퍼지 및 지능시스템학회 논문지 2001, Vol.1, No. 1, pp. 45-51

이산 시간 TS 퍼지 시스템의 출력 추종 제어기 설계

Output Tracking Controller Design of Discrete-Time TS Fuzzy Systems

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요 약

본 논문은 이산 시간 Takagi-Sugeno (TS) 퍼지 시스템에 대한 출력 추종 제어기 설계에 관하여 연구한다. 출력 추종 제어기의 설계를 위하여 이산 시간 TS 퍼지 시스템을 불확실성을 포함한 선형 시스템의 집합으로서 표현하는 기법을 제시한다. 시스템의 상태에 대하여 어파인 변환을 하여 출력 추종 제어문제를 안정화 문제로 변환한다. 점근적 추종성능을 보장하는 제어기 설계를 위한 충분조건은 선형 행렬 부등식의 형태로 표현되며 주어진 제어기 설계의 해는 여러 가지 수치적 기법을 이용하여 효율적으로 구해질 수 있다. 트레일러 트럭의 임의의 위치에 후진 주차시키기 위한 제어기 설계의 예를 통하여 본 논문에서 제안한 추종 제어 기법의 효용성을 검증한다.

ABSTRACT

In this paper, an output tracking control technique of discrete-time Takagi-Sugeno (TS) fuzzy systems is developed. In order to remove the theoretical difficulties in controller desiogn, the TS fuzzy system is represented as a set of uncertain linear systems. The tracking problem of TS fuzzy system is converted into the stabilization problem of a set of uncertain linear systems using a simple affinc transformation technique. A sufficient condition for asymptotic tracking is obtained in terms of linear matrix inequalities (LMIs). A design example is illustrated to show the effectiveness of the proposed control method.

Key Words : 이산시간 TS 퍼지 모델, 어파인 변환, 선형 행렬 부등식, 추종 제어기, 트럭 트레일러

1. Introduction

Many frameworks in real world have hard nonlinearity, so a lot of control techniques have been developed and the fuzzy control is one of the major nonlinear control theories. However, the main drawback of fuzzy control is that it is difficult to analyze the stability of a fuzzy system. The Takagi-Sugeno (TS) fuzzy model is widely used, since it is possible to apply the systematic linear control theory to design a controller. References in this area are actually too many to cite. To name a few, we only mention the studies on fuzzy-model-based controllers and applications to complex nonlinear systems, such as chaotic system, robot manipulators with computer simulations [1-5,7,8], or real experiments [3]. This signifies that there have been extensive and persistent works related to fuzzy-model-based control, and that analytic control theory has made it safer, more reliable and more efficient.

For a few years, the stabilization problem of TS fuzzy system is extensively studied [1-5]. Tanaka proposed some sufficient condition for the stability of TS fuzzy model [3]. However, the common positive definite matrix that guarantees their stability condition of the controlled system is difficult and time-consuming to be found. On the other hand Cao et. al. developed the switching type controller design technique by applying the multiple linear system theory [2]. It is believed that this approach is more suitable and less conservative since there is no need to find common positive definite matrix.

In real industrial process, such as control of robot manipulators, chemical process control, etc., the tracking control is also a challenging and more important problem than the stabilization problem. Despite the extensive studies published in the *fuzzy-model-based control literature to date, there are* relatively few research results regarding tracking control by fuzzy systems. Taniguchi *et al.* studied a model-following control based on the TS fuzzy model [9] and Ying suggested tracking control scheme for a

접수일자 : 2000년 11월 18일
완료일자 : 2001년 01월 15일
본 연구는 두뇌 한국 21 프로젝트에 의해 일부 지원받았습니다.

discrete-time TS fuzzy model using the feedback linearization method [10]. Chang *et al.* suggested tracking control strategies by combine static feedback control with sliding mode control [8].

The main contribution of this paper is that novel and systematic design technique is developed for output tracking control of the discrete-time TS fuzzy system. Specifically, in this paper, a new describing technique for a discrete-time TS fuzzy system of this type is first developed. Using a simple affine transformation technique, the output tracking problem is converted to the stabilization problem. To this end, a sufficient condition for the output tracking to an arbitrary reference signal, with a guaranteed cost and global stability, is formulated under the linear matrix inequality (LMI) framework. The advantage of the studied results in this paper are verified from the computer simulation of the truck trailer system.

The organization of this paper is as follows: Section 2 briefly reviews the discrete-time TS fuzzy system. In Section 3, the output tracking problem for the discrete-time TS fuzzy systeml is formulated. The controller design method for output tracking of the TS fuzzy system is then proposed in Section 4. Section 5 shows a computer simulation of output tracking control for a backing-up truck trailer system. Finally, conclusions are drawn in Section 6.

2. Preliminaries

Consider a discrete-time uncertain nonlinear system of the form:

$$x(t+1)=f(x(t))+g(x(t))u(t) \tag{1}$$

where $x(t)\in R^n$ is the state vector, $u(t)\in R^m$ is the control input vector, $f(x(t))$ and $g(x(t))$ are nonlinear vector functions. The nonlinear system (1) can be modeled as the following TS fuzzy system:

Plant Rule i

$$\begin{aligned}&\text{If } x_1(t) \text{ is } \Gamma_1^i \text{ and } \cdots \text{ and } x_n(t) \text{ is } \Gamma_n^i\\&\text{THEN } x(t+1)=A_i x(t)+B_i u(t)\end{aligned} \tag{2}$$

where Γ_j^i $(j=1,\cdots,n,\ i=1,\cdots,q)$ is the fuzzy set, Rule i denotes the ith fuzzy inference rule. The defuzzified output of this TS fuzzy system (2) is represented as follows:

$$x(t+1)=\sum_{i=1}^{q}\mu_i(x(t))\,(A_i x(t)+B_i u(t)) \tag{3}$$

where

$$\mu_i(x(t))=\frac{\omega_i(x(t))}{\sum_{i=1}^{q}\omega_i(x(t))},\qquad \omega_i(x(t))=\prod_{j=1}^{n}\Gamma_j^i(x_j(t))$$

in which $\Gamma_j^i(x_j(t))$ is the grade of membership of $x_j(t)$ in Γ_j^i. In ith subspace divided by the fuzzy membership functions, the TS fuzzy system has much highly *nonlinear interaction among the fuzzy rules*, which complicates the analysis and control of the TS fuzzy system [2]. In order to get rid of these theoretical difficulties, we represent the uncertain TS fuzzy system as a set of uncertain linear systems with the following subspace [1].

$$\begin{aligned}\Theta_i=\{x(t)|\mu_i(x(t))\le\mu_j(x(t)),\ j=1,2,\cdots,q,\ i\neq j\}\\ i=1,2,\cdots,r.\end{aligned} \tag{4}$$

The characteristic function of Θ_i is defined by

$$\eta_i(x(t))=\begin{cases}1, & x(t)\in\Theta_i\\ 0, & x(t)\notin\Theta_i\end{cases},\qquad \sum_{i=1}^{r}\eta_i(x(t))=1 \tag{5}$$

Then, on every subspace the fuzzy system (3) can be represented with a set of uncertain linear systems as follows:

$$x(t+1)=\sum_{i=1}^{r}\eta_i(x(t))((A_i+\Delta A_i)x(t)+(B_i+\Delta B_i))u(t)) \tag{6}$$

where

$$\begin{aligned}&\Delta A_i=\sum_{j=1,j\neq i}^{r}\mu_j(x(t))\Delta A_{ij},\ \Delta B_i=\sum_{j=1,j\neq i}^{r}\mu_j(x(t))\Delta B_{ij}\\&\Delta A_{ij}=A_j-A_i,\ \Delta B_{ij}=B_j-B_i,\ i=1,2,\cdots,q.\end{aligned}$$

3. Problem Statement

This section deals with the output tracking controller design problem for the discrete-time TS fuzzy system. The state-space representation of the fuzzy system can be described as follows:

$$x(t+1)=\sum_{i=1}^{q}\mu_i(x(t))(A_i x(t)+B_i u(t)) \tag{7}$$

This TS fuzzy system can be represented by a set of uncertain linear system of the form:

$$\begin{aligned}x(t+1)=&\sum_{i=1}^{r}\eta_i(x(t))((A_i+\Delta A_i)x(t)\\&+(B_i+\Delta B_i)u(t))\end{aligned} \tag{8}$$

Remark 1: The uncertain matrices ΔA_i, ΔB_i, in the set of uncertain linear systems (8), represent the highly complex and nonlinear interaction among uncertain subsystems of TS fuzzy system by the fuzzy inference rules. It is stressed that the proposed design method is somewhat different from that of [2], In their approaches, the uncertainties are considered as uncstructured uncertainties. However, One can see that these uncertainties are norm-bounded norm-bounded and can be decomposed of the form:

$$[\Delta A_i\ \Delta B_i] = D_i F_i(t)[E_{1i}\ E_{2i}], \tag{9}$$

where D_i, E_{1i}, and E_{2i} are known real constant matrices of appropriate dimensions, and $F_i(t)$ is an unknown matrix function with Lebesgue-measurable elements and satisfies $F_i(t)^T F_i(t) \le I$, in which I is the identity matrix of appropriate dimension.

Throughout this paper, the reference signal to be tracked is the output $r(t)$ generated by the exogenous system

$$w(t+1) = Fw(t) \tag{10}$$
$$r(t) = Gw(t) \tag{11}$$

where $w(t) \in R^k$ is the state vector of exogenous system and $r(t) \in R^l$ is the output vector to be tracked by the output of the TS fuzzy system (7). It is further required that the state of this exogenous system should be uniformly bounded.

problem 1: The objective in this paper is to design a TS fuzzy-model-based controller which stabilize the plant (7) and track the reference signal vector $r(t)$ such that the tracking error

$$\begin{aligned} e(t) :&= y(t) - r(t) \\ &= Cx(t) - Gw(t) \end{aligned} \tag{12}$$

asymptotically to be zero.

In order to construct the error system, a new state vector is defined as

$$z(t) := x(t) - T_i w(t) \ \text{for} \ all\ x(t) \in \Theta_i,\ i = 1, 2, \cdots, q. \tag{13}$$

where T_i is a solution to the following matrix equations:

$$\begin{bmatrix} A_i & B_i \\ C & 0 \end{bmatrix} \begin{bmatrix} T_i \\ L_i \end{bmatrix} = \begin{bmatrix} T_i & 0 \\ 0 & I \end{bmatrix} \begin{bmatrix} F \\ G \end{bmatrix} \quad i = 1, 2, \cdots, q \tag{14}$$

For the exogenous signal model, the matrix equations (14) are assumed to be solvable. To solve (14), following assumption must be satisfied [6].

$$\text{rank} \begin{bmatrix} A_i & B_i \\ C & 0 \end{bmatrix} = n + l$$

This assumption is satisfied if each nominal subsystem in the TS fuzzy system (7) is controllable and the number of outputs is less than or equal to the number of inputs, i.e., $m \ge l$. Assuming that T_i and L_i have been found to satisfy (14), consider the tracking control law of the following form:

$$u(t) = \sum_{i=1}^{q} \eta_i(x(t))(L_i w(t) + v(t)) \tag{15}$$

where $v(t)$ remains to be defined. Using this control law, and the matrix equations (14), the newly defined state vector $z(t)$ in (13) satisfies

$$z(t+1) = \sum_{i=1}^{q} \eta_i(x(t))((A_i + \Delta A_i)z(t) + (B_i + \Delta B_i)v(t)) \tag{16}$$

$$e(t) = Cz(t) \tag{17}$$

If the newly constructed system (16) is globally asymptotically stable, then the tracking error $e(t)$ converge to zero. Therefore Problem 1 is equivalent to the following problem statement.

Problem 2: The objective in this paper is to design a TS fuzzy-model-based state feedback controller $v(t) = \sum_{i=1}^{q} \eta(x(t))K_i z(t)$ which asymptotically stabilize the dynamic system (16).

2. Controller Design

This section represent the controller synthesis of the output tracking problem of the discrete-time TS fuzzy system. Before proceeding, we first recall the following matrix inequalities which will be needed in the proof of our main result below.

Lemma 1: Given constant symmetric matrices, N, O, and L of appropriate dimensions, the following two inequalities are equivalent:

(a) $O > 0$, $\quad N + L^T O L < 0$,

(b) $\begin{bmatrix} N & L^T \\ L & -O^{-1} \end{bmatrix} < 0$, or $\begin{bmatrix} -O^{-1} & L \\ L^T & N \end{bmatrix} < 0$.

Lemma 2: Given constant matrices D, E, and a symmetric constant matrix S of appropriate dimensions, the following inequality holds:

$$S+DFE+E^TF^TD^T<0,$$

where F satisfies $F^TF\leq R$, if and only if for some $\varepsilon>0$,

$$S+[\varepsilon^{-1}E^T \ \ \varepsilon D]\begin{bmatrix} R & 0 \\ 0 & I \end{bmatrix}\begin{bmatrix} \varepsilon^{-1}E \\ \varepsilon D^T \end{bmatrix}<0.$$

The main result on the output tracking control of the discrete-time TS fuzzy system is summarized in the following theorem.

Theorem 1: If there exist symmetric positive definite matrices, P_i, a symmetric positive definite matrix, Q, R and matrices, K_i such that the following LMIs are satisfied, then the TS fuzzy system (7) is asymptotically stabilizable via TS fuzzy-model-based controller (15) with guaranteed-cost $J=\sum_0^\infty(z^T(t)Qz(t)+v^T(t)Rv(t))$.

$$\begin{bmatrix} -W_i & * & * & * & * & * \\ A_iW_i+B_iM_i & -W_i & * & * & * & * \\ E_{1i}W_i+E_{2i}M_j & 0 & -\varepsilon_iI & * & * & * \\ 0 & D_i^T & 0 & -\varepsilon_i^{-1}I & * & * \\ W_i & 0 & 0 & 0 & -Q^{-1} & * \\ M_i & 0 & 0 & 0 & 0 & -R^{-1} \end{bmatrix}<0, \quad (18)$$

$$i=1,2,\cdots,r.$$

where $W_i=P_i^{-1}, M_i=K_iP_i^{-1}$, and $*$ denotes the transposed elements in the symmetric positions.

Proof: Define a set of the piecewise linear Lyapunov function as follows

$$V(t)=\sum_{i=1}^r\eta_i(x(t))z(t)^TP_iz(t)$$

The rate of increases of $V(t)$ is

$$\begin{aligned}\Delta V(t) &= V(t+1)-V(t)\\ &=\sum_{i=1}^r\eta_i(x(t))(z(t+1)^TPz(t+1)-z(t)^TPz(t))\\ &=\sum_{i=1}^r\eta_i(x(t))z(t)^T(A_i+\Delta A_i\\ &\quad+(B_iK_i+\Delta B_iK_i))^TP\\ &\quad\times(A_i+\Delta A_i+(B_iK_i+\Delta B_iK_i))-P)z(t)\end{aligned} \quad (19)$$

Based on Assumption , (19) is equal to

$$\begin{aligned}\Delta V(t) &= V(t+1)-V(t)\\ &=z(t+1)^TP_iz(t+1)-z(t)^TP_iz(t)\\ &=\sum_{i=1}^r\eta_i(x(t))z(t)^T(A_i+B_iK_i\\ &\quad+D_iF_i(t)(E_{1i}+E_{2i}K_i))P_i\\ &\quad\times(A_i+B_iK_i+D_iF_i(t)(E_{1i}+E_{2i}K_i)\\ &\quad-P_i+Q-Q+K_i^TRK_i-K_i^TRK_i)z(t)\end{aligned} \quad (20)$$

If the following matrix inequalities hold,

$$\begin{aligned}&(A_i+B_iK_i+D_iF_i(t)(E_{1i}+E_{2i}K_i)P_i\\ &\times(A_i+B_iK_i+D_iF_i(t)(E_{1i}+E_{2i}K_i)\\ &-P_i+Q+K_i^TRK_i<0\end{aligned} \quad (21)$$

then, the set of uncertain linear systems is asymptotically stable, therefore, the TS fuzzy system can track arbitrary uniformly bounded signals. Furthermore,

$$\Delta V(t)<-z(t)^T(Q+K_i^TRK_i)z(t) \quad (22)$$

Summing (22) from time index $t=0$ to $t=\infty$ yields

$$\begin{aligned}&z(\infty)^TP_iz(\infty)-z(0)^TP_iz(0)\\ &\quad<-\sum_{t=0}^\infty z(t)^T(Q+K_i^TRK_i)z(t)\end{aligned} \quad (23)$$

Since $z(\infty)^TP_iz(\infty)=0$, we can conclude

$$z(0)^TP_iz(0)>\sum_{t=0}^\infty z(t)^T(Q+K_i^TRK_i)z(t)$$

Applying Lemma to (21), for all $F_i(t)$ satisfying $F_i(t)^TF_i(t)<I$ if and only if there exists a constant $\varepsilon_i>0$ such that

$$\begin{aligned}&\Omega_i+\begin{bmatrix}0\\ D_i\end{bmatrix}F_i(t)[E_{1i}+E_{2i}K_i \ \ 0]\\ &\quad+[E_{1i}+E_{2i}K_i \ \ 0]^TF_i(t)^T[0 \ \ D_i]^T<0\end{aligned} \quad (24)$$

where

$$\Omega_i=\begin{bmatrix}-P_i+Q+K_i^TRK_i & * \\ A_i+B_iK_i & -P_i^{-1}\end{bmatrix}.$$

With some efforts, applying Lemma 2 Lemma 1 gives

$$\begin{bmatrix} -P_i & * & * & * & * & * \\ A_i+B_iK_i & -P_i^{-1} & * & * & * & * \\ E_{1i}+E_{2i}K_j & 0 & -\varepsilon_i I & * & * & * \\ 0 & D_i^T & 0 & -\varepsilon_i^{-1} I & * & * \\ I & 0 & 0 & 0 & -Q^{-1} & * \\ K_i & 0 & 0 & 0 & 0 & -R^{-1} \end{bmatrix} < 0 \quad (25)$$

Define the following transformation matrix

$$\begin{bmatrix} P^{-1} & 0 & 0 & 0 & 0 & 0 \\ 0 & I & 0 & 0 & 0 & 0 \\ 0 & 0 & I & 0 & 0 & 0 \\ 0 & 0 & 0 & I & 0 & 0 \\ 0 & 0 & 0 & 0 & I & 0 \\ 0 & 0 & 0 & 0 & 0 & I \end{bmatrix}$$

and taking the conguruence transforamtion results in the LMI of Theorem 1. This completes the proof.

Q.E.D.

3. Illustrative Example

We now apply the above design technique to the control of a computer simulated truck trailer. The control objective of this simulation is to design a controller such that the truck trailer follows backward the given reference trajectory. We use the following truck trailer model formulated in [3]:

$$\begin{aligned} x_1(t+1) &= (1-v\cdot t/L)x_1(t) + v\cdot t/l\cdot u(t) \\ x_2(t+1) &= x_2(t) + v\cdot t/L\cdot x_1(t) \\ x_3(t+1) &= v\cdot t\cdot \sin(x_2(t) + v\cdot t\cdot x_1(t)/2L) + x_3(t) \end{aligned}$$

The following fuzzy model is used to design a fuzzy controller:

R^1: *If* $x_2(t)+v\cdot t/L\cdot x_1(t)$ *is about* 0
Then, $x(t+1)=A_1x(t)+B_1u(t)$

R^2: *If* $x_2(t)+v\cdot t/L\cdot x_1(t)$ *is about* π
Then, $x(t+1)=A_2x(t)+B_2u(t)$

where

$$A_1=\begin{bmatrix} 1-v\cdot t/L & 0 & 0 \\ v\cdot t/L & 0 & 0 \\ (v\cdot t)^2/2L & v\cdot t & 1 \end{bmatrix},$$

$$A_2=\begin{bmatrix} 1-v\cdot t/L & 0 & 0 \\ v\cdot t/L & 0 & 0 \\ g\cdot(v\cdot t)^2/2L & g\cdot v\cdot t & 1 \end{bmatrix},$$

$$B_1=B_2=\begin{bmatrix} v\cdot t/l \\ 0 \\ 0 \end{bmatrix},$$

and $l=0.2, L=0.32, v=-0.1, t=0.5$, and $g=20^{-1}\pi$. The membership functions are

$$\mu_1(x(t)) = \frac{\sin(x_2(t)+v\cdot t/2L\cdot x_1(t)) - g\cdot x_2(t)+v\cdot t/2L\cdot x_1(t)}{(x_2(t)+v\cdot t/2L\cdot x_1(t))(1-g)}$$

$$\mu_2(x(t)) = 1-\mu_1(x(t))$$

The reference signal model is defined as follows:

$$\begin{aligned} w(t+1) &= Fw(t), \\ r(t) &= Gw(t), \end{aligned}$$

where

$$F=[1], \qquad G=[1],$$

and $w(0)=1$. Solving (14), we get

$$T_1=T_2=\begin{bmatrix} 0 \\ 0 \\ 1 \end{bmatrix},$$

$$L_1=4.5475\text{ e}-013, , L_2=-1.4552\text{ e}-011.$$

Based on Theorem 1, we obtain

$$P_1=1.0\text{ e}-5\begin{bmatrix} 0.1057 & -0.1072 & 0.0675 \\ -0.1072 & 0.2796 & -0.1718 \\ 0.0675 & -0.1718 & 0.3562 \end{bmatrix},$$

$$P_2=1.0\text{ e}-4\begin{bmatrix} 0.0010 & -0.0008 & 0.0009 \\ -0.0008 & 0.0021 & -0.0021 \\ 0.0009 & -0.0021 & 0.1889 \end{bmatrix},$$

$$K_1=[2.2806 \ \ -0.4016 \ \ -0.0002],$$

$$K_2=[2.3171 \ \ -0.4090 \ \ 0.0002],$$

$$Q=1.0\text{ e}-7\begin{bmatrix} 0.7497 & -0.1473 & 0.0710 \\ -0.1473 & 0.7043 & -0.2311 \\ 0.0710 & -0.2311 & 0.7208 \end{bmatrix},$$

$$R=4.4272\text{ e}-8$$

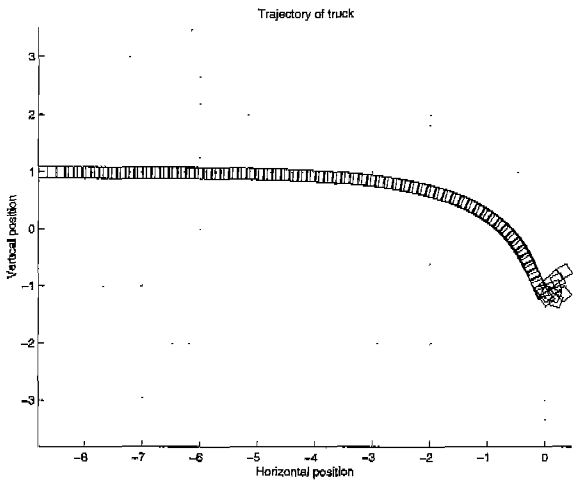

Fig. 1. The controlled trajectory of the backing-up truck trailer.

The initial value is set to $x(0)=[0.523\ -0.174\ 0.698]^T$. Figure 1 shows the computer simulation results. From Fig. 1, we can see the controlled output trajectory of the truck trailer is quickly guided to the output of the exogenous system, $r(t)=1$. This means that the output tracking control of discrete-time TS fuzzy system based on the proposed technique in this paper is excellent.

4. Conclusions

In this paper, the output tracking controller design technique for discrete-time TS fuzzy system is presented. The stabilization problem of uncertain TS fuzzy system was converted into the stabilization problem of a set of uncertain linear systems. The sufficient condition was formulated in LMI framework. The simulation example ensured us the feasibility of the developed design technique. It im-plies that this control strategy has strong feasibility in the in-dustrial applications.

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