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Decentralized Robust Control for Nonlinear Interconnected Systems Based on T-S Fuzzy Bilinear Model

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Abstract: This paper focuses on the decentralized robust control problem for a class of nonlinear interconnected systems which are composed by Takagi-Sugeno (T-S) fuzzy bilinear models with interconnections. Based on the Lyapunov stability analysis theory, some robust stabilization sufficient conditions are derived for the whole closed-loop fuzzy interconnected systems. The corresponding decentralized fuzzy controller design is converted into a convex optimization problem with linear matrix inequality (LMI) constraints. The simulation examples show the effectiveness of the proposed approach. *Copyright © 2013 IFSA.*

Keywords: Fuzzy control, Decentralized control, Robust stabilization, Fuzzy bilinear model, Linear matrix inequality (LMI).

1. Introduction

In recent years, T-S model-based fuzzy control has attracted wide attention, essentially because the fuzzy model is an effective and flexible tool for control of nonlinear systems [1, 2]. The T-S fuzzy model is employed to represent or approximate a nonlinear system, which is described by a family of fuzzy IF-THEN rules that represent local linear input-output relations of the system. The overall fuzzy model of the system is achieved by smoothly blending these local linear models together through membership functions. The control design is carried out based on the fuzzy model via the so-called parallel distributed compensation (PDC) scheme [2].The idea is that for each local linear model, a linear feedback control is designed and the resulting overall controller, which is nonlinear in general, is fuzzy blending of each individual linear controller. Just because of this, T-S fuzzy model is widely used to the control design of nonlinear systems.

Large-scale interconnected systems can be found in many real-life practical applications such as electric power systems, nuclear reactors, economic systems, process control systems, computer networks, and urban traffic networks, etc. The properties of interconnected systems have been widely studied and many different approaches have been proposed to stabilize the interconnected linear systems [3, 4]. At the same time, T-S fuzzy model is widely used to the control design of nonlinear interconnected systems [5, 6]. However, it is noted that the above nonlinear interconnected systems are all based on T-S fuzzy linear model.

It is known that bilinear system can describe many physical systems and dynamical processes in engineering fields [7, 8]. There are two main advantages of the bilinear system. One is that it provides a better approximation to a nonlinear system than a linear one. Another is that many real physical processes may be appropriately modeled as bilinear systems when the linear models are inadequate. A good example of a bilinear system is the population of biological species described by $\frac{d\theta}{dt} = \theta v$, where v is the birth rate minus death rate, and θ denotes the population. It is impossible to approximate the aforementioned equation by a linear model [7].

Most of the existing results focus on the stability analysis and synthesis based on T-S fuzzy model with linear local model. However, when a nonlinear system has complex nonlinearities, the constructed T-S model will have to consist of a number of fuzzy local models. This will lead to very heavy computational burden. Considering the advantages of bilinear systems and T-S fuzzy control, the fuzzy system based on the T-S fuzzy model with bilinear rule consequence was attracted the interest of researchers [8-13]. The fuzzy bilinear model may be suitable for some classes of nonlinear plants [8]. The robust stabilization for continuous-time fuzzy system with bilinear model was studied in [8], then the result was extended to the delay fuzzy system [9]. The problem of robust stabilization for discrete-time fuzzy system with bilinear model was investigated in [10]. In [11], we extended the idea in [8] to multiple input bilinear systems with uncertainties, and proposed a robust H-infinity control strategy. We also obtained the non-fragile control law for the fuzzy systems with bilinear model in [12]. So far, the decentralized control of fuzzy interconnected systems with bilinear model has not been discussed.

Motivated by the above observation, in this paper, the problem of decentralized robust control is studied for the interconnected systems with fuzzy local bilinear model. Based on the PDC scheme, new robust stabilization conditions for the closed-loop fuzzy systems are derived. The three main contributions of this paper are the following: 1) The fuzzy bilinear model is extended to the interconnected nonlinear systems; 2) A decentralized controller is presented for the fuzzy interconnected system with uncertainties in state, input and interconnected term; 3) The decentralized robust stability conditions for the fuzzy system are described by LMIs. Finally, two simulation examples are given to demonstrate the results

The paper is organized as follows. Section 2 introduces the fuzzy interconnected system with local bilinear model and decentralized robust controller law for such system. Results of decentralized robust control are given in Section 3. Two simulation examples are used to illustrate the effectiveness of the proposed method in Section 4, which is followed by conclusions in Section 5.

Notation 1: Throughout this paper, a real symmetric matrix $P > 0 (P \geq 0)$ denotes P being a positive definite (or positive semi-definite) matrix. In symmetric block matrices, we use an asterisk (*) to represent a term that is induced by symmetry and $diag\{....\}$ stands for a block-diagonal matrix. The notion $\sum_{i,j=1}^{s}$ means $\sum_{i=1}^{s}\sum_{j=1}^{s}$. Matrices, if the dimensions are not explicitly stated, are assumed to have compatible dimensions for algebraic operations.

2. System Description and Assumptions

Consider a nonlinear interconnected large-scale system Ω composed of S subsystems $\Omega_i, i = 1, 2, ..., S$. Each fuzzy rule of the subsystem Ω_i can be represented by the T-S bilinear model. The m -th rule for the subsystem Ω_i is proposed as the following form:

$$
\begin{aligned}
R_i^m \; if \quad & \xi_{i1}(t) \; is \; F_{i1}^m \; and \; ... \; and \; \xi_{iv_i}(t) \; is \; F_{iv_i}^m \\
then \quad & \dot{x}_i(t) = (A_{im} + \Delta A_{im})x_i(t) + (N_{im} + \Delta N_{im})x_i(t)u_i(t) + (B_{im} + \Delta B_{im})u_i(t) \\
& + \sum_{j=1, j\neq i}^{S} (C_{jim} + \Delta C_{jim})x_j(t) \qquad m = 1, 2, ..., r_i
\end{aligned} \tag{1}
$$

where r_i is the number of the fuzzy rules for the i -th subsystem. $\xi_{ij}(t)$ and $F_{ij}^m, j = 1, 2, ..., v_i$ are some measurable premise variables and fuzzy sets. $x_i(t) \in R^{n_i}, u_i(t) \in R$ are the state vector and control input of the subsystem, respectively. $A_{im} \in R^{n_i \times n_i}, B_{im} \in R^{n_i \times 1}$, $N_{im} \in R^{n_i \times n_i}$ denote the subsystem matrices with appropriate dimensions. $C_{jim} \in R^{n_i \times n_j}$ represents the interconnection matrix between the i -th and the j -th subsystems. $\Delta A_{im}, \Delta B_{im}, \Delta N_{im}$ and ΔC_{jim} are real bounded matrices containing time-varying parameter uncertainties. We assume , as usual, that the uncertainties should satisfy the following assumption.

Assumption 1 [8]: The parameter uncertainties considered here are norm-bounded and presented by the form

$$
\begin{bmatrix} \Delta A_{im} & \Delta N_{im} & \Delta B_{im} \end{bmatrix} = H_{im} F_{im}(t) \begin{bmatrix} E_{i1m} & E_{i2m} & E_{i3m} \end{bmatrix}
$$

$$\Delta C_{jim} = Y_{jim} F_{jim}(t) T_{jim},$$

where $E_{i1m}, E_{i2m}, E_{i3m}, H_{im}, Y_{jim}, T_{jim}$ are known real constant matrices of appropriate dimension, and $F_{im}(t)$, $F_{jim}(t)$ are unknown matrix functions with Lebesgue-measurable elements and satisfies $F_{im}^{\mathrm{T}}(t)F_{im}(t) \le I$, $F_{jim}^{\mathrm{T}}(t)F_{jim}(t) \le I$ for all t.

By using singleton fuzzifier, product inferred, and weighted defuzzifier, the system can be expressed by the following global model:

$$\begin{aligned}\dot{x}_i(t) = \sum\nolimits_{m=1}^{r_i} h_{im}(\xi_i(t))[(A_{im} + \Delta A_{im})x_i(t) + (N_{im} + \Delta N_{im})x_i(t)u_i(t) \\ + (B_{im} + \Delta B_{im})u_i(t) + \sum\nolimits_{j=1, j\ne i}^{S}(C_{jim} + \Delta C_{jim})x_j(t)]\end{aligned}, \tag{2}$$

where $h_{im}(\xi_i(t)) = \dfrac{\omega_{im}(\xi_i(t))}{\sum_{m=1}^{r_i}\omega_{im}(\xi_i(t))}$, $\omega_{im}(\xi_i(t)) = \prod_{j=1}^{v_i}\mu_{imj}(\xi_i(t))$. $\mu_{imj}(\xi_i(t))$ is the grade of membership of $\xi_{ij}(t)$ in F_{ij}^m. In this paper, it is assumed that $\omega_{im}(\xi_i(t)) \ge 0$ and $\sum_{m=1}^{r_i}\omega_{im}(\xi_i(t)) > 0$ for all t. Then we have the following conditions $h_{im}(\xi_i(t)) \ge 0$ and $\sum_{m=1}^{r_i} h_{im}(\xi_i(t)) = 1$ for all t. In what follows, we will drop the argument of $h_{im}(\xi_i(t))$ for simplicity.

Based on PDC, the fuzzy controller shares the same premise parts with (1), the i-th fuzzy controller is formulated as follow

$$\begin{aligned}&\textit{if} \quad \xi_{i1}(t) \;\; \textit{is} \;\; F_{i1}^m \;\; \textit{and ... and} \;\; \xi_{iv_i}(t) \;\; \textit{is} \;\; F_{iv_i}^m \\ &\textit{then} \quad u_i(t) = \frac{\rho_i K_{im} x_i(t)}{\sqrt{1 + x_i^{\mathrm{T}} K_{im}^{\mathrm{T}} K_{im} x_i}} = \rho_i \sin\theta_{im} = \rho_i \cos\theta_{im} K_{im} x_i(t)\end{aligned} \tag{3}$$

where $K_{im} \in R^{1\times n_i}$ is a local controller gain to be determined and $\rho_i > 0$ is a scalar to be assigned. $\sin\theta_{im} = \dfrac{K_{im}x_i(t)}{\sqrt{1 + x_i^{\mathrm{T}} K_{im}^{\mathrm{T}} K_{im} x_i}}, \cos\theta_{im} = \dfrac{1}{\sqrt{1 + x_i^{\mathrm{T}} K_{im}^{\mathrm{T}} K_{im} x_i}}, \theta_{im} \in [-\dfrac{\pi}{2}, \dfrac{\pi}{2}],$
$m = 1, 2, ..., r_i,\ i = 1, 2, ..., S.$

The overall fuzzy control law can be represented by

$$u_i(t) = \sum\nolimits_{m=1}^{r_i} h_{im}\rho_i \sin\theta_{im} = \sum\nolimits_{m=1}^{r_i} h_{im}\rho_i \cos\theta_{im} K_{im} x_i(t) \tag{4}$$

By substituting (4) into (2), the i -th closed-loop subsystem can be represented as

$$\dot{x}_i(t) = \sum\nolimits_{m,n=1}^{r_i} h_{im}h_{in}[(\Lambda_{i,mn} + \Delta\Lambda_{i,mn})x_i(t) + \sum\nolimits_{j=1, j\ne i}^{s}(C_{jim} + \Delta C_{jim})x_j(t)], \tag{5}$$

where $\Lambda_{i,mn} = A_{im} + \rho_i \sin\theta_{in} N_{im} + \rho_i \cos\theta_{in} B_{im} K_{in}, \Delta\Lambda_{i,mn} = \Delta A_{im} + \rho_i \sin\theta_{in} \Delta N_{im} + \rho_i \cos\theta_{in} \Delta B_{im} K_{in}$.

The objective of the paper is to design decentralized fuzzy controllers (4) such that the closed-loop systems (5) is decentralized robust stable.

3. Main Results

Before proceeding with the following theorems, we introduce the following lemmas which will be used in our results.

Lemma 1 [14]: Given any matrices M and N with appropriate dimensions such that $\varepsilon > 0$, we have

$$M^{\mathrm{T}}N + N^{\mathrm{T}}M \le \varepsilon M^{\mathrm{T}}M + \varepsilon^{-1}N^{\mathrm{T}}N .$$

Lemma 2 [15]: Let M, N and $F(t)$ be real matrices of appropriate dimensions with $F(t)^{\mathrm{T}}F(t) \le I$. For scalar $\varepsilon > 0$, we have $M^{\mathrm{T}}F(t)N + N^{\mathrm{T}}F^{\mathrm{T}}(t)M \le \varepsilon M^{\mathrm{T}}M + \varepsilon^{-1}N^{\mathrm{T}}N$.

The following theorem gives the sufficient condition for the existence of the fuzzy decentralized controller for the interconnected system (5).

Theorem 1 For given scalars $\rho_i > 0, \varepsilon_{1i} > 0, \varepsilon_{2i} > 0, \varepsilon_{3i} > 0, i = 1, 2, ..., S$, the interconnect system (5) is robust stable if there exist positive definite matrices $P_i > 0, i = 1, 2, ..., S$ and matrices K_{im}, $m = 1, 2, ..., r_i$, $i = 1, 2, ..., S$ such that the following inequalities (6)-(7) are satisfied.

$$\Phi_{i,mm} < 0, \quad m = 1, 2, ..., r_i,\ i = 1, 2, ..., S \tag{6}$$

$$\Phi_{i,mn} + \Phi_{i,nm} < 0 , \quad 1 \le m < n \le r_i, i = 1, 2, ..., S , \tag{7}$$

where

$$\Phi_{i,mn} = \phi_{i,mn} + \sum_{j=1,\, j\ne i}^{S} P_i C_{jim} C_{jim}^{\mathrm{T}} P_i + (S-1)I + \sum_{j=1,\, j\ne i}^{S} P_i Y_{jim} Y_{jim}^{\mathrm{T}} P_i + \sum_{j=1,\, j\ne i}^{S} T_{ijm}^{\mathrm{T}} T_{ijm},$$

$$\begin{aligned}\phi_{i,mn} = {} & A_{im}^{\mathrm{T}} P_i + P_i A_{im} + \varepsilon_{1i}\rho_i^2 P_i P_i + \varepsilon_{1i}^{-1} N_{im}^{\mathrm{T}} N_{im} + \varepsilon_{1i}^{-1}(B_{im}K_{in})^{\mathrm{T}}(B_{im}K_{in}) + \varepsilon_{2i}^{-1} E_{i1m}^{\mathrm{T}} E_{i1m} \\ & + (\varepsilon_{2i} + \varepsilon_{3i}\rho_i^2) P_i H_{im} H_{im}^{\mathrm{T}} P_i + \varepsilon_{3i}^{-1} E_{i2m}^{\mathrm{T}} E_{i2m} + \varepsilon_{3i}^{-1}(E_{i3m}K_{in})^{\mathrm{T}}(E_{i3m}K_{in}).\end{aligned}$$

Proof: Take the Lyapunov function candidate as

$$V(t) = \sum_{i=1}^{S} V_i(t) = \sum_{i=1}^{S} x_i^{\mathrm{T}}(t) P_i x_i(t) \tag{8}$$

The time derivatives of $V(t)$, along the trajectory of the system (5) is given by

$$\begin{aligned}\dot V(t) &= \sum_{i=1}^{S} [\dot x_i^{\mathrm{T}}(t) P_i x_i(t) + x_i^{\mathrm{T}}(t) P_i \dot x_i(t)] \\ &= \sum_{i=1}^{S} \sum_{m,n=1}^{r_i} h_{im} h_{in} [x_i^{\mathrm{T}}(t)(\Lambda_{i,mn}^{\mathrm{T}} P_i + P_i \Lambda_{i,mn} + \Delta\Lambda_{i,mn}^{\mathrm{T}} P_i + P_i \Delta\Lambda_{i,mn}) x_i(t) \\ &\quad + \sum_{j=1,\, j\ne i}^{S} x_j^{\mathrm{T}}(t) C_{jim}^{\mathrm{T}} P_i x_i(t) + x_i^{\mathrm{T}}(t) P_i \sum_{j=1,\, j\ne i}^{S} C_{jim} x_j(t) \\ &\quad + \sum_{j=1,\, j\ne i}^{S} x_j^{\mathrm{T}}(t) \Delta C_{jim}^{\mathrm{T}} P_i x_i(t) + x_i^{\mathrm{T}}(t) P_i \sum_{j=1,\, j\ne i}^{S} \Delta C_{jim} x_j(t)]\end{aligned} \tag{9}$$

Applying Lemma 1, we have the following inequalities

$$\begin{aligned}& \Lambda_{i,mn}^{\mathrm{T}} P_i + P_i \Lambda_{i,mn} \le A_{im}^{\mathrm{T}} P_i + P_i A_{im} + \varepsilon_{1i}\rho_i^2 P_i P_i + \varepsilon_{1i}^{-1} N_{im}^{\mathrm{T}} N_{im} + \varepsilon_{1i}^{-1}(B_{im}K_{in})^{\mathrm{T}}(B_{im}K_{in}), \\ & \sum_{i=1}^{S} \sum_{m=1}^{r_i} h_{im} [\sum_{j=1,\, j\ne i}^{S} x_j^{\mathrm{T}}(t) C_{jim}^{\mathrm{T}} P_i x_i(t) + x_i^{\mathrm{T}}(t) P_i \sum_{j=1,\, j\ne i}^{S} C_{jim} x_j(t)] \\ & \qquad \le \sum_{i=1}^{S} \sum_{m=1}^{r_i} h_{im} [x_i^{\mathrm{T}}(t) P_i \sum_{j=1,\, j\ne i}^{S} C_{jim} C_{jim}^{\mathrm{T}} P_i x_i(t) + \sum_{j=1,\, j\ne i}^{S} x_j^{\mathrm{T}}(t) x_j(t)] \\ & \qquad = \sum_{i=1}^{S} \sum_{m=1}^{r_i} h_{im} [x_i^{\mathrm{T}}(t) P_i \sum_{j=1,\, j\ne i}^{S} C_{jim} C_{jim}^{\mathrm{T}} P_i x_i(t) + (S-1) x_i^{\mathrm{T}}(t) x_i(t)].\end{aligned} \tag{10}$$

Similar, applying Lemma 2, we get

$$\Delta\Lambda_{i,mn}^{\mathrm{T}}P_i + P_i\Delta\Lambda_{i,mn} \le \varepsilon_{2i}P_iH_{im}H_{im}^{\mathrm{T}}P_i + \varepsilon_{2i}^{-1}E_{i1m}^{\mathrm{T}}E_{i1m} + \varepsilon_{3i}\rho_i^2P_iH_{im}H_{im}^{\mathrm{T}}P_i + \varepsilon_{3i}^{-1}E_{i2m}^{\mathrm{T}}E_{i2m} + \varepsilon_{3i}^{-1}(E_{i3m}K_{in})^{\mathrm{T}}(E_{i3m}K_{in}),$$

$$\begin{aligned}\sum_{i=1}^{S}\sum_{m=1}^{r_i}h_{im}[\sum_{j=1,j\ne i}^{S}x_j^{\mathrm{T}}(t)\Delta C_{jim}^{T}P_ix_i(t) + x_i^{\mathrm{T}}(t)P_i\sum_{j=1,j\ne i}^{S}\Delta C_{jim}x_j(t)] \\ \le \sum_{i=1}^{S}\sum_{m=1}^{r_i}h_{im}[x_i^{\mathrm{T}}(t)P_i\sum_{j=1,j\ne i}^{S}Y_{jim}Y_{jim}^{\mathrm{T}}P_ix_i(t) + x_j^{\mathrm{T}}(t)\sum_{j=1,j\ne i}^{S}T_{jim}^{\mathrm{T}}T_{jim}x_j(t)] \\ = \sum_{i=1}^{S}\sum_{m=1}^{r_i}h_{im}[x_i^{\mathrm{T}}(t)P_i\sum_{j=1,j\ne i}^{S}Y_{jim}Y_{jim}^{\mathrm{T}}P_ix_i(t) + x_i^{\mathrm{T}}(t)\sum_{j=1,j\ne i}^{S}T_{ijm}^{\mathrm{T}}T_{ijm}x_i(t)].\end{aligned} \quad (11)$$

Then, substituting (10) and (11) into (9) yields

$$\begin{aligned}\dot V(t) &\le \sum_{i=1}^{S}\sum_{m,n=1}^{r_i}h_{im}h_{in}x_i^{\mathrm{T}}(t)\Phi_{i,mn}x_i(t) \\ &= \sum_{i=1}^{S}\sum_{m=1}^{r_i}h_{im}^2x_i^{\mathrm{T}}(t)\Phi_{i,mm}x_i(t) + \sum_{i=1}^{S}\sum_{1=m<n}^{r_i}h_{im}h_{in}x_i^{\mathrm{T}}(t)(\Phi_{i,mn}+\Phi_{i,nm})x_i(t)\end{aligned} \quad (12)$$

Therefore, it is noted that (6) and (7) imply $\dot V(t) < 0$, so the interconnected system (5) is robust stable. Thus, we complete the proof.

It is noted that the matrix inequalities (6)-(7) are nonlinear matrix inequalities. In the following theorem, we will derive a sufficient condition such that the matrix inequalities (6)-(7) can be transformed into an LMI problem.

Theorem 2 For given scalars $\rho_i > 0, \varepsilon_{1i} > 0, \varepsilon_{2i} > 0, \varepsilon_{3i} > 0, i = 1,2,...,S$, the interconnect system (5) is robust stability if there exist positive definite matrices $Z_i > 0, i = 1,2,...,S$ and matrices $G_{im}, i = 1,2,...,S;\ m = 1,2,...,r_i$ such that the matrix inequalities (13)-(14) are satisfied. Moreover, the feedback gains are given by $K_{im} = G_{im}Z_i^{-1}, i = 1,2,...,S; m = 1,2,...,r_i$.

$$\begin{bmatrix} \varphi_{i,m} & * & * & * & * & * & * & * \\ Z_i & -\frac{I}{S-1} & * & * & * & * & * & * \\ N_{im}Z_i & 0 & -\varepsilon_{1i}I & * & * & * & * & * \\ B_{im}G_{im} & 0 & 0 & -\varepsilon_{1i}I & * & * & * & * \\ E_{i1m}Z_i & 0 & 0 & 0 & -\varepsilon_{2i}I & * & * & * \\ E_{i2m}Z_i & 0 & 0 & 0 & 0 & -\varepsilon_{3i}I & * & * \\ E_{i3m}G_{im} & 0 & 0 & 0 & 0 & 0 & -\varepsilon_{3i}I & * \\ \overline{TZ}_{i,m} & 0 & 0 & 0 & 0 & 0 & 0 & -I \end{bmatrix} < 0, \quad (13)$$

$$i = 1,2,\ldots,S;\quad m = 1,2,\ldots,r_i.$$

$$\begin{bmatrix} \varphi_{i,m}+\varphi_{i,n} & * & * & * & * & * & * & * \\ 2Z_i & -\frac{2I}{S-1} & * & * & * & * & * & * \\ \overline{NZ}_{i,mn} & 0 & -\varphi_{33} & * & * & * & * & * \\ \overline{BG}_{i,mn} & 0 & 0 & -\varphi_{44} & * & * & * & * \\ \overline{E_1Z}_{i,mn} & 0 & 0 & 0 & -\varphi_{55} & * & * & * \\ \overline{E_2Z}_{i,mn} & 0 & 0 & 0 & 0 & -\varphi_{66} & * & * \\ \overline{E_3G}_{i,mn} & 0 & 0 & 0 & 0 & 0 & -\varphi_{77} & * \\ \overline{\overline{TZ}}_{i,mn} & 0 & 0 & 0 & 0 & 0 & 0 & -I \end{bmatrix} < 0, \quad (14)$$

$$i = 1,2,\ldots,S;\quad 1 \le m < n \le r_i.$$

where

$$\varphi_{i,m} = Z_iA_{im}^{\mathrm{T}} + A_{im}Z_i + \varepsilon_{1i}\rho_i^2I + (\varepsilon_{2i}+\varepsilon_{3i}\rho_i^2)H_{im}H_{im}^{\mathrm{T}} + \sum_{j=1,j\ne i}^{S}C_{jim}C_{jim}^{\mathrm{T}} + \sum_{j=1,j\ne i}^{S}Y_{jim}Y_{jim}^{\mathrm{T}},$$

$$\overline{TZ}_{i,m} = [\overbrace{T_{i1m}Z_i\ \ T_{i2m}Z_i\ \ \cdots\ \ T_{ii-1m}Z_i\ \ T_{ii+1m}Z_i\ \ \cdots\ \ T_{iSm}Z_i}^{S-1}]^{\mathrm{T}},\ \overline{NZ}_{i,mn} = \begin{bmatrix} N_{im}Z_i \\ N_{in}Z_i \end{bmatrix},$$

$$\overline{BG}_{i,mn}=\begin{bmatrix}B_{im}G_{in}\\B_{in}G_{im}\end{bmatrix},\overline{E_1Z}_{i,mn}=\begin{bmatrix}E_{i1m}Z_i\\E_{i1n}Z_i\end{bmatrix},\overline{E_2Z}_{i,mn}=\begin{bmatrix}E_{i2m}Z_i\\E_{i2n}Z_i\end{bmatrix},\overline{E_3G}_{i,mn}=\begin{bmatrix}E_{i3m}G_{in}\\E_{i3n}G_{im}\end{bmatrix},$$

$$\overline{\overline{TZ}}_{i,mn}=[\overbrace{T_{i1m}Z_i\ \ T_{i1n}Z_i\ \ldots\ T_{ii-1m}Z_i\ \ T_{ii-1n}Z_i\ \ T_{ii+1m}Z_i\ \ T_{ii+1n}Z_i\ \ldots\ T_{iSm}Z_i\ \ T_{iSn}Z_i}^{2(S-1)}]^{\mathrm{T}},$$

$$\varphi_{33}=\varphi_{44}=diag\{\varepsilon_{1i}I,\varepsilon_{1i}I\},\ \varphi_{55}=diag\{\varepsilon_{2i}I,\varepsilon_{2i}I\},\ \varphi_{66}=\varphi_{77}=diag\{\varepsilon_{3i}I,\varepsilon_{3i}I\}.$$

Proof: letting $P_i=Z_i^{-1}$ and noting $G_{im}=K_{im}Z$.

Then, pre-multiplying and post-multiplying $diag\{P_i,\overbrace{I,I,...,I,I}^{S+5}\}$ to (13) results in

$$\begin{bmatrix}P_i\varphi_{i,m}P_i & * & * & * & * & * & * & *\\ I & -\frac{I}{S-1} & * & * & * & * & * & *\\ N_{im} & 0 & -\varepsilon_{1i}I & * & * & * & * & *\\ B_{im}K_{im} & 0 & 0 & -\varepsilon_{1i}I & * & * & * & *\\ E_{i1m} & 0 & 0 & 0 & -\varepsilon_{2i}I & * & * & *\\ E_{i2m} & 0 & 0 & 0 & 0 & -\varepsilon_{3i}I & * & *\\ E_{i3m}K_{im} & 0 & 0 & 0 & 0 & 0 & -\varepsilon_{3i}I & *\\ \overline{T}_{i,m} & 0 & 0 & 0 & 0 & 0 & 0 & -I\end{bmatrix}<0, \tag{15}$$

$$i=1,2,...,S;\ \ m=1,2,...,r_i,$$

where $\overline{T}_{i,m}=[\overbrace{T_{i1m}\ \ T_{i2m}\ \cdots\ T_{ii-1m}\ \ T_{ii+1m}\ \cdots\ T_{iSm}}^{S-1}]^{\mathrm{T}}$.

Applying the Schur complement to (15) results in the condition (6). It is similar to prove that the (14) is equivalent to the condition (7). Therefore, it follows from Theorem 1 that the interconnected system (5) is robustly stable. Thus, the proof is completed.

4. Simulation Examples

In this section, two simulation examples are presented to illustrate the fuzzy controller design method developed in this paper.

Example 1: Consider a nonlinear interconnected system composed of two subsystems which are described as follows

$$\begin{aligned}&Subsystem\ 1:\\&\dot{x}_{11}(t)=0.2\sin(t)x_{11}(t)-1.5x_{12}(t)+0.1x_{11}(t)x_{12}(t)+u_1(t)(1-x_{11}(t)\\&\qquad+0.1\sin(t)x_{11}(t))-0.3x_{21}(t)+0.2x_{22}(t)-0.1x_{22}^3(t);\\&\dot{x}_{12}(t)=x_{11}(t)-(3+0.2\cos t)x_{12}(t)+(1-0.2\cos t-x_{12}(t))u_1(t)\\&\qquad+0.1x_{21}(t)-0.4x_{22}(t)-0.1x_{22}^3(t);\\&Subsystem\ 2:\\&\dot{x}_{21}(t)=0.4\sin(t)x_{21}(t)+x_{21}(t)-0.2x_{11}(t)x_{12}(t)+u_2(t)(1-2x_{21}(t)\\&\qquad+0.2\sin(t)x_{21}(t))-0.3x_{11}(t)+0.2x_{12}(t)-0.1x_{12}^3(t);\\&\dot{x}_{22}(t)=-x_{21}(t)+(1-0.1\cos t)x_{12}(t)+(0.1\cos(t)x_{22}(t)-0.2\cos t\\&\qquad-x_{22}(t))u_2(t)-0.1x_{11}(t)\ -0.8x_{12}(t)-0.7x_{12}^3(t).\end{aligned}\tag{16}$$

Then, we establish the T-S fuzzy bilinear model for each interconnected subsystem. Thus, the nonlinear subsystem (16) are approximated by the following fuzzy models

$$\begin{aligned}
&\textit{Subsystem } 1:\\
&R_1^1: \ \textit{if} \quad x_{11} \quad \textit{is} \quad F_{11}^1\\
&\quad \textit{then} \quad \dot{x}_1(t) = (A_{11} + \Delta A_{11})x_1(t) + (N_{11} + \Delta N_{11})x_1(t)u_1(t) + (B_{11} + \Delta B_{11})u_1(t)\\
&\qquad\qquad + (C_{211} + \Delta C_{211})x_2(t);\\
&R_1^2: \ \textit{if} \quad x_{11} \quad \textit{is} \quad F_{11}^2\\
&\quad \textit{then} \quad \dot{x}_1(t) = (A_{12} + \Delta A_{12})x_1(t) + (N_{12} + \Delta N_{12})x_1(t)u_1(t) + (B_{12} + \Delta B_{12})u_1(t)\\
&\qquad\qquad + (C_{212} + \Delta C_{212})x_2(t);
\end{aligned} \tag{17}$$

where

$$A_{11} = \begin{bmatrix} 0 & -1 \\ 1 & -3 \end{bmatrix}, A_{12} = \begin{bmatrix} 0 & -2 \\ 1 & -3 \end{bmatrix}; B_{11} = B_{12} = \begin{bmatrix} 1 \\ 1 \end{bmatrix}; N_{11} = N_{12} = \begin{bmatrix} -1 & 0 \\ 0 & -1 \end{bmatrix}; C_{211} = \begin{bmatrix} -0.3 & 0.2 \\ 0.1 & -0.4 \end{bmatrix},$$

$$C_{212} = \begin{bmatrix} -0.3 & 0.1 \\ 0.1 & 0.5 \end{bmatrix}; E_{111} = E_{112} = \begin{bmatrix} 0.4 & 0 \\ 0 & 0.1 \end{bmatrix}; E_{121} = E_{122} = \begin{bmatrix} 0.1 & 0 \\ 0 & 0 \end{bmatrix}; E_{131} = E_{132} = \begin{bmatrix} 0 \\ 0.2 \end{bmatrix};$$

$$T_{211} = T_{212} = \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix}, H_{11} = H_{12} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}; Y_{211} = Y_{212} = \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix}.$$

The membership functions of subsystem 1 are chosen as

$$\mu_{F_{11}^1}(x_{11}) = \begin{cases} 0, & x_{11}(t) < -5 \\ 0.1x_{11} + 0.5, & -5 \le x_{11}(t) < 5, \\ 1, & x_{11}(t) > 5 \end{cases} \quad \mu_{F_{11}^2}(x_{11}) = 1 - \mu_{F_{11}^1}(x_{11})$$

$$\begin{aligned}
&\textit{Subsystem } 2:\\
&R_2^1: \ \textit{if} \quad x_{21} \quad \textit{is} \quad F_{21}^1\\
&\quad \textit{then} \quad \dot{x}_2(t) = (A_{21} + \Delta A_{21})x_2(t) + (N_{21} + \Delta N_{21})x_2(t)u_2(t) + (B_{21} + \Delta B_{21})u_2(t)\\
&\qquad\qquad + (C_{121} + \Delta C_{121})x_1(t);\\
&R_2^2: \ \textit{if} \quad x_{21} \quad \textit{is} \quad F_{21}^2\\
&\quad \textit{then} \quad \dot{x}_2(t) = (A_{22} + \Delta A_{22})x_2(t) + (N_{22} + \Delta N_{22})x_2(t)u_2(t) + (B_{22} + \Delta B_{22})u_2(t)\\
&\qquad\qquad + (C_{122} + \Delta C_{122})x_1(t);
\end{aligned} \tag{18}$$

where

$$A_{21} = \begin{bmatrix} 1 & 0 \\ -1 & -1 \end{bmatrix}, A_{22} = \begin{bmatrix} 1 & 0 \\ -1 & 1 \end{bmatrix}; B_{21} = B_{22} = \begin{bmatrix} 1 \\ 0 \end{bmatrix}; N_{21} = N_{22} = \begin{bmatrix} -2 & 0 \\ 0 & 1 \end{bmatrix}; C_{121} = \begin{bmatrix} -0.3 & 0.2 \\ 0.1 & -0.8 \end{bmatrix};$$

$$C_{122} = \begin{bmatrix} -0.3 & 0.1 \\ 0.1 & -1.5 \end{bmatrix}; E_{211} = E_{212} = \begin{bmatrix} 0.4 & 0 \\ 0 & 0.1 \end{bmatrix}; E_{221} = E_{222} = \begin{bmatrix} 0.2 & 0 \\ 0 & 0.1 \end{bmatrix}; E_{231} = E_{232} = \begin{bmatrix} 0 \\ -0.1 \end{bmatrix};$$

$$T_{121} = T_{122} = \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix}; H_{21} = H_{22} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}; Y_{121} = Y_{122} = \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix}.$$

The membership functions of subsystem 2 are chosen as

$$\mu_{F_{21}^1}(x_{21}) = \begin{cases} 0, & x_{21}(t) < -5 \\ 0.1x_{21} + 0.5, & -5 \le x_{21}(t) < 5, \\ 1, & x_{21}(t) > 5 \end{cases} \quad \mu_{F_{21}^2}(x_{21}) = 1 - \mu_{F_{21}^1}(x_{21}) \cdot$$

Based on Eqs. (13) and (14), for $\rho_1 = 0.46, \rho_2 = 0.83$ and $\varepsilon_{11} = \varepsilon_{12} = 1.45, \varepsilon_{21} = \varepsilon_{22} = 0.68,$ $\varepsilon_{31} = \varepsilon_{32} = 0.01$, we can thereby obtained the following feasible solution:

$$P_1 = \begin{bmatrix} 12.0440 & 5.1447 \\ 5.1447 & 23.1160 \end{bmatrix}, P_2 = \begin{bmatrix} 4.3347 & 1.0980 \\ 1.0980 & 5.0469 \end{bmatrix},$$

$$K_{11} = [-0.4652 \;\; -03452], K_{12} = [-0.8562 \;\; -0.2867]; K_{21} = [-0.2024 \;\; -0.3851]; K_{22} = [-0.3797 \;\; -0.3682].$$

Figs. 1 - 3 illustrate the simulation results of applying the robust controller to the fuzzy interconnected system under initial conditions $x_{10} = [1.2 \quad -1.6]^{\mathrm{T}}$ and $x_{20} = [-1.9 \quad 1.2]^{\mathrm{T}}$. It can be seen that with the fuzzy control law (4) the closed-loop system is robustly stable.

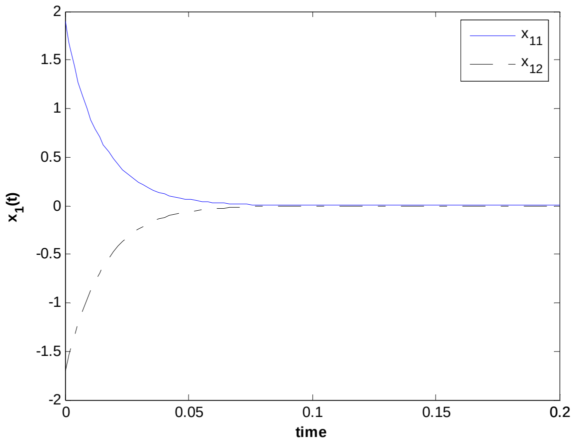

Fig. 1. State responses of subsystem 1.

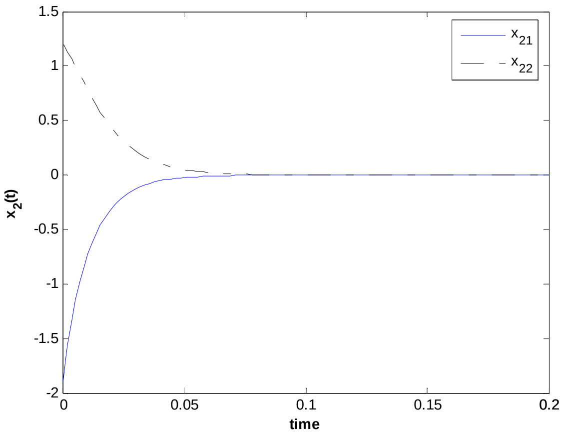

Fig. 2. State responses of subsystem 2.

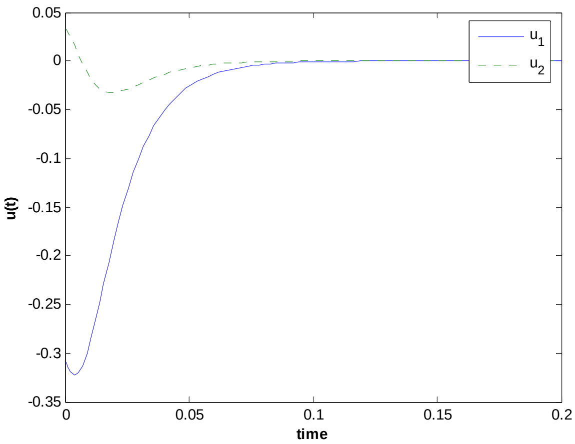

Fig. 3. Control trajectories.

Example 2: Consider the dynamics of an isothermal continuous stirred tank reactor for the Van de Vusse

$$\begin{aligned} &\textit{Subsystem } 1: \\ &\quad \dot{x}_{11}(t) = -50x_{11}(t) - 100x_{11}^2(t) + u_1(10 - x_{11}(t)) + 10x_{21}(t) \\ &\quad \dot{x}_{12}(t) = 50x_{11}(t) - 50x_{12}(t) - u_1 x_{12}(t) + 20x_{21}(t) + 5x_{22}(t) \\ &\textit{Subsystem } 2: \\ &\quad \dot{x}_{21}(t) = 50x_{21}(t) - 50x_{21}^2(t) + u_2(10 + x_{21}(t)) + 8x_{11}(t) \\ &\quad \dot{x}_{22}(t) = 100x_{22}(t) + u_2(x_{12}(t) + 10) + 5x_{12}(t) \end{aligned} \tag{19}$$

From the system equation (19), some equilibrium points are tabulated in Table 1. According to these equilibrium points, $[x_e \;\; u_e]$, which are also chosen as the desired operating points, $[x_e^{'} \;\; u_e^{'}]$, we can use the similar modeling method that is described in [8].

Table 1 Data for equilibrium points.

x_{1e}^{T}	u_{1e}	x_{2e}^{T}	u_{2e}
[2.3 -4.1616]	40.9756	[2.8 3.4845]	10.7031
[4.5 -3.4770]	139.3103	[4.6 3.6745]	41.3014
[5.4 -2.9495]	188.7013	[5.6 3.9398]	79.5313

Thus, the system (19) can be represented by

$$\begin{aligned}
&Subsystem\ 1:\\
&R_1^1:\ if\quad x_{11}\quad is\quad about\ 2.3\\
&\quad then\quad \dot{x}_{1\delta}(t)=A_{11}x_{1\delta}(t)+B_{11}u_{1\delta}(t)+N_{11}x_{1\delta}(t)u_{1\delta}(t)+C_{211}x_{2\delta}(t)\\
&R_1^2:\ if\quad x_{11}\quad is\quad about\ 4.5\\
&\quad then\quad \dot{x}_{1\delta}(t)=A_{12}x_{1\delta}(t)+B_{12}u_{1\delta}(t)+N_{12}x_{1\delta}(t)u_{1\delta}(t)+C_{212}x_{2\delta}(t)\\
&R_1^3:\ if\quad x_{11}\quad is\quad about\ 5.4\\
&\quad then\quad \dot{x}_{1\delta}(t)=A_{13}x_{1\delta}(t)+B_{13}u_{1\delta}(t)+N_{13}x_{1\delta}(t)u_{1\delta}(t)+C_{213}x_{2\delta}(t)
\end{aligned}\tag{20}$$

where

$$A_{11}=\begin{bmatrix}-75.2383 & 7.7946\\ 50 & -100\end{bmatrix},A_{12}=\begin{bmatrix}-87.3005 & 11.7315\\ 50 & -100\end{bmatrix},A_{13}=\begin{bmatrix}-98.6262 & 14.8277\\ 50 & -100\end{bmatrix},$$
$$N_{11}=N_{12}=N_{13}=\begin{bmatrix}-1 & 0\\ 0 & -1\end{bmatrix};B_{11}=B_{12}=B_{13}=\begin{bmatrix}10\\ 0\end{bmatrix};C_{211}=C_{212}=C_{213}=\begin{bmatrix}10 & 0\\ 20 & 5\end{bmatrix};$$
$$x_{1\delta}=x_1(t)-x_{1e}^{'},u_{1\delta}={}_{u1}\ (t)-u_{1e}^{'},$$

$$\begin{aligned}
&Subsystem\ 2:\\
&R_2^1:\ if\quad x_{21}\quad is\quad about\ 2.8\\
&\quad then\quad \dot{x}_{2\delta}(t)=A_{21}x_{2\delta}(t)+B_{21}u_{2\delta}(t)+N_{21}x_{2\delta}(t)u_{2\delta}(t)+C_{121}x_{1\delta}(t)\\
&R_2^2:\ if\quad x_{21}\quad is\quad about\ 4.6\\
&\quad then\quad \dot{x}_{2\delta}(t)=A_{22}x_{2\delta}(t)+B_{22}u_{2\delta}(t)+N_{22}x_{2\delta}(t)u_{2\delta}(t)+C_{122}x_{1\delta}(t)\\
&R_2^3:\ if\quad x_{21}\quad is\quad about\ 5.6\\
&\quad then\quad \dot{x}_{2\delta}(t)=A_{23}x_{2\delta}(t)+B_{23}u_{2\delta}(t)+N_{23}x_{2\delta}(t)u_{2\delta}(t)+C_{123}x_{1\delta}(t)
\end{aligned}\tag{21}$$

where

$$A_{21}=\begin{bmatrix}-55.5332 & 11.3308\\ 50 & -50\end{bmatrix},A_{22}=\begin{bmatrix}-45.8303 & 9.7505\\ 50 & -50\end{bmatrix},A_{23}=\begin{bmatrix}-37.7909 & 8.9544\\ 50 & -50\end{bmatrix};$$
$$N_{21}=N_{22}=N_{23}=\begin{bmatrix}-1 & 0\\ 0 & -1\end{bmatrix};B_{21}=B_{22}=B_{23}=\begin{bmatrix}10\\ 0\end{bmatrix};C_{121}=C_{122}=C_{123}=\begin{bmatrix}10 & 0\\ 20 & 5\end{bmatrix};$$
$$x_{2\delta}=x_2(t)-x_{2e}^{'},u_{2\delta}=u_2(t)-u_{2e}^{'}.$$

Now, we want to consider the fuzzy system with uncertainties, where the system parameters are randomly varied within 50 % of their nominal values. Based on the Assumption 1, we can define the matrices and as follows:

$$E_{111}=E_{112}=E_{113}=\begin{bmatrix}50 & 100\\ 0 & 50\end{bmatrix};E_{121}=E_{122}=E_{123}=\begin{bmatrix}1 & 0\\ 0 & 0\end{bmatrix};E_{131}=E_{132}=E_{133}=\begin{bmatrix}0\\ 1\end{bmatrix};$$
$$T_{211}=T_{212}=T_{213}=\begin{bmatrix}0 & 0\\ 0 & 0\end{bmatrix},H_{11}=H_{12}=H_{13}=\begin{bmatrix}1 & 0\\ 0 & 1\end{bmatrix};Y_{211}=Y_{212}=Y_{213}=\begin{bmatrix}0 & 0\\ 0 & 0\end{bmatrix};$$

$$E_{211} = E_{212} = E_{213} = \begin{bmatrix} 50 & 50 \\ 0 & 50 \end{bmatrix}; E_{221} = E_{222} = E_{223} = \begin{bmatrix} 1 & 0 \\ 0 & 2 \end{bmatrix}; E_{231} = E_{232} = E_{233} = \begin{bmatrix} 0 \\ -1 \end{bmatrix};$$
$$T_{121} = T_{122} = T_{123} = \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix}; H_{21} = H_{22} = H_{23} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}; Y_{121} = Y_{122} = Y_{123} = \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix}.$$

The membership functions of two subsystems are illustrated in Fig. 4 and Fig. 5, respectively.

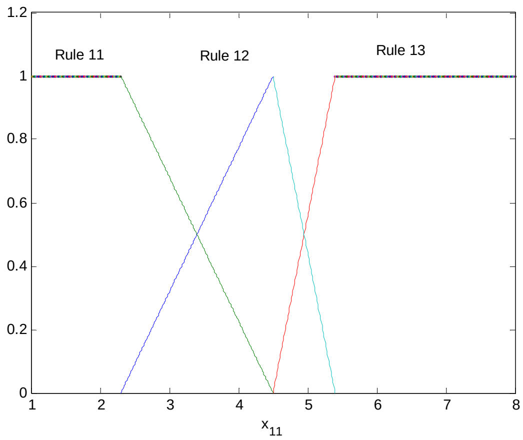

Fig. 4. Membership functions of subsystem 1.

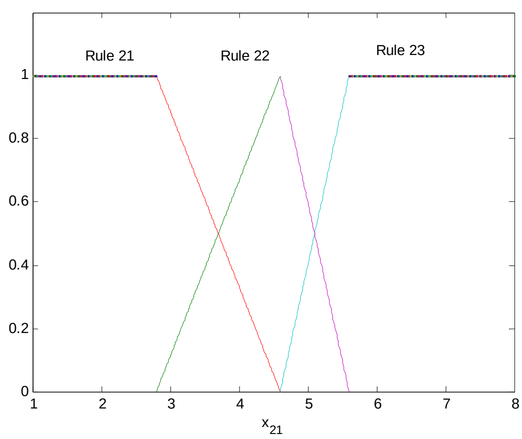

Fig. 5. Membership functions of subsystem 2.

By applying Theorem 2 with for $\rho = 0.45, \lambda = 1.02$, $\varepsilon_{11} = \varepsilon_{12} = \varepsilon_{13} = 0.9, \varepsilon_{21} = \varepsilon_{22} = \varepsilon_{23} = 0.3,$ $\varepsilon_{31} = \varepsilon_{32} = \varepsilon_{33} = 1.4$ and solving the corresponding LMIs, we can obtain the following feasible solution:

$$P_1 = \begin{bmatrix} 4.2727 & -1.3007 \\ -1.3007 & 6.4906 \end{bmatrix}, P_2 = \begin{bmatrix} 14.1872 & -1.9381 \\ -1.9381 & 13.0104 \end{bmatrix};$$

$$K_{11} = [-0.4233 \quad -0.5031], K_{12} = [-0.5961 \quad -0.7049], K_{13} = [-1.0372 \quad 0.2120];$$

$$K_{21} = [-0.4593 \quad -0.3874], K_{22} = [-0.4121 \quad -0.4113], K_{23} = [-0.6371 \quad -0.5911].$$

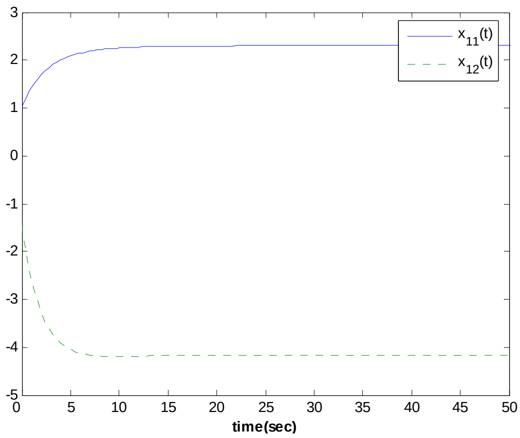

Fig. 6. State responses of Subsystem 1.

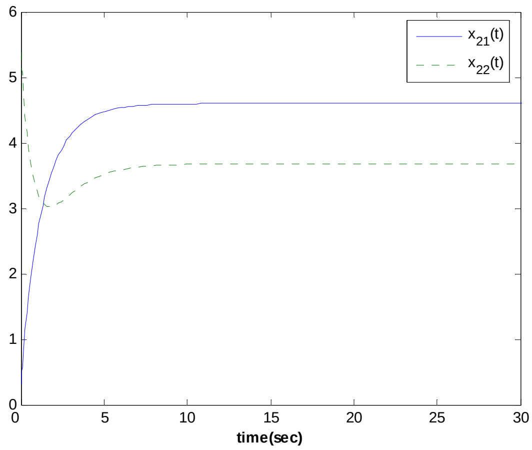

Fig. 7. State responses of Subsystem 2.

The simulation results of applying the fuzzy control (4) to the systems (20)-(21) with $x'_{1e} = [2.3 \quad -4.1616]^T, u'_{1e} = 40.9756$ and $x'_{2e} = [4.6 \quad 3.6745]^T, u'_{2e} = 41.3014$, under initial conditions

$\begin{bmatrix}1.2 & -1.5\end{bmatrix}^T$ and $\begin{bmatrix}0.5 & 3.2\end{bmatrix}^T$ are shown in Fig. 6 and Fig. 7, respectively. One can find that all the states of subsystem 1 approach to the equilibrium state $\begin{bmatrix}2.3 & -4.1616\end{bmatrix}^T$ after 10 s and the states of subsystem 2 approach to the equilibrium state $\begin{bmatrix}4.6 & 3.6745\end{bmatrix}^T$ after 12 s. These simulation results verify that the proposed decentralized fuzzy controller (4) can render the robust stability of the closed-loop systems.

5. Conclusions

In this paper, a T-S fuzzy bilinear model is proposed to study the robust control problems for nonlinear interconnected systems using fuzzy decentralized control. Based on the Lyapunov criterion, the sufficient conditions for robust stabilization of the interconnected system are presented. The decentralized controllers designing problems can be formulated as a convex optimization problem with LMI constraints. The simulation examples are included to show the effectiveness of the proposed approach. The delay-dependent control and robust non-fragile control based on bilinear model will further investigate in the future work.

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