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Uniform global asymptotic stability of adaptive cascaded nonlinear systems with unknown high-frequency gains

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ABSTRACT

We study adaptive tracking problems for nonlinear systems with unknown control gains. We construct controllers that yield uniform global asymptotic stability for the error dynamics, and hence tracking and parameter estimation for the original systems. Our result is based on a new explicit, global, strict Lyapunov function construction. We illustrate our work using a brushless DC motor turning a mechanical load. We quantify the effects of time-varying uncertainties on the motor electric parameters.

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1. Introduction

Lyapunov functions provide the foundation for much of current research on the stabilization of nonlinear systems; see, e.g., [1–3]. One important application of Lyapunov functions arises in adaptive control. Given a nonlinear system

$$\dot{\mathbf{q}} = \mathcal{J}(t, \mathbf{q}, \boldsymbol{\Theta}, \boldsymbol{u}), \tag{1}$$

having a vector $\boldsymbol{\Theta}$ of uncertain constant parameters and a reference trajectory $\mathbf{q}_r$, the *adaptive tracking control* problem is to design a dynamic feedback

$$\boldsymbol{u} = \boldsymbol{u}(t, \mathbf{q}, \boldsymbol{\Theta}_e), \qquad \dot{\boldsymbol{\Theta}}_e = \tau(t, \mathbf{q}, \boldsymbol{\Theta}_e), \tag{2}$$

where $\boldsymbol{\Theta}_e$ is the estimate of $\boldsymbol{\Theta}$, such that (a) $\mathbf{q}_r(t) - \mathbf{q}(t) \to 0$ as $t \to \infty$ and (b) all closed loop signals remain bounded [4–7]. In general, solving the adaptive tracking problem does not necessarily guarantee parameter identification, i.e., we might not have $\boldsymbol{\Theta} - \boldsymbol{\Theta}_e(t) \to 0$ as $t \to \infty$. In fact, one does not even know, in general, whether $\boldsymbol{\Theta}_e$ converges to a *constant* vector [8]. Hence, it is not possible to prove *asymptotic stability* for adaptive closed loop systems in general.

From a Lyapunov theory point of view, the fact that an adaptive tracking controller does not yield asymptotic stability implies that the corresponding closed loop system does not admit a *strict* Lyapunov function (which has a negative definite time derivative along the system trajectories). Rather, only a *nonstrict* Lyapunov function (which has a negative semi-definite time derivative along the trajectories) can be constructed in this case; see Section 2 for the precise Lyapunov function definitions.

The asymptotic stability of adaptive systems usually depends on satisfying the *persistency of excitation (PE)* condition [9]. That is, a necessary (and sometimes sufficient) condition for parameter identification is that the reference trajectory be

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