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Adaptive output-feedback neural tracking control for a class of nonstrict-feedback nonlinear systems☆

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ABSTRACT

This paper focuses on the problem of adaptive neural output-feedback control for a class of nonstrict-feedback nonlinear systems where the system coefficient functions are unknown. First, the original system is transformed into a new defined system by a linear state transformation. Then, by using the dynamic surface control (DSC) technique, an improved input-driven filter is proposed. Based on this filter and the approximation property of radial basis function (RBF) neural networks, an adaptive neural output-feedback controller is designed via backstepping technique, which can guarantee that all the signals in the closed-loop system are ultimately bounded. The main contribution of this paper lies in that a simpler and more effective design procedure of adaptive neural output-feedback tracking controller is proposed for the underlying system which is more general than some existing ones in literature. Finally, simulation results are given to demonstrate the feasibility and effectiveness of the new design algorithm.

1. Introduction

During the past decades, adaptive backstepping technique has become one of the most popular systematic design approach for a class of nonlinear systems, particularly for nonlinear strict-feedback systems. Many significant developments have achieved [10,11,33,42]. On the other hand, it is well known that neural networks and fuzzy logic systems have been found to be powerful tools for nonlinear control because of their universal approximation properties. With the help of approximation ability of neural networks (or fuzzy logic systems), one can avoid spending lots effort on system modeling, see [12,13,18–21,37,41,44] for instance. Therefore, the control design methods based on adaptive neural (or fuzzy) backstepping have grown to be very useful tools for nonlinear systems. The advantages of adaptive neural (or fuzzy) backstepping control approaches lie in that the system nonlinear functions are not necessary to satisfy some matching conditions, and one does not need to acquire any priori knowledge on these functions neither. In short, adaptive neural (or fuzzy) backstepping control provides a systematic control methodology for

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nonlinear systems with unknown functions, and has been widely studied for such systems in recent years. In [7,9,24,25,28,29,31], the adaptive method was applied to single-input single-output (SISO) nonlinear systems. Then, researches on multi-input multi-output (MIMO) systems were considered and many achievements were obtained, see [2,4,5,27] for example. Meanwhile, such control methods were also developed for switched nonlinear systems [16,32,43], stochastic nonlinear systems [3,6,35], etc.

However, all the aforementioned control schemes are only applicable under the presupposition that the system has a strict-feedback structure. To relax such a restriction on system structure, some efforts have been made. In [40], the concept of semistrict-feedback system was proposed, and in [8], this lower triangular structure was considered for multi-input and multi-output systems. Similar achievements can be found in [14,17,26]. On the other hand, some interesting results on adaptive neural control have been reported for nonlinear pure-feedback systems. To list a few, in [45], a backstepping-based procedure was developed for the design of adaptive neural controllers for pure-feedback systems. Then, in [30], an observer-based adaptive fuzzy controller was designed for uncertain MIMO pure-feedback nonlinear systems. In [23], a robust adaptive neural control scheme was proposed for a class of uncertain pure-feedback nonlinear systems. The result was further extended to nonaffine pure-feedback systems in [38]. However, when the subsystem functions of nonlinear systems contain all of the state variables, the aforementioned control methodologies may be invalid. It is worth pointing out that, in recent a few years, some interesting results have been reported on nonstrict-feedback systems. In [1], a backstepping-based adaptive fuzzy controller was designed for a class of unknown nonlinear systems with nonstrict-feedback structure. Then, an adaptive neural tracking controller was proposed for in [36] stochastic nonlinear systems with unknown backlash-like hysteresis. In [15], the result was further extended to time-varying delay systems with unknown hysteresis.

However, these results for nonstrict-feedback nonlinear systems are obtained by using state-feedback controllers under the assumption that all states are available. Besides, the system coefficient functions in these results are required to be known. To the best of the authors' knowledge, so far, the output-feedback control problem for nonstrict-feedback nonlinear systems with unknown system coefficient functions and uncertain functions still remains an open problem.

Inspired by the above discussions, we will develop a backstepping-based adaptive output-feedback control approach for a more general class of nonlinear systems with nonstrict-feedback structure. The main difficulties and idea of this study are listed in the following: (1) The system coefficient functions and uncertain functions contain all state variables, and each state variable may be unavailable. Therefore, it is necessary to introduce an appropriate input-driven filter. Then, the estimation state will be used as the control input signal for each subsystem, and the virtual control is designed to guarantee the stability of each subsystem. To ensure the existence of the virtual control, it must be a function of known states; and (2) Based on a set of coordinates transformation, the procedure of adaptive control design is carried out by the new defined system. However, in the transformation procedure, the new defined system must be equivalent to the original system. Moreover, how to deal with the functions descend from the previous design step to the current step is a difficult problem. To solve these difficulties, first, the dynamic surface control (DSC) technique and RBF neural networks are applied. Then, we introduce an improved input-driven filter to give the estimation of state, such that the control design becomes feasible. Besides, bounding functions for system functions are utilized to develop the variable separation technique, while the structure feature of the used filter and RBF neural networks are employed to set up the relationships among some used variables. Finally, an adaptive neural output-feedback controller is designed for such systems under some suitable assumptions on system nonlinear functions. It is proved that the proposed adaptive controller guarantees that all the signals in the closed-loop systems remain bounded and the output achieves required tracking performances.

The remainder of this paper is organized as follows. Section 2 gives the problem formulation and preliminaries. Adaptive neural control design and stability analysis are presented in Section 3. In Section 4, two simulation examples are given to illustrate the effectiveness and advantages of the proposed controller. Finally, this paper is concluded in Section 5.

Notations: The notations used in this paper are listed below. R^n denotes the n-dimensional Euclidean space; the notation $\|\cdot\|$ represents the Euclidean vector norm; the notation $P > 0$ means that P is real symmetric and positive definite; $\lambda_{\min}(P)$ denotes the minimal eigenvalue of matrix P and $\lambda_{\max}(Q)$ denotes the maximum eigenvalue of matrix Q; the notation $m!$ represents the m factorial; the notation $o(\cdot)$ denotes the higher order infinitesimal remainder; the notation $X_{\max}$ denotes $\max\{X_1, X_2, ..., X_n\}$.

2. Problem formulation and preliminaries

2.1. Nonlinear control problem

Consider a class of nonstrict-feedback nonlinear systems with the following form:

$$\begin{aligned} \dot{x}_i &= g_i(x)x_{i+1} + f_i(x),\ 1 \le i \le n-1 \\ \dot{x}_n &= g_n(x)u + f_n(x) \\ y &= x_1 \end{aligned} \tag{1}$$

where $x = [x_1, x_{2,...,}x_n]^T \in R^n$, $y \in R$, $u \in R$, are respectively state variables, system output and control input; $g_i(x)$ and $f_i(x)$ are unknown smooth nonlinear functions satisfying the Lipschitz condition and $f_i(0) = 0$. Here, the system state is assumed to be unmeasurable. In this paper, the control coefficient functions $g_i(x)$ are also assumed to be unknown, due to which, some difficulties will be encountered in the output-feedback control design.