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Adaptive tracking control for a class of switched uncertain nonlinear systems under a new state-dependent switching law

Ding Zhai [a,*], An-Yang Lu [a], Dan Ye [b], Qing-Ling Zhang [a]

[a] College of Sciences, Northeastern University, Shenyang 110819, PR China

[b] College of Information Science and Engineering, Northeastern University, Shenyang 110004, PR China

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ABSTRACT

This paper deals with the problem of adaptive fuzzy tracking control for a class of switched uncertain nonlinear systems. Fuzzy logic systems are utilized to approximate the unknown nonlinear functions, and the adaptive backstepping and dynamic surface control techniques are adopted. First, a new state-dependent switching method is proposed. By introducing convex combination technique and designing a state-dependent switching law, only the solvability of the adaptive tracking control problem for a convex combination of the subsystems is necessary. Second, a new common Lyapunov function with switched adaptive parameters is constructed to reduce the conservatism. Third, to avoid Zeno behavior, a modified state-dependent switching law with dwell time is proposed. It is shown that under the proposed control and switching laws, all the signals of the closed-loop system are bounded and all the state tracking errors can converge to a priori accuracy, even if some subsystems are uncontrollable. Finally, the effectiveness of the proposed method is illustrated through two simulation examples.

1. Introduction

Over the last decades, adaptive control of uncertain nonlinear systems has received much attention using universal function approximators, such as fuzzy logic systems (FLSs) [1–3] or neural networks (NNs) [4] to parameterize the unknown nonlinearities. As a base strategy in adaptive backstepping, the main objective is to cancel the unknown nonlinearity of system by constructing the virtual control functions and adaptive laws [5]. It has been shown in the literature [6–8], backstepping-based adaptive control technique is accepted as a popular approach to deal with uncertain nonlinear strict feedback systems. Especially, as stated in [9], because an FLS can combine the knowledge and experience of designers or experts, the FLS is a universal approximator that is superior to NNs. FLS adaptive control technique for uncertain nonlinear systems in strict-feedback form has been widely studied, such as [10] where the single-input and single-output (SISO) systems are considered, [11] where multiple-input and multiple-output (MIMO) systems are considered.

On the other hand, switched system is a dynamical system that consists of a finite number of subsystems and a logical rule that orchestrates switching between these subsystems. In recent years, the study of switched systems has attracted more and more attention of the scientific community since it can be used to describe a large number of physical and engineering

* Corresponding author.
E-mail address: zhaiding@163.com (D. Zhai).

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systems, such as robot manipulators and biological systems [12], near space vehicle control systems [13], circuit and power systems [14] and references therein. As the most important issues, stability analysis and control synthesis of switched linear or nonlinear systems are discussed extensively by a lot of researchers. Specifically, switched nonlinear strict-feedback systems were studied systematically by backstepping technique, such as the switched systems under arbitrary switching law are considered in [5,15,16] based on the common Lyapunov function (CLF), the switched systems with average dwell time are considered in [17–20] and the multiple Lyapunov functions (MLFs) method is applied in [21]. Obviously, all the above mentioned adaptive control approaches are proposed for the switched systems with all controllable subsystems and the switching laws are arbitrary or constrained. As discussed in [22], a switched system does not necessarily inherit the properties of its subsystems. Besides, the switched nonlinear system may be possible to be stabilized by means of suitably constrained switching even if all individual subsystems are unstable. Therefore, how to design a proper switching law for the switched system is one of the most important problem. In [22], a class of switched uncertain nonlinear systems with extra state z is considered. The MLFs method is exploited to deal with the extra state and a state-dependent switching law is designed. However, it may be difficult to find the proper MLFs and the proposed switching law cannot be applied to the switched system in strict-feedback form. To the best of the authors' knowledge, the adaptive tracking control problem for the switched uncertain nonlinear system with unstable subsystems has not been fully investigated and still remain open and challenging. This is the first and main motivation of this paper.

Further, the conventional backstepping technique suffers from the problem of "explosion of complexity", which is caused by repeated differentiations of the virtual controls at each step. As a result, the complexity of controller grows drastically as the order of the system increases. Nowadays, by introducing a first order filter at each step of the backstepping design procedure, the dynamic surface control (DSC) approach is proposed in [23] to avoid the problem. Besides, while the tracking performance in most methods converges to a small residual set, whose size depends on the design parameters and some unknown bounded terms, tracking accuracy given a priori is guaranteed in [24,25]. However the switched systems with a priori known tracking accuracy have not been considered until now. This is the second motivation of this paper.

In this paper, the adaptive fuzzy tracking control problem for a class of switched uncertain nonlinear systems in strict-feedback form is investigated. To ensure the continuousness of the Lyapunov functions at the switching instants, a new CLF is proposed. Compared to the existing CLF with common adaptive parameters in [5], the proposed CLF with switched adaptive parameters is more general. The contributions of this paper can be concluded as follows. First, by introducing the convex combination technique, a new state-dependent switching method is proposed. For the proposed method, only solvability of the tracking control problem for a convex combination of the subsystems is necessary. Thus, the considered switched systems are more general than those in [17,18]. It is shown that under the proposed control laws and state-dependent switching law, all the signals of the closed-loop system are bonded even if some subsystems are uncontrollable. This is the most important contribution of this paper. Second, the DSC approach is applied to deal with the problem of "explosion of complexity" and the tracking errors converge to a predefined accuracy. Third, to avoid Zeno behavior or switching too quickly, a modified state-dependent switching law with dwell time is proposed. Finally, two simulation examples are illustrated to show the effectiveness of the proposed method.

The article unfolds as follows: in Section 2, some preliminaries and the problem statement are given. The main results are shown in Section 3. In Section 4, two simulation examples are given to illustrate the effectiveness of the new proposed method. Finally, conclusions are presented in Section 5.

Notation. $\mathbb{R}^n$ denotes the n-dimensional Euclidean space. The notation $\|x\|$ refers to the Euclidean vector norm of vector $x \in \mathbb{R}^n$. $sgn(\cdot)$ is the sign function. $\mathbb{C}^n$ denotes the set of functions that have continuous derivatives up to the order n. For unknown constant θ, $\tilde{\theta} = \theta - \hat{\theta}$ and $\hat{\theta}$ is the estimation of θ.

2. Preliminaries and problem statement

2.1. System descriptions and assumptions

Consider a class of switched nonlinear systems which can be described as follows:

$$\begin{aligned} \dot{x}_i &= g_{i,\sigma(t)}(\underline{x}_{i-1})x_{i+1} + f_{i,\sigma(t)}(\underline{x}_i) + \omega_{i,\sigma(t)}(t,x), \quad i = 1,\ldots,n-1 \\ \dot{x}_n &= g_{n,\sigma(t)}(\underline{x}_{n-1})u + f_{n,\sigma(t)}(\underline{x}_n) + \omega_{n,\sigma(t)}(t,x) \\ y &= x_1 \end{aligned} \tag{1}$$

where $\underline{x}_i = [x_1,\ldots,x_i]^T \in \mathbb{R}^i$; $x = \underline{x}_n \in \mathbb{R}^n$ is the measurable state vector, n is the dimension of the state; $y \in \mathbb{R}$ is the system output; $u \in \mathbb{R}$ is the control input; $\sigma(t) : [0,\infty) \to \mathbb{N} = \{1,\ldots,N\}$ is a switching signal, N is the number of the subsystems; $g_{i,k}(\underline{x}_{i-1}) = \mathfrak{g}_{i,k} g_i(\underline{x}_{i-1})(i \in \mathbb{I} = \{1,\ldots,n\})$ where $\mathfrak{g}_{i,k}$ are known nonnegative constants, $g_i(\underline{x}_{i-1}) : \mathbb{R}^{i-1} \to \mathbb{R}(i \in \{2,\ldots,n\})$ are unknown smooth functions and $g_1(\underline{x}_0) := g_1$ is an unknown constant; $f_{i,k}(\underline{x}_i) : \mathbb{R}^i \to \mathbb{R}$ are unknown smooth functions; $\omega_{i,k}(t,x)$ are external disturbance inputs and satisfy $|\omega_{i,k}(t,x)| \le \bar{\omega}_{i,k}$ with $\bar{\omega}_{i,k}$ being an unknown constant. For any $k \in \mathbb{N}$, there exist $i \in \mathbb{I}$ such that $\mathfrak{g}_{i,k} > 0$.

Remark 1. Compared with the system studied in [5,26], system (1) with $g_{i,k}(\underline{x}_{i-1})$ is more general. Similar to [24], $g_i(\underline{x}_{i-1})$ is only dependent on $\underline{x}_{i-1}$. Moreover, for each $i \in \mathbb{I}$, it is allowed that there exist $k \in \mathbb{N}$ such that $g_{i,k}(\underline{x}_{i-1}) = 0$, but not for all $k \in \mathbb{N}$. To the best of our knowledge, the cases where partial $g_{i,k} = 0$ have not been considered in the existing results.