Information Sciences 289 (2014) 225–240

Contents lists available at ScienceDirect

Information Sciences

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

# Adaptive fuzzy decentralized tracking fault-tolerant control for stochastic nonlinear large-scale systems with unmodeled dynamics ☆

Shaocheng Tong, Shuai Sui, Yongming Li *

*Department of Basic Mathematics, Liaoning University of Technology, Jinzhou 121001, China*

ARTICLE INFO

*Article history:*
Received 7 October 2013
Received in revised form 30 March 2014
Accepted 26 June 2014
Available online 13 August 2014

*Keywords:*
Fault-tolerant control
Actuator fault
Fuzzy logic system
Stochastic nonlinear large-scale system
Backstepping technique
Unmodeled dynamics

ABSTRACT

This paper studies the adaptive fuzzy decentralized tracking fault-tolerant control design problem for a class of unknown stochastic nonlinear strict-feedback systems with actuator faults. The stochastic systems under study have the characterizations of unknown functions, unmodeled dynamics and without the direct measurements of state variables. Fuzzy logic systems are employed to identify the unknown stochastic nonlinear systems, and a fuzzy state observer is established for estimating the immeasurable states. The dynamic surface control (DSC) design approach based on the backstepping technique is presented to design adaptive decentralized tracking fault-tolerant controller. It is proved that proposed control approach guarantees that all the variables of the closed-loop system are bounded in probability, and also that the tracking errors converge to an adjustable neighborhood of the origin regardless of actuator faults and unmodeled dynamics. The simulation results are provided to illustrate the effectiveness of the proposed control approach.


## 1. Introduction

A large-scale system is often considered as a set of interconnected subsystems, such as power systems, computer and telecommunications networks, economic systems and multiagent systems. Owing to the complexity of control synthesis and the physical restrictions on information exchange among subsystems, it is often required to design a decentralized controller depending only on local measurements, even if to achieve an objective for the whole large-scale system.

In the past decade, the backstepping design technique has been widely used for control design of nonlinear large-scale systems with interactions unmatched in control input, and many adaptive decentralized control approaches have been developed (see [6,9,10,13,22,45], and the references therein). Adaptive decentralized full state-feedback controllers using the backstepping technique were actively proposed for nonlinear large-scale systems in strict feedback form [9]. These results were extended to adaptive decentralized output feedback control design in order to relax the requirement of additional sensors for measuring all state variables of nonlinear large-scale systems [10,13]. Subsequently, adaptive decentralized output feedback control approaches were developed for nonlinear large-scale systems with unmodeled dynamics or unknown dead-zones [6,22,45]. Since the aforementioned results are only suitable for those nonlinear large-scale systems,

☆ This work was supported by the National Natural Science Foundation of China (Nos. 61374113 and 61203008), and Program for Liaoning Innovative Research Team in University (LT2012013).
* Corresponding author.
*E-mail address:* l_y_m_2004@163.com (Y. Li).

http://dx.doi.org/10.1016/j.ins.2014.06.042
0020-0255/

in which the nonlinearities are known exactly or can be linearly parameterized, they cannot be applied to those nonlinear large-scale systems with completed unknown nonlinear functions. To solve the above problem, many approximation-based adaptive decentralized control schemes have been proposed for uncertain nonlinear large-scale systems by using fuzzy logic systems or neural networks, for example, see [3,7,8,30]. The works in [8,33] developed adaptive fuzzy and neural network (NN) decentralized backstepping state feedback control approaches for the uncertain large-scale systems with or without time delays. The works in [3,7,30] investigated adaptive fuzzy and NN decentralized backstepping output feedback controllers for a class of the uncertain large-scale systems, while the works in [32] developed adaptive NN decentralized backstepping controllers for a class of the uncertain large-scale systems via DSC method. Consequently, they avoid the so-called "explosion of complexity" problem existing in previous works [3,7,8,30], which is incurred by repeating differentiations of nonlinear functions with respect to virtual control variables.

In recent years, the study on stochastic systems has received considerable attention, and many novel results on stochastic systems have been obtained [37–40,44]. Specifically, an $L_2$–$L_\infty$ fuzzy dynamic output feedback control was designed for nonlinear fuzzy Itô stochastic delay systems in [37]; the dissipativity-based sliding mode control problem was investigated for switched stochastic systems in [38]; the dissipativity analysis and synthesis problems were studied for discrete-time T–S fuzzy stochastic systems in [39]; and the fault detection problem was addressed for nonlinear Itô stochastic systems by using fuzzy filtering technique [40]. It should be pointed out that the methods developed in [37,39,40] are original, and they provide novel and effective solutions in a uniform fuzzy framework to solve the control and the filter design problems for nonlinear stochastic systems, thus are very important and significant. A novel fault detection filter was designed for two-dimensional discrete-time Markovian jump systems in [41]. More recently, adaptive control design for stochastic nonlinear systems has received increasing attention [4,11,39,40], and many adaptive backstepping control design methods for deterministic nonlinear large-scale systems have been extended to the case of stochastic nonlinear large-scale systems, see for example [5,21,31,33,35,42,46], and references therein. The authors in [5,21,42] investigated adaptive decentralized output feedback stabilization control design of stochastic nonlinear large-scale systems. T. Wang et al. [35] proposed adaptive decentralized output feedback stabilization control method for stochastic nonlinear large-scale systems with unmodeled dynamics, the proposed control method can not only ensure the stability of the closed-loop system, but also accommodate the unmodeled dynamics. More recently, H.Q. Wang et al. [33] proposed an adaptive fuzzy decentralized state feedback control scheme for a class of uncertain stochastic nonlinear large-scale systems. S.C. Tong et al. [31,46] studied adaptive fuzzy decentralized output feedback DSC stabilization and robust stabilization problem for a class of uncertain stochastic large-scale nonlinear systems with unmodeled dynamics. Despite the great progress has been made for control design of stochastic large-scale nonlinear systems, however, the existing control approaches all assume that all the components of the nonlinear large-scale systems are in good operating conditions, that is, the controlled systems are free of the actuator faults. As we know, in practical control mechanisms, various components such as actuators, sensors and processors may undergo abrupt failures individually or simultaneously during operation. The adverse effects due to the failures require being compensated and enhance the reliability and safety of the system. It is thus important to design a fault-tolerant control (FTC) scheme to accommodate such failures and maintain acceptable system performance [12,15,16,19,20,27,43].

It should be mentioned that in recent years, many effective adaptive FTC approaches have been developed for deterministic nonlinear systems [17,18,26,28,29]. Among them, the authors in [17,18,26,29] developed adaptive FTC methods for a class of single-input and single-output (SISO) nonlinear systems and multi-input and multi-output (MIMO) nonlinear systems with both loss of effectiveness and lock-in-place actuator faults. The proposed control schemes not only guarantee the stability of the control system, but also obtain the robust control performance. On the basis of the results in [17,18,26] proposed adaptive fuzzy state feedback FTC schemes for a class of unknown SISO or MIMO nonlinear systems in strict-feedback form, in which fuzzy logic systems are employed to approximate the unknown nonlinearities, and new adaptive fuzzy FTC schemes were constructed recursively in the framework of the backstepping design technique. More recently, [28,29] extended the adaptive fuzzy FTC results in [17,18] to the output feedback FTC problem, and proposed adaptive fuzzy backstepping output-feedback FTC schemes for unknown MIMO and large-scale nonlinear systems in strict feedback form, respectively. The proposed adaptive fuzzy FTC schemes relax the requirement of the states being available for measurement. However, the above control approaches in [28,29] do not consider the problem of the unmodeled dynamics or dynamical disturbances. Therefore, the designed controllers lack the robustness to the unmodeled dynamics or dynamical disturbances. In addition, the "explosion of complexity" problem has not been investigated in [28,29]. To the best of our knowledge, to date, not much of an attempt has been made on the adaptive decentralized fuzzy fault-tolerant control design for uncertain stochastic large-scale systems with actuator faults and unmolded dynamics, which motivates us for this study.

In this paper, an adaptive fuzzy decentralized fault-tolerant control design is firstly developed for a class of uncertain stochastic large-scale nonlinear systems with actuator faults. The stochastic systems under study have the characterizations of unknown functions, unmodeled dynamics and without the direct measurements of state variables. In the controller design, fuzzy logic systems are employed to identify the unknown stochastic nonlinear functions, and a fuzzy state observer is established for estimating the immeasurable states. By using the backstepping design technique and DSC design method, an adaptive fuzzy decentralized output feedback tracking fault-tolerant control scheme is developed. The stability of the closed-loop system is proved by using the Lyapunov function method and combining with the ISpS property. The main contributions of this paper can be summarized as follows: (i) by designing a state observer to estimate the unmeasured states, the proposed adaptive fuzzy decentralized FTC approach can solve the output feedback control problem for a class of uncertain stochastic large-scale nonlinear systems, in which the states are not required to be available for control design; (ii) by incorporating