Neurocomputing 186 (2016) 35–43

Contents lists available at ScienceDirect

Neurocomputing

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

Fuzzy adaptive state-feedback fault-tolerant control for switched stochastic nonlinear systems with faults ☆

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ARTICLE INFO

Article history:
Received 18 November 2015
Received in revised form
20 December 2015
Accepted 22 December 2015
Communicated by Hongyi Li
Available online 4 January 2016

Keywords:
Nonlinear switched stochastic systems
Common Lyapunov function
Fault-tolerant control
Backstepping technique

ABSTRACT

In this paper, the fault-tolerant control (FTC) problem is investigated for a class of uncertain switched stochastic nonlinear systems. The controlled system contains unknown nonlinear functions and actuator faults, which are modeled as both lock-in-place and loss of effectiveness. With the help of fuzzy logic systems to approximate the unknown nonlinear functions and by utilizing the common Lyapunov function (CLF) method, a fuzzy adaptive state-feedback fault-tolerant tracking control approach is developed. It is shown that all the variables of the closed-loop system are semi-globally uniformly bounded (SGUUB) in probability, the tracking error converges to an arbitrary small neighborhood of the origin. A simulation is given to demonstrate the effectiveness of the proposed approach.

1. Introduction

In the past decades, adaptive control design for stochastic nonlinear systems has attracted more and more attention and many important control methods have been developed, see [1–6] and references therein. Among them, [1,2] proposed the backstepping control design method for stochastic single-input-single-output (SISO) nonlinear systems by utilizing Quartic Lyapunov function. In [3,4], according to changing supply function and small-gain theorem, the adaptive fuzzy backstepping design schemes were developed for nonlinear stochastic SISO systems in the presence of unmodeled dynamics. Then, [5,6] proposed the adaptive fuzzy output-feedback decentralized control methods for stochastic nonlinear large-scale systems. However, the main limitation in [1–6] is that these approaches are only suitable for those stochastic nonlinear systems, in which the nonlinear uncertainties must be linearly parameterized. To cope with the above limitation, many novel adaptive control methods have been developed, see [7–14]. [7–10] proposed some adaptive state-feedback control methods for the nonlinear stochastic systems that the states can be directly used, and [11–14] proposed several adaptive output-feedback control schemes for the nonlinear stochastic systems in the presence of the unmeasured states.

On the other hand, switched systems have gained considerable interest in the past decades and many physical and engineering systems can be constructed as nonlinear switched systems [15–17]. As we know that the stability of the switched system can be guaranteed if a CLF exists under arbitrary switching (see [18]). In recently years, some backstepping control schemes have been investigated [19–21] for the nonlinear switched systems on the basis of the CLF stability theory, but the nonlinear functions of considered systems are both known. Furthermore, due to the existence of stochastic disturbances in practical systems, some researchers begin to put more time and energy into the investigations of switched stochastic systems. Many remarkable consequences of stability analysis (see [22–24]) and controller design (see [25–27]) have been acquired. Among them, [24] proposed an adaptive control scheme for a class of stochastic nonlinear systems in the presence of irreducible homogeneous Markovian switching. Based on the common Lyapunov function method, [27] proposed the state feedback and output feedback control approaches for a class of stochastic nonlinear systems with measured and unmeasured states, respectively. However, the above control schemes assume that all the components of the considered systems are in good operating conditions, and they did not consider the problem of faults.

In general, there always exist some faults [28] in the practical control systems, like actuator and sensor faults, these faults often reduce the control characteristics and influence the stability of the considered system, and more serious result is the catastrophic accidents. Thus, many FTC design methods have been proposed to accommodate the actuator faults involved in the nonlinear systems [29–34]. The works in [29,30] investigated the adaptive fuzzy FTC schemes for a class of unknown SISO nonlinear strict-feedback systems in the presence of actuator failures. Based on their results,

☆This work was supported by the National Natural Science Foundation of China (Nos. 61374113 and 61573175).
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http://dx.doi.org/10.1016/j.neucom.2015.12.080
0925-2312/

a fuzzy adaptive FTC design method was proposed in [31] for a class of nonlinear multi-input–multi-output (MIMO) systems. To handle the unmeasured states problems, [32] proposed a fuzzy adaptive output-feedback tracking FTC method for large-scale nonlinear systems. The fuzzy adaptive output feedback tracking FTC approaches were proposed in [33, 34] for the stochastic nonlinear MIMO and large-scale systems. However, the aforementioned methods are only applied to the nonlinear non-switched systems.

Inspired by the above observations, in this paper, a fuzzy adaptive state-feedback fault-tolerant tracking control scheme is developed for a class of switched stochastic nonlinear systems, under arbitrary switching. It is shown that the proposed control approach can guarantee that all the variables of the closed-loop switched stochastic system are SGUUB in probability and the tracking error regulates to a small neighborhood of the origin regardless of actuator faults. Compared with previous results, this paper owns two contributions:

(1) This paper proposed a fuzzy adaptive FTC design scheme for a class of switched stochastic nonlinear systems. The proposed adaptive control method has solved the actuator faults problem. Note that the previous Refs. [19–27] assumed that all the components in the considered systems are in good operating conditions. Thus, they cannot be used for dealing with the switched stochastic nonlinear systems with actuator faults.

(2) The considered nonlinear systems of this paper contain stochastic disturbance, actuator faults and switched signals. Consequently, based on the common Lyapunov function stability theory and FTC design method, the proposed adaptive controller can not only have the robustness to stochastic disturbance and accommodate the actuator faults, but also guarantee the stability of the whole controlled systems, thus the existing results in [33–38] cannot be applied to control the switched stochastic nonlinear systems considered in this paper.

2. Problem formulations and preliminaries

2.1. System descriptions and assumptions

Consider a class of uncertain switched stochastic nonlinear systems:

$$\begin{cases} dx_i = (f_{\sigma(t),i}(\bar{x}_i) + x_{i+1})dt + g^T_{\sigma(t),i}(\bar{x}_i)dw & 1 \le i \le n-1 \\ dx_n = (f_{\sigma(t),n}(\bar{x}_n) + \bar{q}_n^T(\bar{x}_n)u)dt + g^T_{\sigma(t),n}(\bar{x}_n)dw & n \ge 2 \\ y = x_1 \end{cases} \quad (1)$$

where $\bar{x}_i = [x_1, \cdots, x_i]^T \in R^i$, $i = 1, \cdots, n$ are the state vectors, $u = [u_1, u_2, \cdots, u_m]^T \in R^m$ is the input vector of the system, $y \in R$ is the system output. $\sigma(t) : [0, \infty) \to \Xi =^{def} \{1, 2, \cdots, N\}$ is the switching signal, which takes its values in the compact set Ξ. Moreover, $\sigma(t) = p$, $p = 1, \cdots, N$means that p-th subsystem is active. $\bar{q}_n(\bar{x}_n) = [q_{n1}(\bar{x}_n), \cdots, q_{nm}(\bar{x}_n)]^T \in R^m$, $f_{p,i}$, q_{nj} and $g_{p,i}$ for $i = 1, \cdots, n$, $j = 1, \cdots, m$ are unknown nonlinear smooth functions. $w \in R$ is an independent r-dimension standard Wiener process.

The actuator faults involved in this paper are both lock-in-place and loss of effectiveness are defined by [29–34] as follows.

Lock-in-place fault model:

$$u_j(t) = \bar{u}_j, \quad t \ge t_j, j \in \{j_1, j_2, \cdots, j_h\} \subset \{1, 2, \cdots, m\} \quad (2)$$

Loss of effectiveness fault model:

$$u_i(t) = \vartheta_i v_i(t) \; t \ge t_i, i \in \overline{\{j_1, j_2, \cdots, j_h\}} \cap \{1, 2, \cdots, m\} , \vartheta_i \in [\underline{\vartheta}_i, 1] , 0 < \vartheta_i \le 1 \quad (3)$$

where $\bar{u}_j$ is the unknown constant where the j-th actuator stuck at, $v_i(t)$ is the applied control signal which experiences loss of effectiveness fault, t_j and t_i are the time instants at which the$j$-th lock-in-place and i-th loss of effectiveness fault occurs respectively. ϑ_i is still effective proportion of the actuator after losing some effectiveness, $\underline{\vartheta}_i$ is the lower bound of ϑ_i. In particular, $\underline{\vartheta}_i$ is 1 means that the actuator $u(t)$ is in the failure-free case.

Taking the actuator faults (2) and (3) into account, the input vector $u(t)$ can be expressed as

$$u(t) = \vartheta v(t) + s(\bar{u} - \vartheta v(t)) \quad (4)$$

where $\bar{u} = [\bar{u}_1, \cdots, \bar{u}_m]^T$, $v(t) = [v_1(t), \cdots, v_m(t)]^T$, and

$$\vartheta = diag\{\vartheta_1, \vartheta_2, \cdots, \vartheta_m\}$$

$$s = diag\{s_1, s_2, \cdots, s_m\}$$

$$s_j = \begin{cases} 1, & \text{if the } j-\text{th actuator fails as (2) i.e.} u_j = \bar{u}_j, \\ 0, & \text{otherwise.} \end{cases} \quad (5)$$

In this paper, our control objective is to design a fuzzy adaptive state-feedback fault-tolerant tracking controller u_0 with parameter adaptive laws for the systems (1) with actuator faults (2) and (3) to ensure all the variables of the closed-loop system are bounded in probability and the output $y(t)$ follows the ideal reference signal y_r under arbitrary switching.

In order to accomplish the control purpose, the nominal plant is proposed in the following form:

$$\begin{cases} dx_i = (f_{\sigma(t),i}(\bar{x}_i) + x_{i+1})dt + g^T_{\sigma(t),i}(\bar{x}_i)dw & 1 \le i \le n-1 \\ dx_n = (f_{\sigma(t),n}(\bar{x}_n) + q_n(\bar{x}_n)u_0)dt + g^T_{\sigma(t),n}(\bar{x}_n)dw & n \ge 2 \\ y = x_1 \end{cases} \quad (6)$$

where $q_n(\bar{x}_n)$ is an unknown smooth nonlinear function. u_0 is the designed controller by the following backstepping proof procedures.

Starting from the control target, it is required that at least one actuator does not stuck at, of course, the remaining actuators can lose effectiveness or be normal, Supposed that all but one actuator have been stuck and the values are equal to zero, i.e., $u_j(t) = \bar{u}_j(t) = 0, j = 1, 2, \cdots, i-1, i+1, \cdots, m$, the considered system can still match the nominal system (6), i.e.,

$$q_{ni}(\bar{x}_n)u_i = q_n(\bar{x}_n)u_0 \quad (7)$$

This will require such constants ξ^*_{1j} such that$\xi^*_{1j} q_{nj}(\bar{x}_n) = q_n(\bar{x}_n)$, $j = 1, \cdots, m$. The values of ξ^*_{1j} are unknown, but it is necessary to design parameters adaptive laws for the sign of each ξ^*_{1j}.

To facilitate the control design, the following assumptions are given.

Assumption 1. [29]: The system (1) is constructed that for any up to $m-1$ actuators stuck at some places and the remaining actuators may lose effectiveness, the controlled system can still accomplish the control purpose.

Assumption 2. [30]: There exist constants $0 < q_{n0} \le q_{n1}$ such that $q_{n0} \le q_n(\bar{x}_n) \le q_{n1}$, $q_n(\bar{x}_n)$ is given in (6).

Assumption 3. [30]: There exist constants $q_{nd} > 0$ such that $|\dot{q}_n(\bar{x}_n)| \le q_{nd}$, $\forall \bar{x}_n \in \Omega_i \subset R^n$.

Assumption 4. [30]: The known values $sign[\xi^*_{1j}]$, $j \in \{1, 2, \cdots, m\}$ take the place of the sign of the constant ξ^*_{1j}.

2.2. Fuzzy logic systems

In this paper, we employ fuzzy logic systems in [35] to approximate the unknown nonlinear functions. The common form of fuzzy logic systems is described as $y(x) = \theta^T \phi(x)$, where $\theta \in R^N$ is the estimate parameter vector, and $\phi(x)$ is the vector of the fuzzy basis function.