ROBUST STABILIZATION OF NONLINEAR DISCRETE-TIME SYSTEMS BASED ON T-S MODEL

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ABSTRACT

A robust stabilization problem is considered about nonlinear discrete-time system based on T-S fuzzy model. In order to represent the system exactly, the parametric uncertainty is employed to the T-S model. A necessary and sufficient condition for the existence of such controllers through Lyapunov theorem is given. And it is further shown that this condition is equivalent to the solvability of a certain linear matrix inequality. An illustrative example of truck-trailer shows the feasibility of the proposed method.
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*Keywords: D*iscrete systems, fuzzy control, linear matrix inequality.

1. INTRODUCTION

It has been shown recently that fuzzy control is one of the rather useful control techniques for uncertain and nonlinear, and other classes of complicated systems. The conventional fuzzy control is composed of some if-then linguistic rules. The property of it makes the control algorithm to be understood easily. Its main drawback, however, comes from the lack of a systematic control design methodology.

Particularly, the stability analysis and robustness are not easy. To solve these problems, the idea that a linear system is adopted as the consequent part of a fuzzy rule has evolved in the T-S model, which becomes quite popular today.

With development of computer, the discrete system has attracted great attention, and the fuzzy control has been extended to nonlinear discrete system, but the reference research results are too limited. The robust stabilization of linear

system (see, for instance, Yu, 1999) is discussed by using LMI techniques. The stability of nonlinear system is considered by using fuzzy control (see, for instance, Ma and San, 2001; Ma and Sun, 1998, Takagi and Sugeno, 1992, Jagannathan, S., Vandegrift, and Lewis, 2000, Nesic, Teel, and Kokotovic, 1999), but its consequent part of T-S model is linear normal system without uncertainties. The following authors (Tong, Wang and Li, 2002, Wang and Unbehauen, 2000, Mahmoud, 2000, Nesic, Teel, and Kokotovic, 1999, Ordonez and Passino, 2003, Jiang and Wang, 2001) have investigated the analysis and synthesis problem including continuous and discrete time delay systems. But their respective works, there is only one time delay part in the T-S model. The fuzzy robust tracking control for uncertain nonlinear system has been studied in (Cao and Frank, 2000, Wang., 1994, Chang and Sun, 2003). In there, the parametric uncertainty is employed to the consequent part of the T-S model, and so the T-S model can represent the original system exactly. However, the method has not been applied to the discrete-time systems.

A survey of most recent literature has shown that the T-S model with consequent uncertainty has not been applied for a class of nonlinear discrete systems. Based on these intentions, in this paper, the robust stabilization problem is considered for nonlinear discrete systems. In order to represent the original systems exactly, the parametric uncertainty is employed to the T-S model. And it is shown that this stabilization problem is equivalent to the solvability of a certain linear matrix inequality. In the last, an illustrative example of truck-trailer shows the feasibility of the proposed method.

2. PROBLEM FORMULATION

The consequent part of T-S model has exact mathematics description, so the fuzzy T-S model as in paper by Cao, et al. (2000) is used in the present study. The i-th rule of the fuzzy model for the nonlinear discrete system is assumed to have the following form

Plant Rule i

If $z_1(k)$ is F_1^i and $\ldots$ and $z_n(k)$ is F_n^i then

$$x(k+1) = (A_i + \Delta A_i)x(k) + (B_i + \Delta B_i)u(k)$$
$$y(k) = C_i x(k) \qquad i = 1, \ldots q \tag{1}$$

where: $z(k) = [z_1(k)\ldots z_n(k)]^T$ is the premise variable vector; $x(k) = [x_1(k), \ldots x_n(k)]^T$ is the state vector $(j = 1, \cdots, n)$; F_j^i are fuzzy sets; $A_i \in R^{n \times n}$ denotes the system state matrices; $B_i \in R^{n \times m}$ and $C_i \in R^{l \times n}$ denote input and output matrices, respectively; ΔA_i and ΔB_i are matrices with appropriate dimensions, representing parametric uncertainties in the plant model; and q represents the number of rules of this T-S fuzzy model.

Here, by using a standard fuzzy inference method, that is, using a singleton fuzzifier product fuzzy inference and weighted average defuzzifier for system (1), the final state of the fuzzy system is inferred as follows:

$$x(k+1) = \sum_{i=1}^{q} h_i(z(k))[A_i x(k) + B_i u(k)] +$$
$$+ \sum_{i=1}^{q} h_i(z(k))[\Delta A_i x(k) + \Delta B_i u(k)]$$
$$y(k) = \sum_{i=1}^{q} h_i(z(k)) C_i x(k)$$

$$\tag{2}$$

where

$$w_i(z(k)) = \prod_{j=1}^{n} F_j^i(z_j(k)), \quad \text{(2 a)}$$

$$h_i(z(k)) = \frac{w_i(z(k))}{\sum_{i=1}^{q} w_i(z(k))}, \quad \text{(2 b)}$$

and F_j^i is fuzzy set h_i is the grade of membership of F_j^i. Some of the basic properties of system (2) are given in terms of the following inequalities

$$w_i(k) \geq 0, \ \sum_{i=1}^{q} w_i(k) > 0, \ i = 1, 2, \ldots q.$$

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It is obvious that

$$h_i(z(k)) \geq 0, \ \sum_{i=1}^{q} h_i(z(k)) = 1, \ i = 1, \dots q .$$

The main goal of this paper is to study the synthesis and design of fuzzy T-S model based controller, which resolves the stabilization of the system (2).

For convenience of the proof, the following assumption is adopted.

Assumption 2.1 : The parametric uncertainties in system (1) are norm bounded satisfying the following equations and inequalities, respectively

$$[\Delta A_i, \Delta B_i] = D_i F_i(k)[E_{i1,} E_{i2}]$$

$$F_i^T(k)F_i(k) \leq I$$

In here, D_i, E_{i1}, E_{i2} are known real-valued constant matrices of appropriate dimensions, $F_i(k)$ denotes an unknown matrix function with Lebesgue-measurable elements, and I is the identity matrix of appropriate dimension.

3. DESIGN OF FUZZY STATE FEEDBACK CONTROL

Based on the concept of parallel distributed compensation (PDC), we consider the following fuzzy control law for the plant (1) represented by means of the inference based fuzzy model (2) derived:

Regulator R i

If $z_1(k)$ is F_1^i and … and $z_n(k)$ is F_n^i , then

$$u(k) = K_i x(k) \ i = 1, \dots q , \quad (3)$$

where $K_i \in R^{m \times n}$ is a constant gain feedback matrix to be determined. Then, of course, the overall state feedback fuzzy control law is represented by means of

$$u(k) = \sum_{i=1}^{q} h_i(z(k))K_i x(k) . \quad (4)$$

Substituting 4 into 2 yields

$$x(k+1) = \sum_{i=1}^{q}\sum_{j=1}^{q} h_i(z(k))h_j(z(k)) \times$$
$$\times ((A_i + \Delta A_i)x(k) + \quad (5)$$
$$+ (B_i + \Delta B_i)K_j x(k))$$

For the purpose of the necessity part of the proof, two lemmas from the literature are presented first. These are as follows:

Lemma 3.1: Given constant matrices A, P, X where $P = X^{-1}$ and $P = P^T > 0$ then $A^T PA - P < 0$ if and only if

$$\begin{bmatrix} -X & AX \\ XA^T & -X \end{bmatrix} < 0 .$$

Lemma 3.2: For any real matrix Y, H, F and E with appropriate dimension and $F^T F \leq I$ there exists constant $\varepsilon > 0$, it follows that $Y + HFE + E^T F^T H^T < 0$ if and only if

$$Y + \varepsilon HH^T + \varepsilon^{-1} EE^T < 0 .$$

The main result on fuzzy robust stabilization control of T-S model with parametric uncertainties is summarized in terms of the theorem stated below.

Theorem 3.1: If there exist a symmetric and positive definite matrix $X > 0$ and some real-valued matrices $K_i (i = 1,2,\dots q)$ such that matrix inequalities (6) are satisfied, then the stability of system (4) is guaranteed via the T-S fuzzy model based state-feedback controller (3).

$$\begin{bmatrix} \varepsilon D_i D_i^T - X & A_i X + B_i K_j X & 0 \\ XA_i^T + XK_j^T B_i^T & -X & XE_{i1}^T + XK_j^T E_{i2} \\ 0 & E_{i1} X + E_{i2} K_j X & -\varepsilon I \end{bmatrix} < 0$$
$$(6)$$

Proof Let us define $P = X^{-1}$. Construct a standard Lyapunov function for system (5) by means of the equation

$$V(k) = x^T Px . \quad (7)$$

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Upon deriving the first difference of (7), we get

$$\Delta V(k) = V(k+1) - V(k)$$
$$= x^T(k+1)Px(k+1) - x^T(k)Px(k)$$
(8)

Then substituting 5 into 8 yields:

$$\Delta V(k) = [\sum_{i=1}^{q}\sum_{j=1}^{q} h_i h_j (A_i + \Delta A_i)x(k) +$$

$$(B_i + \Delta B_i)K_j x(k)]^T * P[\sum_{i=1}^{q}\sum_{j=1}^{q} h_i h_j (A_i + \Delta A_i)x$$

$$+ (B_i + \Delta B_i)K_j x(k)] - x^T(k)Px(k)$$

$$= \sum_{i=1}^{q}\sum_{j=1}^{q} h_i h_j x^T (A_i + B_i K_j + \Delta A_i + \Delta B_i K_j)^T$$

$$* P(A_i + B_i K_j + \Delta A_i + \Delta B_i K_j)x - x^T(k)Px(k)$$
(9)

So, it follows, system (2) can be stabilized if and only if there exists a symmetric and positive definite matrix $P > 0$ and some matrices K_i such that the following inequality is satisfied:

$$(A_i + B_i K_j + \Delta A_i + \Delta B_i K_j)^T P$$
$$* (A_i + B_i K_j + \Delta A_i + \Delta B_i K_j) - P < 0$$
(10)

It should be noted that Theorem 3.1 gives the sufficient condition of ensuring the stability of the fuzzy system (2). However, it does not give the method of obtaining the solution of a common matrix P and feedback gains K_i. Fortunately inequality (10) can be transferred into an LMI problem, hence the parametric matrices P and K_i can be determined by the virtue of the solvability of LMI problems. This is shown in the sequel and thereby the proof is completed with a proposed design technique.

From Assumption 2.1, it is readily seen that $[\Delta A_i, \Delta B_i] = D_i F_i(k)[E_{i1}, E_{i2}]$. Thus inequality (10 is equivalent to the inequality

$$[A_i + B_i K_j + D_i F_i(k)(E_{i1} + E_{i2})K_j]^T P$$
$$* [A_i + B_i K_j + D_i F_i(k)(E_{i1} + E_{i2})] - P < 0$$
(11)

It is seen from Lemma 2.1 that 11 equals to the following linear matrix inequality

$$\begin{bmatrix} -X & M \\ N & -X \end{bmatrix} < 0, \quad (12)$$

where

$$M = [A_i + B_i K_j + D_i F_i(k)(E_{i1} + E_{i2}K_j)]X$$
,
$$N = X[A_i + B_i K_j + D_i F_i(k)(E_{i1} + E_{i2}K_j)]^T$$
.

For convenience of the design procedure, we adopt the following matrix Y as given below:

$$Y = \begin{bmatrix} -X & (A_i + B_i K_j)X \\ X(A_i + B_i K_j)^T & -X \end{bmatrix}.$$

Then it becomes apparent that 12 equals to

$$Y + \begin{bmatrix} D_i \\ 0 \end{bmatrix} F_i \begin{bmatrix} 0 & (E_{i1} + E_{i2}K_j)X \end{bmatrix} +$$

$$\begin{bmatrix} 0 \\ X(E_{i1} + E_{i2}K_j)^T \end{bmatrix} F_i^T \begin{bmatrix} D_i^T & 0 \end{bmatrix} < 0$$
(13)

Now it seen from Lemma 3.2 that (13) is satisfied if and only if the following inequality

$$Y + \varepsilon \begin{bmatrix} D_i \\ 0 \end{bmatrix} \begin{bmatrix} D_i^T & 0 \end{bmatrix} + \varepsilon^{-1} \begin{bmatrix} 0 \\ X(E_{i1} + E_{i2}K_j)^T \end{bmatrix}$$
$$* \begin{bmatrix} 0 & (E_{i1} + E_{i2}K_j)X \end{bmatrix} < 0$$
(14)

be satisfied. This inequality (14) equals to the linear matrix equality

$$\begin{bmatrix} \varepsilon D_i D_i^T - X & (A_i + B_i K_j)X \\ X(A_i + B_i K_j)^T & \varepsilon^{-1}X(E_{i1} + E_{i2}K_j)^T(E_{i1} + E_{i2}K_j)X - X \end{bmatrix} < 0$$
(15)

and inequality 15 can be transformed to

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$$\begin{bmatrix} \mathit{d}D_iD_i^T - X & (A_i + B_iK_j)X & 0 \\ X(A_i + B_iK_j)^T & -X & X(E_{i1} + E_{i2}K_j)^T \\ 0 & (E_{i1} + E_{i2}K_j)X & -\mathit{d} \end{bmatrix} < 0 \quad (16)$$

Let define $Y_j = K_jX$. By using LMI software of Matlab the parametric uncertainty X and K_i can be solved. Hence the synthesized controller can be determined computationally.

4. A DESIGN EXAMPLE AND SIMULATION RESULTS

To illustrate the proposed fuzzy robust control approach, the benchmark control problem of a truck-trailer is considered. The respective discrete-time model (see, for instance, Cao, et al.,) is

$$x_1(k+1) = (1 - v\frac{\bar{k}}{L})x_1(k) + v\frac{\bar{k}}{l}u(k) + a(k)x_1(k)$$

$$x_2(k+1) = x_2(k) + v\frac{\bar{k}}{L}x_1(k) + a(k)x_2(k)$$

$$x_3(k+1) = x_3(k) + v\bar{k}\sin(x_2(k) + v\frac{\bar{k}}{2L}x_1(k)) + a(k)x_3(k)$$

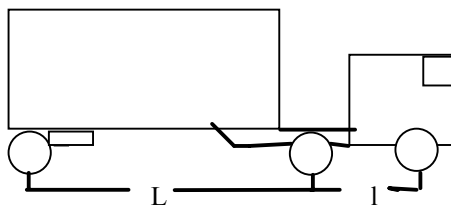The schematic of the truck-trailer is drawn as depicted in the following Figure 1.

Figure 1. Schematic sketch of the truck-trailer plant

Where l is the length of the truck, L is the length of the trailer, $\bar{k}$ is the sampling time, and v is the constant speed of the backward movement, $a(k) = 0.2\sin(k)$ is parameter uncertainty. Take fuzzy rule model is as follows:

R^1

If $z(k) = x_2(k) + v\frac{\bar{k}}{2L}x_1(k)$ is about 0, then

$$x(k+1) = (A_1 + \Delta A_1)x(k) + (B_1 + \Delta B_1)u(k)$$

R^2

If $z(k) = x_2(k) + v\frac{\bar{k}}{2L}x_1(k)$ is about π or $-\pi$, then

$$x(k+1) = (A_2 + \Delta A_2)x(k) + (B_2 + \Delta B_2)u(k)$$

.

In the above equations we have employed the following matrices:

$$A_1 = \begin{bmatrix} 1 - \dfrac{v\bar{k}}{L} & 0 & 0 \\ \dfrac{v\bar{k}}{L} & 1 & 0 \\ \dfrac{v^2\bar{k}^2}{2L} & v\bar{k} & 1 \end{bmatrix} \quad B_1 = \begin{bmatrix} \dfrac{v\bar{k}}{l} \\ 0 \\ 0 \end{bmatrix}$$

$$\Delta A_1 = \begin{bmatrix} 0.2\sin(k) & 0 & 0 \\ 0 & 0.2\sin(k) & 0 \\ 0 & 0 & 0.2\sin(k) \end{bmatrix}$$

,

$$A_2 = \begin{bmatrix} 1 - \dfrac{v\bar{k}}{L} & 0 & 0 \\ \dfrac{v\bar{k}}{L} & 1 & 0 \\ \dfrac{dv^2\bar{k}^2}{2L} & dv\bar{k} & 1 \end{bmatrix} \quad B_2 = \begin{bmatrix} \dfrac{v\bar{k}}{l} \\ 0 \\ 0 \end{bmatrix}$$

$$\Delta A_2 = \begin{bmatrix} 0.2\sin(k) & 0 & 0 \\ 0 & 0.2\sin(k) & 0 \\ 0 & 0 & 0.2\sin(k) \end{bmatrix}$$

.

The parameter values in the above matrices are as follows:

$$l = 2.8,\ L = 5.5,\ v = -1.0,\ \bar{k} = 2.0.$$

From the parallel distributed compensation principle, we can construct the fuzzy control law for the plant fuzzy model as follows:

R^1

If $z(k) = x_2(k) + v\dfrac{\bar{k}}{2L}x_1(k)$ is about 0

then $u(k) = K_1 x(k)$,

R^2

If $z(k) = x_2(k) + v\dfrac{\bar{k}}{2L}x_1(k)$ is about π or -π,

then $u(k) = K_2 x(k)$.

The fuzzy set membership functions are taken as follows:

$$h_1(z(k)) = (1 - \frac{1}{1 + \exp\{-3[z(k) - \frac{\pi}{2}]\}}) \times$$

$$\frac{1}{1 + \exp\{-3[z(k) + \frac{\pi}{2}]\}}$$

$$h_2(z(k)) = 1 - h_1(z(k)$$

$$z(k) = x_2(k) + v\frac{\bar{k}}{2L}x_1(k)$$

where ΔA_1 and ΔA_2 are parameter uncertainty.

From the equation (16) we have obtained

$$\begin{bmatrix} \varepsilon D_i D_i^T - X & (A_i + B_i K_j)X & 0 \\ X(A_i + B_i K_j)^T & -X & X(E_{i1} + E_{i2}K_J)^T \\ 0 & (E_{i1} + E_{i2}K_j)X & -\varepsilon I \end{bmatrix} < 0$$

Now we can take advantage of the LMI software of Matlab available to solve for the parametric uncertainty X and gains K_i. The solutions found are given below:

$$X = \begin{bmatrix} 0.0104 & 0.0026 & 0.0000 \\ 0.0026 & 0.0013 & 0.0007 \\ 0.0000 & 0.0007 & 0.0029 \end{bmatrix},$$

$$Y_1 = [0.0231 \quad 0.0036 \quad 0.0001],$$

$$Y_2 = [0.0231 \quad 0.0036 \quad 0.0001],$$

$$P = 1.0e + 0.03 *$$

$$\begin{bmatrix} 0.2239 & -0.5121 & 0.1173 \\ -0.5121 & 2.0489 & -0.4727 \\ 0.1173 & -0.4727 & 0.4597 \end{bmatrix},$$

$$K_1 = [3.3673 \quad -4.5910 \quad 1.0729],$$

$$K2 = [3.3673 \quad -4.5910 \quad 1.0729].$$

With the solutions of the LMI problem, the controller for the truck-trailer system is completely determined.

The simulation results for closed-loop control system are presented in Figure 4.2 to 4.3 below.
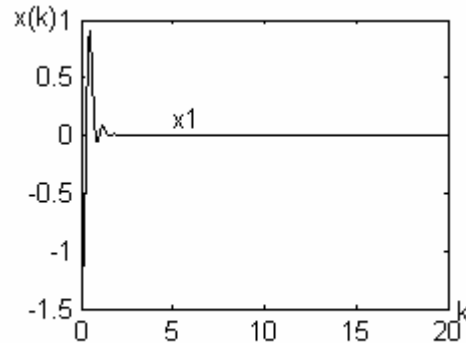

Fig.1. The trajectory of the state variable x1

Figure 2. Trajectory of the state variable x_1

From Figures 2 to 4, presenting the simulation results, it is seen that these all exhibit rather rapid convergence to the equilibrium state of trajectories of state variables x_1, x_2, and x_3 comparable to those in the literature cited. The state trajectories of the system in closed loop asymptotically tend to zero.
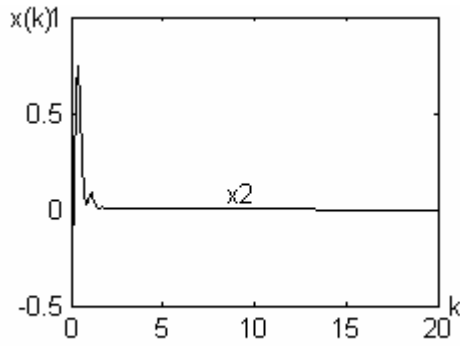
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Fig.2. The trajectory of the state variable x2

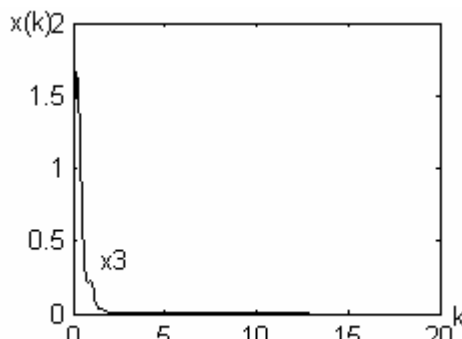**Figure 3.** Trajectory of the state variable x_2

Fig.3. The trajectory of the state variable x3

Figure 4. Trajectory of the state variable x_3

These results confirm that the controller proposed in this paper can stabilize the plant in closed loop as predicted by Theorem 3.1. Besides, the LMI based solving method presented is relatively simple and easy to use. Hence the proposed controller synthesis is practically feasible.

5. CONCLUSIONS

In this paper, the synthesis of robust fuzzy stabilization control for a class nonlinear discrete-time systems, which possess uncertainties, has been investigated and solved. In order to represent the system exactly, the parameter uncertainty is employed into to the T-S fuzzy model of the plant. A stability condition has been derived and its necessity proved by applying Lyapunov stability theory in terms of Theorem 3.1. This condition has been transformed into the solvability of the LMI problem and thereby a practical solving method

has been derived too. The method has been applied to solve the stabilization control of the truck-trailer benchmark case study. The simulation results for the overall system in the closed loop with the proposed fuzzy controller have demonstrated a rapid asymptotic stabilization process with short-lasting insignificant transient oscillations. Thus the proposed controller synthesis and practical design technique have been shown to be feasible and guarantee good control performance.

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