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Adaptive output feedback control of nonlinear systems with prescribed performance and MT-filters

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ABSTRACT

In this paper, adaptive prescribed performance output feedback control is investigated for a class of nonlinear systems with unmodeled dynamics. Neural networks are used to approximate the unknown nonlinear functions. MT-filters are employed to estimate the unmeasured states. The unmodeled dynamics is dealt with by introducing an available dynamic signal. Adaptive output feedback dynamic surface control and parameter adaptive laws are proposed based on introducing the prescribed performance function and output error transformation. It is proved that all the signals in the closed-loop system are semi-globally uniformly ultimately bounded. Simulation results are provided to demonstrate the effectiveness of the proposed approach.

1. Introduction

In the past decades, adaptive backstepping control of nonlinear systems has been paid much attention in [1,2]. However, the problem of "explosion of complexity", which is caused by the repeated differentiations of certain nonlinear functions such as virtual control in the traditional backstepping method in [1,2], has become an obvious drawback. In order to overcome this drawback, adaptive dynamic surface control (DSC) was proposed by introducing a first-order filter in each step of backstepping in [3]. Furthermore, many adaptive DSC schemes were developed for nonlinear uncertain systems based on the approximation of neural networks in [4–6]. In [6], decentralized adaptive fuzzy output feedback control was proposed by using DSC for a class of interconnected nonlinear pure-feedback systems.

It is well known that unmodeled dynamics exists in many nonlinear systems. The unmodeled dynamics is caused by many factors such as external disturbances, measurement noises and modeling simplifications. They have severely effects on the stability of the closed-loop systems and can degrade the system performance. To deal with such systems with unmodeled dynamics, a few different approaches were proposed. Adaptive DSC was presented for nonlinear systems with unmodeled dynamics in [7]. When the states of system were not measured, several adaptive output feedback control approaches were proposed in [8–13]. In [8], based on a reduced-order partial-state observer and small gain approach, an adaptive output feedback control approach was proposed for a class of nonlinear systems with unmodeled dynamics. K-filters were introduced in [9]. In [10], adaptive fuzzy output feedback control problem was discussed for a class of single-input single-output (SISO) nonlinear systems with unmodeled dynamics. K-filters were combined with neural networks to discuss the adaptive output feedback DSC in [11,12]. However, K-filters only obtained the virtual estimates of the unmeasured states, they cannot give the true estimates of the unmeasured states. In [9], MT-filters were also proposed. From [9], we knew that the dynamic order of K-filers is $n(q+2)$ and it was reduced to $(n-1)(q+2)$ through the reduced-order observer technique. The total dynamic order of MT-filters is $(n-1)(q+2)$. So, MT-filters realized the function of reduced order filters. An adaptive fuzzy output feedback control approach was developed for a class of SISO nonlinear uncertain systems with unmeasured states and unknown virtual control coefficients based on MT-filters in [13]. In [14], the problem of actuator failure compensation for a class of nonlinear systems in the form of output-feedback was discussed and MT-filters were exploited to estimate the unmeasured states. In [15], observer-based adaptive neural network (NN) control was investigated for a class of SISO strict-feedback nonlinear stochastic systems with unknown time delays. In [16], adaptive neural network control was proposed by combining backstepping with dynamic surface control for a class of multi-input multi-output (MIMO) nonlinear systems.

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From the above discussion, we know that the steady performance has been widely discussed in the existing literature. However, the transient performance is seldom investigated based on DSC. The concept of prescribed performance was proposed in [17]. The prescribed performance means that the tracking error should converge to an arbitrarily predefined small residual set, with convergence rate no less than a prespecified value, exhibiting a maximum overshoot less than a sufficiently small prespecified constant. Based on the prescribed performance, the steady state and transient performance was discussed. Adaptive prescribed performance control of SISO feedback linearizable systems with disturbances was discussed in [17]. An output feedback control scheme with prescribed performance was proposed in [18]. In [19], the prescribed performance backstepping control of strict-feedback nonlinear systems was investigated. Two decentralized adaptive output feedback control schemes were considered for deterministic interconnected time-delay systems and stochastic interconnected time-delay systems with prescribed performance in [20,21], respectively. In [22], distributed adaptive neural network output tracking of leader-following high-order stochastic nonlinear multiagent systems with unknown dead-zone input was addressed. A partial tracking error constrained fuzzy output-feedback DSC scheme was proposed for a class of uncertain MIMO nonlinear systems in [23]. Nevertheless, few of the existing papers discussed adaptive output feedback dynamic surface control for nonlinear systems with unmodeled dynamics and prescribed performance based on MT-filters.

Motivated by the previous works, adaptive output feedback control is proposed by combining MT-filters with DSC for a class of uncertain nonlinear systems with unmodeled dynamics and prescribed performance. The main contributions in this paper are summarized as follows.

(i) MT-filters in the system with unmodeled dynamics and prescribed performance are designed to estimate the unmeasured states. The advantage of the proposed approach is that they can effectively reduce the order of the observers compared with K-filters.
(ii) MT-filters based adaptive output feedback control is proposed by using DSC approach in this paper while the similar control scheme is constructed by using backstepping method in [13]. Therefore, the tuning function is avoided using DSC approach in this paper while the approximation error needs to be assumed to be bounded before the closed-loop system is shown to be stable in the existing adaptive fuzzy/neural control results in [1,2,10,13,15,16,23].
(iii) Both the steady-state and transient performance of the system are considered by introducing a prescribed performance function in this paper while the steady-state performance was only discussed in [13,14].

The rest of the paper is organized as follows. In Section 2, the problem description and preliminaries are given. The new state transformation is introduced with prescribed performance control in Section 3. Based on radial basis function neural networks, a new state observer design is proposed by using MT-filters in Section 4. In Section 5, the output feedback controller and adaptive laws are designed by using dynamic surface control. The stability of the closed-loop system is analyzed in Section 6. Two numerical simulation examples demonstrate the effectiveness of the proposed method in Section 7. Finally, this paper is concluded in Section 8.

2. Problem statement and preliminaries

Consider the following uncertain nonlinear systems:

$$\begin{cases} \dot{z} = q(z, y) \\ \dot{x} = Ax + f(y) + G\sigma(y)u + \Delta(z, y, t) \\ y = x_1 \end{cases} \tag{1}$$

where

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

$$G = \begin{bmatrix} 0_{(n-m-1)} \times 1 \\ b \end{bmatrix}, \quad b = \begin{bmatrix} b_m \\ \vdots \\ b_1 \\ b_0 \end{bmatrix}$$

u and y are the input and output of the system; $x = [x_1, \ldots, x_n]^T \in R^n$ is the unmeasured state; $\sigma(y)$ is a known positive continuous function; z is the unmodeled dynamics; $f_i(y)$ is the unknown smooth function; $\Delta_i(z, y, t)$ is the unknown smooth nonlinear dynamic disturbance; $B(s) = b_m s^m + \cdots + b_1 s + b_0$ is a Hurwitz polynomial and $q(z, y)$ is the unknown Lipschitz function.

The control objective is to design an adaptive output feedback control u for system (1) such that all the signals in the closed-loop system are bounded and the tracking error $e(t) = y(t) - y_d(t)$ satisfies the prescribed performance with the known specified desired trajectory y_d.

Assumption 1. There exists a known positive constant $b_{\max}$ such that the following inequality $0 < b_m^2 \le b_{\max}$ holds.

Assumption 2 (*Jiang and Praly [24]*). For each $i = 1, 2, \ldots, n$, there exist unknown smooth functions $\phi_{i1}(\cdot)$ and unknown nonnegative increasing smooth functions $\phi_{i2}(\cdot)$ such that

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

where $\|\cdot\|$ denotes Euclidean norm.

Assumption 3. The known desired trajectory vector x_d is defined as $x_d = [y_d, \dot{y}_d, \ddot{y}_d]^T \in \Omega_d$, where $\Omega_d = \{x_d: y_d^2 + \dot{y}_d^2 + \ddot{y}_d^2 \le B_0\}$, and B_0 is a known constant.

Assumption 4 (*Jiang and Praly [24]*). The unmodeled dynamics z is said to be exponentially input-state-practically stable (exp-ISps), for system $\dot{z} = q(z, y)$, if there exists a Lyapunov function $V(z)$ such that

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

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

where $\alpha_1(\cdot), \alpha_2(\cdot), \gamma(\cdot)$ are the class k_∞ functions, $c > 0$ and $d \ge 0$ are the known constants.

Lemma 1 (*Jiang and Praly [24]*). *If V is an exp-ISpS Lyapunov function for a system $\dot{z} = q(z, y)$, i.e. Assumption 4 holds, then, for any constant $\bar{c} \in (0, c)$, any initial instant $t_0 > 0$, any initial condition $z_0 = z(t_0)$, $v_0 > 0$, for any continuous function $\bar{\gamma}$ such that $\bar{\gamma}(|y|) \ge \gamma(|y|)$, there exist a finite $T_0 = \max\{0, \ln[V(z_0)/v_0]/(c - \bar{c})\} \ge 0$, a nonnegative function $D(t_0, t)$, defined for all $t \ge t_0$ and a signal described by $\dot{v} = -\bar{c}v + \bar{\gamma}(|y|) + d$, $v(t_0) = v_0 > 0$ such that $D(t_0, t) = 0$ for $t \ge t_0 + T_0$, and $V(z) \le v(t) + D(t_0, t)$ with $D(t_0, t) = \max\{0, e^{-c(t-t_0)}V(z_0) - e^{-\bar{c}(t-t_0)}v_0\}$. Without loss of generality, we choose $\bar{\gamma}(|y|) = \gamma(|y|)$.*

Lemma 2 (*Lin and Qian [25]*). *There exist positive smooth scalar functions $\phi(x) \ge 0$ and $\psi(y) \ge 0$ for any real continuous function*