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Decentralized robust fuzzy controller with nonlinear local models for large-scale interconnected systems

Long Teng, Youyi Wang, Wenjian Cai, and Hua Li

Abstract—In this paper, a kind of decentralized robust fuzzy controller which uses nonlinear local models is designed for the control of large-scale interconnected systems. The approach of T-S fuzzy model with nonlinear local models rather than with linear local model can bring some advantages. Especially for large-scale interconnected systems which often contain a lot of complex nonlinear interconnection functions, the number of fuzzy rules can be decreased as well as the computational burden can be reduced. Meanwhile, the parameter uncertainties within each subsystem and in the interconnection of subsystems are also considered to achieve robustness of the system's performance. In addition, guaranteed cost control (H_2 control) is realized and the control synthesis conditions are given by solving a set of linear matrix inequalities (LMIs). Simulation result is given to illustrate the effectiveness of the proposed method.

I. INTRODUCTION

Due to that there exist a lot of complexities, e.g. the number of subsystems is large, severe nonlinearities within one subsystem and between the interconnection of subsystems together with parameter uncertainties and time delays are combined, it is usually hard to only apply a centralized controller to fulfill the requirements of large-scale interconnected systems which contain many subsystems. Compared with centralized control, decentralized control can achieve the stability of the whole system without relying on the feedback information from other subsystems.

In recent years, extensive work can be seen on decentralized control of interconnected nonlinear systems together with fuzzy logic systems [1]–[11]. However, it can be seen that most of the existing fuzzy control methods utilize T-S fuzzy model with linear local models. A novel fuzzy control method using T-S fuzzy model with nonlinear local models is firstly proposed in [12]. By applying the new fuzzy control method, the number of fuzzy rules could be decreased and the computational burden could be reduced, while it can also achieve a good control performance.

In this paper, a kind of decentralized robust fuzzy controller which adopts fuzzy control strategy in [12] is designed for the control of large-scale interconnected systems. The advantage of applying this kind of fuzzy

controller on interconnected systems is that, considering such a kind of systems which often contain a lot of nonlinearities, the fuzzy control method which uses nonlinear local models can decrease the number of fuzzy local models and fuzzy rules. Thus, the complexity of designing fuzzy controller is reduced.

Meanwhile, the parameter uncertainties within each subsystem and in the interconnection of subsystems are also considered to achieve robustness of the system's performance. In addition, guaranteed cost control (H_2 control) is realized and the control synthesis conditions are given by solving a set of linear matrix inequalities (LMIs). The previous works on decentralized robust control of large-scale interconnected systems can be seen in [13], [14]. However, the control strategy in [13] and [14] can only be used on linear systems with parameter uncertainties and nonlinear interconnections. While the proposed fuzzy controller based on T-S fuzzy models with nonlinear local models can be used on nonlinear interconnected systems which contain more and severer nonlinearities. The advantages of the proposed method are that, compared with decentralized robust fuzzy control method based on local linear models, the number of fuzzy rules is decreased and the computational cost is reduced.

The rest of the paper is organized as follows. In Section II, the problem is stated and some preliminary knowledge and conditions are given. In Section III, the results of designing decentralized robust fuzzy controller based on nonlinear local models are provided. Simulation is shown in Section IV. Finally, some conclusions are given in Section V.

II. PROBLEM STATEMENT AND PRELIMINARIES

A. Uncertain interconnected systems model

A class of uncertain systems which consist of N interconnected subsystems is shown as follows:

$$\begin{aligned} \dot{x}_i(t) = & f_i(x_i(t)) + (B_i + \Delta B_i)u_i(t) + \sum_{j=1}^N p_{1ij}(G_{1ij} + \Delta G_{1ij})g_{1ij}(x_i, x_j) \\ & + \sum_{j=1}^N p_{2ij}(G_{2ij} + \Delta G_{2ij})g_{2ij}(x_i, x_j) \end{aligned} \quad (1)$$

Dividing $f_i(x_i(t))$ into two parts:

$$f_i(x_i(t)) = (A_i + \Delta A_i)x_i(t) + (G_i + \Delta G_i)\phi_i(t) \quad (2)$$

where $\phi_i(t) \in co\{0, M_i x_i(t)\}$, $\phi_i(t)$ is a nonlinear term of the state variables. Then (1) becomes the following equation:

$$\begin{aligned} \dot{x}_i(t) = & (A_i + \Delta A_i)x_i(t) + (B_i + \Delta B_i)u_i(t) + (G_i + \Delta G_i)\phi_i(t) \\ & + \sum_{j=1}^N p_{1ij}(G_{1ij} + \Delta G_{1ij})g_{1ij}(x_i, x_j) + \sum_{j=1}^N p_{2ij}(G_{2ij} + \Delta G_{2ij})g_{2ij}(x_i, x_j) \end{aligned} \quad (3)$$

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where $i = 1, 2, \dots, N$. $x_i \in R^{n_i}$, $u_i \in R^{m_i}$ are the state and input for the i -th subsystem, respectively. Matrices A_i , B_i , G_i , G_{lij} , G_{2ij} , are known real constant matrices that describe the model. Matrices ΔA_i , ΔB_i , ΔG_i , ΔG_{lij} , ΔG_{2ij} are parameter uncertainties. $g_{lij}(x_i, x_j) \in R^{n_{ij}}$ and $g_{2ij}(x_i, x_j) \in R^{s_{ij}}$ are unknown nonlinear vector functions that represent nonlinearities in the i -th subsystem and in the interconnection between the i -th subsystem and the j -th subsystem, and the parameters p_{lij} and p_{2ij} are constants of either 1 or 0 (if they are 0, it means that the j -th subsystem has no interconnection with the i -th subsystem).

B. Assumption

Some assumptions are defined to the system uncertainties and interconnected in this part.

Assumption 1:

$$[\Delta A_i \quad \Delta B_i \quad \Delta G_i] = H_{li} F_i [E_{li} \quad E_{2i} \quad E_{3i}]$$

where F_i is an unknown matrix function satisfying

$$F_i^T F_i \leq I$$

, and H_{li} , E_{li} , E_{2i} , E_{3i} are known real constant matrices that structure the uncertainty.

Assumption 2:

(a)

$$\Delta G_{lij}(t) = L_{lij} F_{lij} N_{lij}$$

$$\Delta G_{2ij}(t) = L_{2ij} F_{2ij} N_{2ij}$$

where F_{lij} and F_{2ij} are unknown matrix functions satisfying

$$F_{lij}^T F_{lij} \leq I, F_{2ij}^T F_{2ij} \leq I, \text{ and } L_{lij}, N_{lij}, L_{2ij}, N_{2ij} \text{ are}$$

known real constant matrices with appropriate dimensions.

(b) there exist real constant matrices W_{li} , W_{lij} , W_{2i} , W_{2ij} ,

such that, for all $x_i \in R^{n_i}$, $x_j \in R^{n_j}$, $i, j = 1, 2, \dots, N$:

$$\begin{aligned} \|g_{lij}(x_i, x_j)\| &\leq \|W_{li} x_i\| + \|W_{lij} x_j\| \\ \|g_{2ij}(x_i, x_j)\| &\leq \|W_{2i} x_i\| + \|W_{2ij} x_j\| \end{aligned}$$

C. Useful lemmas

Lemma 1 [15]. If the following conditions hold

$$\Phi_{mm} < 0 \quad 1 \leq m \leq r$$

$$\frac{1}{r-1} \Phi_{mm} + \frac{1}{2} (\Phi_{mm} + \Phi_{nn}) < 0 \quad 1 \leq m \neq n \leq r$$

Then the following inequality holds

$$\sum_{m=1}^r \sum_{n=1}^r \alpha_m \alpha_n \Phi_{mn} < 0$$

where α_m , $1 \leq m \leq r$ satisfy $0 \leq \alpha_m \leq 1$, $\sum_{m=1}^r \alpha_m = 1$.

Lemma 2 ([12]). For $\phi(k) = [\phi_1(k) \quad \phi_2(k) \quad \dots \quad \phi_s(k)]^T$,

$$M = [M_1 \quad M_2 \quad \dots \quad M_s], \Lambda^{-1} = \text{diag}[\rho_1 \quad \rho_2 \quad \dots \quad \rho_s]^{-1},$$

$\rho_i > 0$, $1 \leq i \leq s$, given $\phi_i(k) \in \text{co}\{0, M_i x(k)\}$, then

$$\phi^T \Lambda^{-1} M x - \phi^T \Lambda^{-1} \phi \geq 0$$

where $\text{co}\{\cdot\}$ means that it is a convex combination.

III. CONTROLLER DESIGN

A. T-S fuzzy modeling and control scheme

In this subsection, T-S fuzzy modeling and control scheme for decentralized interconnected systems are given.

Plant Rule m:

IF $v_{i,1}(t)$ is $\Gamma_{i,1m}$, $\dots$, $v_{i,k}(t)$ is $\Gamma_{i,km}$, $\dots$, $v_{i,p}(t)$ is $\Gamma_{i,pm}$

THEN

$$\begin{aligned} \dot{x}_i(t) &= (A_{i,m} + \Delta A_i) x_i(t) + (B_{i,m} + \Delta B_i) u_i(t) + (G_{i,m} + \Delta G_i) \phi_i(t) \\ &+ \sum_{j=1}^N p_{lij} (G_{lij} + \Delta G_{lij}) g_{lij}(x_i, x_j) + \sum_{j=1}^N p_{2ij} (G_{2ij} + \Delta G_{2ij}) g_{2ij}(x_i, x_j) \end{aligned} \quad (4)$$

where $m = 1, \dots, r$. r is the number of fuzzy rules.

$v_i(t) = [v_{i,1}(t) \quad v_{i,2}(t) \quad \dots \quad v_{i,p}(t)]^T \in R^{p \times 1}$ are the premise

variables. $\Gamma_{i,km}$ are the fuzzy sets. By using the fuzzy inference method with a singleton fuzzier, product inference and center average defuzzifiers, the final T-S fuzzy model can be obtained as follows:

$$\begin{aligned} \dot{x}_i(t) &= (A_i(\alpha) + \Delta A_i) x_i(t) + (B_i(\alpha) + \Delta B_i) u_i(t) + (G_i(\alpha) + \Delta G_i) \phi_i(t) \\ &+ \sum_{j=1}^N p_{lij} (G_{lij} + \Delta G_{lij}) g_{lij}(x_i, x_j) + \sum_{j=1}^N p_{2ij} (G_{2ij} + \Delta G_{2ij}) g_{2ij}(x_i, x_j) \end{aligned} \quad (5)$$

with

$$A_i(\alpha) = \sum_{m=1}^r \alpha_{i,m} A_{i,m}, B_i(\alpha) = \sum_{m=1}^r \alpha_{i,m} B_{i,m}, G_i(\alpha) = \sum_{m=1}^r \alpha_{i,m} G_{i,m}$$

$\alpha_{i,m}(v(t))$ is said to be normalized membership functions,

The control rule is given as follows:

Control Rule m:

IF $v_{i,1}(t)$ is $\Gamma_{i,1m}$, $\dots$, $v_{i,k}(t)$ is $\Gamma_{i,km}$, $\dots$, $v_{i,p}(t)$ is $\Gamma_{i,pm}$

THEN $u_i(t) = K_{ai,m} x(t) + K_{bi,m} \phi(t)$ (6)

By using the fuzzy inference method with a singleton fuzzier, product inference and center average defuzzifiers, the final control output can be obtained as follows:

$$u_i(t) = K_{ai}(\alpha) x(t) + K_{bi}(\alpha) \phi(t) \quad (7)$$

where

$$K_{ai}(\alpha) = \sum_{m=1}^r \alpha_{i,m}(v(t)) K_{ai,m}, K_{bi}(\alpha) = \sum_{m=1}^r \alpha_{i,m}(v(t)) K_{bi,m}$$

In this paper, the problem of H_2 control is considered. The quadratic cost function is shown as follows:

$$J = \sum_{i=1}^N \int_0^\infty (x_i^T(t) R_{xi} x_i(t) + u_i^T(t) R_{ui} u_i(t)) dt \quad (8)$$

where $R_{xi} = R_{xi}^T > 0$, $R_{ui} = R_{ui}^T > 0$ are given weighting matrices.

B. Result

Putting the controller (6) into the system model (1), thus

$$\begin{aligned} \dot{x}_i &= (A_i + B_i K_{ai}) x_i + (\Delta A_i + \Delta B_i K_{ai}) x_i \\ &+ (G_i + B_i K_{bi}) \phi_i + (\Delta G_i + \Delta B_i K_{bi}) \phi_i \\ &+ \sum_{j=1}^N p_{lij} (G_{lij} + \Delta G_{lij}) g_{lij}(x_i, x_j) + \sum_{j=1}^N p_{2ij} (G_{2ij} + \Delta G_{2ij}) g_{2ij}(x_i, x_j) \end{aligned} \quad (9)$$

Choosing the Lyapunov function candidate

$$V(x) = x^T P x = \sum_{i=1}^N x_i^T P_i x_i \quad (10)$$

where $x = [x_1^T, x_2^T, \dots, x_N^T]^T$, $P = \text{diag}[P_1 \ \dots \ P_N]$, then

$$\begin{aligned} \dot{V}(x) &= \sum_{i=1}^N (\dot{x}_i^T P_i x_i + x_i^T P_i \dot{x}_i) \\ &= \sum_{i=1}^N \left\{ \begin{aligned} &x_i^T \left[(A_i + B_i K_{ai})^T P_i + P_i (A_i + B_i K_{ai}) \right] x_i \\ &+ x_i^T \left[(\Delta A_i + \Delta B_i K_{ai})^T P_i + P_i (\Delta A_i + \Delta B_i K_{ai}) \right] x_i \\ &+ 2x_i^T P_i (G_i + B_i K_{bi}) \phi_i \\ &+ 2x_i^T P_i (\Delta G_i + \Delta B_i K_{bi}) \phi_i \\ &+ \sum_{j=1}^N 2p_{ij} x_i^T P_i (G_{lij} + \Delta G_{lij}) g_{lij}(x_i, x_j) \\ &+ \sum_{j=1}^N 2p_{2ij} x_i^T P_i (G_{2ij} + \Delta G_{2ij}) g_{2ij}(x_i, x_j) \end{aligned} \right\} \quad (11) \end{aligned}$$

Adding some positive items to the left side of (11) to reach the performance of guaranteed cost control, then

$$\begin{aligned} \dot{V}(x) &+ \sum_{i=1}^N \left\{ 2(\phi_i^T \Lambda_i^{-1} M_i x_i - \phi_i^T \Lambda_i^{-1} \phi_i) + x_i^T R_{xi} x_i + u_i^T R_{ui} u_i \right\} \\ &= \sum_{i=1}^N \left\{ \begin{aligned} &x_i^T \left[(A_i + B_i K_{ai})^T P_i + P_i (A_i + B_i K_{ai}) \right] x_i \\ &+ x_i^T \left[(\Delta A_i + \Delta B_i K_{ai})^T P_i + P_i (\Delta A_i + \Delta B_i K_{ai}) \right] x_i \\ &+ 2x_i^T P_i (G_i + B_i K_{bi}) \phi_i \\ &+ 2x_i^T P_i (\Delta G_i + \Delta B_i K_{bi}) \phi_i \\ &+ \sum_{j=1}^N 2p_{ij} x_i^T P_i (G_{lij} + \Delta G_{lij}) g_{lij}(x_i, x_j) \\ &+ \sum_{j=1}^N 2p_{2ij} x_i^T P_i (G_{2ij} + \Delta G_{2ij}) g_{2ij}(x_i, x_j) \\ &+ 2(\phi_i^T \Lambda_i^{-1} M_i x_i - \phi_i^T \Lambda_i^{-1} \phi_i) \\ &+ x_i^T R_{xi} x_i \\ &+ u_i^T R_{ui} u_i \end{aligned} \right\} < 0 \quad (12) \end{aligned}$$

where $2(\phi_i^T \Lambda_i^{-1} M_i x_i - \phi_i^T \Lambda_i^{-1} \phi_i) \geq 0$ is proofed in Lemma 2.

Consider the following equalities and inequalities:

$$x_i^T \left[(\Delta A_i + \Delta B_i K_{ai})^T P_i + P_i (\Delta A_i + \Delta B_i K_{ai}) \right] x_i \quad (13)$$

$$= x_i^T \left[(E_{li} + E_{2i} K_{ai})^T F_i^T H_{li}^T P_i + P_i H_{li} F_i (E_{li} + E_{2i} K_{ai}) \right] x_i$$

$$\leq x_i^T \left[\varepsilon_i P_i H_{li} H_{li}^T P_i + \frac{1}{\varepsilon_i} (E_{li} + E_{2i} K_{ai})^T (E_{li} + E_{2i} K_{ai}) \right] x_i$$

$$\begin{aligned} 2x_i^T P_i (\Delta G_i + \Delta B_i K_{bi}) \phi_i &= 2x_i^T P_i F_{li} F_i (E_{3i} + E_{2i} K_{bi}) \phi_i \\ &\leq \eta_i x_i^T P_i H_{li} H_{li}^T P_i x_i + \frac{1}{\eta_i} \phi_i^T (E_{3i} + E_{2i} K_{bi})^T (E_{3i} + E_{2i} K_{bi}) \phi_i \quad (14) \end{aligned}$$

$$\begin{aligned} &\sum_{i=1}^N \left\{ \sum_{j=1}^N 2p_{ij} x_i^T P_i (G_{lij} + \Delta G_{lij}) g_{lij}(x_i, x_j) + \sum_{j=1}^N 2p_{2ij} x_i^T P_i (G_{2ij} + \Delta G_{2ij}) g_{2ij}(x_i, x_j) \right\} \\ &\leq \sum_{i=1}^N x_i^T \left\{ \sum_{j=1}^N P_i p_{ij} (G_{lij} + \Delta G_{lij}) (G_{lij} + \Delta G_{lij})^T P_i + \sum_{j=1}^N p_{ij} (W_{li}^T W_{li} + W_{1ji}^T W_{1ji}) \right. \\ &\quad \left. + \sum_{j=1}^N P_i p_{2ij} (G_{2ij} + \Delta G_{2ij}) (G_{2ij} + \Delta G_{2ij})^T P_i + \sum_{j=1}^N p_{2ij} (W_{2i}^T W_{2i} + W_{2ji}^T W_{2ji}) \right\} x_i \quad (15) \end{aligned}$$

$$2(\phi_i^T \Lambda_i^{-1} M_i x_i - \phi_i^T \Lambda_i^{-1} \phi_i) = \begin{bmatrix} x_i \\ \phi_i \end{bmatrix}^T \begin{bmatrix} 0 & * \\ \Lambda_i^{-1} M_i & -2\Lambda_i^{-1} \end{bmatrix} \begin{bmatrix} x_i \\ \phi_i \end{bmatrix} \quad (16)$$

$$u_i^T R_{ui} u_i = \begin{bmatrix} x_i \\ \phi_i \end{bmatrix}^T \begin{bmatrix} K_{ai}^T \\ K_{bi}^T \end{bmatrix} R_{ui} \begin{bmatrix} K_{ai} & K_{bi} \end{bmatrix} \begin{bmatrix} x_i \\ \phi_i \end{bmatrix} \quad (17)$$

Then sufficient condition for (12) can be derived:

$$\begin{aligned} &\sum_{i=1}^N \left\{ \begin{bmatrix} x_i \\ \phi_i \end{bmatrix}^T \left[\begin{aligned} &\left[(A_i + B_i K_{ai})^T P_i + P_i (A_i + B_i K_{ai}) \right] \\ &+ \left[\varepsilon_i P_i H_{li} H_{li}^T P_i + \frac{1}{\varepsilon_i} (E_{li} + E_{2i} K_{ai})^T (E_{li} + E_{2i} K_{ai}) \right] \\ &+ \eta_i P_i H_{li} H_{li}^T P_i \\ &+ \sum_{j=1}^N P_i p_{ij} (G_{lij} + \Delta G_{lij}) (G_{lij} + \Delta G_{lij})^T P_i \\ &+ \sum_{j=1}^N p_{ij} (W_{li}^T W_{li} + W_{1ji}^T W_{1ji}) \\ &+ \sum_{j=1}^N P_i p_{2ij} (G_{2ij} + \Delta G_{2ij}) (G_{2ij} + \Delta G_{2ij})^T P_i \\ &+ \sum_{j=1}^N p_{2ij} (W_{2i}^T W_{2i} + W_{2ji}^T W_{2ji}) \\ &+ R_{ui} \end{aligned} \right] \begin{bmatrix} x_i \\ \phi_i \end{bmatrix} \right\} < 0 \quad (18) \end{aligned}$$

(19) holds if

$$\begin{aligned} &\left[\begin{aligned} &\left[(A_i + B_i K_{ai})^T P_i + P_i (A_i + B_i K_{ai}) \right] \\ &+ \left[\varepsilon_i P_i H_{li} H_{li}^T P_i + \frac{1}{\varepsilon_i} (E_{li} + E_{2i} K_{ai})^T (E_{li} + E_{2i} K_{ai}) \right] \\ &+ \eta_i P_i H_{li} H_{li}^T P_i \\ &+ \sum_{j=1}^N P_i p_{ij} (G_{lij} + \Delta G_{lij}) (G_{lij} + \Delta G_{lij})^T P_i \\ &+ \sum_{j=1}^N p_{ij} (W_{li}^T W_{li} + W_{1ji}^T W_{1ji}) \\ &+ \sum_{j=1}^N P_i p_{2ij} (G_{2ij} + \Delta G_{2ij}) (G_{2ij} + \Delta G_{2ij})^T P_i \\ &+ \sum_{j=1}^N p_{2ij} (W_{2i}^T W_{2i} + W_{2ji}^T W_{2ji}) \\ &+ R_{ui} \end{aligned} \right] \begin{bmatrix} x_i \\ \phi_i \end{bmatrix} < 0 \quad (19) \end{aligned}$$

Define

$$\tilde{R}_{xi} = R_{xi} + \sum_{j=1}^N p_{ij} (W_{li}^T W_{li} + W_{1ji}^T W_{1ji}) + \sum_{j=1}^N p_{2ij} (W_{2i}^T W_{2i} + W_{2ji}^T W_{2ji})$$

$$P_i (G_{li} + \Delta G_{li}) (G_{li} + \Delta G_{li})^T P_i = \sum_{j=1}^N P_i p_{ij} (G_{lij} + \Delta G_{lij}) (G_{lij} + \Delta G_{lij})^T P_i$$

$$P_i p_{2i} (G_{2i} + \Delta G_{2i}) (G_{2i} + \Delta G_{2i})^T P_i = \sum_{j=1}^N P_i p_{2ij} (G_{2ij} + \Delta G_{2ij}) (G_{2ij} + \Delta G_{2ij})^T P_i$$

where

$$G_{li} = [p_{li1} G_{li1} \ \dots \ p_{liN} G_{liN}], \quad G_{2i} = [p_{2i1} G_{2i1} \ \dots \ p_{2iN} G_{2iN}]$$

$$\Delta G_{li} = [p_{li1} \Delta G_{li1} \ \dots \ p_{liN} \Delta G_{liN}], \quad \Delta G_{2i} = [p_{2i1} \Delta G_{2i1} \ \dots \ p_{2iN} \Delta G_{2iN}]$$

Thus (19) is equivalent to

$$\begin{aligned} &\left[\begin{aligned} &\left[(A_i + B_i K_{ai})^T P_i + P_i (A_i + B_i K_{ai}) \right] \\ &+ \varepsilon_i P_i H_{li} H_{li}^T P_i + \eta_i P_i H_{li} H_{li}^T P_i + \tilde{R}_{xi} \\ &+ \frac{1}{\varepsilon_i} (E_{li} + E_{2i} K_{ai})^T (E_{li} + E_{2i} K_{ai}) \\ &+ P_i (G_{li} + \Delta G_{li}) (G_{li} + \Delta G_{li})^T P_i \\ &+ P_i p_{2i} (G_{2i} + \Delta G_{2i}) (G_{2i} + \Delta G_{2i})^T P_i \end{aligned} \right] \begin{bmatrix} x_i \\ \phi_i \end{bmatrix} < 0 \quad (20) \end{aligned}$$

Applying schur complement to (20), then

$$\begin{bmatrix}
\begin{bmatrix} (A_i + B_i K_{ai})^T P_i + P_i (A_i + B_i K_{ai}) \\ + \varepsilon_i P_i H_{1i} H_{1i}^T P_i + \eta_i P_i H_{1i} H_{1i}^T P_i + \bar{R}_{xi} \\ + \frac{1}{\varepsilon_i} (E_{1i} + E_{2i} K_{ai})^T (E_{1i} + E_{2i} K_{ai}) \end{bmatrix} & * & * & * & * \\
(G_i + B_i K_{bi})^T P_i + \Lambda_i^{-1} M_i & \begin{bmatrix} -2\Lambda_i^{-1} \\ + \frac{1}{\eta_i} (E_{3i} + E_{2i} K_{bi})^T (E_{3i} + E_{2i} K_{bi}) \end{bmatrix} & * & * & * \\
K_{ai} & K_{bi} & -R_{ai}^{-1} & * & * \\
(G_{1i} + \Delta G_{1i})^T P_i & 0 & 0 & -I & * \\
(G_{2i} + \Delta G_{2i})^T P_i & 0 & 0 & 0 & -I
\end{bmatrix} < 0 \quad (21)$$

which is equivalent to

$$\begin{bmatrix}
\begin{bmatrix} (A_i + B_i K_{ai})^T P_i + P_i (A_i + B_i K_{ai}) \\ + \varepsilon_i P_i H_{1i} H_{1i}^T P_i + \eta_i P_i H_{1i} H_{1i}^T P_i + \bar{R}_{xi} \\ + \frac{1}{\varepsilon_i} (E_{1i} + E_{2i} K_{ai})^T (E_{1i} + E_{2i} K_{ai}) \end{bmatrix} & * & * & * & * \\
(G_i + B_i K_{bi})^T P_i + \Lambda_i^{-1} M_i & \begin{bmatrix} -2\Lambda_i^{-1} \\ + \frac{1}{\eta_i} (E_{3i} + E_{2i} K_{bi})^T (E_{3i} + E_{2i} K_{bi}) \end{bmatrix} & * & * & * \\
K_{ai} & K_{bi} & -R_{ai}^{-1} & * & * \\
G_{1i}^T P_i & 0 & 0 & -I & * \\
G_{2i}^T P_i & 0 & 0 & 0 & -I
\end{bmatrix} + \begin{bmatrix} 0 & * & * & * & * \\ 0 & 0 & * & * & * \\ 0 & 0 & 0 & * & * \\ \Delta G_{1i}^T P & 0 & 0 & 0 & * \\ \Delta G_{2i}^T P & 0 & 0 & 0 & 0 \end{bmatrix} < 0 \quad (22)$$

Since

$$\begin{bmatrix}
\begin{bmatrix} 0 & * & * & * & * \\ 0 & 0 & * & * & * \\ 0 & 0 & 0 & * & * \\ \Delta G_{1i}^T P & 0 & 0 & 0 & * \\ \Delta G_{2i}^T P & 0 & 0 & 0 & 0 \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & P_i L_{1i} & P_i L_{2i} \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ 0 \\ F_{1i} \\ F_{2i} \end{bmatrix} \begin{bmatrix} 0 \\ 0 \\ 0 \\ N_{1i} \\ N_{2i} \end{bmatrix} \\
+ \begin{bmatrix} 0 \\ 0 \\ 0 \\ N_{1i} \end{bmatrix}^T \begin{bmatrix} 0 \\ 0 \\ 0 \\ F_{1i} \end{bmatrix} \begin{bmatrix} 0 & 0 & 0 & P_i L_{1i} & P_i L_{2i} \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \end{bmatrix}^T \\
\leq \begin{bmatrix} P_i L_{1i} \Gamma_{1ai} L_{1i}^T P_i & 0 & 0 & 0 & 0 \\ + P_i L_{2i} \Gamma_{2ai} L_{2i}^T P_i & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & N_{1i}^T \Gamma_{1\beta i} N_{1i} & 0 \\ 0 & 0 & 0 & 0 & N_{2i}^T \Gamma_{2\beta i} N_{2i} \end{bmatrix} \quad (23)$$

where

$$\begin{aligned}
L_{1i} &= [p_{1i1} L_{1i1} \quad \cdots \quad p_{1iN} L_{1iN}] \\
L_{2i} &= [p_{2i1} L_{2i1} \quad \cdots \quad p_{2iN} L_{2iN}] \\
F_{1i} &= \text{diag}[F_{1i1} \quad \cdots \quad F_{1iN}] \\
F_{2i} &= \text{diag}[F_{2i1} \quad \cdots \quad F_{2iN}] \\
N_{1i} &= \text{diag}[p_{1i1} N_{1i1} \quad \cdots \quad p_{1iN} N_{1iN}] \\
N_{2i} &= \text{diag}[p_{2i1} N_{2i1} \quad \cdots \quad p_{2iN} N_{2iN}] \\
\Gamma_{1\alpha i} &= \text{diag}[\gamma_{1i1} I_{\alpha_{1i1}} \quad \cdots \quad \gamma_{1iN} I_{\alpha_{1iN}}] \\
\Gamma_{1\beta i} &= \text{diag}[\gamma_{1i1} I_{\beta_{1i1}} \quad \cdots \quad \gamma_{1iN} I_{\beta_{1iN}}] \\
\Gamma_{2\alpha i} &= \text{diag}[\gamma_{2i1} I_{\alpha_{2i1}} \quad \cdots \quad \gamma_{2iN} I_{\alpha_{2iN}}] \\
\Gamma_{2\beta i} &= \text{diag}[\gamma_{2i1} I_{\beta_{2i1}} \quad \cdots \quad \gamma_{2iN} I_{\beta_{2iN}}]
\end{aligned}$$

Then (22) holds if

$$\begin{bmatrix}
\begin{bmatrix} (A_i + B_i K_{ai})^T P_i + P_i (A_i + B_i K_{ai}) \\ + \varepsilon_i P_i H_{1i} H_{1i}^T P_i + \eta_i P_i H_{1i} H_{1i}^T P_i + \bar{R}_{xi} \\ + \frac{1}{\varepsilon_i} (E_{1i} + E_{2i} K_{ai})^T (E_{1i} + E_{2i} K_{ai}) \\ + P_i L_{1i} \Gamma_{1ai} L_{1i}^T P_i + P_i L_{2i} \Gamma_{2ai} L_{2i}^T P_i \end{bmatrix} & * & * & * & * & * \\
(G_i + B_i K_{bi})^T P_i + \Lambda_i^{-1} M_i & \begin{bmatrix} -2\Lambda_i^{-1} \\ + \frac{1}{\eta_i} (E_{3i} + E_{2i} K_{bi})^T (E_{3i} + E_{2i} K_{bi}) \end{bmatrix} & * & * & * & * \\
K_{ai} & K_{bi} & -R_{ai}^{-1} & * & * & * \\
G_{1i}^T P_i & 0 & 0 & \begin{bmatrix} -I + \\ N_{1i}^T \Gamma_{1\beta i} N_{1i} \end{bmatrix} & * & * \\
G_{2i}^T P_i & 0 & 0 & 0 & \begin{bmatrix} -I + \\ N_{2i}^T \Gamma_{2\beta i} N_{2i} \end{bmatrix} & *
\end{bmatrix} < 0 \quad (24)$$

Applying schur complement, (24) is equivalent to the following equation

$$\begin{bmatrix}
\begin{bmatrix} (A_i + B_i K_{ai})^T P_i + P_i (A_i + B_i K_{ai}) \\ + \varepsilon_i P_i H_{1i} H_{1i}^T P_i + \eta_i P_i H_{1i} H_{1i}^T P_i \\ + P_i L_{1i} \Gamma_{1ai} L_{1i}^T P_i + P_i L_{2i} \Gamma_{2ai} L_{2i}^T P_i \end{bmatrix} & * & * & * & * & * & * & * \\
(G_i + B_i K_{bi})^T P_i + \Lambda_i^{-1} M_i & -2\Lambda_i^{-1} & * & * & * & * & * & * \\
K_{ai} & K_{bi} & -R_{ai}^{-1} & * & * & * & * & * \\
0 & E_{3i} + E_{2i} K_{bi} & 0 & -\eta_i & * & * & * & * \\
\bar{R}_{xi}^{-\frac{1}{2}} & 0 & 0 & 0 & -I & * & * & * \\
E_{1i} + E_{2i} K_{ai} & 0 & 0 & 0 & 0 & -\varepsilon_i I & * & * \\
G_{1i}^T P_i & 0 & 0 & 0 & 0 & 0 & -I + N_{1i}^T \Gamma_{1\beta i} N_{1i} & * \\
G_{2i}^T P_i & 0 & 0 & 0 & 0 & 0 & 0 & -I + N_{2i}^T \Gamma_{2\beta i} N_{2i}
\end{bmatrix} < 0 \quad (25)$$

Pre- and post-multiplying (25) by $\text{diag}[P_i^{-1} \quad \Lambda_i \quad I \quad I \quad I \quad I \quad I \quad I]$

and its transpose, define

$$Q_i = P_i^{-1}, L_{ai} = K_{ai} P_i^{-1}, \text{ and } L_{bi} = K_{bi} \Lambda_i.$$

(26)

Then

$$\begin{bmatrix}
\begin{bmatrix} He(AQ_i + B_i L_{ai}) \\ + \varepsilon_i H_{1i} H_{1i}^T + \eta_i H_{1i} H_{1i}^T \\ + L_{1i} \Gamma_{1ai} L_{1i}^T + L_{2i} \Gamma_{2ai} L_{2i}^T \\ + \Lambda_i G_i^T + L_{bi}^T B_i^T + M_i Q_i \end{bmatrix} & * & * & * & * & * & * & * \\
L_{ai} & L_{bi} & -R_{ai}^{-1} & * & * & * & * & * \\
0 & E_{3i} \Lambda_i + E_{2i} L_{bi} & 0 & -\eta_i & * & * & * & * \\
\bar{R}_{xi}^{-\frac{1}{2}} Q_i & 0 & 0 & 0 & -I & * & * & * \\
E_{1i} Q_i + E_{2i} L_{ai} & 0 & 0 & 0 & 0 & -\varepsilon_i I & * & * \\
G_{1i}^T & 0 & 0 & 0 & 0 & 0 & -I & * \\
G_{2i}^T & 0 & 0 & 0 & 0 & 0 & 0 & -I \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & N_{2i} \quad -\Gamma_{2\beta i}
\end{bmatrix} < 0 \quad (27)$$

Thus, an LMI-based method of designing decentralized robust H_2 fuzzy controllers with nonlinear local models for uncertain interconnected systems can be given by substituting the defuzzified terms with fuzzified terms in (27).

Theorem 1. If there exist some real positive scalars $\varepsilon_i, \eta_i, \gamma_{lij}, \gamma_{2ij}$ and some real constant matrices $Q_i = Q_i^T > 0, L_{ai,m}, L_{bi,m}, i, j = 1, 2, \dots, N, m = 1, 2, \dots, r, \Lambda_i$ with

$$\Lambda_i = \text{diag}[\lambda_{i1} \quad \cdots \quad \lambda_{is}]$$

such that

$$\Xi_{i,mm} < 0 \quad 1 \leq m \leq r \quad (28)$$

$$\frac{1}{r-1} \Xi_{i,mm} + \frac{1}{2} (\Xi_{i,mm} + \Xi_{i,nm}) < 0 \quad 1 \leq m \neq n \leq r \quad (29)$$

where

$$\Xi^{nn} = \begin{bmatrix} He(A_{i,m}Q_i + B_{i,m}L_{ai,m}) & & & & & & & & & \\ +\varepsilon_i H_{i1}H_{i1}^T + \eta_i H_{i1}H_{i1}^T & & & & & & & & & \\ +L_{i1}\Gamma_{1ai}L_{i1}^T + L_{2i}\Gamma_{2ai}L_{2i}^T & & & & & & & & & \\ \Lambda_i G_{i,m}^T + L_{bi,m}^T B_{i,m}^T + M_i Q_i & -2\Lambda_i & & & & & & & & \\ L_{ai,m} & L_{bi,m} & -R_i^{-1} & & & & & & & \\ 0 & E_{3i}\Lambda_i + E_{2i}L_{bi,m} & 0 & -\eta_i & & & & & & \\ \tilde{R}_i^{-1}Q_i & 0 & 0 & 0 & -I & & & & & \\ E_{1i}Q_i + E_{2i}L_{ai,m} & 0 & 0 & 0 & 0 & -\varepsilon_i I & & & & \\ G_{i1}^T & 0 & 0 & 0 & 0 & 0 & -I & & & \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & N_{1i} & -\Gamma_{1\beta i} & \\ G_{2i}^T & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -I & \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & N_{2i} & -\Gamma_{2\beta i} \end{bmatrix} \quad (30)$$

Then the system (1) with the controller (6) and its gain defined by (25) is asymptotically stable, and the cost function (8) satisfies

$$J \leq x^T(0)Q^{-1}x(0) \quad (31)$$

where $x(0) = [x_1^T(0), x_2^T(0), \dots, x_N^T(0)]^T$ is the initial state, and $Q = \text{diag}[Q_1 \ \dots \ Q_N]$.

IV. SIMULATION

Consider the two inverted pendulums connected by a spring [10]. The dynamic model of the system can be depicted by the following equations:

$$\begin{cases} \dot{x}_{i,1} = x_{i,2} + f_{i,1}(x_{i,1}) + \Delta_{i,1}(y_1, y_2) \\ \dot{x}_{i,2} = b_{i0}\sigma_i(y_i)u_i + f_{i,2}(x_{i,2}) + \Delta_{i,2}(y_1, y_2) \\ y_i = x_{i,1} \end{cases} \quad (32)$$

where $x_{i,1} = \theta_i$, $x_{i,2} = \dot{\theta}_i$, $f_{i,1}(\cdot) = 0$, $\Delta_{i,1}(\cdot) = 0$, $i = 1, 2$.

$$f_{1,2}(\cdot) = \frac{g}{l} \sin x_{1,1} - \frac{k_1 a^2}{m_1 l^2} \sin x_{1,1} \cos x_{1,1},$$

$$\Delta_{1,2}(\cdot) = \frac{k_1 a^2}{m_1 l^2} \sin y_2 \cos y_2,$$

$$f_{2,2}(\cdot) = \frac{g}{l} \sin x_{2,1} - \frac{k_1 a^2}{m_2 l^2} \sin x_{2,1} \cos x_{2,1},$$

$$\Delta_{2,2}(\cdot) = \frac{k_1 a^2}{m_2 l^2} \sin y_1 \cos y_1, \quad b_{i0} = 1, \quad \sigma_i(y_i) = 1.$$

Definition and numerical value of the parameters is [10]: θ_i is the angle of the i th pendulum, g is the gravitational acceleration (kg m/s²), m_i is the mass of the i th rod (kg), l is the length of each rod (m), k_1 is the spring constant. The system parameters are given as $g = 9.8$, $l = 9$, $m_1 = 0.2$, $m_2 = 0.4$, $k_1 = 1$, and $a = 3$. For illustration purpose, the models can be rewritten as follows:

For Pendulum 1:

$$\begin{aligned} \dot{x}_1(t) &= (A_1 + \Delta A_1)x_1(t) + (B_1 + \Delta B_1)u_1(t) + (G_1 + \Delta G_1)\phi_1(t) \\ &+ \sum_{j=1}^N p_{11j}(G_{11j} + \Delta G_{11j})g_{11j}(x_1, x_j) + \sum_{j=1}^N p_{21j}(G_{21j} + \Delta G_{21j})g_{21j}(x_1, x_j) \end{aligned} \quad (33)$$

where

$$A_1 = \begin{bmatrix} 0 & 1 \\ \frac{9.8 \sin x_{1,1}}{9x_{1,1}} & 0 \end{bmatrix}, \quad \Delta A_1 = \begin{bmatrix} 0 & 0 \\ \mu_1 & 0 \end{bmatrix}, \quad B_1 = \begin{bmatrix} 0 \\ 1 \end{bmatrix},$$

$$\Delta B_1 = \begin{bmatrix} 0 \\ -\mu_1 \end{bmatrix}, \quad G_1 = \begin{bmatrix} 0 \\ -\frac{1}{1.8} \end{bmatrix}, \quad \Delta G_1 = \begin{bmatrix} 0 \\ \mu_1 \end{bmatrix},$$

$$\phi_1(t) = \sin x_{1,1} \cos x_{1,1}, \quad G_{111} = G_{112} = 0, \quad \Delta G_{111} = \Delta G_{112} = 0,$$

$$g_{111}(x_1, x_1) = g_{112}(x_1, x_2) = 0, \quad G_{211} = 0, \quad G_{212} = \begin{bmatrix} 0 \\ \frac{1}{1.8} \end{bmatrix},$$

$$\Delta G_{211} = 0, \quad \Delta G_{212} = \begin{bmatrix} 0 \\ r_{212} \end{bmatrix}, \quad g_{211}(x_1, x_1) = 0,$$

$$g_{212}(x_1, x_2) = \sin x_{2,1} \cos x_{2,1}.$$

where, the parameter uncertainties are defined as follows:

$$\|\mu_1\| \leq 0.08, \quad \|r_{212}\| \leq 0.05.$$

$$\text{Define } z_1(t) = \frac{\sin x_{1,1}}{x_{1,1}}, \quad x_{1,1} \in \left[-\frac{\pi}{2}, \frac{\pi}{2}\right]. \text{ It can be found}$$

that: $\frac{2}{\pi} \leq z_1(t) \leq 1$. Thus, T-S fuzzy model can be built:

Rule 1: IF $z_1(t)$ is 1, THEN

$$\begin{aligned} \dot{x}_1(t) &= (A_{1,1} + \Delta A_1)x_1(t) + (B_{1,1} + \Delta B_1)u_1(t) + (G_{1,1} + \Delta G_1)\phi_1(t) \\ &+ \sum_{j=1}^N p_{11j}(G_{11j} + \Delta G_{11j})g_{11j}(x_1, x_j) + \sum_{j=1}^N p_{21j}(G_{21j} + \Delta G_{21j})g_{21j}(x_1, x_j) \end{aligned}$$

Rule 2: IF $z_1(t)$ is $\frac{2}{\pi}$ THEN

$$\begin{aligned} \dot{x}_1(t) &= (A_{1,2} + \Delta A_1)x_1(t) + (B_{1,2} + \Delta B_1)u_1(t) + (G_{1,2} + \Delta G_1)\phi_1(t) \\ &+ \sum_{j=1}^N p_{11j}(G_{11j} + \Delta G_{11j})g_{11j}(x_1, x_j) + \sum_{j=1}^N p_{21j}(G_{21j} + \Delta G_{21j})g_{21j}(x_1, x_j) \end{aligned}$$

$$\text{where } A_{1,1} = \begin{bmatrix} 0 & 1 \\ \frac{9.8}{9} & 0 \end{bmatrix}, \quad A_{1,2} = \begin{bmatrix} 0 & 1 \\ \frac{9.8 \times 2}{9 \times \pi} & 0 \end{bmatrix},$$

$$B_{1,1} = B_{1,2} = \begin{bmatrix} 0 \\ 1 \end{bmatrix}, \quad G_{1,1} = G_{1,2} = \begin{bmatrix} 0 \\ -\frac{1}{1.8} \end{bmatrix}.$$

Moreover, for the nonlinear term $\phi_1(t) = \sin x_{1,1} \cos x_{1,1}$, from Fig. 1, it can be seen that

$$\phi_1(t) \in \text{co}\{0, x_{1,1}\}$$

thus M_1 can be got: $M_1 = [1 \ 0]$.

The fuzzy membership functions are defined as follows, which are shown in Fig. 2.

$$F_1 = \frac{\frac{\sin x_{1,1}}{x_{1,1}} - \frac{2}{\pi}}{1 - \frac{2}{\pi}}, \quad F_2 = 1 - F_1.$$

Choose $R_{x1} = 0.005 \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$, $R_{u1} = 0.001$. Then by applying

Theorem 1, the controller gains can be calculated:

$$K_{1,a1} = [-422.0 \quad -120.6], K_{1,a2} = [-421.6 \quad -120.5],$$

$$K_{1,b1} = 0.1676, K_{1,b2} = 0.1708.$$

For Pendulum 2:

Use the similar fuzzy method as for Pendulum 1. The parameter uncertainties are defined as follows:

$$\|\mu_2\| \leq 0.06, \|r_{221}\| \leq 0.04.$$

And choose $R_{x2} = 0.002 \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$, $R_{u2} = 0.001$. Then by

applying Theorem 1, the controller gains can be calculated:

$$K_{2,a1} = [-1180.3 \quad -271.9], K_{2,a2} = [-1225.0 \quad -282.5],$$

$$K_{2,b1} = 0.1597, K_{2,b2} = 0.1865.$$

Set initial states as: $x_1(0) = [1 \quad 1]^T$, $x_2(0) = [-1 \quad 0.9]^T$, and limitation for u_1 and u_2 are set as: $\|u_1\|_2 \leq 20$, $\|u_2\|_2 \leq 20$. Simulation results are shown in Fig. 3.

Fig. 1 The bound of $\phi(t)$

Fig. 2 Membership functions of fuzzy rules

Fig. 3 Curve of system states and inputs

V. CONCLUSION

In this paper, a kind of decentralized robust fuzzy controller which uses nonlinear local models is designed for the control of large-scale interconnected systems. Meanwhile, the parameter uncertainties within each subsystem and in the interconnection of subsystems are also considered to achieve robustness of the system's performance. In addition, H_2 control is realized and the control synthesis conditions are given by solving a set of LMIs. Simulation results show that the proposed fuzzy method for large-scale interconnected systems is effective.

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