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Fuzzy-approximation-based global adaptive control for uncertain strict-feedback systems with a priori known tracking accuracy ☆

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Abstract

In this study, we propose a novel adaptive backstepping fuzzy control scheme for a class of uncertain strict-feedback systems where the tracking accuracy is known *a priori*, and we also introduce a multiswitching-based adaptive fuzzy controller. Compared with the existing method for adaptive fuzzy control, the advantages of the proposed scheme are as follows. First, the controller guarantees that all the closed-loop signals are globally uniformly ultimately bounded, which differs from most existing adaptive fuzzy control approaches where the semi-global boundedness of the closed-loop signals is ensured under a harsh assumption on the approximation domain of the fuzzy logic system. Second, our controller ensures that the tracking error converges to an accuracy that is given *a priori* for the uncertain strict-feedback system, which cannot be achieved using existing adaptive fuzzy control methods. Third, based on some nonnegative functions, we analyze the convergence of the tracking error using Barbalat's Lemma. Fourth, the main technical novelty is the construction of three new nth-order continuously differentiable switching functions, which are used to design the desired controller. Finally, three simulation examples are provided that illustrate the effectiveness of the proposed control strategy.

Keywords: Adaptive backstepping technique; Barbalat's Lemma; Fuzzy logic system; Global stability; Tracking accuracy; Uncertain strict-feedback system

1. Introduction

In the last two decades, approximation-based adaptive control for nonlinear systems with high uncertainty has attracted much attention because extensive uncertainties are present in nonlinear complex systems, which cause great difficulty when establishing accurate system models. Some significant results have been reported previously (e.g., see [1–3] and the references therein). In particular, several approximation-based adaptive backstepping control approaches have been developed by combining some universal approximators with the adaptive backstepping technique

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originally proposed in [4], e.g., adaptive backstepping fuzzy control [5–12,45] and adaptive backstepping neural network control [13–17,33,46]. The basic idea of this control methodology is that fuzzy logic systems (FLSs) or neural networks (NNs) are utilized to approximate the mismatched uncertainties in the system dynamics or controllers online, before adaptive controllers are designed via the adaptive backstepping technique. Undoubtedly, approximation-based adaptive backstepping control is now a powerful method for designing uncertain nonlinear systems, especially lower triangular structured systems because they can deal with nonlinear systems that have mismatching conditions and the uncertainties do not need to be linearly parameterized.

In fact, as stated in [18], because an FLS can combine the knowledge and experience of designers or experts, the FLS is a universal approximator that is superior to NNs. In [5], the adaptive backstepping fuzzy control scheme was originally proposed to deal with the tracking control problem for a class of strict-feedback systems with completely unknown system functions. Since then, adaptive backstepping fuzzy control has been extended successfully to some more general and complex uncertain nonlinear systems. For example, Wang et al. [9] developed a direct adaptive backstepping fuzzy control scheme by combining modified integral Lyapunov functions with the backstepping technique. In [19], an adaptive backstepping fuzzy control approach was presented for a class of nonlinear strict-feedback systems with unknown functions, unknown dead zones, and immeasurable states. An adaptive fuzzy output-feedback controller was designed for single-input single-output strict-feedback nonlinear systems in [20], and the control scheme was then extended directly to multiple-input multiple-output nonlinear systems in [21,22], respectively. The tracking control problem was considered for a class of nonlinear time-delay systems with unknown nonlinearities and strict-feedback structure in [23], where the adaptive fuzzy controller design was independent of the choice of fuzzy membership functions. The advantage of this control scheme is that the "explosion of complexity" problem was avoided by using a dynamic surface control technique. Moreover, adaptive backstepping fuzzy control has also been applied to stochastic systems [24–26], pure-feedback systems [27,28], large-scale systems [29,30], and in other areas.

Although great progress has been achieved, it should be noted that all of the aforementioned adaptive fuzzy control schemes can only guarantee the semi-global boundedness of all the closed-loop signals. To develop effective adaptive fuzzy controllers, it is usually assumed that the approximation ability of the FLSs must remain valid at all times, which is difficult to verify in advance for systems with high nonlinearity and uncertainty, thereby leading to possible deterioration in the tracking performance or even instability in practical applications. However, the assumption mentioned above also implies that the input signals of the FLSs are inside the compact sets given *a priori* at all times, so the input signals are always bounded. Under this assumption, the boundedness of all the closed-loop signals can be proved, which is inappropriate. To develop an adaptive fuzzy control scheme without the inappropriate assumption mentioned above using FLSs as feedforward compensators, a globally stable adaptive backstepping fuzzy control method was proposed recently for a class of output-feedback systems in [31]. Unfortunately, this feedforward compensation scheme cannot be extended directly to some more general nonlinear systems such as strict-feedback systems. Consequently, in the field of adaptive fuzzy control, the problem of the globally stable tracking control of strict-feedback systems with mismatched uncertainties needs to be addressed further.

In addition, all existing adaptive fuzzy control methods can only guarantee that the tracking/regulation error converges to a small neighborhood around the origin, the size of which can be adjusted by selecting appropriate design parameters, although the value cannot be determined accurately before the controller is produced. In fact, the tracking/regulation accuracy must usually be given *a priori* in practical applications. Thus, designers must adjust the design parameters based on repeated testing to achieve the desired accuracy. This process may waste time and incur other costs. Consequently, the design of an ideal adaptive fuzzy controller to ensure that the ultimate tracking/regulation error reaches the desired accuracy and to avoid complex repeated testing is a practical and interesting topic.

Motivated by the observations above, we investigate the problem of globally stable adaptive fuzzy tracking control for a class of strict-feedback systems with the requirement that the ultimate tracking error can achieve an accuracy that is given *a priori*. The system is described by

$$\begin{cases} \dot{x}_i = f_i(\bar{x}_i) + g_i(\bar{x}_{i-1})x_{i+1}, \quad i = 1, \cdots, n-1 \\ \dot{x}_n = f_n(\bar{x}_n) + g_n(\bar{x}_{n-1})u \\ y = x_1, \end{cases} \tag{1}$$

where $x = [x_1, x_2, \cdots, x_n]^{\mathrm{T}} \in R^n$ is the state vector, $y \in R$ is the system output, $u \in R$ is the control input, and $\bar{x}_i := [x_1, \cdots, x_i]^{\mathrm{T}} \in R^i$, $f_i : R^i \to R$ and $g_i : R^{i-1} \to R$ are unknown but continuously differentiable functions. Let $g_1(\bar{x}_0) := g_1$ be an unknown constant. Assume that the state vector x is available for the control input u.