MUHAMMAD AL-XORAZMIY
NOMIDAGI TATU FARG'ONA FILIALI

FERGANA BRANCH OF TUIT
NAMED AFTER MUHAMMAD AL-KHORAZMI

"AL-FARG'ONIY AVLODLARI"

ELEKTRON ILMIY JURNALI | ELECTRONIC SCIENTIFIC JOURNAL

TA'LIMDAGI ILMIY, OMMABOP VA ILMIY TADQIQOT ISHLARI

4-SON 1(4)
2023-YIL

TATU, FARG'ONA
O'ZBEKISTON

ISSN 2181-4252

O‘ZBEKISTON RESPUBLIKASI RAQAMLI TEXNOLOGIYALAR VAZIRLIGI

MUHAMMAD AL-XORAZMIY NOMIDAGI TOSHKENT AXBOROT TEXNOLOGIYALARI UNIVERSITETI FARG‘ONA FILIALI

Muassis: Muhammad al-Xorazmiy nomidagi Toshkent axborot texnologiyalari universiteti Farg‘ona filiali.
Chop etish tili: O‘zbek, ingliz, rus.
Jurnal texnika fanlariga ixtisoslashgan bo‘lib, barcha shu sohadagi matematika, fizika, axborot texnologiyalari yo‘nalishida maqolalar chop etib boradi.

Учредитель: Ферганский филиал Ташкентского университета информационных технологий имени Мухаммада ал-Хоразми.
Язык издания: узбекский, английский, русский.
Журнал специализируется на технических науках и публикует статьи в области математики, физики и информационных технологий.

Founder: Fergana branch of the Tashkent University of Information Technologies named after Muhammad al-Khorazmi.
Language of publication: Uzbek, English, Russian.
The magazine specializes in technical sciences and publishes articles in the field of mathematics, physics, and information technology.

2023 yil, Том 1, №4
Vol.1, Iss.4, 2023 y

ELEKTRON ILMIY JURNALI

ELECTRONIC SCIENTIFIC JOURNAL

«Al-Farg‘oniy avlodlari» («The descendants of al-Fargani», «Potomki al-Fergani») O‘zbekiston Respublikasi Prezidenti administratsiyasi huzuridagi Axborot va ommaviy kommunikatsiyalar agentligida 2022-yil 21 dekabrda 054493-son bilan ro‘yxatdan o‘tgan.

Jurnal OAK Rayosatining 2023-yil 30 sentabrdagi 343-sonli qarori bilan Texnika fanlari yo‘nalishida milliy nashrlar ro‘yxatiga kiritilgan.

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Qo‘lyozmalar taqrizlanmaydi va qaytarilmaydi.

FARG’ONA - 2023 YIL

TAHRIR HAY’ATI

Jurnal quyidagi bazalarda indekslanadi:

Eslatma! Jurnal materiallari to‘plamiga kiritilgan ilmiy maqolalardagi raqamlar, ma’lumotlar haqqoniyligiga va keltirilgan iqtiboslar to‘g‘riligiga mualliflar shaxsan javobgardirlar.

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ALGORITHMS FOR SYNTHESIS OF ADAPTIVE CONTROL SYSTEMS WITH IMPLICIT REFERENCE MODELS BASED ON THE SPEED GRADIENT METHOD

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Abstract: Algorithms for the synthesis of adaptive control are considered, in which the reference model acts as a certain reference equation. To obtain precise statements about the properties of a generalized custom object, some auxiliary conditions such as smoothness and regularity are introduced. The use of such systems has made it possible to reduce the requirements for the structure of the main circuit and for the completeness of the measured information, which is advisable to use in the presence of strong unmeasured disturbances, as well as in problems of controlling high-order multidimensional objects, when the implementation of a reference model in the system is impossible or difficult.

Key words: adaptive control, speed gradient algorithm, control object, reference model, unmeasured disturbance, control action.

Introduction. The current stage of development of control theory and technology is characterized by increasing requirements for control systems, increasing complexity of controlled objects, and high rates of design and commissioning of systems. These circumstances lead, as a rule, to the fact that the available initial information is insufficient to build systems with high quality indicators and it is necessary to replenish the information during the operation of the system. Such systems, in which the information necessary to improve functioning is collected during operation, immediately processed and used for control, are called adaptive. Adaptive systems are currently finding increasing use for managing objects and processes under conditions of uncertainty. An adaptive system uses a control law with variable coefficients. The coefficients are changed by a special algorithm (adaptation algorithm) based on current information about the state of the process obtained during normal operation of the installation. The adaptation algorithm is constructed in such a way as to adapt to a specific situation and ensure the achievement of the control goal for any possible value of the unknown parameters of the object [1-7].

The gradient principle is widely used to synthesize the adaptation algorithm. In this case, the evaluation function, the gradient of which determines the direction of change in the adjustable parameters, may coincide with the evaluation function that sets the control goal, or may differ from it. If the control goal is given to the designer of the adaptive system from the outside, then the adaptation goal is set by the designer himself when synthesizing the adaptation algorithm. The separation of control and adaptation goals, generally speaking, expands the designer's capabilities. However, this makes it more difficult to justify the system’s performance, since achieving the adaptation goal may not directly result from achieving the original control goal. The above considerations explain the origin of speed gradient algorithms. However, our task is to establish the general properties of algorithms that allow us to judge the stability and quality of specific adaptive systems [3,8-14,21].

Formulation of the problem

Let the equation of a generalized custom object be given:

$$dx/dt = F(x,c,t,\xi), \qquad (1)$$

where $x=\{x^{(1)},...,x^{(n)}\}$ – is the state vector of the generalized customizable object (GCO); $c=\{c^{(1)},...,c^{(N)}\}$ – vector of adjustable parameters; $\xi=\{\xi^{(1)},...,\xi^{(q)}\}$ – vector of unknown object parameters and external influences. Let us assume that the adaptation goal is specified using the evaluation functional Q_t, and approaching the goal corresponds to a decrease in the values. We will consider two cases Q_t [2,3,10]:

a) the estimated functional Q_t is a non-negative function of the phase coordinates of GCO: $Q_t = Q(x(t),t)$. We will call such a functional Q_t local.

b) Q_t is the integral functional: $Q_t = \int_0^t R(x(s),c(s),s)ds$, where $R(x,c,t)$ – is some non-negative function..

In each of these cases, it is possible to calculate function $\dot{Q}_t$ – the rate of change of functional Q_t by virtue of equation (1) for a fixed c. Obviously, in case a)

$$\dot{Q}_t = \partial Q(x(t),t)/\partial t + F(x(t),c(t),t,\xi)^T \nabla_x Q(x(t),t),$$

and in case b), $\dot{Q}_t = R(x(t),c(t),t)$ i.e. in both cases:

$$\dot{Q}_t = \psi(x(t),c(t),t),$$

where $\psi(x,c,t)$ – is some function that we will assume is continuously differentiable with respect to the components of vector c.

Let's call the following adaptation algorithm the speed gradient algorithm:

$$dc/dt = -\Gamma\nabla_c \psi(x,c,t), \qquad (2)$$

where $\Gamma = \Gamma^T > 0$ – is a positive definite $N \times N$ – is the matrix of gain factors.

It should be noted that the right-hand side in relation (2) may turn out to depend on unknown parameters ξ or on phase coordinates of the GCO that are inaccessible to measurement, and then algorithm (2) will be unrealizable. The question of the feasibility of the algorithm and the class Ξ of adaptability of the system (1), (2) must be solved separately in each specific problem.

To obtain precise statements about the properties of the system (1), (2), it is necessary to impose some auxiliary conditions such as smoothness and regularity on the right-hand sides of the system and the functional Q_t, excluding “pathological” cases [1,2,15,16]. We will assume that the right-hand sides of (1), (2) are locally bounded uniformly in $t \ge 0$, i.e., for any $\rho > 0$ the following inequality holds:

$$\|F(z,t,\xi)\| + \|\nabla_c \psi(z,t,)\| \le \aleph_\rho < \infty \qquad (3)$$

at $\|z\| \le \rho,\ t \ge 0$, where $z=\{x,c\}$ is the state vector of the system (1), (2). Note that condition (3) does not exclude the possibility of discontinuities along t in the right-hand sides of (1), (2). Function $Q(x,t)$ in the case of local functional Q_t will be considered uniformly continuous in $x,\ t$ in any domain of the form $\{x,t : \|x\| \le \rho,\ t \ge 0\}$. In addition, we will require sufficient smoothness of the functions $Q(x,t),\ F(x,c,t,\xi),\ R(x,c,t)$ so that all their derivatives arising in the formulations of the statements exist and are continuous in $x,\ c$.

Let us assume that the adaptation goal to be achieved by algorithm (2) is given by the relation:

$$\lim_{t\to\infty} Q_t = 0, \qquad (4)$$

(in the case of local functional Q_t) or the relation:

$$\lim_{t\to\infty} R(x(t),c(t),t) = 0, \qquad (5)$$

(in the case of integral functional Q_t). We are interested in the conditions under which goals (4), (5) in systems (1), (2) are achieved for any initial values $x(0), c(0)$. The first of these conditions is the convexity of the c function $\psi(x,c,t)$, i.e., the fulfillment of the inequality [21]:

$$\psi(x,c,t)-\psi(x,c',t)\geq(c-c')^T\nabla_c\psi(x,c',t) \quad (6)$$

for any $c,\ c',\ x,\ t$. Condition (6) is satisfied, for example, in the frequently encountered case when the right side of the GCO equation (1) linearly depends on the adjustable parameters. The second main condition is the fundamental achievability of the goal, i.e. the existence of an "ideal" vector c_* (depending, perhaps, on ξ), such that in system (1) at $c=c_*$ goal (4) or (5) is achieved. More precisely, by the condition of attainability we will understand the fulfillment of the inequality [21]:

$$\psi(x,c_*,t)\leq-\beta Q_t+\mu(t), \quad (7)$$

where $\beta\geq 0,\ \mu(t)\geq 0,\ \int_0^\infty \mu(t)<\infty$.

Solution of the task

It can be shown that from relation (7) it follows that goals (4), (5) are achieved (in the case of goal (4) with the additional requirement $\beta>0$).

Let the functional Q_t be local and the convexity condition (6), the reachability condition (7) for $\beta>0$, and the growth condition are satisfied [2,10]:

$$\inf_t Q(x,t)\to\infty \text{ at } \|x\|\to\infty. \quad (8)$$

Then all trajectories of system (1), (2) are bounded and satisfy (4) [21].

Let the control object be described by the equations:

$$dx/dt=Ax+bu,\ \ y=L^Tx,\ \ u=c^Ty, \quad (9)$$

where $x\in R^n,\ u\in R^1,\ y\in R^l,$ – vector of measured outputs; c – vector of adjustable parameters.

It is required to find an algorithm for adjusting vector $c(t)$ so as to ensure achievement of the goal:

$$x(t)\to 0,\ \ c(t)\to \text{const}. \quad (10)$$

Let us choose the evaluation function $Q_t=0{,}5x^THx$, where $H=H^T>0$, and use the velocity gradient principle. We have $\dot{Q}_t=x^TH(Ax+bc^Ty),\ \nabla_c\dot{Q}_t=x^THby$. Since the value x^THb should depend only on the measured quantities, we arrive at condition $Hb=Lg$, and if it is satisfied, we write the speed gradient algorithm in the form:

$$dc/dt=-g^Ty\Gamma y, \quad (11)$$

where $\Gamma=\Gamma^T>0$.

The only condition (8) that needs special verification is the solvability condition (7). It will be satisfied if there is a vector c_* such that $x^THA_*x<0$, where $A_*=A+bc_*^TL^T$. Therefore, to check (7) we need conditions for the existence of a matrix $H=H^T>0$ and a vector c_* such that

$$HA_*+A_*^TH<0,\ Hb=Lg,\ \ A_*=A+bc_*^TL^T. \quad (12)$$

For the existence of a matrix $H=H^T>0$ and a vector c_* satisfying (12), it is necessary and sufficient that the polynomial $\delta(\lambda)=g^TW(\lambda)$ be a Hurwitz polynomial of degree $n-1$ with positive coefficients, where $W(\lambda)=L^T(\lambda I_n-A)^{-1}b$ – is the transfer vector function of the object, $\delta(\lambda)=\det(\lambda I_n-A)$ – is the common denominator of its components.

As is known [17, 18], systems in which the numerator of the transfer function is a Hurwitz polynomial are called minimum-phase. Minimum-phase systems, the numerator of the transfer function of which has the maximum possible (equal to *n–1*) degree and positive coefficients, will be called strictly minimum-phase. The transfer function of a strictly minimum-phase system will also be called strictly minimum-phase. Taking into account the introduced ones, (12) can be formulated as follows: for the existence of a matrix $H=H^T>0$ and a vector c_* satisfying (12), it is necessary and sufficient that the function $g^TW(\lambda)$ be strictly minimal-phase.

From (12) and (8) it follows that for a given vector, the adaptation goal (10) in the system (9), (11) is achieved for any object (9) such that function $g^TW(\lambda)$ is strictly minimal-phase. If adaptability class

Ξ is specified, then the synthesis of an adaptive stabilization system is reduced to finding a vector *g* that provides for any object from class Ξ strict minimum phase function $g^T W(\lambda)$.

Let's consider a common special case when the object is described by equation

$$A(p)\eta = B(p)u, \qquad (13)$$

$$A(\lambda) = \lambda^n + a_{n-1}\lambda^{n-1} + ... + a_0,\ B(\lambda) = b_m\lambda^m + ... + b_0$$

and the output variable η along with its $l-1$ derivatives is available for observation, i.e. $y = \{\eta, \dot{\eta}, ..., \eta^{(l-1)}\}$. The controller will be described by equation $u = C(p)\eta$, where $C(\lambda) = \sum_{i=0}^{l-1} c_i\lambda^i$. The adaptation algorithm (at $\Gamma = \gamma I_l$) is written by the equations:

$$\dot{c}_i = -\gamma G(p)\eta \cdot \eta^{(i)},\ i = 0,1,...,\ l-1,$$

in which the coefficients of the polynomial $G(p)$ correspond to the components of the vector *g* from (11).

The transfer vector function of the object has the form:

$$W(\lambda) = \frac{B(\lambda)}{A(\lambda)}\{1, \lambda, ..., \lambda^{l-1}\},$$

where $g^T W(\lambda) = G(\lambda)B(\lambda)/A(\lambda),\ \delta(\lambda) = A(\lambda)$. Therefore, the strict minimum phase property of function $g^T W(\lambda)$ means that the polynomials $G(\lambda), B(\lambda)$ are Hurwitz [1, 19], the signs of their coefficients coincide $m + l = n$. Consequently, by choosing a Hurwitz polynomial $G(\lambda)$, of degree $n-m-1$ with coefficients of the same sign as those of $B(\lambda)$, we can guarantee the achievement of the adaptation goal $\eta(t) \to 0$ for any minimum-phase object of the form (13). To implement an adaptive controller, an $n-m-1$ derivative of the controlled object coordinate is required [13,20]. The results of modeling such systems for various special cases show that the adaptation process in them proceeds several times faster than the transition process according to $x(t)$, even in the case of an unstable object (13). In this case, the value $G(p)\eta$ after adaptation becomes close to zero, which allows us to interpret equation $G(p)\eta = 0$ as a reference characterizing the quality of the object’s processes after adaptation is completed.

The described approach can be extended to systems for monitoring the reference influence $r(t)$. In this case, $Q_t = [x - x_0(t)]^T H[x - x_0]$ should be taken as an evaluation function, where $x_0(t)$ – is the equilibrium state of the system with “ideal” regulator coefficients, calculated under the assumption that the setting influence is established at the level of $r(t)$.

For a special case of object (13), the adaptive controller will have the form:

$$u = C(p)\eta - C_1(p)r,\ dc_i/dt = -\gamma_i'\delta(t)\eta^{(i)},\ i = 0,...,n-m-1,$$
$$dc_{1i}/dt = -\gamma_i''\delta(t)r^{(i)},\ i = 0,...,k,\ \delta(t) = G(p)\eta - G_1(p)r(t), \qquad (14)$$

where the degree of polynomial $C(\lambda)$ is equal to $n-m-1$; the power of $C_1(\lambda)$ is equal to the number of k available derivatives of $r(t)$; $C(\lambda)$ – Hurwitz polynomial; $\gamma_i', \gamma_i'' > 0$.

Equation $G(p)\eta_M = G_1(p)r$ can be considered as a reference and polynomials $C(\lambda)$, $C_1(\lambda)$ can be selected based on the desired quality of the system after adaptation. It can be shown, using (8), that $\eta(t) - \eta_M(t) \to 0$ if the setting influence $r(t)$ is established more accurately, if

$$\int_0^\infty \left| r^{(i)}(t) \right|^2 dt < \infty,\ i = 1,...,l+1.$$

Conclusion

Thus, the use of such systems makes it possible to reduce the requirements for the structure of the main circuit and for the completeness of the measured information. It is advisable to use them in the presence of strong unmeasured disturbances, as well as in control problems of high-order multidimensional objects, when implementation of a reference model in the system is impossible or difficult.

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