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Decentralized adaptive delay-dependent neural network control for a class of large-scale interconnected nonlinear systems

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ABSTRACT

This paper investigates the problem of adaptive decentralized control for a class of large-scale interconnected nonlinear systems with unknown time delays, and the unmeasured states. Compared with the existing results, the delay parameters are estimated by utilizing mean value theorem and adaptive mechanism. With the help of the delay estimations, a delay-dependent state observer is designed to make the states available. Based on Lyapunov stability theorem and the backstepping technique, the novel adaptive neural network memory output-feedback controllers are developed. It is proved that the proposed control scheme can guarantee that all the signals in the closed-loop system are bounded and the tracking error converges to the adjustable neighborhood of the origin. The effectiveness of the proposed control scheme is illustrated by the simulation results.

1. Introduction

During the past decades, there has been an increased interest in the development theories and decentralized control for a class of large-scale interconnected systems. Decentralized control issues usually arise in many physical systems such as power system, aerospace system, chemical engineering system, and telecommunication network [1–4]. It is well known that the decentralized control structure naturally alleviates the computational burden associated with a centralized control scheme and enhances the robustness and reliability against interacting operation failures. In the early stage, the works on decentralized control mainly focused on the large-scale linear systems, or the large-scale nonlinear systems which can be linear in a set of unknown parameters [5–8]. Subsequently, decentralized control combined with adaptive backstepping control mechanism have been widely developed for large-scale interconnected nonlinear systems. Specially, decentralized approximation-based adaptive fuzzy or neural network (NN) backstepping control approaches have been used extensively and developed widely [9–12]. Zhang and Feng [9,10] have proposed fuzzy-approximation-based adaptive decentralized control of nonlinear large-scale systems. Huang et al. [11,12] have developed neural-network-based adaptive decentralized control schemes for large-scale uncertain nonlinear systems. Recently, various kinds of problems for large-scale nonlinear systems have been studied [13–15]. Chen and Tao [13] studied adaptive fault-tolerant control of uncertain nonlinear large-scale systems with unknown dead zone. Karimi and Menhaj [14] developed decentralized adaptive control for non-affine non-

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linear large-scale systems. Li et al. [15] dealt with the problems of adaptive decentralized control for nonlinear large-scale systems with expanding construction. The decentralized adaptive backstepping control approach has become one powerful tool for controlling a class of large-scale uncertain nonlinear systems.

It is well known that time delays are often found in various engineering systems, such as electrical networks, microwave oscillators, nuclear reactors, etc. Time delays may destroy the stability or degrade the performance of control systems. Therefore, the research on stability and control design of time-delay systems has received great attention [16–18]. In the early stage, time-delay issues have been intensively investigated for linear systems [19–22]. However, the developed powerful tools for dealing with time-delay linear systems, such as linear matrix inequalities (LMIs), are hard to apply to nonlinear time-delay systems. Therefore, the investigation on stability and control design of nonlinear time-delay systems becomes a challenging and meaningful issue, and has received a great deal of attention in the control community in recent years. Wang et al. [23] developed approximation-based adaptive control methods were proposed for SISO nonlinear time-delay systems, and Zhang and Ge [24] further extended to MIMO nonlinear time-delay systems. Li and Yue [25] investigated the adaptive fuzzy tracking control for stochastic nonlinear time-delay systems. More significant results for controlling nonlinear time-delay systems have been reported in [26–28]. Note that the above common method for controlling nonlinear time-delay systems is choosing appropriate Lyapunov–Krasovskii functionals to compensate for the delay terms and then developing an adaptive memoryless controller.

It is well known that the memoryless controllers, such as [29–31], have feedback of the current state only, and are designed to guarantee the delay-independent stability of the closed-loop systems. Although the memoryless controllers are easy to implement, they tend to be more conservative. In contrast, the memory controllers were proposed for the study on stabilization of time-delay systems, which have a feedback including not only the current state but also the past state. Hence, it is obvious that the memory controller is less conservative and may achieve a better performance than the existing memoryless case. Recently, some literatures [32–35] developed decentralized adaptive control for a class of large-scale interconnected nonlinear time-delay systems. Nevertheless, they developed delay-independent adaptive decentralized control scheme. To the best of our knowledge, there are few results for the case where the delay-dependent adaptive decentralized output-feedback controllers are designed for large-scale interconnected nonlinear systems with unknown time delays.

Motivated by the aforementioned observations, in this paper, the problem of delay-dependent adaptive NN output-feedback control for a class of large-scale interconnected nonlinear time-delay systems is investigated. The considered nonlinear systems are assumed to possess the unstructured uncertainties, unknown time delays, and the unmeasured states. In the control design, radial basis function neural network (RBFNN) is used to approximate the unstructured uncertainties, and the delay parameters are estimated by utilizing mean value theorem and adaptive mechanism. To estimate the unmeasured states, a novel state observer is constructed by utilizing the information of the delay estimations. In addition, the effects on the interaction terms are successfully compensated by introducing a bounded estimation approach and a smooth function. Finally, the proposed adaptive memory control scheme can guarantee that all the signals in the closed-loop system are semi-globally uniformly ultimately bounded (SGUUB) and the tracking error converges to a small neighborhood of the origin. Compared with the existing results, the main contributions can be summarized as follows:

(1) The time-delayed functions related to delayed state variables are addressed by combining the neural-network-approximation technique, mean value theorem and Lipschitz condition, which overcomes the restrictions on the time-delayed functions and avoids the singularity problem in controller design in [38,39].

(2) For the analysis of the stability, the novel cubic Lyapunov functions with absolute value are constructed.

(3) The delay parameters are estimated by establishing the piecewise adaptive laws, and a delay-dependent state observer is designed to make states available. Based on above information, the novel decentralized adaptive memory output-feedback controllers are designed.

The paper is organized as follows. In Section 2, some preliminaries are presented and the problem is formulated. Adaptive NN memory control design and stability analysis are given in Section 3. A simulation study for a practical example verifies the main results in Section 4. Finally, we conclude this paper in Section 5.

2. Preliminaries and problem statement

2.1. System description

Consider a class of large-scale interconnected uncertain nonlinear systems that is composed of N subsystems interconnected by their outputs. The ith subsystem $\sum_i (i = 1, \ldots, N)$ is given as

$$\begin{cases} \dot{x}_{i,k} = x_{i,k+1} + f_{i,k}(\underline{x}_{i,k}) + d_{i,k}(\underline{x}_{i,k}(t-\tau_{i,k})) + \varpi_{i,k}(\bar{y}) \\ y_i = x_{i,1} \end{cases} \tag{1}$$

where $k = 1, \ldots, n_i$, $\underline{x}_{i,k} = [x_{i,1}, \ldots, x_{i,k}]^T \in R^k$, $x_{i,n_i+1} = u_i \in R$ and $y_i \in R$ are state vectors, the control input and the control output, respectively. $\underline{x}_{i,k}(t-\tau_{i,k}) = [x_{i,1}(t-\tau_{i,k}), x_{i,2}(t-\tau_{i,k}), \ldots, x_{i,k}(t-\tau_{i,k})]^T \in R^k$ are the delayed state vectors, $\tau_{i,k}$ are the unknown bounded time delays and the upper bounded are $\tau_{m_{i,k}}$, $\tau_{m_{i,k}}$ are positive constants. $f_{i,k}(\cdot)$: $R^k \to R$ are the unknown smooth nonlinear functions. $d_{i,k}(\cdot)$: $R^k \to R$ are the unknown smooth nonlinear time-delay functions satisfying