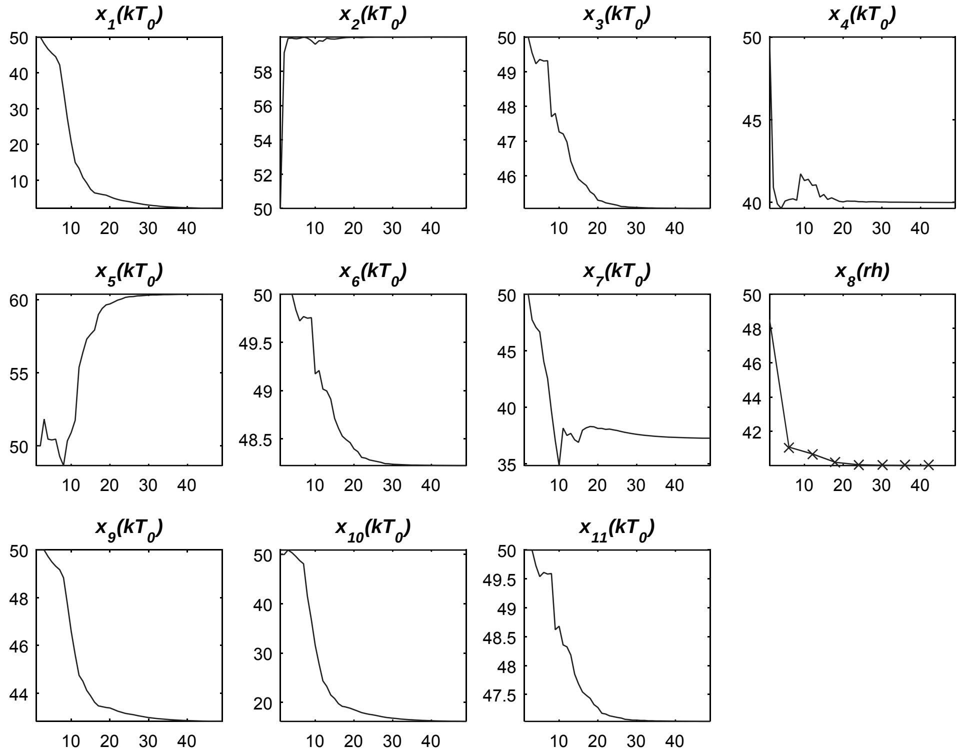

Fig. 2. Nodes coordinates changes

Based on the charts analysis we can formulate the following tendencies in the changes of CM nodes coordinates and controls with multirate sampling.

1. CM nodes coordinates x_2, x_4, x_7, x_8 which are directly controlled by $\Delta u_2(kT_0), \Delta u_4(kT_0), \Delta a_{67}(kT_0), \Delta u_8(rh)$ respectively quickly shift to their new levels $G_2 = 60, G_4 = 40, G_7 = 40, G_8 = 40$.

2. Nodes coordinates x_1, x_3, x_5, x_6 which are not controlled directly move slower to the new natural level, i.e. x_1, x_3, x_6 decrease and x_5 increases.

3. Controls in the form of increments $\Delta u_2(kT_0)$, $\Delta u_4(kT_0)$, $\Delta a_{67}(kT_0)$, $\Delta u_8(rh)$ set at zero levels when transient processes are over.

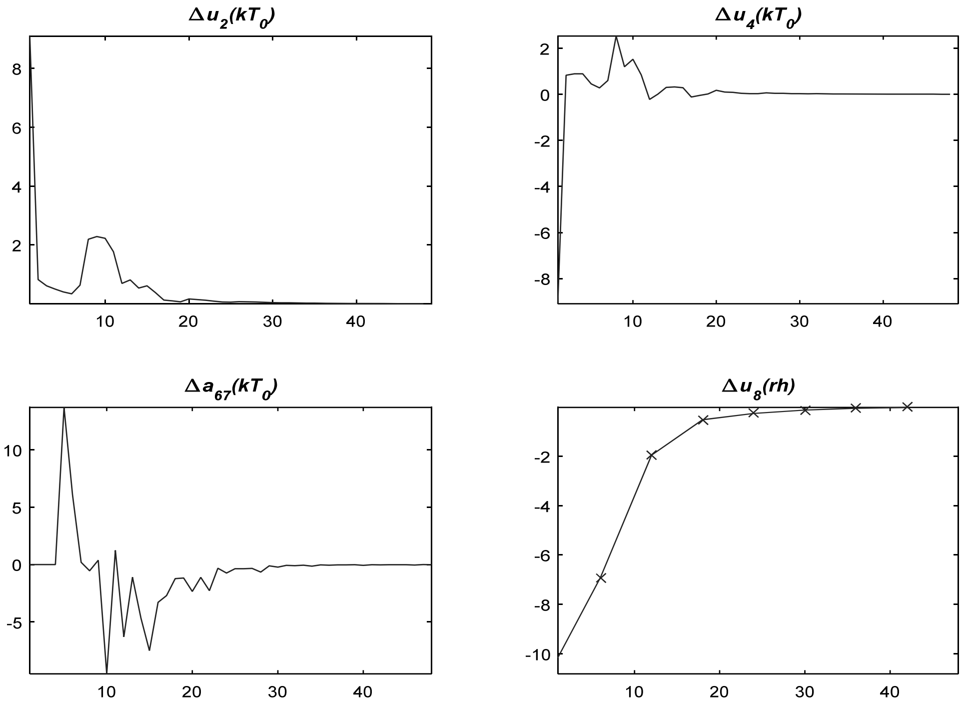

Fig. 3. Controls changes

CONCLUSIONS

This article develops a CM which quantitatively describes interrelations between factors during the spread of COVID-19 morbidity. Based on the CM the IP models are developed which describe dynamic aspects of the morbidity in the form of difference equations. Both measurable and unmeasurable coordinates are accounted for. We also account for presence of both quickly and slowly measured coordinates, which are reflected in the subsystems models with fast and slow sampling. For these subsystems external controls are selected, which are then generated based on the linear quadratic control method using combined resources varying of some nodes coordinates and edges weights in the CM.

Experimental research was conducted by means of computational simulation of the CM IP closed-loop control system. Based on the charts of the transients processes of CM nodes coordinates and incremental controls it is concluded that directly controlled CM nodes quickly shift to the new levels defined by the set-points of the controller. Not directly controlled CM nodes coordinates move to the new levels slower.

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КОМБІНОВАНЕ КЕРУВАННЯ ІМПУЛЬСНИМИ ПРОЦЕСАМИ З РІЗНОТЕМПОВОЮ ДИСКРЕТИЗАЦІЄЮ В КОГНІТИВНІЙ КАРТІ ЗАХВОРЮВАНОСТІ НА COVID-19 / В.Д. Романенко, Ю.Л. Мілявський

Анотація. Побудовано когнітивну карту (КК) розповсюдження захворюваності на COVID-19 в даному регіоні. Розроблено загальну лінійну модель імпульсних процесів (ІП) КК і проведено аналіз вимірюваних і невимірюваних координат вершин КК. Виконано декомпозицію загальної моделі ІП на взаємопов'язані підсистеми з вимірюваними і не вимірюваними координатами вершин. Для підсистеми з вимірюваними координатами вершин проведено різнотемпову дискретизацію координат, у результаті чого розроблено дискретні моделі динаміки для швидковимірюваних і повільновимірюваних координат вершин КК. Вибрано зовнішні керувальні дії в моделях ІП з урахуванням можливого варіювання ресурсами координат вершин і вагових коефіцієнтів ребер КК. Виконано синтез законів керування ІП на основі варіювання координат вершин і вагового коефіцієнта. Розроблено рекурентні процедури формування керувальних дій у замкнених підсистемах керування з різнотемповою дискретизацією. Проведено експериментальні дослідження підсистем керування, які підтверджують високу ефективність по зниженню захворюваності на COVID-19.

Ключові слова: когнітивна карта, імпульсні процеси, закони керування, критерій оптимальності, COVID-19.