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Robust adaptive tracking with an additional plant identifier for a class of nonlinear systems ☆

Boris Mirkin[a,*], Per-Olof Gutman[a], Yuri Shtessel[b]

[a] *Faculty of Civil and Environmental Engineering, Technion – Israel Institute of Technology, Haifa 32000, Israel*
[b] *University of Alabama in Huntsville, 301 Sparkman Drive, Huntsville, AL 35899, USA*

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Abstract

In this paper, we develop two new model reference adaptive control (MRAC) schemes for a class of nonlinear dynamic systems that is robust with respect to an uncertain state (output) dependent nonlinear perturbations and/or external disturbances with unknown bounds. The design is based on a controller parametrization with an adaptive integral action. Two types of adaptive controllers are considered—the state feedback controller with a plant parameter identifier, and the output feedback controller with a linear observer.

Keywords: Model reference adaptive control; Nonlinear systems; SPR-Lyapunov design; Identifier; Stability

1. Introduction

Adaptive control is an effective method for controlling systems with uncertainties, and there is a vast amount of literature on design and analysis of various adaptive control systems using rigorous methods. The main results in this area can be found in numerous papers and books, see e.g. the textbooks [1–7] and references therein. The classic approach is based on the certainty equivalence principle, and can be divided into three groups: direct schemes, indirect schemes and schemes based on the so-called "dynamical certainty equivalence principle" by Morse, e.g. [8,9].

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* Corresponding author.
E-mail addresses: bmirkin@technion.ac.il (B. Mirkin), peo@technion.ac.il (P.-O. Gutman), shtessel@ece.uah.edu (Y. Shtessel).

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In the framework of the certainty equivalence principle for uncertain linear dynamic systems [10–12] proposed a useful technique to design model reference adaptive controllers by using a combination of direct (direct adjusting of control law parameters) and indirect (with plant parameter estimates) adaptive control. This technique makes it possible to improve the transient behaviour. Continuous linear systems are considered in [10], discrete systems are studied in [11], and continuous systems with state delay are treated in [12]. The on-line connection between direct and indirect adaptive control methods are expressed by so-called closed-loop estimation errors which are also used in the adaptation loops. Note, however, that the solutions reported in [10–12] were obtained only for the undisturbed linear plants.

The purpose of this paper is to develop, within a Lyapunov-based framework, a new MRAC controller parametrization which is robust with respect to an uncertain state dependent nonlinear plant perturbation, and an external disturbance with unknown bounds. Two types of adaptive controllers are considered—the controller with a state feedback and the controller with an output feedback. As soon as plant states are available, the controller includes a static adjustable feedback driven by the tracking error vector, a scalar integral-type adaptive tracking-feedback, and an additional closed-loop estimation contour for adjusting the controller parameters. In the output feedback case the static adjustable feedback is replaced by an adjustable dynamic block that includes a linear observer.

2. State feedback MRAC

2.1. Plant model and problem statement

Plant model: The class of nonlinear plants with parametric uncertainty considered in this paper is of the form

$$\dot{x}(t) = Ax(t) + bu(t) + bf(x(t), t) \tag{1}$$

where, $x \in \mathbb{R}^n$ is the state vector, $u(t) \in \mathbb{R}$ is the control input. The constant matrices $A \in \mathbb{R}^{n \times n}$ and $b \in \mathbb{R}^{n \times 1}$ have unknown elements. $f(x,t)$ is an unknown bounded function that represents the system nonlinearities, model uncertainties and the external disturbances.

The problem is to design an adaptive feedback control, and tune, on-line, the controller parameters in order to achieve the desired closed loop specifications.

Control objective: The desired specifications in this paper are that all signals of the closed loop system remain bounded, and that the plant state $x(t)$ asymptotically exact follows the state $x_r(t)$ of a stable reference model

$$\dot{x}_r(t) = A_r x_r(t) + b_r r(t) \tag{2}$$

where $A \in \mathbb{R}^{n \times n}$, $b_r \in \mathbb{R}^n$ are known constant matrices, and $r(t) \in \mathbb{R}$ is a known bounded reference input signal, i.e. we demand that $\lim_{t\to\infty} e_x(t) = x(t) - x_r(t) = 0$.

Assumptions: To meet these control specifications, we assume as usual in MRAC theory e.g. [4,7] that

(A1) There exist a constant vector $\theta_e^* \in \mathbb{R}^n$ and a nonzero constant scalar θ_0^* that satisfy the following equations:

$$A - A_r + b\theta_e^{*T} = 0, \quad b\theta_0 - b_r = 0 \tag{3}$$