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Adaptive fuzzy tracking control of switched uncertain nonlinear systems with unstable subsystems ☆

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Abstract

This paper is concerned with the problem of adaptive fuzzy tracking control for a class of switched uncertain nonlinear systems where the solvability of the fuzzy tracking control problem for subsystems is unnecessary. Fuzzy logic systems are utilized to approximate the unknown nonlinear functions, and a new adaptive fuzzy tracking control technique for the problem under study is set up. Based on the technique above, we design a switching law and construct adaptive fuzzy controllers of subsystems explicitly by a recursive design algorithm to guarantee that all the signals in the resulting closed-loop system remain bounded and the system output of the closed-loop system converges to a small neighborhood of the reference signal. Multiple Lyapunov functions are exploited to get out of the conservativeness caused by adoption of a common Lyapunov function for all subsystems, which is commonly required when applying the backstepping-like recursive design scheme. A mass–spring–damper system is provided to demonstrate the effectiveness of the proposed design method.

Keywords: Adaptive fuzzy control; Output tracking; Switched nonlinear systems; Multiple Lyapunov functions

1. Introduction

Uncertainty is inherent in practical systems. Design control capability of dealing with uncertainty is of practical interest and is academically challenging in the nonlinear control community. For non-switched nonlinear systems, adaptive control of uncertain nonlinear systems has received much attention using universal function approximators such as fuzzy logic systems [38–41,43,45] or neural networks [46] to parameterize the unknown nonlinearities [3,9,10,16,26,31,34,44]. In recent years, for systems with special structure, e.g., strict-feedback form, adaptive fuzzy or

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neural backstepping approaches have been developed for controlling non-switched nonlinear systems [5–7,12,27,35,37], which provide some systematic methodologies to solve tracking control problem [8,11,29,30,36,42].

On the other hand, a 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 the last two decades, switched systems have drawn considerable attention because of their importance from two aspects: From practical points of view, lots of real-world systems, such as aircraft control systems, mechanical systems, and switching power converters, can be modeled as switched systems which exhibit switching among subsystems depending on various environmental factors [14,15,25,20]. From a theoretical perspective, the main concern in the study of switched systems is the issue of stability, which is very difficult to handle due to the hybrid nature of switched systems operation since, in general, a switched system does not necessarily inherit the properties of its subsystems [2,4,27,32]. For example, a switched system consisting of linear exponentially stable subsystems may be unstable [15]. Hence, the research on the control of switched systems is of great significance. Also, different properties of switched systems, especially stability issues, were extensively studied in the literature [1,24,33]. Specifically, for a special class of switched systems, switched nonlinear strict-feedback systems were studied systematically by backstepping. In [22,28], global stabilization for switched nonlinear systems in strict-feedback form under arbitrary switchings is achieved by constructing a common Lyapunov function; Based on the multiple Lyapunov functions (MLFs) method, adaptive disturbance rejection and H_∞ control problem for switched nonlinear systems in strict-feedback form and p-normal form are studied in [23,21], respectively. In the aforementioned literature, the results obtained are based on the assumption that all system nonlinearities are known. In practical systems, however, sometimes no precise knowledge about the system nonlinearities is known, or the nonlinearities may change with time. Therefore, the practical applications of the results [21–23,28] are limited when no prior knowledge of the system nonlinearities is available.

Adaptive fuzzy or neural control approaches based on backstepping have been developed to control non-switched nonlinear systems with unknown nonlinearities. Naturally, it is also of interest to consider such an application to switched uncertain nonlinear systems. Meanwhile, for a switched nonlinear system with known nonlinearities, it may be possible to stabilize the system by means of suitably constrained switching even if all individual subsystems are unstable [15]. It is natural to ask that, for a switched nonlinear system with unknown nonlinearities, if all subsystems are unstable, can we still achieve global stabilization of such a switched system? For non-switched uncertain nonlinear systems the answer is negative [5,12,11,29]. For switched uncertain nonlinear systems, it might be possible to achieve stabilization by some proper switchings. The key point is to design a proper switching law. However, to the best of our knowledge, there has been relatively little work for switched uncertain nonlinear systems up to now. Recently, an adaptive neural networks tracking control scheme for switched nonlinear strict-feedback systems is proposed by backstepping in [13]. However, in [13], the solvability of the adaptive tracking control problem for individual subsystems is assumed. Meanwhile, compared with neural networks control, there are no results available in switched uncertain nonlinear systems on adaptive fuzzy tracking control by backstepping design approach. Therefore, in this paper, we attempt to exploit adaptive fuzzy backstepping approach and switched system theory, and provide a systematic design method for switched nonlinear strict-feedback systems with unknown nonlinearities. But, three main issues naturally arise: When no adaptive fuzzy tracking control problem for subsystems is solvable, how to solve the fuzzy control problem for switched nonlinear systems with unknown nonlinearities? It might be possible to achieve fuzzy control by some proper switchings. If this is possible, then how to construct a MLFs based switching law and fuzzy logic systems? Moreover, the main difficulty in the design is to choose a coordinate transformation at each step of backstepping since for switched nonlinear systems, applying the backstepping recursive design scheme results in different coordinate transformations for different subsystems. How to overcome this difficulty is also a challenging issue.

Motivated by the above considerations, this paper studies the adaptive fuzzy tracking control problem for switched uncertain nonlinear systems in strict-feedback form. The solvability of the adaptive fuzzy tracking control problem for individual subsystems is not assumed. Compared with the vast existing literature on switched and non-switched nonlinear systems, the results of this paper have four distinct features. First of all, a main result about adaptive fuzzy tracking control for switched uncertain nonlinear systems is established for the first time. A sufficient condition for the adaptive fuzzy tracking control problem is derived by exploiting the MLFs method and the adaptive fuzzy backstepping technique. Second, in order to avoid different coordinate transformations for different subsystems, a common fuzzy basis function for different subsystems at each step of backstepping is constructed. Third, the dual design of adaptive fuzzy controllers and a switching law are constructive by designing the MLFs. Finally, the proposed re-