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Adaptive neural tracking control for stochastic nonlinear strict-feedback systems with unknown input saturation

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ABSTRACT

In this paper, the problem of adaptive neural tracking control is considered for a class of single-input/single-output (SISO) strict-feedback stochastic nonlinear systems with input saturation. To deal with the non-smooth input saturation nonlinearity, a smooth nonaffine function of the control input signal is used to approximate the input saturation function. Classical adaptive technique and backstepping are used for control synthesis. Based on the mean-value theorem, a novel adaptive neural control scheme is systematically derived without requiring the prior knowledge of bound of input saturation. It is shown that under the action of the proposed adaptive controller all the signals of the closed-loop system remain bounded in probability and the tracking error converges to a small neighborhood around the origin in the sense of mean quartic value. Two simulation examples are provided to demonstrate the effectiveness of the presented results.

1. Introduction

It is well known that stochastic disturbance, which is usually a source of instability of control systems, often exists in practical systems. Therefore, the control design of nonlinear stochastic systems has attracted increasing attention in recent years [9,10,16,27,29,30,36–38,49–54]. Many control design approaches for deterministic nonlinear systems have been successfully extended to stochastic nonlinear systems. Especially, backstepping technique [18] has been a popular tool for control design of stochastic nonlinear systems, see, e.g., [9,10,16,27,29,30,49–52] and the reference therein. In [30], the quadratic Lyapunov function is used to solve the stabilization problem for stochastic nonlinear strict-feedback systems based on a risk-sensitive cost criterion, and the proposed controller guarantees globally asymptotic stability in probability. In [9,10], a quartic Lyapunov function is applied for control design and stability analysis of stochastic nonlinear strict-feedback and output-feedback systems. Compared with the quadratic Lyapunov function, the quartic Lyapunov function can be used to easily deal with the high-order Hessian term. Since then, the quartic Lyapunov function has been widely applied for control design of stochastic nonlinear systems [16,29,49–52]. However, the aforementioned control schemes maybe invalid to control stochastic systems with unknown nonlinear function, because they require that the nonlinear dynamics models are known precisely or the unknown parameters appear linearly with respect to known nonlinear functions.

During the past decades, many approximation-based adaptive neural (or fuzzy) control approaches have been developed to control uncertain lower-triangular nonlinear systems, and lots of significant results have been reported, for example, see [2–5,12–14,19,22,23,25,26,28,35,39–42,44,46,55–58] for deterministic nonlinear systems and [8,21,33,43,47] for stochastic

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nonlinear systems. In these proposed control schemes, radial basis function (RBF) neural networks (or fuzzy logic systems) are used to approximate uncertain smooth nonlinear functions, and then adaptive backstepping technique is applied to design controllers. For the deterministic systems, Ge et al. [12–14] develop several adaptive neural control schemes for SISO nonlinear systems and multi-input and multi-output (MIMO) nonlinear systems. In [57,58], the problem of adaptive neural tracking control is considered for MIMO nonlinear systems with dead-zone. Then, for stochastic systems, Psillakis and Alexandridis [33] proposes an adaptive neural network control scheme to solve the problem of output tracking control for uncertain stochastic nonlinear strict-feedback systems with unknown covariance noise. Alternatively, in [47], a fuzzy-based adaptive control scheme is presented for a class of uncertain strict-feedback stochastic nonlinear systems with unknown virtual control gain function. The proposed controller guarantees that all the signals in the closed-loop systems are semi-globally uniformly bounded in probability. Recently, in [8,21,24,43], several approximation-based adaptive control approaches are proposed for some classes of stochastic nonlinear strict-feedback time-delay (or delay-free) systems.

In many practical systems, input saturation is one of the most important non-smooth nonlinearities. It often severely limits the system performance, gives rise to undesirable inaccuracy or leads to instability [32]. Therefore, the phenomenon of input saturation has to be considered when the controller is designed in practical industrial process control field. So far, many significant results on control design of the systems with input saturation have been obtained, for example, see [6,7,11,48,59]. In [59], a globally stable adaptive control approach is presented for minimum phase SISO systems with input saturation. Chen et al. [6] proposes a robust adaptive neural control for a class of MIMO nonlinear systems with input nonlinearities. By introducing auxiliary design systems to analyze the effect of input constraints, in [7], an adaptive tracking control is proposed for a class of uncertain nonlinear systems with non-symmetric input constraints, and the derived controller guarantees that the closed-loop system is semi-globally uniformly ultimately bounded stability. Wen et al. [48] considers the problem of adaptive control for a class of uncertain nonlinear systems in the presence of input saturation and external disturbance, in which two new schemes are developed to compensate for the effects of the saturation nonlinearity and disturbances. Though the aforementioned results take input saturation nonlinearity into account, the effect of stochastic disturbance is ignored.

Note that stochastic disturbance and input constraint could be existed in many practical systems. Motivated by the above observations, this paper considers the problem of adaptive neural tracking control for the case of nonlinear strict-feedback systems with stochastic disturbance and input saturation simultaneously. The proposed adaptive neural control scheme guarantees that all the signals in the closed-loop system are bounded in probability and the tracking error eventually converges to a small neighborhood around the origin in the sense of mean quartic value. Compared with the existing results, the main idea of control design in this paper is that a smooth non-affine function of the control input signal is firstly used to approximate the saturation function, and furthermore, the mean-value theorem is used to transform the non-affine function into affine form, i.e., $g(v) = g_{v_\mu} v$. Then, the classical adaptive technique and backstepping are used to design controller. The proposed design approach does not require the prior knowledge of the bound of input saturation. In addition, the number of adaptive parameters just depends on the order of the considered systems. So, it is reduced considerably. In this way, the computational burden is significantly alleviated.

This paper is organized as follows. The preliminaries and problem formulation are given in Section 2. A novel adaptive neural control scheme is presented in Section 3. Section 4 gives two simulation examples to illustrate the effectiveness of our results, and Section 5 concludes the work.

2. Preliminaries and problem formulation

The following notations are used throughout this paper. R denotes the set of all real numbers; R^n indicates the real n-dimensional space. For a given vector or matrix X, X^T denotes its transpose; $Tr\{X\}$ is its trace when X is a square matrix; and $\|X\|$ denotes the Euclidean norm of a vector X. C^i denotes the set of all functions with continuous ith partial derivative.

Consider the following strict-feedback stochastic nonlinear system given by:

$$\begin{cases} dx_i = (g_i(\bar{x}_i)x_{i+1} + f_i(\bar{x}_i) + d_i(t,x))dt + \psi_i^T(\bar{x}_i)dw, \quad 1 \leqslant i \leqslant n-1, \\ dx_n = (g_n(\bar{x}_n)u(v) + f_n(\bar{x}_n) + d_n(t,x))dt + \psi_n^T(\bar{x}_n)dw, \\ y = x_1, \end{cases} \tag{1}$$

where $\bar{x}_i = [x_1, x_2, \ldots, x_i]^T \in R^i$, $x = [x_1, x_2, \ldots, x_n]^T \in R^n$ and $y \in R$ are the state variables and the system output, respectively; w denotes an r-dimensional standard Brownian motion defined on the complete probability space (Ω, F, P) with Ω being a sample space, F being a σ-field, and P being a probability measure; $f_i(\cdot)$, $g_i(\cdot)$: $R^i \to R$, $\psi_i(\cdot)$: $R^i \to R^r$, $(i = 1, 2, \ldots, n)$ stand for the unknown smooth nonlinear functions with $f_i(0) = 0$ and $\psi_i(0) = 0$ $(1 \leqslant i \leqslant n)$, $d_i(\cdot)$, $i = 1, 2, \ldots, n$ are the external disturbance uncertainties of the system. v is the control signal to be designed, and $u(v)$ denotes the plant input subject to saturation nonlinearity described by

$$u(v) = sat(v) = \begin{cases} sign(v)u_{\max}, & |v| \geqslant u_{\max}, \\ v, & |v| < u_{\max}, \end{cases} \tag{2}$$

where $u_{\max}$ is a unknown parameter of input saturation.