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Command filter-based adaptive fuzzy backstepping control for a class of switched nonlinear systems ☆

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Abstract

This paper considers the adaptive fuzzy output feedback control design problem for a class of switched nonlinear systems. The considered switched nonlinear systems contain unknown nonlinearities, the switching signals with average dwell time, and without requiring that state variables are available for measurement. Fuzzy logic systems are used to approximate the unknown nonlinearities, and a fuzzy switched state observer is designed to estimate the immeasurable states. In the framework of observer-based output feedback control design technique, and by introducing a command filter into the backstepping design algorithm, a command filter-based adaptive fuzzy backstepping output feedback control scheme is developed. The stability of the closed-loop system and the convergence of the tracking error are proved via average dwell time and multiple Lyapunov function. A numerical example is provided to illustrate the effectiveness of the proposed approach.

Keywords: Nonlinear switched systems; Fuzzy adaptive control; Command filter; Backstepping design

1. Introduction

In the past decade, fuzzy logic systems (FLS) have been extensively used for controller design for uncertain nonlinear systems [1] due to its ability of approximating the nonlinear smooth functions. Various adaptive fuzzy control approaches have been developed for uncertain nonlinear systems, for example see [2–15] and the references therein. [2–7] developed adaptive fuzzy control schemes for a class of uncertain nonlinear systems based on the feedback linearization method. [8–15] developed adaptive fuzzy control approaches for uncertain nonlinear systems based on the backstepping design technique.

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The above mentioned adaptive fuzzy backstepping control methods in [8–15] can solve the control problem of the uncertain nonlinear systems without satisfying the matching condition. However, an obvious drawback with them is the problem of "explosion of complexity". In fact, the explosion of complexity is caused by repeating differentiations of certain nonlinear functions and virtual controls [16]. To overcome the problem of explosion of complexity inherent in the adaptive backstepping design methods, an adaptive fuzzy backstepping control approach was proposed by [17] for a class of uncertain nonlinear systems based on the so-called dynamic surface control (DSC) technique. The proposed controller solves this problem by introducing a filter at each step of the backstepping approach. After [17], several adaptive fuzzy backstepping DSC schemes have been developed [18,19]. However, this DSC scheme takes no account of the problem of compensating the errors caused by the first-order filter, which will add the difficulty to gain a better control quality. The command filtered backstepping design was first proposed in [20] and then it was extended to adaptive case for strict-feedback systems in [21]. By utilizing the output of a command filter to approximate the derivative of the virtual control at each step of the adaptive backstepping approach, the problem of explosion of terms can thus be eliminated. In addition, the errors caused by command filter can be reduced by introducing compensation signals. [22] proposed an adaptive fuzzy output feedback control method for a class of strict-feedback systems with parametric uncertainty and immeasurable states based on command filter. Note that all the aforementioned adaptive fuzzy control schemes are focused on the uncertain non-switched nonlinear systems. Therefore, these control methods can't be applied to those switched nonlinear systems.

In recent years, the switched systems have attracted much attention because the study for these systems is not only academically challenging, but also of practice importance. It should be mentioned that the control design and stability analysis for a switched system have major difference from those of a non-switched system. For instance, if a switched system consists of two stable subsystems, it would be unstable if an unsuitable switching rule is applied to this switched system. Conversely, if these two subsystems are unstable, then we adopt suitable switching law to make the switched system be stable [23,24]. Recently, some fuzzy or NN adaptive backstepping control approaches have been investigated for several classes of uncertain switched nonlinear systems [25–30]. In [25–28], the adaptive fuzzy or neural backstepping control methods have been developed for a class of single-input and single-output (SISO) or multi-input multi-output (MIMO) uncertain switched nonlinear systems. [29,30] expanded the results of state feedback control in [25–28] to the output feedback control for uncertain switched nonlinear systems with immeasurable states. Although the proposed fuzzy or neural adaptive backstepping control approaches in [25–32] can achieve the control tasks, the problem of "explosion of complexity" exists in these control methods. To solve this problem, [33] first proposed neural adaptive control method for a class of pure-feedback switched nonlinear system with command filter. However, the proposed control method required that the states are measured directly, it can not be applied to uncertain switched nonlinear systems with immeasurable states.

Motivated by the aforementioned observations, an adaptive fuzzy output feedback control method is proposed for a class of switched nonlinear systems. The considered switched systems contain unknown nonlinearities and unmeasured states. Fuzzy logic systems are used to approximate the unknown nonlinearities, and a fuzzy switched state observer is designed to estimate the immeasurable states. In the framework of observer-based output feedback control design technique, and by introducing a command filter into the backstepping design algorithm, a command filter-based adaptive fuzzy backstepping output feedback control scheme is developed. The stability of the closed-loop system and the convergence of the tracking error are proved via average dwell time and Lyapunov function. The main contributions of this paper can be summarized as follows:

i) By designing a fuzzy switched state observer to estimate the unmeasured states, the proposed adaptive fuzzy control approach can cancel the restrictive condition in [25–28] that all the states of the controlled switched nonlinear systems are available for measurement. Moreover, the proposed control method can solve the output tracking control problem. Therefore, it extends the result of the stabilization control problem in [30].

ii) By using the command filter method, the proposed fuzzy adaptive control approach can overcome the defect of "explosion of complexity" existing in the references [29,30], thus the computational burden of the control algorithm can be reduced greatly. In addition, the new command filter technique design in this paper can also remove the restrictive assumption imposed on the previous literature [16–19] that the bounds of the derivative of virtual control functions are known.