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Decentralized output feedback adaptive NN tracking control of interconnected nonlinear time-delay systems with prescribed performance

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ABSTRACT

This paper studies the decentralized output feedback adaptive NN tracking control problem for interconnected nonlinear time-delay systems with prescribed performance. By using the novel states transformation, the prescribed tracking performance can be guaranteed. Firstly, we design the decentralized filters independent of time delay to estimate the unmeasured state variables. By estimating the bounds of the unknown parameters instead of themselves, it can avoid the over-estimation problem. Then, by using RBF (radial basis function) neural network (NN) to approximate the unavailable time-delay functions, we construct the adaptive neural network output feedback controller with corresponding adaptive laws. It is proved that all the signals of the overall closed-loop systems are ultimately uniformly bounded. Finally, simulation examples are presented to verify the effectiveness of the theoretic results obtained.

1. Introduction

Interconnected systems can be found in many practical applications such as power networks, manufacturing processes, and communication. Researches on the decentralized control for interconnected systems have received considerable attentions. The decentralized control can alleviate the computational burden associated with centralized control, and make the control implementation more feasible since the controller of each subsystem uses its own state variables. In the past decades, many stability analysis methods and controller design approaches have been developed, see, for instance, [1–4] and the references therein. In [5], the author proposed a new totally decentralized adaptive output tracking scheme for interconnected nonlinear systems in the presence of external disturbances, and local filters were designed to estimate system states. A decentralized output feedback dynamic surface adaptive controller for a class of uncertain interconnected nonlinear systems based on a kind of high-gain k-filters was proposed in [6]. The decentralized stabilization problem of unknown interconnected systems with unknown hysteresis was considered in [7,8].

It is well known that time-delay exists in a variety of practical systems, for example, power systems, teleoperation systems, chemical reactor systems, etc. The existence of time-delay is a source of instability for control systems and it also makes the decentralized controller design become more difficult and challenging, see [9,10]. Meanwhile, rapid progress has been made on the problem of decentralized stabilization for large-scale systems with delays. In [11], the author considered the control problem of a class of nonlinear large-scale pure-feedback interconnected systems with time-varying delays. Two adaptive neural network (NN) decentralized output feedback control approaches were proposed for uncertain nonlinear interconnected systems in [12], the one was traditional backstepping technique, and the other was dynamic surface control technique. In [13], systems with deadzone input nonlinearities and higher order nonlinear interactions were considered. Based on backstepping approach, the adaptive law and output feedback controller for nonlinear systems were developed in [14].

In the process of industrial control, the systems are commonly characterized by unknown nonlinear functions. To deal with such kinds of uncertainties, adaptive control method is widely used for nonlinear systems which exhibit unknown nonlinearities. Especially fuzzy logic systems (FLSs) and neural network (NN) control strategies have been widely used for nonlinear systems to approximate the unknown nonlinear functions. Thus the decentralized adaptive controllers were investigated by using backstepping technique in [15,16]. Cai and Xiang [17] investigated the

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adaptive finite-time stabilization controller for a class of switched nonlinear systems using RBFNN.

It should be mentioned that practical engineering always requires that the controller we proposed satisfies certain quality of the performance indices. Considering the nonlinear characteristics of the systems in the presence of unknown uncertainties and external disturbances, the controller design will be more difficult and challenging. A remarkable prescribed performance constraint method was recently developed by Bechlioulis and Rovithakis [18,19] using a prescribed error transformation function technique. An improved prescribed performance constraint control method for the nonlinear dynamic system was proposed in [20], and it alleviated the problem of excessive computational burdens caused by the adoption of the transformation function and its inverse function. An output feedback controller with prescribed performance was first proposed for a class of nonlinear large-scale systems with time delays in [21]. In [22], by employing the prescribed performance control technique, a novel decentralized adaptive backstepping control scheme was developed for a class of interconnected nonlinear time-varying systems in the sense that all parameters were allowed to vary with time.

In this paper, we consider the problem of adaptive output feedback control of interconnected time-delay systems with prescribed performance. Firstly, we estimate the bounds of the unknown parameters instead of themselves. By this way, we can avoid over-estimation problem. Secondly, the decentralized filters are designed to estimate the unmeasurable states and Lyapunov Krasovskii functions are chosen to deal with the time-delay terms. Then, by employing the prescribed performance control technique, the output feedback controller is constructed by using backstepping method and RBF neural network. It is shown that the controller we designed can render all the signals of the overall closed-loop systems ultimately uniformly bounded, and the prescribed performance of the tracking error can be guaranteed. Finally, simulation examples are performed to verify the effectiveness of the proposed method.

2. System formulation and preliminaries

2.1. System formulation

In this paper, we consider an interconnected nonlinear systems consisting of N subsystems described by

$$\begin{cases} \dot{x}_{i1}(t) = x_{i2}(t) + \Phi_{i1}^T(y_i(t))\theta_i + f_{i1}(y_1(t-d_{i11}(t)), \dots, y_N(t-d_{i1N}(t))) \\ \vdots \\ \dot{x}_{i(\rho_i-1)}(t) = x_{i\rho_i}(t) + \Phi_{i(\rho_i-1)}^T(y_i(t))\theta_i + f_{i(\rho_i-1)}(y_1(t-d_{i(\rho_i-1)1}(t)), \dots, y_N(t-d_{i(\rho_i-1)N}(t))) \\ \dot{x}_{i\rho_i}(t) = b_{im_i}u_i(t) + x_{i(\rho_i+1)}(t) + \Phi_{i\rho_i}^T(y_i(t))\theta_i + f_{i\rho_i}(y_1(t-d_{i\rho_i1}(t)), \dots, y_N(t-d_{i\rho_iN}(t))) \\ \vdots \\ \dot{x}_{i(n_i-1)}(t) = b_{i1}u_i(t) + x_{in_i}(t) + \Phi_{i(n_i-1)}^T(y_i(t))\theta_i + f_{i(n_i-1)}(y_1(t-d_{i(n_i-1)1}(t)), \dots, y_N(t-d_{i(n_i-1)N}(t))) \\ \dot{x}_{in_i}(t) = b_{i0}u_i(t) + \Phi_{in_i}^T(y_i(t))\theta_i + f_{in_i}(y_1(t-d_{in_i1}(t)), \dots, y_N(t-d_{in_iN}(t))) \\ y_i(t) = x_{i1}(t) \end{cases} \quad (1)$$

where $1 \le i \le N, N$ is the total number of the subsystems which is known for controller design; $x_i(t) = [x_{i1}(t), x_{i2}(t), \dots, x_{in_i}(t)]^T \in R^{n_i}$, $u_i(t) \in R$, $y_i(t) \in R$ are the state variables, control input, and output of the plant, respectively; $b_i = [b_{im_i}, \dots, b_{i0}]^T \in R^{m_i+1}$ and $\theta_i \in R^{v_i}$ are unknown constant vectors; $\Phi_{ij}(y_i(t)) \in R^{v_i}$ is a known C^1 function matrix; $f_{ij}(\cdot)$, $(j = 1, 2, \dots, n_i)$ are unknown smooth interaction functions among subsystems; the time-varying delays $d_{ijk}(t)$ satisfy $d_{ijk}(t) \le \overline{d}_{ijk}$ and $\dot{d}_{ijk} \le d_{ijk}^* < 1$.

For system (1), the following additional conditions are assumed.

Assumption 1. The relative degree $\rho_i = n_i - m_i$, and the sign of b_{im_i}, say, $sign(b_{im_i})$, is known constant, and $\iota_i = \inf|b_{im_i}| > 0$, where $i = 1, 2, \dots, N$.

Assumption 2. The polynomial $B_i(s) = b_{im_i}s^{m_i} + \dots + b_{i1}s + b_{i0}$ is Hurwitz.

Assumption 3. The unknown time-varying nonlinear functions $f_{ij}(\cdot)$, $j = 1, 2, \dots, n_i$, satisfy the following inequalities:

$$\left|f_{ij}(y_1(t-d_{ij1}(t)), y_2(t-d_{ij2}(t)), \dots, y_N(t-d_{ijN}(t)))\right|^2 \le \sum_{k=1}^{N} \overline{f}_{ijk}^2(y_k(t-d_{ijk}(t))) \quad (2)$$

where $\overline{f}_{ijk}(\cdot)$ is the unknown smooth function with $\overline{f}_{ijk}(0) = 0$.

Remark 1. Assumption 1 implies that the sign of the actual control input coefficients b_{im_i} is known. It means that b_{im_i} is either strictly positive or strictly negative with $b_{im_i} \ne 0$. It should be noted that ι_i is unknown constant.

Remark 2. Assumption 3 represents that unknown time-varying nonlinear function $f_{ij}(\cdot)$ with combinations of interconnected delay outputs can be separated into unknown smooth nonlinear function $\overline{f}_{ijk}(\cdot)$. We define the tracking error $e_i(t) = y_i(t) - y_{ri}(t)$ where y_{ri} is a given reference signal and we assume that y_{ri} is bounded and ρ_i times continuously differentiable. For the function $\overline{f}_{ijk}(\cdot)$, we have

$$\overline{f}_{ijk}^2(y_k(t-d_{ijk}(t))) \le e_k(t-d_{ijk}(t))\phi_{ijk}(e_k(t-d_{ijk}(t))) + \overline{\epsilon}_{ij}$$

where $\overline{\epsilon}_{ij} \ge \overline{\phi}_{ijk}(y_{rk}(t-d_{ijk}(t)))$ is the positive constant.

In this paper, the problem of output feedback control for system (1) with prescribed performance will be investigated. The objective of this paper is to design the decentralized controller $u_i(t)$, such that (P1) all the signals of the closed-loop systems are ultimately uniformly bounded. (P2) By using the prescribed performance control, the stability and transient performance of tracking error can be guaranteed.

2.2. RBF neural network

In the control engineering, RBF neural network is usually used as a tool for modeling nonlinear functions because of their good capabilities in function approximation. The RBF neural network can be considered as a two-layer network in which the hidden