Neurocomputing 143 (2014) 312–321

Contents lists available at ScienceDirect

Neurocomputing

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

Adaptive output feedback dynamic surface control of nonlinear systems with unmodeled dynamics and unknown high-frequency gain sign

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ARTICLE INFO

Article history:
Received 2 January 2014
Received in revised form
27 March 2014
Accepted 29 May 2014
Communicated by H. Zhang
Available online 9 June 2014

Keywords:
Adaptive control
Output feedback control
Dynamic surface control
Unmodeled dynamics
K-filters
Nussbaum gain

ABSTRACT

In this paper, two adaptive output feedback control schemes are proposed for a class of nonlinear systems with unmodeled dynamics and unmeasured states as well as unknown high-frequency gain. Radial basis function (RBF) neural networks (NNs) are used to approximate the unknown nonlinear functions. K-filters are designed to estimate the unmeasured states. An available dynamic signal is introduced to dominate the unmodeled dynamics. By introducing the dynamic surface control (DSC) method, the bounded condition of the approximation error is removed, and the tracking control is achieved. Moreover, the number of adjustable parameters and the complexity of the design are both reduced. By theoretical analysis, the closed-loop system is shown to be semi-globally uniformly ultimately bounded (SGUUB). Simulation results are provided to illustrate the effectiveness of the proposed approach.

1. Introduction

Since adaptive tracking control was proposed based on backstepping for a class of strict-feedback nonlinear systems in [1], backstepping has become one of the most popular design methods and has been widely used to design adaptive control for a large class of nonlinear systems with a triangular structure in [1–4]. As we know, unmodeled dynamics exists in many practical nonlinear systems, due to some factors, such as measurement noises, modeling errors, external disturbances, and modeling simplifications, and they can severely degrade the closed-loop system performance. Therefore, some different methods were discussed to deal with such systems with unmodeled dynamics using backstepping in [5–7]. By introducing an available dynamic signal and using backstepping design method, robust adaptive control was proposed for a class of nonlinear systems with unknown parameters and unmodeled dynamics as well as uncertain nonlinearities in [5]. Furthermore, a novel adaptive control was developed for similar systems in [6]. In contrast to [5], the adaptive control laws in [6] did not require any dynamic dominating signal to guarantee the robustness property of global stability. In [7], robust adaptive backstepping control was presented for a class of nonlinear systems with unmodeled dynamics and unit virtual gains by applying input-to-state stability property. In [8], robust adaptive neural tracking control was proposed for a class of pure-feedback nonlinear systems with unmodeled dynamics and unknown gain signs.

An obvious drawback in the traditional backstepping is the problem of “explosion of complexity”, which is caused by the repeated differentiations of certain nonlinear functions such as virtual control in [2–4]. To overcome the ‘explosion of complexity’, several dynamic surface control schemes were developed for a class of strict-feedback or pure-feedback nonlinear systems in [9–13]. Using implicit function theorem and DSC method as well as integral type Lyapunov function, adaptive neural dynamic surface control was proposed for a class of pure-feedback nonlinear systems with unknown dead-zone in [11,12]. Two adaptive tracking DSC schemes were developed for a class of strict-feedback and non-affine pure-feedback nonlinear systems using radial basis function neural networks (RBFNNs). Using mean value theorem and Young's inequality, only one learning parameter needs to be tuned online in the whole controller design, and the computational burden was effectively alleviated in [13]. Combining backstepping with dynamic surface control, an adaptive control scheme was presented for a class of nonlinear systems in pure feedback form with unmodeled dynamics in [14].

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http://dx.doi.org/10.1016/j.neucom.2014.05.061
0925-2312/

However, the above results were only suitable for the nonlinear systems with measurable states. When the states of system are not measured, several adaptive output feedback control approaches were proposed in [15–18]. Adaptive output feedback control was proposed for a class of nonlinear systems with unmodeled dynamics using a reduced-order partial-state observer and small gain approach in [15]. K-filters were introduced in [16]. Using the nonlinear small-gain approach and backstepping, adaptive fuzzy output feedback control was developed for a class of SISO nonlinear systems with the unstructured uncertainties, dynamic disturbances, and unmodeled dynamics in [17]. An adaptive dynamic surface control was developed in [18] for a class of output-feedback nonlinear systems discussed in [16]. In [19], an adaptive output feedback control approach is developed using K-filers and DSC for a class of uncertain nonlinear systems in the parametric output feedback form. In [20], globally stable adaptive output-feedback tracking control was proposed by using backstepping and Nussbaum function. In [21], adaptive fuzzy output feedback DSC was proposed by using K-filters and Nussbaum function for a class of nonlinear systems with unknown dead-zone and control direction. In [22], adaptive fuzzy output feedback control approach was proposed based on backstepping for a class of SISO nonlinear strict-feedback systems with unknown high-frequency gain sign and unmodeled dynamics. In [20–22], K-filters were designed to estimate unmeasured states. In [23], decentralized adaptive fuzzy output feedback control approach was proposed for a class of large-scale strict-feedback nonlinear systems with the unmeasured states. K-filters were designed to estimate the unmeasured states, and a dynamical signal was introduced to cope with dynamic uncertainties. Using Ito differential formula and fuzzy observer, two adaptive fuzzy output feedback control were proposed for a class of uncertain stochastic nonlinear systems with the known or unknown control direction in [24,25]. Typically, the above methods used fuzzy systems or neural networks as approximation models for unknown system nonlinearities. A key condition in most of these methods was that the approximation error or the observer error was assumed to be bounded before the stability analysis of the closed-loop system was implemented.

Motivated by the previous works in [5,16,20–22], in this paper, adaptive neural network output feedback control is developed by combining K-filters with dynamic surface control. The main contributions and some comparisons of the paper are summarized as follows:

(i) Two adaptive output feedback neural tracking control schemes are proposed for a class of nonlinear systems with unmodeled dynamics and unmeasured states by combining K-filters with DSC techniques in this paper while the considered systems do not include unmodeled dynamics in [18–21], and all the states need to be measurable in [7–14]. The first control scheme deals with unknown high-frequency gain by constructing appropriate virtual control at the first step of backstepping without using a Nussbaum gain compared with [20,22], and the second scheme tackles unknown high-frequency gain by using a Nussbaum gain, whereas the control gain sign needs to be known in [16].

(ii) The upper bound of the dynamic uncertain term is assumed to be the sum of two unknown continuous functions in unmodeled dynamics and output in this paper while it is supposed to be a polynomial in unmodeled dynamics and output with unknown coefficients in [22].

(iii) The extra term $Q(y,v)$ which the approximation errors and the dynamic uncertainties bring about is effectively dealt with using the defined compact sets of DSC in the final step of the stability analysis without discussing two cases in [8].

(iv) The circular arguments and the tuning function are avoided using DSC approach in this paper while the approximation error is assumed to be bounded before the closed-loop system is shown to be stable compared with the existing adaptive fuzzy /neural control results in [2–4,7,8,14,19,22–25], and backstepping method and the tuning function are employed in [20,22]. Moreover, the tracking control is carried out in this paper while the tuning objective is implemented in [22].

The rest of the paper is organized as follows. The problem formulation and preliminaries are given in Section 2. The filter design is proposed based on radial basis function neural networks in Section 3. Adaptive output feedback dynamic surface control is developed without using Nussbaum gain, and the stability of the closed-loop system is analyzed in Section 4. In Section 5, adaptive output feedback dynamic surface control is discussed using a Nussbaum gain. Simulation results are performed to demonstrate the effectiveness of the approach in Section 6. Section 7 contains the conclusions.

2. Problem statement and preliminaries

Consider the following uncertain nonlinear systems with unmodeled dynamics in the output feedback form:

$$\begin{cases} \dot{z} = q(z,y) \\ \dot{x} = Ax + f(y) + G\sigma(y)u + \Delta(z,y,t) \\ y = e_1^T x \end{cases} \tag{1}$$

where

$$A = \begin{bmatrix} 0 & I_{n-1} \\ 0 & 0 \end{bmatrix}, \quad f(y) = \begin{bmatrix} f_1(y) \\ \vdots \\ f_n(y) \end{bmatrix}, \quad \Delta(z,y,t) = \begin{bmatrix} \Delta_1(z,y,t) \\ \vdots \\ \Delta_n(z,y,t) \end{bmatrix}$$

$$x = \begin{bmatrix} x_1 \\ \vdots \\ x_n \end{bmatrix}, \quad e_1 = \begin{bmatrix} 1 \\ 0 \\ \vdots \\ 0 \end{bmatrix}, \quad G = \begin{bmatrix} 0_{(n-m-1)\times 1} \\ b \end{bmatrix}$$

$b = [b_m, \ldots, b_1, b_0]^T \in R^{m+1}$, x is the unmeasured state; $u \in R$ is the input, and $y \in R$ is the output; $\sigma(y) \neq 0$ is a known positive continuous function; $f_i(y)$ is the unknown smooth function; $z \in R^{n_0}$ is the unmodeled dynamics, and $\Delta_i(z,y,t)$ is the unknown smooth nonlinear dynamic disturbance; $B(s) = b_m s^m + \cdots + b_1 s + b_0$ is a Hurwitz polynomial; $q(z,y)$ is the unknown Lipschitz function.

The control objective is to design adaptive output feedback control u for system (1) such that the output y follows the specified desired trajectory y_d.

Assumption 1 (*Jiang and Praly [5]*). The unknown nonlinear dynamic disturbances $\Delta_i(z,y,t), i = 1,2,\ldots,n$, satisfy

$$\Delta_i(z,y,t) \leq \varphi_{i1}(|y|) + \varphi_{i2}(\|z\|) \tag{2}$$

where $\varphi_{i1}(\cdot)$ are unknown smooth functions, and $\varphi_{i2}(\cdot)$ are unknown nonnegative increasing smooth functions. $\|\cdot\|$ denotes Euclidean norm.

Assumption 2 (*Jiang and Praly [5]*). The unmodeled dynamics z is said to be exponentially input-state-practically stable (exp-ISpS), i.e., for system $\dot{z} = q(z,y)$, if there exists a Lyapunov function $V(z)$ such that

$$\alpha_1(\|z\|) \leq V(z) \leq \alpha_2(\|z\|) \tag{3}$$

$$\frac{\partial V(z)}{\partial z} q(z,y) \leq -cV(z) + \gamma(|y|) + d \tag{4}$$