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Decentralized Robust Model Reference Adaptive Control for Interconnected Time-delay Systems

Changchun Hua*, Xinping Guan*, Peng Shi**
*Institute of Electrical Engineering, Yanshan University,
Qinghuangdao, 066004, P.R.C.
**Division of Mathematics and Statistics,
School of Technology, University of Glamorgan, Pontypridd, Wales, CF37 1DL United Kingdom

***Abstract*— In this paper, the problem of decentralized robust model reference control for a class of interconnected time-delay systems is investigated. The interconnections with time-varying time delays considered are high order and the gains are not known. A class of decentralized adaptive feedback controllers are proposed, which can render the resulting closed-loop error system asymptotically stable.**

I. INTRODUCTION

Various engineering systems, such as electrical networks, turbojet engines, microwave oscillators, nuclear reactors, and hydraulic systems, have the characteristics of time-delay. Due to the effect of time delay, these systems possess instability, the control performance of these system are hardly assured. So far, the stability analysis and robust control for dynamic time-delay systems attracted a number of researchers over the past years, see for example, to name a few on this general topic, [1-19] and the references therein.

On the other hand, in the real world many practical systems are found to be large-scale systems which are composed of a set of interconnected subsystems, such as power systems, digital communication networks, economic systems and urban traffic networks. Robust control for large-scale time-delay systems have been one of the focused study topics in the past years, and a lot of achievements have been made, see for example, [5-10, 18-19]. In [5], the problem of robust control for a class of interconnected systems with bounded uncertainties was considered. The same system was further discussed by using the decentralized sliding mode control method in [6]. The problem of stabilization of large-scale stochastic systems with time delay was studied in [7], while stabilization of a class of time-varying large scale systems subject to multiple time-varying delays in the interconnections was investigated in [8]. In the work of [9], the robust control problem was investigated by using a linear function as a bound for the uncertain interconnections and the controller was designed based on the bounds. The adaptive control problem of a class of interconnected time-delay systems without knowledge of bounds of uncertain interconnections was considered in [10].

In another research front line, model reference approach has been extensively studied and widely used in control problem and its applications. However, to the best of the authors' knowledge, very few attempts have been made to tackle time-delay systems by using model reference method. Literature [11] firstly investigated the problem and designed the controller for a class of uncertain time delay systems. Model reference adaptive control for interconnected systems with time delays are considered in [12], but the obtained controller are dependent of the delays and the interconnections need to be precisely known.

In this paper we consider a class of nonlinear interconnected time-delay systems. The uncertain interconnections are bounded by high-order nonlinear functions and the gains are unknown. The model reference adaptive control problem is studied. Decentralized feedback adaptive controller is designed, which is independent of the time delays and can render the closed-loop error system asymptotically stable.

II. SYSTEM FORMULATION AND PRELIMINARIES

The interconnected system considered in this paper includes N subsystems with the ith subsystem described by

$$S_i: \ \dot{x}_i = A_i x_i + B_i u_i + \sum_{j=1}^{N} H_{ij}\left(x_j, x_j\left(t - d_{ij}(t)\right), t\right) \qquad (1)$$

where $x_i \in R^{n_i}$ and $u_i \in R^{m_i}$ represent the state and control vectors respectively of the subsystem. A_i and B_i are constant matrices with proper dimensions. $H_{ij}\left(x_j, x_j\left(t - d_{ij}(t)\right), t\right)$ are uncertain nonlinear interconnections, which indicate the interconnections among the current states and the delayed states of systems S_i and S_j, while $d_{ij}(t)$ are bounded time-varying delay and differentiable satisfying

$$0 \le d_{ij}(t) \le d_{ij} < \infty, \ \dot{d}_{ij}(t) \le d_{ij}^* < 1 \qquad (2)$$

where d_{ij} and d_{ij}^* are positive scalars, and initial conditions are given as follows

$$x_i(t) = \Omega_i(t), t \in [t_0 - d_{ij}, t_0], i = 1, 2, \cdots, N$$

where $\Omega_i(t)$ are continuous functions.

For the purpose of model reference, the local reference model of the ith subsystem is given by

$$\dot{x}_{mi}(t) = A_{mi} x_{mi} + B_{mi} r_i(t) \qquad (3)$$

where $x_{mi} \in R^{n_i}$ is the state vector, $r_i(t)$ is the known piecewise continuous and bounded reference input to the ith reference model. A_{mi} and B_{mi} are known matrices.

Further from (1) and (3), we obtain the following error system

$$\begin{aligned}\dot{e}_i &= A_{mi}e_i+(A_i-A_{mi})x_i+B_iu_i \\ &\quad +\sum_{j=1}^{N}H_{ij}(x_j,x_j(t-d_{ij}(t)),t)-B_{mi}r_i(t)\end{aligned} \tag{4}$$

where $e_i=x_i-x_{mi}$.

In the following, some standard assumptions are imposed on system (4).

Assumption 1: There exist matrices K_i and positive matrices P_i satisfying the following inequality for $i=1,2,\cdots,N$

$$(A_{mi}+B_iK_i)^T P_i+P_i(A_{mi}+B_iK_i)=-Q_i \tag{5}$$

where Q_i $(i=1,\cdots N)$ are positive matrices.

Assumption 2: The following conditions are satisfied

$$\begin{aligned}H_{ij}(x_j,x_j(t-d_{ij}(t)),t) &= B_i\widetilde{H}_{ij}(x_j,x_j(t-d_{ij}(t)),t)\\ (A_i-A_{mi}) &= B_iN_i\\ B_{mi} &= B_iM_i\end{aligned}$$

where $\widetilde{H}_{ij}(\cdot)$ are proper vector function, M_i and N_i are constant matrices.

Assumption 3: The interconnections satisfy the following inequalities

$$\begin{aligned}&\sum_{j=1}^{N}\left\|\widetilde{H}_{ij}(x_j,x_j(t-d_{ij}(t)),t)\right\| \\ \leq &\sum_{j=1}^{N}\sum_{s=1}^{p_{ij}}\alpha_{ijs}\left\|x_j\right\|^s+\sum_{j=1}^{N}\sum_{l=1}^{q_{ij}}\beta_{ijl}\left\|x_j(t-d_{ij}(t))\right\|^l\end{aligned} \tag{6}$$

where p_{ij} and q_{ij} are known positive scalars, α_{ijs} and β_{ijl} are unknown scalars.

Assumption 4: The states of model reference system (3) are bounded.

Remark 1: It should be noted that Assumption 1 is to guarantee that the pair $\{A_{mi},B_i\}$ can be stabilizable. If $\{A_{mi},B_i\}$ is completely controllable, Assumption 1 will always hold. Assumption 2 is the so-called matching condition which has been widely used in robust control and filtering problems (see for example, [13-19]). Different from the existing literatures investigating the control problem of interconnected time-delay systems, we assume that the interconnected terms are bounded by high-order functions and the gains are unknown in Assumption 3. Therefore, the results obtained in this paper will be applicable to a large class of interconnected time delay systems. Assumption 4 is to assure that the underlying model reference system is bounded stable.

For interconnected time-delay system (1) satisfying above assumptions, we will propose a class of decentralized adaptive feedback controllers to achieve the model reference's objective.

III. MAIN RESULTS

From Assumption 3, we further obtain the following inequalities with the help of Assumption 4

$$\begin{aligned}&\sum_{j=1}^{N}\left\|\widetilde{H}_{ij}(x_j,x_j(t-d_{ij}(t)),t)\right\| \\ \leq &\sum_{j=1}^{N}\sum_{s=1}^{p_{ij}}\alpha_{ijs}\left\|x_j\right\|^s+\sum_{j=1}^{N}\sum_{l=1}^{q_{ij}}\beta_{ijl}\left\|x_j(t-d_{ij}(t))\right\|^l \\ = &\sum_{j=1}^{N}\sum_{s=1}^{p_{ij}}\alpha_{ijs}\left\|x_{mj}+e_j\right\|^s \\ &+\sum_{j=1}^{N}\sum_{l=1}^{q_{ij}}\beta_{ijl}\left\|x_{mj}(t-d_{ij}(t))+e_j(t-d_{ij}(t))\right\|^l \\ \leq &\sum_{j=1}^{N}\sum_{s=1}^{p_{ij}}\overline{\alpha}_{ijs}\left\|e_j\right\|^s+\sum_{j=1}^{N}\sum_{l=1}^{q_{ij}}\overline{\beta}_{ijl}\left\|e_j(t-d_{ij}(t))\right\|^l+\delta_i \\ = &\sum_{j=1}^{N}\overline{\alpha}_{ij}^TU_{ij}(\left\|e_j\right\|)+\sum_{j=1}^{N}\overline{\beta}_{ij}^TW_{ij}(\left\|e_j(t-d_{ij}(t))\right\|)+\delta_i\end{aligned} \tag{7}$$

where $\overline{\alpha}_{ijs}$, $\overline{\beta}_{ijl}$ and δ_i are unknown positive scalars, and

$$\overline{\alpha}_{ij}=(\overline{\alpha}_{ij1},\overline{\alpha}_{ij2},\cdots\overline{\alpha}_{ijp_{ij}})^T,\overline{\beta}_{ij}=\left(\overline{\beta}_{ij1},\overline{\beta}_{ij2},\cdots\overline{\beta}_{ijq_{ij}}\right)^T,$$

$$U_{ij}(\cdot)=\left(\left\|e_j\right\|,\left\|e_j\right\|^2,\cdots\left\|e_j\right\|^{p_{ij}}\right)^T,$$

$$\begin{aligned}&W_{ij}(\cdot)\\ = &\begin{pmatrix}\left\|e_j(t-d_{ij}(t))\right\|,\left\|e_j(t-d_{ij}(t))\right\|^2,\\ \cdots\left\|e_j(t-d_{ij}(t))\right\|^{q_{ij}}\end{pmatrix}^T\end{aligned}$$

Since the states x_{mi} of reference model system are bounded, there always exist positive scalars $\overline{\alpha}_{ijs}$, $\overline{\beta}_{ijl}$ and δ_i such that inequality (7) holds.

Now, we are ready to present our main result in this paper.

Theorem 1: For system (1), the following adaptive feedback controller

$$u_i=u_{i1}+u_{i2}+u_{i3} \tag{8}$$

where

$$\begin{aligned}u_{i1} &= -N_ix_i+M_ir_i+K_ie_i\\ u_{i2} &= -\theta_i(t)B_i^T\frac{\partial V_i^T(e_i)}{\partial e_i}\\ u_{i3} &= \frac{-\vartheta_i(t)B_i^T\frac{\partial V_i^T(e_i)}{\partial e_i}}{\left\|B_i^T\frac{\partial V_i^T(e_i)}{\partial e_i}\right\|}\end{aligned} \tag{9}$$

in which $\theta_i(t)$ and $\vartheta_i(t)$ are adaptive parameters with adaptive laws

$$\begin{aligned}\dot{\theta}_i &= \frac{1}{2}\Gamma_i\left\|B_i^T\frac{\partial V_i^T(e_i)}{\partial e_i}\right\|^2\\ \dot{\vartheta}_i &= \frac{1}{2}\Phi_i\left\|B_i^T\frac{\partial V_i^T(e_i)}{\partial e_i}\right\|\end{aligned} \tag{10}$$

where Γ_i and Φ_i are positive scalars,

$$V_i(e_i) = \sum_{k=1}^{h_i} \frac{1}{k}\left(e_i^T P_i e_i\right)^k, h_i = \max\left\{p_{ji}, q_{ji}\right\}(j \in [1,N]) \tag{11}$$

and K_i and P_i are matrices satisfying (5), will render the closed-loop error system asymptotically stable.

Proof: Define the following Lyapunov function candidate

$$\begin{aligned}\widetilde{V}(e,\theta,t) &= \sum_{i=1}^{N} \overline{V_i}(e,\theta,t) \\ &= \sum_{i=1}^{N}\{V_i(e_i) + \Gamma_i^{-1}\left(\theta_i - \widetilde{\theta}_i\right)^2 \\ &\quad + \Phi_i^{-1}(\delta_i - \vartheta_i)^2 \\ &\quad + \sum_{j=1}^{N} \nu_{ij}\int_{t-d_{ij}(t)}^{t} \left\|e_j(\xi)\right\|^{2k} d\xi\}\end{aligned} \tag{12}$$

where ν_{ij} are sufficiently small positive scalars, and $\widetilde{\theta}_i$ are also positive scalars defined in (15) (below).

Then by taking the time derivative of $\widetilde{V}(\cdot)$ along the trajectories of the closed-loop system, we have

$$\begin{aligned}\dot{\widetilde{V}}(e,\theta,t) &= \sum_{i=1}^{N} \dot{\overline{V}}_i(e,\theta,t) \\ &\leq \sum_{i=1}^{N}\sum_{k=1}^{h_i}\left(e_i^T P_i e_i\right)^{k-1} \\ &\quad e_i^T\left(\left(A_{mi} + B_i K_i\right)^T P_i + P_i\left(A_i + B_i M_i\right)\right) e_i \\ &\quad + \sum_{i=1}^{N} \frac{\partial V_i(e_i)}{\partial e_i} B_i \sum_{j=1}^{N} \widetilde{H}_{ij}\left(x_j, x_j\left(t - d_{ij}(t)\right), t\right) \\ &\quad + \sum_{i=1}^{N}\sum_{j=1}^{N} \nu_{ij}\left(\left\|e_j\right\|^{2k} - \left(1 - d_{ij}^*\right)\left\|e_j\left(t - d_{ij}(t)\right)\right\|^{2k}\right) \\ &\quad + \sum_{i=1}^{N}\left(2\Gamma_i^{-1}\left(\theta_i - \widetilde{\theta}_i\right)\dot{\theta}_i - 2\Phi_i^{-1}\left(\delta_i - \vartheta_i\right)\dot{\vartheta}_i\right) \\ &\quad - \sum_{i=1}^{N} \frac{\partial V_i(e_i)}{\partial e_i} B_i u_{i3} - \sum_{i=1}^{N} \theta_i \left\|B_i^T \frac{\partial V_i^T(e_i)}{\partial e_i}\right\|^2\end{aligned} \tag{13}$$

Also, the following inequality holds

$$\begin{aligned}&\frac{\partial V_i(e_i)}{\partial e_i} B_i \sum_{j=1}^{N} \widetilde{H}_{ij}\left(x_j, x_j\left(t - d_{ij}(t)\right), t\right) \\ \leq\ &\sum_{j=1}^{N} \overline{\alpha}_{ij}^T U_{ij}\left(\left\|e_j\right\|\right)\left\|B_i^T \frac{\partial V_i(e_i)^T}{\partial e_i}\right\| + \delta_i\left\|B_i^T \frac{\partial V_i(e_i)^T}{\partial e_i}\right\| \\ &+ \sum_{j=1}^{N} \overline{\beta}_{ij}^T W_{ij}\left(\left\|e_j\left(t - d_{ij}(t)\right)\right\|\right)\left\|B_i^T \frac{\partial V_i(e_i)^T}{\partial e_i}\right\| \\ \leq\ &\sum_{j=1}^{N}\left(\frac{\left\|\overline{\alpha}_{ij}\right\|^2}{4\varepsilon_{ij}}\left\|B_i^T \frac{\partial V_i(e_i)^T}{\partial e_i}\right\|^2 + \varepsilon_{ij}\left\|U_{ij}\left(\left\|e_j\right\|\right)\right\|^2\right) \\ &+ \sum_{j=1}^{N}\left(\frac{\left\|\overline{\beta}_{ij}\right\|^2}{4\nu_{ij}\left(1 - d_{ij}^*\right)}\left\|B_i^T \frac{\partial V_i(e_i)^T}{\partial e_i}\right\|^2\right. \\ &\left. + \nu_{ij}\left(1 - d_{ij}^*\right)\left\|W_{ij}\left(\left\|e_j\left(t - d_{ij}(t)\right)\right\|\right)\right\|^2\right) \\ &+ \delta_i\left\|B_i^T \frac{\partial V_i(e_i)^T}{\partial e_i}\right\|\end{aligned} \tag{14}$$

Let

$$\widetilde{\theta}_i = \sum_{j=1}^{N}\left(\frac{\left\|\alpha_{ij}\right\|^2}{4\varepsilon_{ij}} + \frac{\left\|\beta_{ij}\right\|^2}{4\left(1 - d_{ij}^*\right)\nu_{ij}}\right) \tag{15}$$

Then, we have

$$\begin{aligned}&\frac{\partial V_i(e_i)}{\partial e_i} B_i \sum_{j=1}^{N} \widetilde{H}_{ij}\left(x_j, x_j\left(t - d_{ij}(t)\right), t\right) \\ \leq\ &\widetilde{\theta}_i\left\|B_i^T \frac{\partial V_i(e_i)^T}{\partial e_i}\right\|^2 + \delta_i\left\|B_i^T \frac{\partial V_i(e_i)^T}{\partial e_i}\right\| \\ &+ \sum_{j=1}^{N}\sum_{k=1}^{q_{ij}}\left(1 - d_{ij}^*\right)\nu_{ij}\left\|e_j\left(t - d_{ij}(t)\right)\right\|^{2k} \\ &+ \sum_{j=1}^{N}\sum_{k=1}^{p_{ij}} \varepsilon_{ij}\left\|e_j\right\|^{2k}\end{aligned} \tag{16}$$

We know

$$-\frac{\partial V_i(e_i)}{\partial e_i} B_i u_{i3} = -\vartheta_i(t)\left\|B_i^T \frac{\partial V_i^T(e_i)}{\partial e_i}\right\| \tag{17}$$

Substituting (16) and (17) into (13), we further have

$$
\begin{aligned}
\dot{\tilde{V}}(e,\theta,t) &= \sum_{i=1}^{N}\dot{\tilde{V}}_i(e_i,\theta,t)\\
&\leq \sum_{i=1}^{N}\sum_{k=1}^{h_i}\left(e_i^TP_ie_i\right)^{k-1}\left(-e_i^TQ_ie_i\right)\\
&\quad+\sum_{i=1}^{N}\sum_{j=1}^{N}\left(\sum_{k=1}^{q_{ij}}\nu_{ij}\left\|e_j\right\|^{2k}+\sum_{k=1}^{p_{ij}}\varepsilon_{ij}\left\|e_j\right\|^{2k}\right)\\
&\quad+\sum_{i=1}^{N}\left(2\Gamma_i^{-1}\left(\theta_i-\widetilde{\theta}_i\right)\dot{\theta}_i-2\Phi_i^{-1}\left(\delta_i-\vartheta_i\right)\dot{\vartheta}_i\right)\\
&\quad-\sum_{i=1}^{N}\left(\theta_i-\widetilde{\theta}_i\right)\left\|B_i^T\frac{\partial V_i^T(e_i)}{\partial e_i}\right\|^2\\
&\quad+\sum_{i=1}^{N}\left(\delta_i-\vartheta_i(t)\right)\left\|B_i^T\frac{\partial V_i^T(e_i)}{\partial e_i}\right\|
\end{aligned}
$$

By applying (10), one has

$$
\begin{aligned}
\dot{\tilde{V}}(x,\theta,t) \leq \sum_{i=1}^{N}\Bigg\{&-\sum_{k=1}^{h_i}\left(e_i^TP_ie_i\right)^{k-1}\left(e_i^TQ_ie_i\right)\\
&+\sum_{j=1}^{N}\left(\sum_{k=1}^{q_{ij}}\nu_{ij}\left\|e_j\right\|^{2k}+\sum_{k=1}^{p_{ij}}\varepsilon_{ij}\left\|e_j\right\|^{2k}\right)\Bigg\}
\end{aligned}
\tag{18}
$$

If we choose parameters

$$
\nu_j=\max_i\left\{\nu_{ij}\right\},\varepsilon_j=\max_i\left\{\varepsilon_{ij}\right\},\ \text{for } i\in[1,N] \tag{19}
$$

the following inequality will hold

$$
\begin{aligned}
&\sum_{i=1}^{N}\Bigg\{-\sum_{k=1}^{h_i}\left(e_i^TP_ie_i\right)^{k-1}\left(e_i^TQ_ie_i\right)\\
&\quad+\sum_{j=1}^{N}\left(\sum_{k=1}^{q_{ij}}\nu_{ij}\left\|e_j\right\|^{2k}+\sum_{k=1}^{p_{ij}}\varepsilon_{ij}\left\|e_j\right\|^{2k}\right)\Bigg\}\\
\leq\ &\sum_{i=1}^{N}\Bigg\{-\sum_{k=1}^{h_i}\left(e_i^TP_ie_i\right)^{k-1}\left(e_i^TQ_ie_i\right)\\
&\quad+\sum_{j=1}^{N}\left(\sum_{k=1}^{h_j}\nu_j\left\|e_j\right\|^{2k}+\sum_{k=1}^{h_j}\varepsilon_j\left\|e_j\right\|^{2k}\right)\Bigg\}\\
=\ &\sum_{i=1}^{N}\sum_{k=1}^{h_i}\Big\{-\left(e_i^TP_ie_i\right)^{k-1}\left(e_i^TQ_ie_i\right)\\
&\quad+N\nu_i\left\|e_i\right\|^{2k}+N\varepsilon_i\left\|e_i\right\|^{2k}\Big\}
\end{aligned}
$$

where $\nu_j=0\ (q_{ij}<j\leq h_j)$ and $\varepsilon_j=0\ (p_{ij}<j\leq h_j)$. Then we have

$$
\begin{aligned}
\dot{\tilde{V}}(e,\theta,t) \leq \sum_{i=1}^{N}\sum_{k=1}^{h_i}\Big\{&-\lambda_{\min}(P_i)^{k-1}\lambda_{\min}(Q_i)\\
&\left\|e_i\right\|^{2k}+N\nu_i\left\|e_i\right\|^{2k}+N\varepsilon_i\left\|e_i\right\|^{2k}\Big\}
\end{aligned}
\tag{20}
$$

For P_i and Q_i are positive matrices, parameters ν_{ij} and ε_{ij} can be selected to be small enough to render that the following inequality holds

$$
\begin{aligned}
&-\lambda_{\min}^{k-1}(P_i)\lambda_{\min}(Q_i)+N\nu_i+N\varepsilon_i\\
=\ &-\Pi_i<0
\end{aligned}
\tag{21}
$$

where Π_i are positive scalars. Furthermore, one has

$$
\dot{\tilde{V}}(e,\theta,t)\leq-\sum_{i=1}^{N}h_i\Pi_i\left\|e_i\right\|^{2k}
$$

Based on Lyapunov stability theory, the proposed decentralized state feedback controller (8)-(10) will guarantee the closed-loop error system asymptotically stable. ∎

Remark 2: For the controller u_{i3} in (9), we can choose the following candidate to avoid zero appearing in the denominator

$$
u_{i3}=\frac{-\vartheta_i(t)B_i^T\frac{\partial V_i^T(e_i)}{\partial e_i}}{\left\|B_i^T\frac{\partial V_i^T(e_i)}{\partial e_i}\right\|+\varepsilon e^{-rt}}
$$

where ε and r are positive scalars. With the controller above, it is easy for us to obtain the closed-loop system is also asymptotically stable.

Remark 3: To improve the robust performance of control system, we can employ the σ-modification adaptive law. The following can be used in (10)

$$
\begin{aligned}
\dot{\theta}_i &= \frac{1}{2}\Gamma_i\left\|B_i^T\frac{\partial V_i(e_i)}{\partial e_i}^T\right\|^2-\Gamma_i\sigma_{1i}\theta_i\\
\dot{\vartheta}_i &= \frac{1}{2}\Phi_i\left\|B_i^T\frac{\partial V_i^T(e_i)}{\partial e_i}\right\|-\Phi_i\sigma_{2i}\vartheta_i
\end{aligned}
$$

where σ_{1i} and σ_{2i} are positive scalars. By using the adaptive laws above, we can obtain that the closed-loop system is uniformly ultimately bounded stable and the stable bounds can be adjusted by selecting proper parameters σ_{1i} and σ_{2i}.

Remark 4: In this section we have investigated the control problem for interconnected time-delay systems with the uncertainties bounded by high-order polynomials. With the gains unknown, we employed adaptive control idea and designed the controllers. Specially, if the uncertainties are bounded by first-order polynomials, that is: $p_{ij}=q_{ij}=1$, the model reference adaptive control problem is considered in [12]. In [12] the time delay interconnections are needed to be precisely known and the controllers designed are dependent of the time delays. In this paper, the conditions imposed on the interconnected systems are looser and the controllers constructed are independent of the time delays. Therefore, the results obtained in this part are expected to solve the decentralized model reference control problem for a larger class of interconnected time-delay systems.

IV. CONCLUSION

In this paper, model reference adaptive control problem for a class of large-scale time delay systems is investigated. The decentralized feedback controllers and corresponding adaptive laws are designed. Based on Lyapunov stability theory, we prove the resulting closed-loop error system is asymptotically stable. Different from the existing literatures, in this paper the uncertain interconnections with time varying time delays are bounded by high order nonlinear functions and the gains need not to be known. Therefore, the results obtained are expected to apply to a large class of interconnected systems.

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