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Approximation-based adaptive neural output feedback control for a class of uncertain switched stochastic nonlinear systems with average dwell time condition

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ABSTRACT

This paper studies the problem of adaptive neural output feedback controller design for a class of uncertain switched stochastic nonlinear systems in strict-feedback form. In the design procedure, a common coordinate transformation for all subsystems is constructed to overcome the design difficulty caused by adoption of different coordinate transformation for different subsystems. Then, by using switched state observer to estimate the unmeasured states and different update laws for different subsystems, a novel neural output-feedback controller is designed via backstepping approach. Furthermore, based on the Lyapunov method and the average dwell time condition, the stability of the resulting closed-loop system can be achieved. It is shown that all the signals of the closed-loop system are bounded under a class of switching signals with average dwell time. Finally, simulation results are included for validating the advantages of the proposed approaches.

1. Introduction

Switched systems, which consist of a finite number of dynamical subsystems together with a switching rule that determines the switching among them, have received a great deal of attention by their strong engineering background in various areas [1], such as mechanical systems, chemical engineering processing, constrained robotics, just to name a few. It is well known that how to design appropriate switching laws to stabilize the switched system is one of the most interesting and serious challenges for switched systems.

On the other hand, stochastic disturbance often exists in practical systems and is a source of instability of control systems. Therefore, the investigation on stochastic nonlinear systems has received much attention in the control community in recent years [2–5]. Particularly, approximation-based adaptive fuzzy or neural backstepping controllers have become one of the most popular design approaches to a large class of uncertain nonlinear systems, and some interesting results have been reported in [6–24]. However, the abovementioned results focus on the control problem of nonswitched stochastic systems and less attention has been paid to the control problem of switched stochastic systems.

To solve this problem, significant research efforts have been devoted to the problems of analysis and synthesis for switched stochastic systems. For example, [25] solved the problems of dissipativity analysis and sliding mode control (SMC) for a class of continuous-time switched stochastic systems based on the average dwell time approach and the piecewise Lyapunov function technique. By using a supplementary variable technique and a plant transformation, the state estimation and sliding mode control problems for phase-type semi-Markovian jump systems were studied in [26]. In [27], the problem of SMC of Markovian jump singular time-delay systems was investigated with bounded $\mathcal{L}_2$ gain performance. In [28], the problems of stochastic stability and sliding mode control for a class of linear continuous-time systems with stochastic jumps were considered. In [29], a class of nonlinear uncertain stochastic systems with Markovian switching was studied based on the SMC method. All the aforementioned control approaches, however, focus on the linear systems with matched uncertainty satisfying linear growth. As a matter of fact, this assumption does not hold in many practical systems. To overcome this difficulty, the backstepping control approach of stochastic nonlinear systems with Markovian switching was studied in [30,31]. Recently, the authors in [32] proposed a state feedback control scheme for switched stochastic nonlinear systems in strict-feedback form under arbitrary

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switchings based on the assumption that all system nonlinearities are known. However, this assumption is usually unrealistic in practice. In fact, many complex system dynamics in real world are too difficult to be explicitly formulated. In such case, the results in [30,31] and [32] are not directly applicable.

The recent literature on controller synthesis has devoted to the research of the adaptive control of switched nonlinear systems, and different approaches have been proposed based on the assumption that the system states are measured directly [33–35]. The aforementioned results in [33–35], however, required that the states of nonlinear systems were available for measurement. In practice, state variables are often unmeasurable for many nonlinear systems, which makes the aforementioned state feedback control algorithms invalid. Therefore, a new approximation-based adaptive control approach will be required for switched uncertain stochastic nonlinear systems without the measurements of the system states. However, to the best of our knowledge, there is not a publication when the states of systems are not measured and the nonlinear functions are unknown in output feedback for switched uncertain stochastic systems. Therefore, research in this area will be of both theoretical and practical importance, and it is the aim of this research.

Motivated by these observations, this paper studies the problem of adaptive output feedback neural tracking control for a class of switched uncertain stochastic nonlinear systems. A switched state observer is designed to estimate the unmeasurable state variables. By combining the adaptive backstepping technique with RBF neural networks' universal approximation capability, the adaptive neural output feedback control scheme is proposed. Also, in order to avoid different coordinate transformations for subsystems, a common basis function vector for different subsystems at each step of backstepping is chosen. The main contributions of this paper are summarized as follows.

(1) Unlike the existing result of switched stochastic nonlinear systems in [32], where all system functions are known and the states of the system are measurable directly, the system functions and the system states are unknown. By using a switched observer to estimate the unmeasurable system states and the NN to approximate the unknown and desired control input signals directly, a novel neural output feedback controller is designed by exploring the backstepping and the average dwell time for the first time.

(2) A switched observer is designed to estimate the unmeasurable system states, hence, the conservativeness caused by adoption of a common observer for all subsystems is reduced. Meanwhile, a common coordinate transformation for different subsystems at each step of backstepping is designed to avoid different coordinate transformations for subsystems.

(3) Since the exponential decline property of Lyapunov functions for individual subsystems is no longer assumed in this paper, the classical average dwell time method in [37] cannot be directly applied to handle the adaptive neural output-feedback control problem of switched uncertain stochastic nonlinear systems. To solve this problem, we improve the classical average dwell time method. Also, we simultaneously construct the adaptive output-feedback controllers of subsystems and give a class of switching signals with average dwell time.

(4) By using direct adaptive NN control method, the proposed controller for each subsystem contains only one adaptive parameter that needs to be updated online, which is not related to the numbers of the system states and the NN nodes used in the NN. Therefore, the computation burden is significantly reduced.

Notation: Throughout the paper, the following notations are used, R^n denotes the n-dimensional Euclidean space and $\|\cdot\|$ represents Euclidean norm of vectors or matrices. R_+ denotes the set of all nonnegative real numbers. I stands for the identity matrix with an appropriate dimension. A^T represents the transpose of matrix A. $P>0$ means that P is a positive-definite matrix with an appropriate dimension.

2. Preliminaries and problem formulation

In this section, the definition of stochastic switched systems and some useful preliminaries are first presented in Section 2.1, and then Section 2.2 introduces the definition of radial basis function NN, and then the problem formulation is presented in Section 2.3.

2.1. Mathematical preliminaries

Consider a family of stochastic nonlinear systems described by

$$dx = f_k(x)\,dt + g_k(x)\,d\omega, \quad k \in M \tag{1}$$

where $M=\{1,2,\ldots,m\}$, $x\in R^n$ is the state of the system, ω is an r-dimensional independent standard Brownian motion defined on the complete probability space (Ω, F, F_t, P) with Ω being a sample space, F a σ-field, $\{F_t\}_{t\geq 0}$ a filtration and P a probability measure, and $f_k(\cdot)$ and $g_k(\cdot)$ are locally Lipschitz functions in x and satisfy $f_k(0)=0$ and $g_k(0)=0$, respectively, which means that the kth system has a local solution. In addition, we assume that the state of the system (1) does not jump at the switching instants, i.e., the solution is everywhere continuous [34–36].

In the following, the definition of average dwell time will be given, which plays a key role in the present paper.

Definition 1 (*Hespanha and Morse [37]*). For any $T\geq t\geq 0$, denoting $N_\sigma(T,t)$ is the number of switching of $\sigma(t)$ occurring in the interval $[t,T)$, if there exist numbers $N_0>0, \tau_a>0$ such that

$$N_\sigma(T,t) \leq N_0 + \frac{(T-t)}{\tau_a} \tag{2}$$

then τ_a is called average dwell time.

Let $T>0$ be an arbitrary time. Denote by $t_1,\ldots,t_{N_\sigma(T,0)}$ the switching times on the interval $(0,T)$ (by convention, $t_0=0$). A time-dependent switching rule is given by

$$\sigma(t) = k_j, \quad t\in(t_j, t_{j+1}),\ j=0,1,\ldots,N_\sigma(T,0) \tag{3}$$

that is, the k_j th subsystem is active. Also, we assume $k_j \neq k_{j+1}$ for all j.

Assumption 1 (*Wu et al. [38]*). The preliminary assumption about switch is that switching instants t_j are stopping times and the corresponding active system has a unique solution in the interval $[t_j, t_{j+1})$.

Therefore, the switched system generated by family (1) and switching signal (3) can be presented nominally as

$$dx = f_\sigma(x)\,dt + g_\sigma(x)\,d\omega, \quad \forall x \in R^n \tag{4}$$

The following result shows the existence of the unique solution under local Lipschitz condition.

Lemma 1. *System (4) has a unique solution $x(t_0, x_0 : t)$ on the maximal existence interval $(0,T)$. When $T=\infty$, the solution is global.*

Proof. The functions $f_k(x)$ and $g_k(x)$ are locally Lipschitz functions in x and satisfy $f_k(0)=0$ and $g_k(0)=0$, respectively, which means that the kth system has a local solution. Next, follow the same steps as in [38], system (4) has a unique solution $x(t_0, x_0 : t)$ on the maximal existence interval $(0,T)$. When $T=\infty$ we say that the