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Algorithms for Synthesis of Adaptive Decentralized Control of Interconnected Systems by The Speed Gradient Method

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Abstract. *Synthesizing algorithms of decentralized adaptive control for a class of interconnected systems with nonlinear local dynamics and uncertainty are considered, ensuring the stability of isolated subsystems of the entire system, taking into account interactions. When connected to a stable isolated subsystem, the system's stability may be violated and the objective function will cease to be a Lyapunov function for a system with connections. Very strong connections can significantly change the dynamics of the system, and the behavior of subsystems in an isolated state will be radically different from the behavior in a coupled system. Therefore, the law of control of a complex system, which ensures only the stability of isolated subsystems, cannot guarantee the stability of the entire system considering interactions. At the same time, to solve the problem of taking into account the interactions of subsystems, an adaptation algorithm based on the speed gradient method was introduced into the general control law. The results of the numerical analysis confirmed their effectiveness, which allows them to be used in solving applied problems of synthesizing systems for decentralized adaptive control of technological objects.*

Keywords: *adaptive decentralized control, interconnected systems, speed gradient algorithm, control object, objective function, control action*

Introduction

According to theoretical point of view, completely centralized systems in control theory are considered ideal, allowing for the greatest effect. However, the implementation of a single controller that measures the entire set of state variables and generates the entire set of controls in a complex system is fraught with great difficulties and requires high costs. In practice, a system is often built in such a way that, due to its design features, it is divided into localized subsystems that have a certain degree of autonomy in the sense that the subsystem can function and be controlled not only by a system-wide body but also independently by a local regulator. If the original system allows for division into a number of interacting systems, then the decentralized control algorithm for each subsystem generates a control action based on information about the state of only this subsystem, without taking into account the state of other subsystems [1-8]. In this case, control synthesis is usually preceded by a simplification of the problem, which consists in discarding connections between subsystems. Therefore, the problems of adaptive decentralized control of interconnected systems occupy an important place in the theory of control of complex systems.

1. Problem formulation

Let us consider a control object (CO), consisting of interacting subsystems, the dynamics of each N of which is described by the following equations:

$$\dot{x}_i = f_i(x_i) + b_i(x_i, u_i) + h_i(x); \; i = 1,2,...,N, \tag{1}$$

where $x_i \in R^{n_i}$ – state vector of the i^{th} subsystem, $u_i \in R^{m_i}$ – input vector of the i^{th} subsystem, $n = \sum_{i=1}^{N} n_i$, $m = \sum_{i=1}^{N} m_i$, $x = col(x_1, x_2, ..., x_N) \in R^n$ – cumulative system state vector, $f_i(\cdot)$, $b_i(\cdot)$, $h_i(\cdot)$ – continuously differentiable vector functions.

Thus, CO (1) is a complex system consisting of N interconnected nonlinear subsystems, where the $f_i(\cdot)$, $b_i(\cdot)$ functions characterize the own dynamics of the i^{th} subsystem, and the $h_i(\cdot)$ functions describe the connections (interactions) between the subsystems. We will assume that all the uncertainty of the subsystems lies in the connection functions $h_i(\cdot)$ satisfying the following inequality:

$$h_i \le \sum_{j=1}^{N} \xi_{i,j} \left| x_j \right|, \; \xi_{i,j} \ge 0, \; i = 1,2,...,N. \tag{2}$$

Setting the task: to build a decentralized control algorithm:

$$u_i = U_i(x_i, \hat{\theta}_i), \tag{3}$$

$$\dot{\hat{\theta}}_i = \Theta_i(x_i, \hat{\theta}_i), \tag{4}$$

where $\hat{\theta}_i \in R^r$ – adjustable parameters ensuring the limited trajectories of the closed-loop system (1), (3), (4) and achieving the control goal:

$$Q_i(x_i(t)) \to 0 \text{ при } t \to \infty, \tag{5}$$

where $Q_i(x_i) \geq 0$ – given smooth objective functions, $i = 1,2,...,N$.

The task is significantly simplified if we discard connections between subsystems and consider the CO (1) as a set of isolated subsystems, i.e.

$$\dot{x}_i = f_i(x_i) + b_i(x_i, u_i),\ i = 1,2,...,N. \tag{6}$$

Then control algorithms $u_i^*(x_i)$ that ensure the fulfillment of quadratic type inequalities for local objective functions [2, 3, 9-12]

$$\begin{gathered}\alpha_{1i}|x_i|^2 \leq Q_i(x_i) \leq \alpha_{2i}|x_i|^2,\\ |\nabla Q_i(x_i)| \leq \beta_i |x_i|^2,\\ \dot{Q}_i(x_i, u_i)\Big|_{u_i = u_i^*(x_i)} \leq -\rho_i |x_i|^2,\end{gathered} \tag{7}$$

where $Q_i(x_i)\Big|_{u_i = u_i^*(x_i)} = \nabla Q_i(x_i)^T (f_i(x_i) + b_i(x_i, u_i^*(x_i)));$ $\alpha_{1i}, \alpha_{2i}, \beta_i, \rho_i > 0,\ i = 1,2,...,N$, guarantee exponential stability of the entire CO.

However, the presence of interactions between subsystems qualitatively changes the behavior of a complex system (1), and the fulfillment of inequalities (7) for each isolated subsystem obviously does not mean the stability of the entire system (1). Indeed, for a system without interactions (6), the derivative of the objective function AA has the form:

$$\dot{Q}_i(x_i, u_i) = Q_i(x_i)^T (f_i(x_i) + b_i(x_i, u_i)),$$

and for a system with connections (1):

$$\dot{Q}_i(x_i, u_i) = \nabla Q_i(x_i)^T (f_i(x_i) + b_i(x_i, u_i) + h_i(x)),$$

i.e. the stability of each subsystem depends on other subsystems. Thus, when connected to a stable isolated subsystem of connections, stability may be violated and the objective function will cease to be a Lyapunov function for a subsystem with connections.

Very strong connections can significantly change the dynamics of the system, and the behavior of subsystems in an isolated state will be radically different from the behavior in a connected system [3, 12-14]. Therefore, the control law for a complex system (1), which ensures only the stability of isolated subsystems, cannot guarantee the stability of the entire system taking into account interactions.

2. Construction of a decentralized adaptive control law

Let assume that each i^{th} isolated subsystem (6) is exponentially stabilized, i.e., control laws $u_i^*(x_i)$, $i = 1,2,...,N$ are known that satisfy inequalities of type (7).

Let's assume that the functions $u_i^*(x_i)$ can be represented as follows:

$$u_i^*(x_i) = U_i(x_i, \theta_i),\ i = 1,2,...,N,$$

where θ_i –some constant parameters (for example, gains involved in the control law).

Then the control algorithm for the system with interactions (1) is chosen as following:

$$u_i = U_i(x_i, \hat{\theta}_i),\ i = 1,2,...,N, \quad (8)$$

Where the function $U_i(\cdot)$ – the same as before, however, instead of the known constant parameters θ_i in the control law (8), their settings $\hat{\theta}_i$ are used, calculated by the adaptation algorithm, based on the speed gradient method.

To synthesize the adaptation algorithm, following the speed gradient method, the total derivative of the objective function $Q_i(x_i)$ along the trajectories of the system was calculated (6), (8):

$$\dot{Q}_i(x_i, \hat{\theta}_i) = \nabla Q_i(x_i)^T (f_i(x_i) + b_i(x_i, U_i(x_i, \hat{\theta}_i))).$$

Then the velocity gradient looks like this:

$$\nabla_{\hat{\theta}_i} \dot{Q}_i(x_i, \hat{\theta}_i) = \nabla_{\hat{\theta}_i} (Q_i(x_i)^T b_i(x_i, U_i(x_i, \hat{\theta}_i))),$$

and the adaptation algorithm looks like:

$$\dot{\hat{\theta}}_i = -\gamma_i \nabla_{\hat{\theta}_i} (\nabla Q_i(x_i)^T b_i(x_i, U_i(x_i, \hat{\theta}_i))),\ i = 1,2,...,N. \quad (9)$$

Taking into account the constructed adaptive control law (8), (9), we will consider new Lyapunov functions $V_{ia}(x_i, \hat{\theta}_i)$ for subsystems (6), depending on the adjustable parameters $\hat{\theta}_i \in R^r$ and having the following form:

$$V_{ia}(x_i, \hat{\theta}_i) = Q_i(x_i) + \frac{1}{2\gamma_i}(\hat{\theta}_i - \theta_i)^T(\hat{\theta}_i - \theta_i). \quad (9)$$

3. Properties of a synthesized control system

Let the following conditions be satisfied for CO (1):

a) for each i^{th} isolated subsystem (6) there are smooth functions $U_i(x_i, \hat{\theta}_i)$, vectors and positive numbers $\alpha_{1i}, \alpha_{2i}, \beta_i, \rho_i, i = 1,2,...,N$ such that the following inequalities are satisfied:

$$\alpha_{1i}|x_i|^2 \le Q_i(x_i) \le \alpha_{2i}|x_i|^2,$$
$$|\nabla Q_i(x_i)| \le \beta_i |x_i|, \quad (10)$$
$$\dot{Q}_i(x_i, u_i)\Big|_{u_i = U_i(x_i, \theta_i)} \le -\rho_i Q_i(x_i),$$

where $\dot{Q}_i(x_i, \hat{\theta}_i)\Big|_{u_i = U_i(x_i, \theta_i)} = \dot{Q}_i(x_i, \theta_i) = \nabla Q_i(x_i)^T (f_i(x_i) + b_i(x_i, U_i(x_i, \theta_i))),$ – condition of stabilization of the i^{th} isolated subsystem;

b) the complete derivatives of the objective functions $Q_i(x_i)$ are convex in $\hat{\theta}_i$, i.e. for any $\hat{\theta}_i, \hat{\theta}_i', x_i$, the convexity conditions are satisfied—the following inequalities:

$$Q_i(x_i, \hat{\theta}_i') = \dot{Q}_i(x_i, \hat{\theta}_i) \ge (\hat{\theta}_i - \hat{\theta}_i')^T \nabla_{\hat{\theta}_i}(\dot{Q}_i(x_i, \hat{\theta}_i)), \quad (11)$$

c) interaction functions $h_i(\cdot),\ i = 1,2,...N$ satisfy condition (2) and the additional condition:

$$\beta_i^2 + \sum_{j=1}^{N} \xi_{ij}^2 < 2\rho_i \alpha_{1i} / \sqrt{N}, \quad i = 1, 2, ..., N. \tag{12}$$

Then the decentralized adaptive control law:

$$\begin{aligned} u_i &= U_i(x_i, \hat{\theta}_i), \\ \dot{\hat{\theta}}_i &= -\gamma_i \nabla_{\hat{\theta}_i} (\nabla Q_i^T b_i(x_i, U_i(x_i, \hat{\theta}_i))), \end{aligned} \tag{13}$$

where $\gamma_i > 0,\ i = 1, 2, ... N$, ensures the limited trajectories of the closed-loop system (1), (13) and the achievement of the control goal (5).

Let us define the Lyapunov function for a complex system (1) as the sum of the Lyapunov functions of subsystems (9):

$$V_a(x, \hat{\theta}) = \sum_{i=1}^{N} V_{ia}(x_i, \hat{\theta}_i) = \sum_{i=1}^{N} \{Q_i(x_i) + \frac{1}{2\gamma_i}(\hat{\theta}_i - \theta_i)^T (\hat{\theta}_i - \theta_i)\}$$

and calculate its total derivative. By virtue of system (1), (13), we write:

$$V_a = \sum_{i=1}^{N} \left\{ \nabla Q_i^T \left(f_i(x_i) + b_i(x_i, U_i(x_i, \hat{\theta}_i)) + h_i(x) \right) + \frac{1}{\gamma_i} (\hat{\theta}_i - \theta_i)^T \dot{\hat{\theta}}_i \right\} =$$

$$= \sum_{i=1}^{N} \left\{ \nabla Q_i^T \left(f_i(x_i) + b_i(x_i, U_i(x_i, \hat{\theta}_i)) \right) + \nabla Q_i^T h_i(x) - (\hat{\theta}_i - \theta_i)^T \nabla_{\hat{\theta}_i} (\nabla Q_i^T b_i) \right\}.$$

Using the convexity condition, we have:

$$V_a = \sum_{i=1}^{N} \left\{ \dot{Q}_i(x_i, \hat{\theta}_i) - (\hat{\theta}_i - \theta_i)^T \nabla_{\hat{\theta}_i}(Q_i) + \nabla Q_i^T h_i(x) \right\} \le \sum_{i=1}^{N} \left\{ \dot{Q}_i(x_i, \theta_i) + \nabla Q_i^T h_i(x) \right\}.$$

Then from the condition of stabilizability of isolated subsystems and restrictions on the functions of relationships $h_i(\cdot)$ (2) and target functions $Q_i(\cdot)$ (10) it follows that:

$$\dot{V}_a \le -\sum_{i=1}^{N} \rho_i Q_i(x_i) + \sum_{i=1}^{N} \beta_i |x_i| \sum_{j=1}^{N} \xi_{ij} |x_j| \le -\sum_{i=1}^{N} \alpha_{1i} \rho_i |x_i|^2 + \sum_{i=1}^{N} \beta_i |x_i| \sum_{j=1}^{N} \xi_{ij} |x_j|.$$

Applying to the last expression the well-known scalar inequality $2ab \le a^2 / c + b^2 c$ valid for $c > 0$, we have:

$$\sum_{i=1}^{N} \beta_i |x_i| \sum_{j=1}^{N} \xi_{ij} |x_j| \le \sum_i \sum_j \left(\frac{\beta_i^2 |x_i|^2}{2\sqrt{N}} + \frac{\xi_{ij}^2 |x_j|^2}{2} \sqrt{N} \right) =$$

$$= \sum_i \frac{\sqrt{N}}{2} \beta_i^2 |x_i|^2 + \sum_j \frac{\sqrt{N}}{2} |x_j|^2 \sum_i \xi_{ij}^2 = \sum_i \left\{ |x_i|^2 \frac{\sqrt{N}}{2} \left(\beta_i^2 + \sum_j \xi_{ij}^2 \right) \right\}.$$

Let us introduce the following notation:

$$\eta_i \overset{\Delta}{=} \frac{\sqrt{N}}{2} \left(\beta_i^2 + \sum_j \xi_{ij}^2 \right) - \rho_i.$$

By choosing $h_i(\cdot)$, satisfying inequalities (2) and (12), we obtain that $\eta_i > 0$. As a result we have:

$$\dot{V}_a \le -\sum_{i=1}^{N} \eta_i |x_i|^2 \le -\sum_{i=1}^{N} \frac{\eta_i}{\alpha_{2i}} Q_i(x_i), \tag{14}$$

where $\eta_i / \alpha_{2i} > 0$.

Thus, $\dot{V}_a(x, \hat{\theta}) \le 0$, whence it follows that $V_a(x(t), \hat{\theta}(t)) \le V_a(x(0), \hat{\theta}(0))$, i.e. $V_a(x(t), \hat{\theta}(t))$, does not increase and is bounded from below, and therefore has a finite limit at $t \to \infty$.

Integrating (14) over the interval [0, t], we obtain the following inequality:

$$0 \le \sum_{i=1}^{N} Q(x_i(t)) \le V_a(x(t), \hat{\theta}(t)) \le V_a(x(0),\ \hat{\theta}(0)) - \sum_{i}^{N} \frac{\eta_i}{\alpha_{2i}} \int_0^t Q_i(x_i(s))ds,$$

whence it follows that $\int_0^\infty Q_i(x_i(t))dt \;\; i = 1, 2, ..., N$, exist and are finite.

The boundedness of the trajectories $x(t), \hat{\theta}(t)$ of the system (1), (13) follows from the growth condition (10) of the functions $Q_i(\cdot), i = 1, ..., N$.

Further, taking into account the boundedness of the right-hand sides of the closed-loop system (1), (13), it can be shown that all $x_i(t)$ are uniformly continuous, and, therefore, all functions $Q_i(x_i(t))$ are uniformly continuous and integrable on $[0, \infty)$. Then, using Barbalata's lemma [3,14–17], we obtain that $Q_i(x_i(t)) \to 0$ for $t \to \infty$.

The adaptation algorithm in (13) can be obtained using the so-called diagonal dominance principle [3, 18]. Note also that condition (*a*) ensures the achievement of the control goal (CG) in each i^{th} isolated subsystem, and condition (*c*) determines the permissible degree of interconnection of subsystems. Connections that satisfy condition (*b*) can be called connections of a homogeneous type.

Consideration of interactions of a heterogeneous type, subject to weakened inequalities:

$$h_i(x) \le \sum_{j=1}^{N} \xi_{ij} |x_j| + d_i, \tag{15}$$

where $d_i > 0,\ i = 1, ..., N$, allows you to take into account the influence of limited disturbances. In this case, we cannot guarantee that the original control goal (4) will be achieved. However, as will be shown below, it turns out to be possible to provide a weakened control center that ensures the convergence of system trajectories into a certain limited limit set in the state space of the system. It should be noted that the adaptive control law (13) cannot ensure the achievement of even the specified weakened goal [17-19], therefore the control algorithm (13) must be coarsened in various ways: for example, by introducing a dead zone or, as shown in the following theorem, by introducing negative feedback adaptation algorithm.

Let the interaction functions satisfy condition (15), and the additional condition:

$$\beta_i^2 + \sum_{j=1}^{N} \xi_{ij}^2 < 2 p_i \alpha_{1i} / \sqrt{N},\ i = 1, 2, ..., N. \tag{16}$$

Then the decentralized adaptive control law:

$$u_i = U_i(x_i, \hat{\theta}_i),$$
$$\dot{\hat{\theta}}_i = -\lambda_i \{\nabla_{\hat{\theta}}(\nabla Q_i^T b_i(x_i U_i(x_i, \hat{\theta}_i))) - \sigma_i \hat{\theta}_i\}, \quad (17)$$

where $\gamma_i > 0, \alpha_i > 0$ – constant gain factors, $i = 1,2,...,N,$ ensures limited trajectories of the closed-loop system (1), (17) and achieves a weakened control goal:

$$\lim_{t \to \infty} Q_i(x_i(t)) \le \Delta_i, \quad (18)$$

where $\Delta_i \ge 0, i = 1,2,....N.$

Let us define the Lyapunov function for system (1), (15) as the sum of Lyapunov functions (9):

$$V_a(x, \hat{\theta}) = \sum_{i=1}^{N} V_{ia}(x_i, \hat{\theta}_i) = \sum_{i=1}^{N} \{Q_i(x_i) + \frac{1}{2\gamma_i}(\hat{\theta}_i - \theta_i)^T (\hat{\theta}_i - \theta_i)\}.$$

and calculate its total derivative due to system (1), (17):

$$V_a = \sum_{i=1}^{N} \{\nabla Q_i^T (f_i(x_i) + b_i(x_i, U_i(x_i, \hat{\theta}_i))) + \nabla Q_i^T h_i(x_i) - (\hat{\theta}_i - \theta_i)^T \nabla_{\hat{\theta}_i} (\nabla Q_i^T b_i) - (\hat{\theta}_i - \theta_i)^T \sigma_i, \hat{\theta}_i\}.$$

Then, agreeing with the above method, we will have the following:

$$\dot{V}_a = \sum_{i=1}^{N} \{\dot{Q}_i(x_i, \hat{\theta}_i) - (\hat{\theta}_i - \theta_i)^T \nabla_{\hat{\theta}_i}(Q_i) + \nabla Q_i^T h_i(x) -$$
$$-(\hat{\theta}_i - \theta_i)^T \sigma_i \hat{\theta}_i\} \le \sum_{i=1}^{N} \{\dot{Q}_i(x_i, \theta_i) + \nabla Q_i^T h_i(x) - (\hat{\theta}_i - \theta_i)^T \sigma_i \hat{\theta}_i\}.$$

Then from the condition of stabilizability of isolated subsystems and restrictions on the interconnection functions $h_i(\cdot)$ (15) and objective functions $Q_i(\cdot)$ (10) it follows that:

$$\dot{V}_a \le -\sum_{i=1}^{N} \{-p_i \dot{Q}_i(x_i) + \beta_i |x_i| (\sum_{j=1}^{N} \xi_{ij} |x_i| + d_i) - (\hat{\theta}_i - \theta_i)^T \sigma_i \hat{\theta}_i\} \le$$
$$\le -\sum_{i=1}^{N} \alpha_{1i} p_i |x_i|^2 + \sum_{i=1}^{N} \beta_i |x_i| \sum_{i=1}^{N} \xi_{ij} |x_i| + \sum_{i=1}^{N} \beta_i |x_i| d_i - \sum_{i=1}^{N} \sigma_i (\hat{\theta}_i - \theta_i)^T \hat{\theta}_i.$$

При $\sigma_i (\hat{\theta}_i - \theta_i)^T \hat{\theta}_i \ge \frac{\sigma_i}{2} \left|\hat{\theta}_i - \theta_i\right|^2 - \frac{\sigma_i}{2} |\theta_i|^2$ и $\beta_i d_i |x_1| \le \frac{\eta_i}{2} |x_1|^2 + \frac{\beta_i^2 d_i^2}{2\eta_i}$.

It can be written as follows:

$$\dot{V}_a \le \sum_{i=1}^{N} \left\{ -\frac{\eta_i}{2} |x_i|^2 - \frac{\sigma_i}{2} \left|\hat{\theta}_i - \theta_i\right|^2 + \frac{\beta_i^2 d_i^2}{2\eta_i} + \frac{\sigma_i}{2} |\theta_i|^2 \right\} \le$$
$$\le \sum_{i=1}^{N} \left\{ -\frac{\eta_i}{2\alpha_{2i}} Q_i(x_i) - \frac{\sigma_i}{2} \left|\hat{\theta}_i - \theta_i\right|^2 + \frac{\beta_i^2 d_i^2}{2\eta_i} + \frac{\sigma_i}{2} |\theta_i|^2 \right\}.$$

Denoting $p_i' = \min\{\frac{\eta_i}{2\alpha_{2i}}, \sigma_i \gamma_i\}$. Then:

$$\dot{V}_a \le \sum_{i=1}^{N} \left\{ -p_i'(Q_i(x_i) + \frac{1}{2\gamma_i}(\hat{\theta}_i - \theta_i)^T (\hat{\theta}_i - \theta_i)) \right\} + \sum_{i=1}^{N} \frac{\beta_i^2 d_i^2}{2\eta_i} + \frac{\sigma_i}{2} |\theta_i|^2 .$$

Introduce denotation

$$A_i \overset{\Delta}{=} p_i',\ B_i \overset{\Delta}{=} \frac{\beta_i^2 d_i^2}{2\eta_i} + \frac{\sigma_i}{2}\left|\theta_i\right|^2 .$$

Then

$$\dot{V}_a = \sum_{i=1}^{N} \dot{V}_i \le \sum_{i=1}^{N} \{-A_i V_i + B_i\} .$$

Integrating the resulting differential inequality, we obtain:

$$Q_i(x_i(t)) \le V_i(x_i(t)\theta_i(t)) \le V_i(x_i(0)\theta_i(0))y^{-A_i t} + \frac{B_i}{A_i},\ i = 1,2,...,N,$$

whence it follows that the trajectories $x_i(t)$, $\hat{\theta}_i(t)$ are bounded and, in addition,

$$\lim_{t\to\infty} Q_i(x_i(t)) \le \Delta_i ,$$

where $\Delta_i = \dfrac{A_i}{B_i}$, $i = 1, 2, ..., N$.

Conclusion

Obtained results make it possible to ensure not only the stability of isolated subsystems, but also the stability of the entire system, taking into account interactions. At the same time, to solve the problem of taking into account the interactions of subsystems, an adaptation algorithm based on the speed gradient method is introduced into the general control law.

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