Neurocomputing 158 (2015) 100–108

Contents lists available at ScienceDirect

Neurocomputing

journal homepage: www.elsevier.com/locate/neucom

Observer-based fuzzy adaptive prescribed performance tracking control for nonlinear stochastic systems with input saturation[☆]

Shuai Sui, Shaocheng Tong, Yongming Li[*]

Department of Basic Mathematics, Liaoning University of Technology, Jinzhou, Liaoning 121000, China

ARTICLE INFO

Article history:
Received 12 October 2014
Received in revised form
8 December 2014
Accepted 30 January 2015
Communicated by Ning Wang
Available online 9 February 2015

Keywords:
Fuzzy adaptive control
Stochastic nonlinear systems
Prescribed performance
Input saturation
State observer

ABSTRACT

In this paper, the problem of prescribed performance adaptive fuzzy output feedback control is investigated for a class of single-input and single-output nonlinear stochastic systems with input saturation and unmeasured states. Fuzzy logic systems are used to identify the unknown nonlinear system, the input saturation is approximated by a smooth function, and a fuzzy state observer is designed for estimating the unmeasured states. Based on the backstepping recursive design technique and the predefined performance technique, a new fuzzy adaptive output feedback control method is developed. It is shown that all the signals of the resulting closed-loop system are bounded in probability and the tracking error remains an adjustable neighborhood of the origin with the prescribed performance bounds. The simulation example and the comparative results are provided to show the effectiveness of the proposed control approach.

1. Introduction

In the past decades, some novel approaches have been developed to deal with complex system identification and control design based on fuzzy sets theory, for example, see [1–9] and references therein. Especially, by combining fuzzy logic systems with the backstepping design technique, many important adaptive fuzzy backstepping control approaches were developed for uncertain nonlinear systems, see for example [10–19] and references therein. Authors in [10–16] proposed adaptive fuzzy state feedback control approaches for a class of single-input and single -output (SISO) or multi-input and multi-output (MIMO) nonlinear systems, while authors in [17–19] investigated the adaptive fuzzy output feedback control problem for SISO or MIMO nonlinear systems with immeasurable states. However, the above results are only suitable to control the unknown deterministic nonlinear systems. They cannot be applied to control those unknown stochastic nonlinear systems.

In recent years, adaptive fuzzy control design for unknown stochastic nonlinear systems has received increasing attention, based on It ô's stochastic differential equation and backstepping design technique, many novel adaptive fuzzy control design approaches have been developed for some unknown stochastic nonlinear systems, see for example [20–25]. Authors in [20,21] proposed two adaptive fuzzy state feedback control approaches for a class of SISO stochastic nonlinear systems with unknown virtual control gain function and unknown dead-zone. Authors in [22] proposed an adaptive fuzzy backstepping control approach for a class of uncertain stochastic pure-feedback nonlinear systems with time-varying delays. Authors in [23] extended the results of Ref. [22] to a class of unknown stochastic pure-feedback nonlinear systems with unknown control directions, time-varying delays and measurable states, while authors in [24,25] developed adaptive fuzzy output feedback controllers for SISO uncertain stochastic nonlinear systems with immeasurable states.

It should be mentioned that the aforementioned control approaches in [20–25] all assume that the considered nonlinear systems have constraints on their inputs in the form of input saturation [26,27]. In practice, input saturation is one of the most important input constraints which usually appear in many industrial control systems. In addition, since saturation is a potential factor degrading the control system performance, it often gives rise to undesirable inaccuracy, or even affects system stability. Recently, the analysis and control design for stochastic nonlinear systems with saturation nonlinearities has been studied in [28,29], and two adaptive neural and fuzzy tracking control approaches are proposed for a class of stochastic strict-feedback and pure-feedback nonlinear systems, respectively. However, the control approaches in [28,29] assume that the states of the controlled

---

[☆] This work was supported by the National Natural Science Foundation of China (Nos. 61374113, 61074014, 61203008).

[*] Corresponding author. Tel.: +86 416 4199101.
E-mail address: l_y_m_2004@163.com (Y. Li).

http://dx.doi.org/10.1016/j.neucom.2015.01.063
0925-2312/© 2015 Elsevier B.V. All rights reserved.

stochastic nonlinear systems are available for measurement. To solve the unmeasured states problem, [30] proposed an adaptive fuzzy output feedback control approach for a class of MIMO stochastic pure-feedback nonlinear systems. Although the proposed control method can ensure that the tracking performance converge to a small residual set like [28,29], whose size depends on the design parameters and some unknown bounded terms. They cannot offer the guaranteed transient performance at time instants.

As we know, the practical engineering often requires the proposed control scheme to satisfy certain quality of the performance indices, such as overshoot, convergence rate, and steady-state error. Prescribed performance issues are extremely challenging and difficult to be achieved, even in the case of the nonlinear behavior of the system in the presence of unknown uncertainties and external disturbances. More recently, a design solution called prescribed performance control for the problem has been proposed in [31] for a class of feedback linearization nonlinear systems and was extended to the class of nonlinear systems in [32]. Its main idea is to introduce predefined performance bounds of the tracking errors, and is able to adjust control performance indices. However, to the author's best knowledge, by far, the prescribed performance design methodology has not been applied to unknown stochastic nonlinear strict-feedback systems with unknown functions, input saturation and immeasurable states, which is important and more practical, thus has motivated us for this study.

In this paper, an adaptive fuzzy output feedback tracking control design with prescribed performance is developed for a class of uncertain SISO nonlinear stochastic systems with input saturation and unmeasured states. With the help of fuzzy logic systems identifying the unknown nonlinear systems, a fuzzy adaptive observer is developed to estimate the immeasurable states. The backstepping control design technique based on prescribed performance bounds is presented to design adaptive fuzzy output feedback controller. It is proved that all the signals of the resulting closed-loop system are bounded in probability. Moreover, the tracking error converges to an adjustable neighborhood of the origin and remains within the prescribed performance bounds. Compared with the previous adaptive fuzzy control methods, the main advantages of the proposed control scheme are summarized as follows:

(i) This paper proposed an adaptive fuzzy tracking output feedback control method for a class of nonlinear stochastic systems in strict-feedback form. The proposed adaptive control method has solved the state unmeasured problem via designing fuzzy state observer. Although the previous literature [20–24,28,29] also addressed the adaptive fuzzy or neural control design for nonlinear strict-feedback and pure-feedback systems, they all require that states must be available for measurement.

(ii) This paper investigated the fuzzy adaptive prescribed performance tracking control design problem for a class of nonlinear stochastic systems with input saturation. The problem of the input saturation is solved by employing a new auxiliary system. In [28,29], the authors addressed the same problem as this paper, and these control methods in [28,29] can ensure that the tracking performance converge to a small residual set, however, they cannot offer the guaranteed transient performance at time instants. In this paper, by introducing predefined performance, the proposed adaptive control method cannot only ensure the closed-loop system to be stable, but also guarantee the tracking error to converge to a predefined arbitrarily small residual set.

2. System descriptions and preliminaries

2.1. Nonlinear system descriptions

Consider the following SISO strict-feedback nonlinear stochastic system:

$$\begin{cases} dx_1 = (x_2 + f_1(x_1) + \Delta_1(x,t))dt + g_1(x)\,dw \\ dx_2 = (x_3 + f_2(\underline{x}_2) + \Delta_2(x,t))dt + g_2(x)\,dw \\ \vdots \\ dx_{n-1} = (x_n + f_{n-1}(\underline{x}_{n-1}) + \Delta_{n-1}(x,t))dt + g_{n-1}(x)\,dw \\ dx_n = (u(v) + f_n(\underline{x}_n) + \Delta_n(x,t))dt + g_n(x)\,dw \\ y = x_1 \end{cases} \tag{1}$$

where $\underline{x}_i = [x_1, x_2, \ldots, x_i]^T \in R^i$, $i = 1, 2, \ldots, n(x = \underline{x}_n)$ is the state vector; $u \in R$ and $y \in R$ are the control input and system output, respectively. $f_i(\underline{x}_i)$ and $g_i(x)$ $i = 1, 2, \ldots, n$ are unknown continuous nonlinear functions, $\Delta_i(x,t)$, $i = 1, 2, \ldots, n$ is the external disturbance. $w \in R$ is an independent standard Wiener process defined on a complete probability space with the incremental covariance $E\{dw \cdot dw_j^T\} = \sigma(t)\sigma(t)^T dt$. $u(v)$ denotes the plant input subject to saturation type nonlinearly. Throughout this paper, it is assumed that the only output y is available for measurement.

According to [28,29], input saturation $u(v(t))$ is described by

$$u(v(t)) = sat(v(t)) = \begin{cases} sign(v(t))u_M, & |v(t)| \ge u_M \\ v(t), & |v(t)| < u_M \end{cases} \tag{2}$$

where $v \in R$ is the input to the saturator, and u_M is the bound of $u(t)$. Clearly, the relationship between the applied control $u(t)$ and the control input $v(t)$ has a sharp corner when $|v(t)| = u_M$. Thus backstepping technique cannot be directly applied. In order to use this technique, the saturation is approximated by a smooth function defined as

$$h(v) = u_M \times \tanh\left(\frac{v}{u_M}\right) = u_M \frac{e^{v/u_M} - e^{-v/u_M}}{e^{v/u_M} + e^{-v/u_M}} \tag{3}$$

Then $sat(v(t))$ in (2) can be expressed as

$$sat(v) = h(v) + \rho(v) = u_M \times \tanh\left(\frac{v}{u_M}\right) + \rho(v) \tag{4}$$

where $\rho(v) = sat(v) - h(v)$ is a bounded function in time and its bound can be obtained as

$$|\rho(v)| = |sat(v) - h(v)| \le u_M(1 - \tanh(1)) = D_1 \tag{5}$$

Note that in the section $0 \le |v| \le u_M$ the bound $\rho(v)$ increases from 0 to D_1 as $|v|$ changes from 0 to u_M, and outside this range the bound $\rho(v)$ decreases from D_1 to 0. Fig. 1 shows approximation of the saturation function [28,29].

To facilitate the adaptive control design, the following assumptions are made for the system (1).

Assumption 1. The external disturbances Δ_i is bounded by a positive constant Δ_i^*, i.e., $|\Delta_i| \le \Delta_i^*$.

Assumption 2. Assume that functions $f_i(\cdot)$ satisfy the global Lipschitz condition, that is, there exist known constants $m_i, i = 1, 2, \cdots, n$ such that for $\forall X_1, X_2 \in R^i$, the following inequalities hold

$$|f_i(X_1) - f_i(X_2)| \le m_i \|X_1 - X_2\|$$

where $\|X\|$ denotes the 2-norm of a vector X.

Assumption 3. ([33]): The disturbance covariance $g^T \sigma\sigma^T g = \overline{\sigma\sigma}^T$ is bounded, where $g = [g_1, \ldots, g_n]^T$.

Our control objective is to design a stable output feedback control scheme for system (1) to ensure that all the signals are