Chemical Technology, Control and Management

Volume 2021 | Issue 2 Article 12

5-17-2021

# ALGORITHMS FOR SYNTHESIS OF DISCRETE CONTROLLERS IN NONLINEAR CONTROL SYSTEMS WITH DELAY

Alisher Rajabaliyevich Mallayev
*Karshi Engeneering-Economic Institute, Address: Independence, 225 st., 180100, Karshi city, Republic of Uzbekistan E-mail: sayyod@rambler.ru,*, sayyod@rambler.ru

Suban Nurullayevich Xusanov
*Karshi Engeneering-Economic Institute, Address: Independence, 225 st., 180100, Karshi city, Republic of Uzbekistan E-mail: suban1983@mail.ru, Phone: +998-93-902-72-70.*, xusanovsuban@gmail.com



## Recommended Citation

Mallayev, Alisher Rajabaliyevich and Xusanov, Suban Nurullayevich (2021) "ALGORITHMS FOR SYNTHESIS OF DISCRETE CONTROLLERS IN NONLINEAR CONTROL SYSTEMS WITH DELAY," *Chemical Technology, Control and Management*: Vol. 2021 : Iss. 2 , Article 12.
DOI: https://doi.org/10.51346/tstu-02.21.1-77-0012
Available at: https://uzjournals.edu.uz/ijctcm/vol2021/iss2/12

ISSN 1815-4840, E-ISSN 2181-1105
Himičeskaâ tehnologiâ. Kontrol' i upravlenie
CHEMICAL TECHNOLOGY. CONTROL AND MANAGEMENT
2021, №2 (98) pp.80-86. https://doi.org/10.51346/tstu-02.21.1-77-0012
International scientific and technical journal
journal homepage: https://uzjournals.edu.uz/ijctcm/
Since 2005

**UDC 62-503.5**

# ALGORITHMS FOR SYNTHESIS OF DISCRETE CONTROLLERS IN NONLINEAR CONTROL SYSTEMS WITH DELAY

**Mallayev Alisher Rajabaliyevich[1], Xusanov Suban Nurullayevich[2]**

*[1,2]Karshi Engeneering-Economic Institute,*
*Address: Independence, 225 st., 180100, Karshi city, Republic of Uzbekistan*
*E-mail: [1]sayyod@rambler.ru, [2]suban1983@mail.ru, Phone: +998-93-902-72-70;*

***Abstract**: Algorithms for the synthesis of discrete controllers in nonlinear control systems, taking into account the delay, have been proposed. The synthesized vector controller provides a solution to the control problem, for example, the translation of the image point of a closed system from arbitrary initial conditions to the origin of the phase space coordinates. Built on the basis of a series-parallel set of invariant manifolds, the dynamic discrete controller ensures the fulfillment of the specified technological requirements, the asymptotic stability of a closed discrete-continuous system, and has the property of predicting the behavior of the system after sampling. These algorithms have made it possible to effectively solve the problems of synthesis of discrete controllers, taking into account the delay in process control systems.*
***Keywords:** discrete controller, synthesis algorithms, nonlinear dynamic object, delays.*

***Аннотация:** Кечикишларни ҳисобга олган ҳолда ночизиқли бошқариш тизимларида дискрет ростлагичларни синтезлаш алгоритмлари келтирилган. Келтирилган синтезланган векторли ростлагич акси берк тизимнинг нуқтасини ихтиёрий бошланғич шартдан фазонинг координата бошига аксланишини ифодаловчи объектни бошқариш масалаларини ечишни таъминлайди. Инвариант хилма-хилликларнинг кетма-кет-параллелли жамлаш асосида синтезланган динамик дискрет ростлагич берилган технологик талаблар бажарилишини ва ёпиқ дискрет-узлуксиз тизимларнинг асимптотик турғунлигини таъминлайди ҳамда тизимлар хулқини дискретлаш қадами бўйича башоратлаш хоссасига эга. Келтирилган алгоритмлар технологик жараёнларни бошқариш тизимларидаги кечикишларни ҳисобга олган ҳолда дискрет ростлагичларни синтезлаш масалаларини самарали ечиш имконини берди.*
***Таянч сўзлар:** дискрет ростлагичлар, синтезлаш алгоритмлари, ночизиқли динамик объект, кечикишлар.*

***Аннотация:** Приведены алгоритмы синтеза дискретных регуляторов в нелинейных системах управления с учетом запаздывания. Синтезированный векторный регулятор обеспечивает решение задачи управления, объектом, перевод изображающей точки замкнутой системы из произвольных начальных условий в начало координат фазового пространства. Построенный на основе последовательно-параллельной совокупности инвариантных многообразий динамический дискретный регулятор обеспечивает выполнение заданных технологических требований, асимптотическую устойчивость замкнутой дискретно-непрерывной системы и обладает свойством прогнозирования поведения системы каждом дискретизации. Приведенные алгоритмы позволили эффективно решить задачи синтеза дискретных регуляторов с учетом запаздывания в системах управления технологическими процессами.*
***Ключевые слова:** дискретные регулятор, алгоритмы синтеза, нелинейные динамические объект, запаздывание.*

## Introduction

Automatic systems are subject to the action of limited unmeasured external disturbances, which lead to the appearances of control errors that make sense deviations of the controlled variables of the object from the nominal steady-state mode of operation. In the case of deterministic disturbances, the accuracy of the system, as a rule, is estimated by the maximum modulus of the deviation of the controlled variables from zero, i.e. nominal operating mode, since the equations of motion in deviations are used. Under random perturbations, such a characteristics are usually the root-mean-square values of the controlled variables, and with known spectral characteristics of external perturbations, it is the subject of a well-developed stochastic control theory. However, the spectral characteristics of external disturbances are difficult to access as a rule [1-6].

The problem of synthesis of control systems for objects with delayed input is to take into account the influence of the delay time on the stability and quality of transient processes in a closed system [2,7,8]. Therefore, an idea arises about the possibility of synthesizing a control system in which the influence of the delay time is excluded. Insufficient knowledge of the above issues for the case of dynamical multi-connected systems with and without delay determines the relevance of the work. Therefore, problems are relevant when the synthesis of controllers is carried out in the presence of restrictions only on the power (the mean squares of each component are limited) of the external disturbance at an arbitrary spectral power density [9].

**Formulation of the problem**

In many control problems for multiply connected technological or mobile objects, it becomes necessary to use several control channels, which expands the possibilities for ensuring the required dynamic properties of the synthesized systems. Suppose that the mathematical model of the motion of a continuous nonlinear control object is described by the following differential equations:

$$\begin{aligned} &\dot{x}(t) = A(x)x + B(x)u[k]; \\ &u[k] = const; \quad kT_0 \le t < (k+1)T_0, \end{aligned} \tag{1}$$

where $x \in \Re^n$ – is the vector of the state space, $x(t) = [x_1, x_2, ..., x_n]^T$; $A(x)$, $B(x)$ - functional matrices, $\dim(A(x[k]) = (n \times n)$; $\dim(B(x[k]) = (n \times m)$; $u[k] \in \Re^m$ m-control vector, or vector difference equation:

$$x[k+1] = F(x[k])x[k] + D(x[k])u[k], \tag{2}$$

where $x[k] \in \Re^n$ – is the vector of the state space, $x[k] = [x_1, x_2, ..., x_n,]^T$; $F(x[k])$, $D(x[k])$ are functional matrices of dimensions $(n \times n)$ and $(n \times m)$. Applying to the equation (1) the procedure of the difference approximation by the Euler formula, we can obtain expressions due to the equations (1) and (2):

$$F(x[k]) = \mathrm{I}^n x[k] + \mathrm{T}_0 \mathrm{A}(x[k]), \qquad D(x[k]) = \mathrm{T}_0 \mathrm{B}(x[k]). \tag{3}$$

The synthesis task determines the control vector $u[k] \in \Re^m$, which ensures the transfer of the representing point (RP) of the system from an arbitrary initial state $x^0[k]$, in general, $x^0[k] \in \Omega^0$ is in final state $x^f$. We require that the minimum of the optimizing function shoud be ensured on the trajectories of motion:

$$J = \sum_{k=0}^{\infty} \left( \psi_1[k] M^2 \psi_1[k] + \Delta\psi_1[k] C^2 \Delta\psi_1[k] \right), \tag{4}$$

where $\psi_1[k] \in \Re^m$ – is a vector of aggregated macrovariables, $\psi_1[k] = [\psi_{1,1}, \psi_{1,2} ..., \psi_{1,m}]^T$; $M = \|m_{ij}\|$, $C = \|c_{ij}\|$ are numerical matrices with dimensions $(m \times m)$. In this case, asymptotic stability of motion in a certain region of the phase space should be guaranteed. The equation of extremals that provide a minimum to function (4) in the form [4,10,11]:

$$\psi_1[k+1] + \Lambda_1 \psi_1[k] = 0, \tag{5}$$

where matrix $\Lambda_1 = \|\lambda_{1,ij}\|$ is solution to difference equation (5) is asymptotically stable, $\dim(\Lambda_1) = (m \times m)$.

The motion of the RP must satisfy the equation (5) and the solution of this equation which is zero is stable, the motion after the completion of the transient processes in the system (5) must simultaneously satisfy the relation:

$$\psi_1[k] = 0. \tag{6}$$

Thus, the RP moves from the initial state $x^0[k]\in\Omega^0$ to the intersection of manifolds (6) $\bigcap_{i=1}^{m}\psi_{1,i}[k]=0$ and when approaching should move along it in final state $x^f$. Then the problem of vector control synthesis is reduced to ensuring the conditions for the projection of the motion of the original object (2) onto the subspace of manifolds, described by equation (5).

Let us turn to the presentation of the method of synthesis of vector control by the method of analytical design of aggregated discrete controllers (ADADC). The synthesized control $u[k]$ must satisfy the functional equation written in the form (5) with respect to the vector of aggregated macrovariables $\psi_1[k]$. The main idea of the synergetic control theory is the coordinated (interconnected) control of various control objects (CO). In connection with them, it is necessary to pose the problem of synthesizing control actions that would take into account such an important feature of technological control objects as multi-connectivity.

**Research Methods and the Received Results**

We will represent the object model (2) in the following form:

$$\begin{aligned}\bar{x}[k]&=\bar{F}(x[k])x[k];\\ \breve{x}[k]&=\breve{F}(x[k])x[k]+\breve{D}(x[k])u[k],\end{aligned}\qquad(7)$$

where $x[k]=\left|\bar{x}[k]^{T}\vdots\breve{x}[k]^{T}\right|^{T}$, $\breve{x}[k]\in\Re^m$, $\bar{x}[k]\in\Re^l$, $n=m+l$, $F=\begin{vmatrix}\bar{F}\\ \breve{F}\end{vmatrix}$, $\dim\bar{F}=(l\times n)$, $\dim\breve{F}=(m\times n)$, a square $(m\times m)$-matrix $\breve{D}$ is such that $\det\breve{D}\neq 0$, $D=\begin{vmatrix}O_{l,m}\\ \breve{D}\end{vmatrix}$, $O_{l,m}$ is a zero matrix with dimension $(l\times m)$. We will introduce a vector of macrovariables:

$$\psi_1[k]=P_1(\breve{x}[k]+\varphi_1[k]),\qquad(8)$$

where $\varphi_1[k]=[\varphi_{1,1},\varphi_{1,2},\ldots,\varphi_{1,m}]^T$, $\varphi_{1,i}[k]=f_i(\bar{x}[k]),\ i=\overline{1,m}$; $P_1=|p_{1,ij}|$ - is a numeric matrix with dimension $(m\times m)$, while matrix $P_1$ must satisfy that $\det P_1\neq 0$.

Next, by solving jointly equations (2), (5) and (8), we can obtain the following expression:

$$P_1\breve{F}(x[k]x[k])+\Lambda_1P_1(\breve{x}[k]+\varphi_1[k])+P_1\breve{D}(x[k]u[k]+P_1\varphi_1[k+1])=0.\qquad(9)$$

Resolving (9) with respect to $u(k)$, we can obtain the vector control law of the CO (2):

$$u[k]=-(\breve{D}(x[k]))^{-1}\left\{\breve{F}(x[k])x[k]+(P_1)^{-1}\Lambda_1P_1(\bar{x}[k]+\varphi_1[k])+\varphi_1[k+1]\right\},\qquad(10)$$

where $(\cdot)^{-1}$ – is the matrix inverting operation.

When the representative point of the closed-loop system (2), (10) falls into the vicinity of the intersection of manifolds $\bigcap_{i=1}^{m}\psi_{1,i}[k]=0$, its motion will be described by a vector which defines the difference of the dimension $l=n-m$:

$$\bar{x}[k+1]=\tilde{F}(\bar{x}[k],\varphi_1[k])\bar{x}[k]-\tilde{D}(\bar{x}[k],\varphi_1[k])\varphi_1[k],\qquad(11)$$

where $\bar{F}=\left|\tilde{F}\ \ \tilde{D}\right|$, $\dim\tilde{F}=(l\times l)$, $\dim\tilde{D}=(l\times m)$.

Suppose that the structure of the decomposed model (11) can be reduced to the structure of the original model (2), defined vector $\varphi_1[k]=\left|\bar{\varphi}_1[k]^T\vdots\tilde{\varphi}_1[k]^T\right|^T$ in such a way:

$$\begin{aligned}&\tilde{F}(\bar{x}[k],\varphi_1[k])\xrightarrow{\bar{\varphi}_1[k]}\hat{F}(\bar{x}[k]);\\ &\tilde{D}(\bar{x}[k],\varphi_1[k])\xrightarrow{\bar{\varphi}_1[k]}\hat{D}(\bar{x}[k]);\end{aligned}\qquad(12)$$

where $\overline{\varphi}_1[k] \in \Re^s$ – is a vector-function, the component for such founded values of $\overline{\varphi}_{1,i}[k] = f_i(\overline{x}[k]) \; \forall i = \overline{1,s}$ the transformation (12) is true; $\hat{F}(x[k]), \hat{D}(x[k])$ – functional matrices, $\dim \hat{F} = (l \times l), \dim \hat{D} = (l \times r)$, $r = m - s$.

Then the decomposed model (11) will be in following form:

$$\begin{aligned} \tilde{x}[k] &= \overline{F}(\overline{x}[k])\overline{x}[k]; \\ \hat{x}[k] &= \breve{F}_1(\overline{x}[k])\overline{x}[k] + \breve{D}_1(\overline{x}[k])\tilde{\varphi}_1[k], \end{aligned} \tag{13}$$

where $\overline{x}[k] = \left|\tilde{x}[k]^T \vdots \hat{x}[k]^T\right|^T$, $\tilde{x}[k] \in \Re^p$, $\hat{x}[k] \in \Re^r$, $l = r + p$, $\hat{F} = \begin{vmatrix} \overline{F}_1 \\ \breve{F}_1 \end{vmatrix}$, $\dim \overline{F}_1 = (p \times l)$, $\dim \breve{F}_1 = (r \times l)$, $\breve{D}_1 = \begin{vmatrix} O_{p,r} \\ \breve{D}_1 \end{vmatrix}$, $\dim \breve{D}_1 = (r \times r)$, $\det \breve{D}_1 \neq 0$, $O_{p,r}$ – zero dimension matrix $(p \times r)$, vector $\tilde{\varphi}_1[k] \in \Re^r$ can be defined as a vector of "internal" control for system (13).

Let us, we will introduce the second parallel set of aggregated macrovariables:

$$\psi_2[k] = P_2(\hat{x}[k] + \varphi_2[k]), \tag{14}$$

where $\psi_2[k] \in \Re^r$ – is a vector of macro variables; $P = \|p_{2,ij}\|$, $\dim P_2 = (r \times r)$; the elements of vector $\varphi_2[k] = [\varphi_{2,1}, \varphi_{2,2}, ..., \varphi_{2,m}]^T$ are functions $\psi_{2,i}[k] = f_i(\tilde{x}[k])$.

In this case, vector $\psi_2[k]$ must satisfy the solution of the homogeneous difference equation:

$$\psi_2[k+1] + \Lambda_2 \psi_2[k] = 0, \tag{15}$$

Where the matrix $\Lambda_2 = \|\lambda_{2,ij}\|$ is a solution to the difference equation (15). It is asymptotically stable, $\dim(\Lambda_2) = (r \times r)$.

Now, solving equations (13), (14) and (15) together, we will obtain the following expression for the vector of intermediate "internal" controls:

$$\tilde{\varphi}_1[k] = \left(\breve{D}_1(\overline{x}[k])\right)^{-1} \left\{\breve{F}_1(\overline{x}[k])\overline{x}[k] + (P_2)^{-1} \Lambda_2 P_2(\hat{x}[k] + \varphi_2[k]) + \varphi_2[k+1]\right\}. \tag{16}$$

When the RP enters the neighborhood $\psi_2[k] = 0$, the second dynamic decomposition of the mathematical model (2) will occur:

$$\tilde{x}[k+1] = \tilde{F}_1(\tilde{x}[k], \varphi_2[k])\tilde{x}[k] - \tilde{D}_1(\tilde{x}[k], \varphi_2[k])\varphi_2[k], \tag{17}$$

where $\overline{F}_1 = \left|\tilde{F}_1 \vdots \tilde{D}_1\right|$, $\dim \tilde{F}_1 = (p \times p)$, $\dim \tilde{D}_1 = (p \times r)$.

**Discussion**

As a result of the introduction of a series-parallel set of invariant manifolds $\psi_1[k] = 0$, $\psi_2[k] = 0$ in system (2), (10), a double dynamic decomposition was carried out, as a result of which the decomposed model of the object (17) has dimension $p = n - m - r$. At the same time, it is possible to apply the following, similar to the above, stage of sequential-parallel optimization to the mathematical model (17), and this procedure is repeated until the $q \geq 1$ condition is satisfied for the $q$ – order of the final decomposed mathematical model.

Thus, the solution of the ADADC problem on the basis of a series-parallel set of invariant manifolds is reduced to the following stages:

- for the system (2), a parallel collection of invariant manifolds $\psi_1[k] = 0$ is introduced;
- the decomposed system (11) by $\psi_1[k] = 0$ is determined;
- the vector of intermediate "internal" controls $\overline{\varphi}_1[k]$ is determined from the condition of reducing the system (11) to the form (13) or, if this is impossible, the elements of the vector $\varphi_1[k]$ are

selected from the stability condition of the decomposed system (11) and, according to expression (10), the control vector $u[k]$ ;

• for the system (13), the second parallel collection of invariant manifolds $\psi_2[k]=0$ is introduced;

• the decomposed system (17) is determined;

• then the sequence-parallel optimization procedure is repeated up to the introduction of the finishing parallel set of invariant manifolds $\psi_v[k]=0$;

• after determining all intermediate "internal" controls $\varphi_i[k]$, $i=\overline{1,v}$, according to the expression (10), control vector $u[k]$ is calculated.

The main difference between discrete-continuous control systems is the presence of a delay in the control channels. This feature has the greatest impact on the operation of the system when the delay is commensurate with the sampling time. To take into account the delay, it is necessary to introduce a predictor of the op-amp state signals into the structure of the synthesized controller [10, 12].

**Formulation of the problem**

Let the initial model of the controlled object have the following form:

$$\begin{aligned}&\dot{x}(t)=A(x)x+B(x)u[t];\\&u(t)=const;\quad (k-1)T_0\le t<kT_0,\qquad k=1,2,...,\end{aligned}\tag{18}$$

where $x(t)$ – is the n-state vector; $u(t)$ – m-vector of control with a delay of a sampling step in time $T_0$; $A(x)$, $B(x)$ – functional matrices of state and control, $\dim A=(n\times n)$; $\dim B=(n\times m)$.

Applying the difference approximation procedure to (18), we obtain a discrete model of the control plant:

$$x[k+1]=F(x[k])x[k]+D(x[k])u[k-1],\tag{19}$$

where $F(x[k])=\mathrm{I}_n+\mathrm{T}_0\mathrm{A}(x[k])$; $D(x[k])=\mathrm{T}_0B(x[k])$; $I_n$ – unit dimension matrix $n\times n$.

**Research Methods and the Received Results**

We will look for a dynamic discrete controller in the following form [10,13,14]:

$$\begin{aligned}&u[k-1]=y[k];\\&y[k+1]=C(y[k]),x[k]y[k]+Q(x[k])x[k],\end{aligned}\tag{20}$$

where $y[k]$– is the m-vector of the state space of the controller, $C$ and $Q$ – are functional matrices of dimensions $(m\times m)$ and $(m\times n)$, respectively. Taking into account the change of variables:

$$u[k-1]=y[k],\tag{21}$$

and introducing a delay on channel $u$ by one time sampling step, system (19) can be written in an extended form:

$$\begin{aligned}&x[k+1]=F(x[k])x[k]+D(x[k])y[k];\\&u[k+1]=v[k],\end{aligned}\tag{22}$$

where $v[k]$– is a fictitious m-control vector.

For the extended system (22), we will introduce the vector aggregated macro variable:

$$\psi_0[k]=y[k]-\varphi_0[k],\tag{23}$$

where $\varphi_0[k]$– is an m-vector function of $x[k]$, $\varphi_0[k]$– is a m-vector of aggregated macro variables.

In this case, we require that the vector of macrovariables $\varphi_0[k]$ satisfy the solution of the homogeneous difference equation:

$$\psi_0[k+1]+\Lambda_0\psi_0[k]=0,\tag{24}$$

where $(m \times m)$–matrix $\Lambda_0 = \left\| \lambda_{0,ij} \right\|$ is such that the solution to the equation (24) is asymptotically stable; in the simplest case, $\Lambda_0$ – is a numeric matrix. Substituting (23) into (24), taking into account the extended model (22), we will obtain:

$$v[k] = \Lambda_0 y[k] + \Lambda_0 \varphi_0[k] + \varphi_0[k+1]. \tag{25}$$

Then the decomposed system by $\psi_0[k] = 0$ will take the following form:

$$x[k+1] = F(x[k])x[k] + D(x[k])\varphi_0[k], \tag{26}$$

The mathematical model (26) describes the behavior of the CO at discrete moments of time $t = kT_0$, $k = \overline{0,\infty}$, in systems without delay in control channels. Therefore, applying the above procedure for the synthesis of discrete controllers based on a series-parallel set of invariant manifolds, it is not difficult for system (26) to determine such a control vector $\varphi_0[k]$, under the action of which the RP gets into the equilibrium position of the system. The desired control vector will be determined in accordance with the following expression:

$$\begin{aligned} u[k-1] = y[k] = E^{-1}\{\Lambda_0 y[k] - \Lambda_0 \varphi_0[k] + E^{+1}\varphi_0[k]\} = \\ = \Lambda_0 u[k-2] + E^{-1}\{\Lambda_0 \varphi_0[k] + E^{+1}\varphi_0[k]\}, \end{aligned} \tag{27}$$

where $E^{-1}$, $E^{+1}$ – shift operations a clock cycle back and forth.

## Conclusion

As a result, a dynamic discrete controller (27) synthesized on the basis of a series-parallel set of invariant manifolds $\psi_0[k]=0$, $\psi_1[k]=0$, $\psi_2[k]=0$, ... ensures the fulfillment of the given technological requirements, the asymptotic stability of a closed discrete-continuous system (18), (27) and has the property predicting the behavior of the system at a sampling step $T_0$.

Thus, the synthesized vector controller provides a solution to the object control problem, the transfer of an IT closed-loop system from arbitrary initial conditions to the origin of coordinates of the phase space. In addition, a dynamic discrete controller is synthesized on the basis of a series-parallel set of invariant manifolds. It ensures the fulfillment of the given technological requirements and the asymptotic stability of a closed discrete-continuous system. It has the property of predicting the behavior of the system at the discretization step.

**References:**


1. A.A.Krasovskogo, *Spravochnik po teorii avtomaticheskogo upravleniya*, Moskva: Nauka, 1987. (in Russian).
2. Y.Y. Gromov i dr., *Sistemi avtomaticheskogo upravleniya s zapazdivaniyem [Automatic control system with delay]: ucheb, posobiye*, Tambov: Izd-vo Tambov, gos. texn, unta, 2007, 76 p. (in Russian).
3. Kh.Z.Igamberdiev, A.N.Yusupbekov, O.O.Zaripov, *Regular methods for evaluating and managing dynamic objects under conditions of uncertainty*. Tashkent: Tashkent State Technical University, 2012, 320 p.
4. A.A. Kolesnikov, *Modern Applied Control Theory: Synergetic Approach in Control Theory*, Taganrog: Publishing house of TRTU, 2000. Part II.
5. X.Z.Igamberdiyev, J.U. Sevinov, O.O.Zaripov, *Regulyarniye metodi i algoritmi sinteza adaptivnix system upravleniya s nastraivayemimi modelyami [Regular methods and algorithms for the synthesis of adaptive control systems with customizable models]*. Tashkent: TashGTU, 2014, 160 p. (in Russian).
6. N.R.Yusupbekov, H.Z. Igamberdiev, J.U.Sevinov, "Formalization of Identification Procedures of Control Objects as a Process in the Closed Dynamic System and Synthesis of Adaptive Regulators", *Journal of Advanced Research in Dynamical and Control Systems*, vol. 12, no. 06-Special Issue, pp. 77-88. DOI:10.5373/JARDCS/V12SP6/SP20201009.
7. V.A.Bogdanovich, A.G.Vostretsov, *Teoriya ustoychivogo obnarujeniya razlicheniya i otsenivaniya signalov [Theory of sustained difference detection and signal evaluation]*. Izd-vo: Fizmatlit, 2004, 320 p.
8. I.V.Miroshnik, V.O.Nikiforov, A.L.Fradkov, *Nelineynoye i adaptivnoye upravleniye slojnimi dinamicheskimi sistemami [Nonlinear and adaptive control of complex dynamic systems]*. Sankt-Peterburg: Nauka, 2000, 549 p. (in Russian).
9. R.Dorf, R.Bishop, *Sovremenniye sistemi upravleniya [Modern control systems]*. Moscow: Yunimedia-stayl, 2002, 822 p.

10. G.E.Veselov, "Prikladnaya teoriya sinergeticheskogo sinteza iyerarxicheskix sistem upravleniya" [Applied theory of synergetic synthesis of hierarchical control systems], *Izvestiya TRTU. Tematicheskiy vipusk. Prikladnaya sinergetika i sistemniy sintez*, no. 6(61), pp. 73-84, 2006. (in Russian).
11. G.E.Veselov, "Sinergeticheskiy sintez vektornix diskretnix regulyatorov elektroprivodov peremennogo toka" [Synergetic synthesis of vectornix discretnix regulators of AC electric drives], *Izvestiya Tulskogo gosudarstvennogo universiteta. Seriya "Problemi unravleniya elektromexanicheskimi obyektami". Vtoraya vserossiyskaya nauchnoprakticheskaya konferensiya «Sistemi upravleniya elektromexanicheskimi obyektami»*, Tula, 2002. pp. 83-85. (in Russian).
12. A.R.Mallaev, S.N.Xusanov, J.U.Sevinov, "Algorithms of Nonparametric Synthesis of Discrete One-Dimensional Controllers", *International Journal of Advanced Science and Technology*, no. 29(5 Special Issue), pp. 1045-1050, 2020.
13. J.U.Sevinov, A.R.Mallaev, S.N.Xusanov, "Algorithms for the Synthesis of Optimal Linear-Quadratic Stationary Controllers", *In: Aliev R.A., Yusupbekov N.R., Kacprzyk J., Pedrycz W., Sadikoglu F.M. (eds) 11th World Conference "Intelligent System for Industrial Automation" (WCIS-2020). WCIS 2020. Advances in Intelligent Systems and Computing*, vol 1323, 2021. Springer, Cham. https://doi.org/10.1007/978-3-030-68004-6_9.
14. A.R.Mallayev, S.N.Xusanov, "Estimation of Parameters of Settings of Regulators Based on Active Adaptation Algorithm", *International Journal of Advanced Research in Science, Engineering and Technology*, vol. 6, Issue 8, pp.10376-10380, 2019.