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Adaptive fuzzy backstepping output feedback tracking control of MIMO stochastic pure-feedback nonlinear systems with input saturation

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Abstract

In this paper, the adaptive fuzzy backstepping output feedback tracking control problem is considered for a class of uncertain stochastic multi-input and multi-output (MIMO) nonlinear systems in pure-feedback form. The stochastic MIMO nonlinear systems under study have unknown nonlinear functions, input saturation and immeasurable states. By using fuzzy logic systems to identify the uncertain nonlinear system, and a smooth function to approximate the input saturation, a fuzzy state observer is designed and the estimations of the immeasurable states are obtained. Based on the backstepping recursive design technique, an adaptive fuzzy output feedback tracking control approach is developed. It is shown that the proposed control approach guarantees that all the signals of the resulting closed-loop system are semi-globally uniformly ultimately bounded (SGUUB) in mean-square in the sense of probability, and the observer errors and tracking errors can be regulated to a small neighborhood of the origin by choosing design parameters appropriately. A simulation example is provided to show the effectiveness of the proposed approach.

Keywords: Fuzzy adaptive control; Backstepping design technique; Input saturation; MIMO stochastic systems; Pure-feedback form; State observer

1. Introduction

In the past decades, fuzzy logic systems have found extensive applications for complex system identification and control [1] and [2]. By using the fuzzy logic system to approximate the unknown continuous functions, many adaptive fuzzy control design approaches have been developed for uncertain single-input and single-output (SISO) nonlinear systems [3–6], MIMO nonlinear systems [7–12], and large-scale nonlinear systems [13] and [14]. Since the control designs in the above mentioned results are based on feedback linearization principle, the controlled plants are only limited to the uncertain nonlinear system with the strict matching condition, they cannot solve the control problem of the uncertain nonlinear system without satisfying the strict matching condition. To relax the above limitation,

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many adaptive fuzzy control approaches were developed for uncertain nonlinear systems via the backstepping design technique, see for example [15] and [16] and references therein. [15] and [16] proposed adaptive fuzzy state feedback control approaches for a class of SISO nonlinear systems with or without time delays; [17] and [18] developed fuzzy state feedback controllers for MIMO nonlinear systems, while [19] and [20] investigated the adaptive fuzzy output feedback control problem for SISO or MIMO nonlinear systems with immeasurable states based on the state observer [21] and [22].

In recent years, adaptive fuzzy control design for uncertain stochastic nonlinear systems has received increasing attention. Based on Itô's stochastic differential equation and backstepping design technique, many adaptive fuzzy control design results obtained for deterministic nonlinear systems were extended to those stochastic nonlinear systems, see for example [23–33] and references therein. [23–25] proposed adaptive fuzzy state feedback control approaches for a class of SISO stochastic nonlinear systems; [26–29] developed adaptive output feedback controllers for SISO and MIMO stochastic nonlinear systems without unmeasured states, while [30] investigated the adaptive fuzzy or neural network decentralized output feedback stabilization problem for a class of stochastic large-scale nonlinear systems. To handle the unmodeled dynamics involved in the considered stochastic systems, [31] and [32] developed several robust adaptive output-feedback controllers based on changing supply function and small-gain theorem, and the obtained adaptive controllers not only guarantee the stability of the closed-loop systems, but also have strong robustness to the unmodeled dynamics.

Although the adaptive fuzzy backstepping control for stochastic nonlinear systems has achieved a great progress, the considered plants in the previous adaptive control approaches are mainly focused on the stochastic nonlinear systems in strict feedback form, not on the stochastic nonlinear systems in pure-feedback form. As stated in [33–36], a nonlinear pure-feedback system represents a more general class of triangular systems than a nonlinear strict-feedback system. In controller design, a nonlinear pure-feedback system has no affine appearance of the variables to be used as virtual controls. Therefore, it is quite restrictive and difficult to find the explicit virtual controls to stabilizing a nonlinear pure-feedback system by using the backsteppig technique. On the other hand, the aforementioned adaptive control approaches did not consider the input saturation problem. As we know, the input saturation is one of the most important non-smooth nonlinearities and exists in many industrial processes. Its presence severely degrades the control system performance [10,37,38].

Recently, [39–41] have investigated the adaptive fuzzy and neural control problem for a class of the stochastic nonlinear systems in pure-feedback form, and [42] developed an adaptive fuzzy control scheme for a class of the stochastic nonlinear pure-feedback systems with unknown input saturation. However, they are limited to the class of SISO stochastic nonlinear systems and assume that the states of the controlled systems are available for measurement. Therefore, they cannot be applied to those MIMO stochastic nonlinear systems in pure-feedback form, in which the states are unmeasured directly. Although our previous results [43] and [44] discussed the output feedback control problem for uncertain stochastic nonlinear systems with immeasurable states, they are still restricted to SISO or large-scale systems and without considering the input saturation problem. In addition, the adaptive control approaches in [43] and [44] are on the stabilization problem, not on the tracking problem.

This paper investigates the adaptive fuzzy output feedback track control problem for a class of uncertain MIMO stochastic nonlinear systems in pure-feedback form. The stochastic MIMO nonlinear systems under study have unknown nonlinear functions, input saturation and immeasurable states. Fuzzy logic systems and a smooth function are used to identify the uncertain nonlinear system and approximate the input saturation, respectively, and a fuzzy state observer is designed for estimating the unmeasured states. Based on the backstepping design technique, an adaptive fuzzy output feedback tracking control approach is developed and the corresponding stability of the closed-loop system is proved via Lyapunov function method. Compared with the existing results, the main advantages of the proposed adaptive fuzzy control approach are summarized as follows: (i) the proposed adaptive fuzzy control approach can be applied to a larger class of MIMO stochastic pure-feedback nonlinear systems with the input saturation. Note that the same problem has been addressed in [42]. However, they are limited to a class of SISO stochastic nonlinear systems; (ii) by designing a fuzzy state observer, the proposed adaptive control approach can eliminate the restricted assumption condition in [39–42] that the states are available for the control design; (iii) this paper employs the Butterworth low-pass filter technique, instead of the Implicit Theorem adopted in [33,35,36,39–42], to solve the pure-feedback problem in controller design. Subsequently, the assumption in [33,35,36,39–42] that the known bounds and derivatives signs of the nonlinear functions can be eliminated, and (iv) It is proved that the resulting closed-loop system