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Neural-network-based adaptive tracking control for a class of pure-feedback stochastic nonlinear systems with backlash-like hysteresis

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ABSTRACT

In this paper, we are concerned with the problem of adaptive neural network tracking control for a class of pure-feedback stochastic nonlinear systems with backlash-like hysteresis. Unlike some existing control schemes, an affine variable at each step is constructed without using the mean value theorem, and neural networks are used to approximate the unknown and desired control input signals. By introducing the additional first-order low-pass filter for the actual control input signal, the algebraic loop problem arising in pure-feedback stochastic nonlinear systems with backlash-like hysteresis is addressed. It is shown that the proposed controller guarantees that all the signals in the closed-loop system are semi-globally uniformly ultimately bounded in probability while the tracking error converges to a small neighborhood of the origin in the sense of four-moment. Finally, a simulation example is given to verify the effectiveness of the proposed scheme.

1. Introduction

Over the past few decades, much attention has been focused on the study of stochastic nonlinear systems and a serious of prominent results have been obtained in [1–8]. By introducing quartic Lyapunov functions, a backstepping design scheme for single-input single-output strict-feedback stochastic nonlinear systems was studied in [1,2]. Afterwards, this design approach was generalized to stochastic non-minimum-phase nonlinear systems [3], Markovian switching stochastic nonlinear systems [4,5], and large-scale stochastic nonlinear systems [8]. However, the aforementioned results cannot be applied to stochastic nonlinear systems with structured uncertainties. Therefore, the analysis and control design of stochastic nonlinear systems with unknown nonlinear functions have been investigated by using the fuzzy logical systems or neural networks; see e.g. [9–16] and the references therein. In [10], an adaptive neural control scheme was proposed to address the strict-feedback stochastic nonlinear systems with time-delay by Razumikhin functional method, meanwhile Li et al. [12] considered the adaptive fuzzy control for a class of strict-feedback stochastic nonlinear systems with unmodeled dynamics via the small-gain theorem. By designing fuzzy observer to estimate the unmeasurable state, output feedback control methods were proposed for strict-feedback stochastic nonlinear systems [15] and for large-scale stochastic nonlinear systems [16].

However, a drawback in the backstepping design procedure is the problem of explosion of complexity, which is caused by the repeated differentiation of virtual controllers. To eliminate the explosion of complexity, the dynamic surface control (DSC) technique was first introduced in [17] for a class of strict-feedback nonlinear systems. More recently, by incorporating the DSC technique into approximation-based adaptive control design framework, some methods of adaptive neural or fuzzy control for strict-feedback nonlinear systems have been developed in [18–24]. For example, in [19], the decentralized adaptive tracking problem of large-scale nonlinear time-delay systems was investigated via the DSC method, where the tracking errors converged to an adjustable neighborhood of the origin. Zhou et al. [21,22] and Tong et al. [23] extended the DSC technique to address the problem of output-feedback adaptive neural network or fuzzy control for a class of strict-feedback stochastic nonlinear systems, respectively. It is worth noting that these control methods are mainly effective for strict-feedback stochastic nonlinear systems, but they are not valid for the pure-feedback nonlinear systems.

Pure-feedback system is another important class of nonlinear systems and there is no affine appearance of the state variables which can be used as virtual control and the actual control input. Therefore, the control problem of these systems is more difficult than strict-feedback nonlinear systems. Especially, when neural

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networks or fuzzy logical systems are employed to approximate the unknown nonlinear functions, the algebraic loop problem may arise. Based on the mean-value theorem, the problem of approximation-based adaptive control for non-affine pure-feedback nonlinear systems has been investigated in [25–34]. By combining DSC technique with the backstepping design, the pure-feedback nonlinear system with unknown dead zone and perturbed uncertainties was considered in [28], where the $n-1$th and nth state equations were assumed to be affine. It should be pointed out that these methods are not applicable in practice because it is difficult to obtain the priori information of partial derivative for non-affine functions. To relax this assumption, Zhao et al. [35] proposed a novel technique without using mean-value theorem and guaranteed the $\mathcal{L}_\infty$ tracking performance. However, the aforementioned works are not considered the problem of nonsmooth nonlinear inputs in the controlled systems.

Backlash-like hysteresis as nonsmooth nonlinear inputs is common in actuators and sensors, such as mechanical actuators, and electric servomotors, and it deteriorates system performance and even may cause instability. Therefore, the control of problem for nonlinear systems in the presence of backlash-like hysteresis has received considerable attention in the control community [36–42]. Based on a high-gain observer, in [40], an adaptive dynamic surface control scheme was proposed for a class of nonlinear systems with unknown backlash-like hysteresis. To the best of author's knowledge, only one result was reported on the adaptive neural control for stochastic nonlinear systems with backlash-like hysteresis [42], but explosion of complexity and many adaptive parameters occurred in the backstepping design produce as the order of the system increases.

Inspired the previous observation, the problem of adaptive neural network tracking control for a class of pure-feedback stochastic nonlinear systems with backlash-like hysteresis is investigated. The main contributions of this paper are summarized as follows. (1) The explosion of complexity and algebraic loop problem are addressed by incorporating DSC technique and additional first-order low-pass filter for the actual control input signal into the backstepping design produce. (2) Compared with [25–31,33,34], priori information of partial derivative for non-affine functions are removed, and it makes the proposed algorithm to be implemented conveniently. (3) A main advantage of the proposed controller is that only one adaptive parameter is required to be updated online, no matter how many neural networks are used and the order of the systems, which is different from [34,42]. It is proved that the designed controller not only guarantees all the signals in the closed loop to be semi-globally uniformly ultimately bounded in probability but also the tracking error converges to a small neighborhood of origin by choosing the appropriate design parameters.

The remainder of this paper is organized as follows. Section 2 begins with the preliminary results and presents the problem formulation. An adaptive neural network controller is given based on the dynamic surface control and backstepping design technique in Section 3. A simulation example is provided to show the effectiveness of the design method in Section 4. Section 5 concludes the paper.

Notations: The following standard notations are used throughout this paper. R^n is the real n-dimensional space. For a given vector or matrix X, X^T denotes its transpose; $\mathrm{Tr}\{X\}$ denotes its trace when X is square; $\|X\|$ is the Euclidean norm of a vector X; $E[V(x)]$ denotes its expectation; C^i denotes the set of all functions with continuous ith partial derivative. $\mathcal{K}$ denotes the set of all functions: $R^+ \to R^+$, which are continuous, strictly increasing and vanishing at zero; $\mathcal{K}_\infty$ denotes the set of all functions which are of class $\mathcal{K}$ and unbounded.

2. Preliminaries and problem formulation

2.1. Preliminary results

Consider the following stochastic nonlinear system:

$$dx(t) = f(x(t))\,dt + g(x(t))\,dw, \tag{1}$$

where $x(t) \in R^n$ denotes the state variable; $f(x(t)), g(x(t)))$ are locally Lipschitz functions satisfying $f(0)=0$ and $g(0)=0$; w is an r-dimensional independent standard Brownian motion defined on the complete probability space $(\Omega, F, \{F_t\}_{t\ge 0}, P)$ with Ω being a sample space, F being a σ-field, $\{F_t\}_{t\ge 0}$ being a filtration, and P being a probability measure.

Let $\mathcal{L}V(x)$ denotes the infinitesimal generator of any given $V(x) \in C^2 : R^n \longrightarrow R$ along the stochastic nonlinear systems (1) as follows:

$$\mathcal{L}V(x) = \frac{\partial V}{\partial x} f(x) + \frac{1}{2}\mathrm{Tr}\left\{ g^T(x) \frac{\partial^2 V}{\partial x^2} g(x) \right\}, \tag{2}$$

where $\frac{1}{2}\mathrm{Tr}\{g^T(x)(\partial^2 V/\partial x^2)g(x)\}$ is called Itô correction term.

Definition 1 (*Tong et al. [15]*). The trajectory $x(t)$ of the stochastic nonlinear system (1) is said to be semi-globally uniformly ultimately bounded in pth moment, if for some compact set $\Omega \in R^n$ and any initial condition $x_0 = x(t_0)$, there exist a constant $\varepsilon > 0$, and a time constant $T = T(\varepsilon, x_0)$ such that $E[\|x(t)\|^p] < \varepsilon$ for all $t > t_0 + T$. Especially, when $p=2$, it is usually called semi-globally uniformly ultimately bounded in mean square.

Lemma 1 (*Tong et al. [15]*). *Suppose there exists a C^2 function $V(x) : R^n \to R_+$, two constants $C_1 > 0$, and $C_2 > 0$, class $\mathcal{K}_\infty$ functions $\overline{\alpha}_1$, and $\overline{\alpha}_2$ such that*

$$\begin{cases} \overline{\alpha}_1(|x|) \le V(x) \le \overline{\alpha}_2(|x|), \\ \mathcal{L}V(x) \le -C_1 V(x) + C_2, \end{cases} \tag{3}$$

for all $x \in R^n$ and $t \ge t_0$. Then, there is a unique strong solution of system (1) for each $x_0 \in R^n$ and it satisfies

$$E[V(x)] \le V(x_0) e^{-C_1 t} + \frac{C_2}{C_1}, \quad t \ge t_0. \tag{4}$$

If the inequality (4) holds, then the states in system (1) are semi-globally uniformly ultimately bounded in mean square.

Lemma 2 (*Deng and Kristić [1], Young's inequality*). *For $\forall (x,y) \in R^2$, the following inequality holds:*

$$xy \le \frac{\varepsilon^p}{p}|x|^p + \frac{1}{q\varepsilon^q}|y|^q, \tag{5}$$

where $\varepsilon > 0, p > 1, q > 1$, and $(p-1)(q-1) = 1$.

Lemma 3 (*Wang et al. [43]*). *Consider the following dynamic system:*

$$\dot{\hat{\theta}}(t) = -\varrho \hat{\theta}(t) + \kappa w(t), \tag{6}$$

where ϱ and κ are positive constants and $w(t)$ is a positive function. If the initial condition $\hat{\theta}(0) > 0$ holds, then $\hat{\theta}(t) \ge 0$ for all $t \ge 0$.

2.2. Neural networks

In this paper, radial basis function (RBF) neural network is used to approximate unknown continuous function $\Gamma(Z) : R^q \to R$,

$$\Gamma_{nn}(Z) = W^T S(Z), \tag{7}$$

where $Z \in \Omega_Z \subset R^q$ represents the input vector; q denotes the neural networks input dimension. $W = [w_1, w_2, \ldots, w_l]^T \in R^l$ is the weight vector, and $l > 1$ denotes the neural networks node number. $S(Z) = [s_1(Z), s_2(Z), \ldots, s_l(Z)]^T \in R^l$ is the basis function