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Adaptive control of non-stationary linear systems

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Abstract: *The problem of analysis and synthesis of robust and adaptive control algorithms for uncertain non-stationary linear and non-linear systems is a topical issue in the field of dynamic systems control. Despite the presence of numerous publications, many problems in this area remain unsolved or insufficiently studied. In particular, among the topical problems, one can single out the control of linear non-stationary systems with unknown coefficients. Modern control methods, such as robust and adaptive control, allow solving stabilization and tracking problems for non-stationary objects, but there is a limitation on the type of uncertainty and the structure of model matrices.*

Key words: *adaptive control, robust control, non-stationary systems, uncertainties, algorithm synthesis, linear systems, nonlinear systems.*

Introduction

The problem of analysis and synthesis of algorithms for robust and adaptive control of uncertain non-stationary linear and non-linear systems by output is relevant. Despite the fact that the problem of non-stationary systems control is not new and many publications are devoted to it, it should be noted that a number of relevant problems still do not have satisfactory solutions. To date, a number of interesting results have been obtained for linear systems, affecting the problem of control under conditions of slow parameter change [6], periodic parameter change [1], as well as for the case of special structures of matrices for describing non-stationary models [8]. However, a special place is occupied by problems of control of linear non-stationary systems with unknown coefficients. Among the methods of control under uncertainty, as a rule, algorithms that ensure a given behavior of the system for a class of mathematical models of a certain structure prevail. Such approaches, in particular, include adaptive and robust control schemes that allow solving stabilization and tracking problems for non-stationary objects in which the uncertainty is consistent with the control input [9 11]. One can also highlight the work devoted to the stabilization of non-stationary models of a more general structure [2]. However, the class of uncertainties considered in [2] is limited to the case when the uncertainty matrix is less than one in norm.

Recently, a series of publications (e.g., [3, 4, 12, 13]) have appeared devoted to the development of adaptive controllers for linear non-stationary systems. These results were based on the assumption that the parameters of the control object change slowly and act on the system as an external disturbance. Using these assumptions, robust and adaptive control schemes for linear non-stationary systems were synthesized in [3, 4, 12, 13], ensuring a small error in tracking the output of the control object for the command signal. Later, the analysis of parameter change models and the availability of some a priori information about the change in parameters led to the development of new adaptation algorithms that make it possible to control systems with rapidly changing parameters [14, 15, 4]. It should be noted that these algorithms could not guarantee good quality of transient processes [16, 17] and, in general, cannot be extended to nonlinear systems with variable parameters. In [5], these problems were solved using an iterative procedure for synthesizing the control law. However, this procedure is quite complex, and the controller itself has a high dimensionality. Control problems in which the control object is subject to the influence

of unknown disturbances are particularly complex. The problem of controlling a non-stationary object under disturbance conditions was not considered by the authors [5].

Let us consider a class of non-stationary linear systems described by the equation

$$y(t) = x(t)^T \theta(t) + \eta(t), \quad (1)$$

where $y(t)$, $u(t)$ denote the input and output of the system and

$$x(t)^T = \left[\frac{D^{n-1}}{F} y, ..., \frac{1}{F} y, \frac{D^{n-1}}{F} u, ..., \frac{1}{F} u \right]. \quad (2)$$

Here F is a Hurwitz polynomial in the differential operator D.

In (1), $\theta(t)$ denotes the vector of time-varying parameters, and $\eta(t)$ denotes the unmodeled errors.

A number of examples can be used to show that non-stationary differential equations, non-stationary observers in the form of a state space, and generalized non-stationary equations in a state space belong to this type of models.

Let us impose certain restrictions on variations over time.

Assumption A. The time of change of the parameter is uniformly small on average in the sense that there exist $\varepsilon_1 > 0$, $k > 0$ such that

$$\int_t^{t+T} \left\| \dot{\theta}(c) \right\| dc \le \varepsilon_1 T + k_0$$

for all t , T , where ε_1 is sufficiently small.

This assumption easily covers the case of slow drift of the parameter, when

$$\left\| \dot{\theta}(t) \right\| \le \varepsilon_1.$$

It also covers the case of a stepwise change in the parameter if pulses in are assumed $\dot{\theta}(t)$. Assumption A) plays the role of a limit on the magnitude and frequency of the pulses.

Assumption B. There are known constants ε_1, $\sigma > 0$ such that

$$|\eta(t)| \le \varepsilon_2 \sup_{0 \le \tau \le t} \left\{ e^{-\sigma(t-\tau)} \nu(x(\tau)) \right\} \stackrel{\Delta}{=} d(t),$$

Where

$$0 \le \nu(x) \le \|x\| \ \forall x.$$

When solving the problem of parameter estimation, first, for simplicity, we consider the case when $\eta(t) = 0$ and assumption A) is valid.

In the case of non-stationary parameters, traditional estimation schemes do not necessarily lead to bounded estimates.

Let's make the following assumption.

Assumption B. There is a known convex region $C \le R^{n+m+1}$ such that:

$\theta(t) \in C$ for all t;

$\exists k$, so that $\|\theta_1 - \theta_2\|_2 \le k$ for all $\theta_1, \theta_2 \in C$.

We will use the following standard algorithm for parameter estimation:

$$\dot{\hat{\theta}}(t) = P\left\{ \frac{\alpha x(t) e(t)}{1 + x(t)^T x(t)} \right\}; \qquad 0 < \alpha < \infty, \quad (3)$$

Where

$$e(t) \stackrel{\Delta}{=} y(t) - x(t)^T \hat{\theta}(t) \quad (4)$$

and P denotes the projection operator needed to ensure $\hat{\theta} \in C$.

Lemma 1. In the case of using the estimator (3), (4) in the system (1) for $\eta(t) = 0$, under assumptions A) and B) for all t and T, we have:

$$\hat{e}(t) \stackrel{\Delta}{=} \frac{e(t)}{\left[1 + x(t)^T x(t)\right]^{1/2}};$$

where k_0, k and ε_1 correspond to the definitions made in assumptions A) and B), and α corresponds to (3).

When $\eta(t)$ is nonzero, it is necessary to reduce the gain of the parameter estimation block if $\eta(t)$ is large. This can be achieved in various ways. For example, one can use a relative dead zone, in the presence of which the expression for the parameter estimation takes the form

$$\dot{\hat{\theta}} = P\left\{ \frac{\alpha x(t) g(t)}{1 + x(t)^T x(t)} \right\}, \quad (5)$$

Where

$$g(t) \overset{\Delta}{=} e(t) \max\left\{ \frac{|e(t)| - d(t)}{|e(t)|},\ 0 \right\} \tag{6}$$

Then, based on Lemma 1, we can obtain the following result.

Corollary 1. The evaluation block (5) and (6), used in relation to system (2), where η(t) satisfies assumption B), while fulfilling assumptions A) and C), has the following properties for all t , T :

$$\tilde{g} \overset{\Delta}{=} \frac{g}{(1 + x^T x)^{1/2}};$$

$$\int_t^{t+T} \tilde{g}(\tau)^2 d\tau \le \frac{k}{\alpha}\varepsilon_1 T + \frac{k^2}{2\alpha} + \frac{k_0 k}{\alpha};$$

The approach considered above is applied to a wide class of control laws (for example, with a reference model, optimal linear-quadratic, etc.).

For example, consider the control law defined by the expression

$$\hat{L}\left(\frac{1}{F}u\right) = \hat{P}\left(\frac{1}{F}y^* - \frac{1}{F}y\right), \tag{7}$$

where y* denotes the limited reference signal, and $\hat{L}$, $\hat{P}$ have degrees n and n -1, respectively, and satisfy the relation

$$\hat{A}\hat{L} + \hat{B}\hat{P} = \hat{A}^*, \qquad (8)$$

where $\hat{A}^*(\hat{\theta})$ is a polynomial of degree 2 n such that $\partial\hat{A}^*/\partial\hat{\theta}$ is bounded and $\hat{A}^*$ has a uniform margin of stability, i.e. for all $\hat{\theta} \in C$

$$\mathrm{Re}\left\{\lambda_1\left[\hat{A}^*(\hat{\theta})\right]\right\} \le -\sigma < 0,$$

where λ_i [·] denotes *the i* -th zero for the polynomial and Re {·} denotes the real part.

There are technical difficulties with solution (8). In particular, we require that $\left\|\hat{L}\right\|, \left\|\hat{P}\right\|$ were bounded (where $\|\cdot\|$ denotes the norm of the vector of polynomial coefficients). This satisfies the requirement that the estimated model $\hat{A}$, $\hat{B}$ is uniformly controllable if $\hat{A}^*$ is fixed.

Assumption G. The convex region for assumption B) also has the property that for all $\hat{\theta} \in C$ the solution to equation (8) gives bounded values $\hat{L}$ of and $\hat{P}$.

The following theorem can be proved, establishing the stability of adaptive controllers in the sense of a bounded input and a bounded state in the case when η(t)=0.

Theorem 1. If the adaptive control law (7), (8), (3), (4) is used in relation to system (1) for η(t)=0 and assumptions A), B) and D) are valid, then the closed system is globally stable in the sense of a limited input and a limited state, provided that ε_1 in assumption A) is sufficiently small.

In practice, the object contains non-modulated dynamic components satisfying assumption B). For this case, the following corollary can be proven.

Corollary 1. Let the adaptive control law (7), (8), (5), (6) be applied to system (1) under assumptions A), B), C) and D). Then the closed system is globally stable in the sense of limited inputs and state, provided that ε_1 in assumption A) and ε_2 in assumption B) are sufficiently small.

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TABLE OF CONTENTS

Development of an imitation learning method for a neural network system of mobile robot's movement on example of the maze solving **3**

Tatyana Yu. Kim, Ryhor A. Prakapovich

Educational technologies that change the world **11**

Juravlova Valentina Viktorovna

Adaptive control of non-stationary linear systems **13**

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Применение информационно-коммуникационных технологий воспитании этических ценностей у детей дошкольного возраста **17**

Бичурина Сеимбика Усмановна, Воробьева Элина Валерьевна

Формирование экономической культуры старших дошкольников **22**

Бичурина Сеимбика Усмановна, Антипина Анжелика Юрьевна

Improving the speech and intercultural communicative competence of technical academic lyceum students **26**

Polvonova Bashorat Mirobijonovna

Telemedicine – a new direction in modern medicine **30**

Dalibekov Lochinbek Rustambekovich, Dalibekova Dilshoda Mutalibovna

Application and importance of intellectual protection algorithms in specially protected objects **36**

Abduhafizov Tahirjon Ubaidulla ugli

Основные направления организации внеурочной деятельности в условиях ФОП НОО **39**

Замалетдинова Зальфира Исхаковна

Воспитание старшего дошкольника в цифровую эпоху **43**

Новик Наталья Николаевна, Исакова Альбина Гирфановна

Цифровая грамотность родителей: теоретические основы и обзор практических проектов **47**

Новик Наталья Николаевна, Халилова Айгуль Рустемовна

Формирование ассертивности делинквентных подростков: путь к социальной адаптации **52**

Биктагирова Гульнара Фердинандовна, Костюнин Владимир Анатольевич

Формы и методы работы с девиантными подростками **55**

Костюнина Надежда Юрьевна, Курнаева Александра Вячеславовна, Костюнин Владимир Анатольевич

Эмоциональный интеллект как психолого-педагогическая проблема **59**

Костюнина Надежда Юрьевна, Муравьева Вера Александровна

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