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Adaptive fuzzy output-feedback control for output constrained nonlinear systems in the presence of input saturation ☆

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Abstract

In this paper, the problem of adaptive fuzzy output-feedback control is investigated for a class of output constrained uncertain nonlinear systems with input saturation and unmeasured states. To address output constraint and input constraint, a barrier Lyapunov function and an auxiliary design system are employed, respectively. Fuzzy logic systems are utilized to approximate the unknown nonlinear functions, and a fuzzy state observer is designed to estimate the unmeasured states. By utilizing the fuzzy state observer, and combining the adaptive backstepping technique with adaptive fuzzy control design, an observer-based adaptive fuzzy output-feedback control approach is developed. It is proved that the proposed control approach can guarantee that all the signals in the closed-loop system are bounded, and the input and output constraints are circumvented simultaneously. A numerical example is provided to illustrate the effectiveness of the proposed approach.

Keywords: Uncertain nonlinear systems; Fuzzy logic systems; Fuzzy control; Adaptive control; Output constraints; Input saturation

1. Introduction

In the past decades, many approximation-based adaptive backstepping control approaches have been developed to deal with uncertain nonlinear systems in strict-feedback form via fuzzy logic systems, for example, see [1–8] and the references therein. Adaptive fuzzy backstepping control approaches are developed in [1–4] for single-input and single-output (SISO) nonlinear systems, and in [5,6] are for multiple-input and multiple-output (MIMO) nonlinear systems, while those in [7,8] are for nonlinear systems with immeasurable states. In general, the adaptive fuzzy backstepping control can provide a systematic methodology of solving control problems for a larger class of unknown nonlinear systems. The main features of the adaptive control approaches are as follows: (i) they can be used to deal with those nonlinear systems without satisfying the matching condition, and (ii) they do not require the unknown nonlinear

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functions are linearly parameterized. Therefore, the approximator-based adaptive fuzzy backstepping control becomes one of the most popular design approaches to a large class of uncertain nonlinear systems.

Although the adaptive fuzzy backstepping control design has achieved a great progress, the aforementioned control approaches assume that all the components of the considered nonlinear systems are in good operating conditions. As we know, many control systems have constraints on their inputs in the form of input saturation, hysteresis or dead-zone [9–16]. In practice, input saturation constraint is one of the most important input constraints which usually appear in many industrial control systems. There are two main motivations to study the saturation problem. One is that since saturation is a potential problem degrades the control system performance, it often gives rise to undesirable inaccuracy, or even affects system stability. The other is that the control actions are usually limited in energy or magnitude, the saturation of the control output is necessary in practice. Therefore, the analysis and control design of the systems with saturation nonlinearities has been studied by many authors, for example [17–21]. Among them, [17] proposed a robust adaptive control method for a class of uncertain nonlinear systems in the presence of input saturation and external disturbance. The Nussbaum function was introduced to compensate for the nonlinear term arising from the input saturation. However, the control method in [17] requires that the nonlinear functions must be linearly parameterized. To relax the above restriction, [18] presented adaptive neural networks backstepping control approach for a class of uncertain nonlinear systems in the presence of input saturation, [19] investigated the adaptive fuzzy backstepping control approach for a class of uncertain nonlinear time-delay systems in the presence of input saturation. Afterwards, [20] and [21] extended the results in [18] and [19] to the MIMO and interconnected large-scale uncertain nonlinear systems with input saturation. However, the aforementioned control approaches are developed based on the assumption that the states of controlled systems are measured directly. In addition, they did not consider the system output constraint problem. It should be mentioned that many control systems have constraints on their outputs or states in the form of the physical stoppage, performance and safety specifications. During operation, violation of the constraints leads to performance degradation, hazards or system damage. Thus, the output constraints in control design are very important. By far, many control important design methods have been proposed to handle the output constraints, including model predictive control [22], reference governors [23,24], and the use of set invariance notions [25,26]. Besides these, the design based on Barrier Lyapunov function (BLF) is a very effective method since such a function yields a value that approaches infinity whenever its arguments approach some limits. By using the BLF, [27] proposed a control design for the Brunovsky-type systems with output constraints, [28,29] developed the adaptive backstepping state-feedback control designs for a class of output constraint nonlinear systems, [30] studied the problem of output constraint for electrostatic microactuators, and [31] and [32] investigated the problem of control output constraint for switching system and time-varying output constraint system, respectively. However, the control design methods reported in [28–33] limit a class of systems with the states measured. Moreover, they cannot deal with the nonlinear systems with the input saturations. Although [33] proposed an adaptive neural backstepping output-feedback control method for a class of nonlinear systems without state measurement, it requires that the nonlinear functions must be in the form that $f_i(\underline{x}_i) = f_i(y)$, and it does not consider the problem of input saturation.

Motivated by the above observations, an adaptive fuzzy output-feedback control method is proposed for a class of output constrained uncertain nonlinear systems with input saturation and unmeasured states. To address output constraint and input constraint, a barrier Lyapunov function and an auxiliary design system are employed, respectively. Fuzzy logic systems are utilized to approximate the unknown nonlinear functions, and a fuzzy state observer is designed to estimate the unmeasured states. By utilizing the fuzzy state observer, and combining the adaptive backstepping technique with adaptive fuzzy control design, an observer-based adaptive fuzzy output-feedback control approach is developed. It is proved that the proposed control approach can guarantee that all the signals in the closed-loop system are bounded, and the input and output constraints are circumvented simultaneously. The main advantages of the proposed control scheme are as follows: (i) the problems of the input saturation and output constraints are solved by employing the Barrier Lyapunov function and a new auxiliary system, respectively; (ii) the problem of unmeasured state is solved by designing fuzzy state observer; (iii) the stability of the closed-loop system is guaranteed.

The remainder of this paper is organized as follows. The problem formulation and preliminaries are given in Section 2. The adaptive fuzzy output-feedback controller design and stability analysis are in Section 3. The simulation example is given in Section 4, and followed by Section 5 which concludes the work.