SLIDING MODE CONTROL FOR UNCERTAIN T-S FUZZY SYSTEMS WITH INPUT AND STATE DELAYS

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(Communicated by the Wanquan Liu)

Abstract. In this paper, the problem of sliding mode control (SMC) for uncertain T-S (Tagaki-Sugeno) fuzzy systems with input and state delays is investigated, in which the nonlinear uncertain terms are unknown and also unmatched. For the T-S fuzzy model of the controlled object, a method based on sliding mode compensator is designed, and the system is controlled by sliding mode. Based on solving linear matrix inequalities (LMI), we obtain the design method of sliding mode and controller. The sufficient conditions for the asymptotical stability of the sliding mode dynamics are given by using LMI technique and the Lyapunov stability theory, and it has been shown that the state trajectories can be driven onto the sliding surface in a finite time. Finally, a numerical example is provided to illustrate the effectiveness of the proposed theories.

1. Introduction. Time delay means that the expected results in the research process cannot be completed within the expected time due to various inevitable factors. In fact, this is a very common phenomenon. Practice shows that time delay is the main cause of systems poor performance and instability[10]. In practical systems, uncertainties often exist. The uncertainties in the system come from unknown dynamics, unknown parameters in the model, or variable parameters and numerical approximation in the process of model operation [12]. Therefore, the research on uncertain systems with delays has received considerable attention in recent years. The T-S fuzzy model proposed by Takagi and Sugeno in 1985 provided a method for solving the control problem of nonlinear systems. T-S fuzzy system theory has been extensively used in various fields, such as chemistry, circuits and so on. So far, many conclusions about T-S fuzzy systems have been drawn. For example, robust control of uncertain T-S fuzzy systems was studied in [18, 4], control for uncertain T-S fuzzy systems and stability analysis of T-S fuzzy systems were investigated in [2, 24, 23, 16], the robust stabilization problem for discrete time-varying system with parameter uncertainties and disturbances was concerned in [8, 25]. For uncertain T-S fuzzy systems with input delays, most scholars conducted stability analysis by designing Lyapunov function and adopting linear matrix inequality (LMI) method.
So far, SMC has been rarely applied to uncertain T-S fuzzy systems with input delays. [19]. SMC is a design method of control system with switching characteristics in nature. SMC is suitable for linear and nonlinear systems, and its sliding mode is invariant. The advantage of SMC is that it is insensitive to parameter variation and disturbance. The disadvantage is that due to the time delay of the switching device or the influence of some uncontrollable factors, the system state trajectories do not remain above the sliding surface or equilibrium point, but makes a round-trip movement around the sliding surface, resulting in buffeting phenomenon [3].

SMC is used widely in practice, for example, in [13], a fuzzy robust sliding mode control method is proposed to solve the SMC problem for a class of systems with parameter perturbation and unknown external disturbance, but in this paper, for the fuzzy control item, certain amount of time is required for the parameter adjusting of adaptive law. In the adjustment process, the controller parameters are not optimal, which will affect the dynamic performance of the system. In [9, 21], the authors deal with the design of a class of sliding mode observers with time delay. In [5], the authors deal with the unknown input observer design for T-S fuzzy models subjected to measurement noise and stochastic noise. In [1], the authors propose an enhanced model predictive discrete-time sliding mode control with a new sliding function for a linear system with state delay. Through the study of this paper, we can get the discrete time reaching law was improved by applying this new sliding function and a reference trajectory for discrete-time delay systems. In [6, 17], the authors design an integral-type sliding surface function to study the problem of SMC of a class of T-S fuzzy descriptor. In [7], SMC with dissipativity for a class of time-delay Takagi-Sugeno fuzzy singular systems is investigated. In [15], a sliding mode control design for fractional order systems with input and state delays is studied. In [20], a tracking control algorithm based on sliding mode prediction for a class of discrete-time uncertain systems is presented. In [22], the authors consider the robust output regulation problem for linear systems in the presence of state, input and output delays. In [11], the authors propose exponential function based fuzzy sliding-mode control design for uncertain nonlinear systems. In [14], the authors investigate an integral sliding mode control for a class of linear systems with time-varying state and input delays, but the problem of time delay in T-S model is not discussed.

In this paper, the problem of SMC for T-S systems with both state and input delay is considered, in which the nonlinear uncertainty is unknown. Using the method of sliding mode compensator and solutions of LMI, we have obtained the design method of sliding mode and controller. Furthermore, we analyze the stability of the sliding motion via Lyapunov method and LMI, and we can prove that the state trajectories can be driven onto the sliding surface in the finite time. This paper can be extended to uncertain systems with multiple delays.

The rest of the paper is organized as follows. Section 2 gives the system to be studied in this paper. Sliding surface design and stability analysis are presented in Section 3. The design of SMC law is introduced in Section 4. A numerical example is given to support the theory proposed in this paper in Section 5. Finally, some concluding remarks are given in Section 6.
2. System description. We consider the following T-S fuzzy model:

\[
\begin{align*}
\text{Plant Rule } i: Z_i(t) & \text{ is } M_{i1} \text{ and } \cdots \text{ and } Z_p(t) \text{ is } M_{ip} \\
\text{Then } \dot{x}(t) & = A_i x(t) + A_{di} x(t - \tau) + B_i u(t) \\
& + B_{di} u(t - \tau) + f_i(x,t) \\
x(t) & = \phi(t), t \in [-\tau,0] \\
u(t) & = \phi(t), t \in [-\tau,0], i = 1, 2, 3, \ldots, r
\end{align*}
\]

(1)

where \(x(t) \in \mathbb{R}^n\) is the state vector, \(u(t) \in \mathbb{R}^m\) is the control input vector, \(M_{ij}\) is the fuzzy set, \(r\) is the number of fuzzy rules, and \(Z_1(t), Z_2(t), \ldots, Z_p(t)\) is the premise variable vector, \(A_i \in \mathbb{R}^{n \times n}, A_{di} \in \mathbb{R}^{n \times n}, B_i \in \mathbb{R}^{n \times m}\) and \(B_{di} \in \mathbb{R}^{n \times m}\) are known real constant matrices with appropriate dimensions of the \(i^{th}\) local model of the T-S fuzzy descriptor system, \(\phi(t)\) and \(\phi(t)\) are initial-state and initial-input continuous functions respectively, \(\text{Rank}(B_i + B_{di}) = m\).

\(f_i(x,t) \in \mathbb{R}^n\) is an unknown nonlinear function, which represents the uncertainty of the system and satisfies the following condition:

\[t \geq 0, f(0,t) = 0\]

Using fuzzy reasoning and weighted average method, we can get the global T-S fuzzy mode of the system with time-delay can be expressed as follows:

\[
\dot{x}(t) = \sum_{i=1}^{r} h_i(z(t))(A_i x(t) + A_{di} x(t - \tau) + B_i u(t)) + B_{di} u(t - \tau) + f_i(x,t)) \\
x(t) = \phi(t), t \in [-\tau,0] \\
u(t) = \phi(t), t \in [-\tau,0], i = 1, 2, 3, \ldots, r
\]

(2)

where \(h_i(z(t)) = \frac{w_i(z(t))}{\sum_{i=1}^{r} w_i(z(t))}, \quad w_i(z(t)) = \prod_{k=1}^{p} \mu_{M_{ik}}(z_k(t)), z(t) = [z_1(t), z_2(t), \ldots, z_p(t)]^T\)

With \(\mu_{M_{ik}}(z(t))\) representing the grade of membership of \(z_k(t)\) in \(M_{ik}\).

At the same time it satisfies the following formula:

\[
\sum_{i=1}^{r} h_i(z(t)) = 1, \quad \sum_{i=1}^{r} h_i(z(t - \tau)) = 1
\]

The nonlinear function is unknown, and \(f_i(x,t)\) does not need to satisfy the matching condition in the system (2).

In this paper, we can assume that:

(1) \(B_1 = B_2 = \cdots = B_r = B\), where the matrix \(B\) is a column full rank.

(2) The uncertain nonlinear function \(f_i(x,t)\) norm is bounded by

\[
\|f_i(x,t)\| \leq K_1 \|x(t)\| + K_2 \|x(t - \tau)\|
\]

where \(K_1\) and \(K_2\) are known positive real constants. Then there are matrices \(M_1(t), M_2(t)\) satisfying the formula: \(\|M_i(t)\| \leq 1, i = 1, 2, \text{such that}\)

\[
f_i(x,t) = K_1 M_1(t) x(t) + K_2 M_2(t) x(t - \tau)
\]

(3)
Next, we will introduce two lemmas, where $E$ and $H$ are real matrices with appropriate dimensions and $F$ is a matrix with proper dimension satisfying $F^T F < I$

**Lemma 2.1.** There exists $\varepsilon > 0$, such that

$$EF(t)H + H^T F^T(t)E^T \leq \varepsilon^{-1} EE^T + \varepsilon H^T H$$

3. **Sliding surface design and stability analysis.** The sliding mode controller is designed in two steps. Firstly, a suitable sliding mode surface function is designed to make the system have the ideal property of asymptotical stability, and then a control law is designed to drive the state trajectory of the system into the predefined sliding surface in a finite time.

By substituting (3) into (2), system (2) can be represented as

$$\dot{x}(t) = \sum_{i=1}^{r} h_i(z(t))((A_i + K_1 M_1)x(t) + (A_{di} + K_2 M_2)x(t-\tau) + B_i u(t) + B_{di} u(t-\tau))$$

(4)

We will choose switching function for T-S fuzzy time-delay systems (2) as

$$S(t) = Cx(t) + C \sum_{i=1}^{r} h_i(z(t)) \int_{t-\tau}^{t} (A_{di} + K_2 M_2)x(\zeta)d\zeta + \int_{t-\tau}^{t} B_{di} u(\zeta)d\zeta + \Pi$$

(5)

where $C \in R^{l \times n}$, is a constant matrix such that $C(B_i + B_{di})$ is a nonsingular matrix. $\Pi$ is sliding mode compensator satisfying

$$\dot{\Pi} = -C \sum_{i=1}^{r} h_i(z(t))[A_i + K_1 M_1 + A_{di} + K_2 M_2 - (B_i + B_{di})\Gamma]x(t)$$

(6)

where $\Gamma \in R^{m \times n}$ is an undetermined constant matrix.

Differentiating $S(t)$ with respect to time gives

$$\dot{S}(t) = C \sum_{i=1}^{r} h_i(z(t))[(B_i + B_{di})u(t) + (B_i + B_{di})\Gamma x(t)]$$

(7)

Using $\dot{S}(t) = 0$, we get the equivalent control law

$$u_{eq}(t) = -\Gamma x(t)$$

(8)

By substituting (8) into (2), the sliding mode equation is obtained as follows:

$$\dot{x}(t) = \sum_{i=1}^{r} \sum_{j=1}^{r} h_i(z(t)) h_j(z(t-\tau)) [(A_i - B_i\Gamma + K_1 M_1)x(t) + (A_{di} - B_{di}\Gamma + K_2 M_2)x(t-\tau)]$$

(9)

Next, we continue to analyze the stability of equation (9) by using LMI technology, and give sufficient conditions to guarantee the asymptotic stability of sliding mode.

**Theorem 3.1.** For T-S fuzzy systems (2), if exist positive definite matrices $X > 0$, $P > 0$, $Q > 0$, $L > 0$, and matrix $Y$, scalars $\varepsilon_1 > 0$, $\varepsilon_2 > 0$ such that linear matrix inequality

$$\begin{bmatrix}
\Delta_{11} & \Delta_{12} & \Delta_{13} \\
\Delta_{21} & \Delta_{22} & \Delta_{23} \\
\Delta_{31} & \Delta_{32} & \Delta_{33}
\end{bmatrix} < 0$$

(10)
Proof. Selecting Lyapunov function

\[
\Delta_{11} = \begin{bmatrix} A_1 X + X A^T_1 - BY - Y^T B_1^T + W_1 + W_2 & A_{di} \beta X - B_{di} X \\ X A^T_{di} & -W_1 & 0 \\ -Y^T B_{di}^T & 0 & -W_2 \end{bmatrix},
\]

\[
\Delta_{12} = \begin{bmatrix} \beta X & \varepsilon_1 I & B \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}, \quad \Delta_{13} = \begin{bmatrix} B_{di} \beta X & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}, \quad \Delta_{21} = \begin{bmatrix} \beta X & 0 \\ 0 & \varepsilon_1 I \\ B^T & 0 \end{bmatrix},
\]

\[
\Delta_{22} = \begin{bmatrix} -\varepsilon_1 I & 0 & 0 \\ -\varepsilon_1 I & 0 & 0 \\ 0 & -B^T P B \end{bmatrix}, \quad \Delta_{23} = \Delta_{32} = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix},
\]

\[
\Delta_{31} = \begin{bmatrix} B_{di}^T & 0 & 0 \\ 0 & \beta X & 0 \\ 0 & 0 & 0 \end{bmatrix}, \quad \Delta_{33} = \begin{bmatrix} -B^T P B & 0 & 0 \\ 0 & -\varepsilon_2 I & 0 \\ 0 & 0 & -\varepsilon_2 I \end{bmatrix}, \quad \text{and } \ X = P^{-1}, \ W_1 = P^{-1} Q P^{-1}, \ W_2 = P^{-1} L P^{-1}, \ K = Y X^{-1}, \ C = B^T P = B^T X^{-1}
\]

\[
X \geq \varepsilon_2 I
\]

\[
XP = I
\]

hold, then the sliding mode (9) of time-delay uncertain T-S fuzzy system is asymptotically stable.

\[
\dot{V}(x(t), t) = \sum_{i=1}^{r} \sum_{j=1}^{r} h_i(z(t)) h_j(z(t - \tau)) \left[ x^T(t) \quad x^T(t - \tau) \quad x^T(t - \tau) \right] \Psi \left[ x(t) \quad x(t - \tau) \quad x(t - \tau) \right]
\]

where

\[
\Psi = \begin{bmatrix} 3_1 & PA_{di} & -PB_{di} K \\ A_{di}^T P & -Q & 0 \\ K^T B_{di}^T P & 0 & -L + \beta^2 \varepsilon_2^{-1} I \end{bmatrix}
\]

\[
3_1 = P(A_i - BK) + (A_i - BK)^T P + Q + L + \varepsilon_1^{-1} \beta^2 I + \varepsilon_1 P^2 + PB (B^T P B)^{-1} B^T P + \beta^2 \varepsilon_2^{-1} I + PB_{di} (B^T P B)^{-1} B_{di}^T P
\]

Therefore, when \( \Psi < 0 \), we know that \( \dot{V}(x(t), t) < 0 \). According to Schur's Theorem, \( \Psi < 0 \) is equivalent to the following inequality:

\[
[ \Upsilon_{11} \ Upsilon_{12} \ Upsilon_{13} \\ \Upsilon_{21} \ Upsilon_{22} \ Upsilon_{23} \\ \Upsilon_{31} \ Upsilon_{32} \ Upsilon_{33} ] < 0
\]

where

\[
\Upsilon_{11} = \begin{bmatrix} P(A_i - BK) + (A_i - BK)^T P + Q + L & PA_{di} & -PB_{di} K \\ A_{di}^T P & -Q & 0 \\ K^T B_{di}^T P & 0 & -L \end{bmatrix},
\]

\[
\Upsilon_{12} = \begin{bmatrix} \beta I & \varepsilon_1 P & PB \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}, \quad \Upsilon_{13} = \begin{bmatrix} PB_{di} & \beta I & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \beta I \end{bmatrix}, \quad \Upsilon_{21} = \begin{bmatrix} \beta I & 0 & 0 \\ \varepsilon_1 P & 0 & 0 \\ B^T P & 0 & 0 \end{bmatrix},
\]
Further, pre and post multiply (15) by 
\[ N = \text{diag}(P^{-1}, P^{-1}, P^{-1}, I, I, I, I, I, I) \]
and its transposition, then LMI (10) is obtained.

4. Design of sliding mode control law. In Theorem 3.1, the sufficient conditions for the asymptotic stability of the sliding mode dynamic equation (9) are proved. Next, a sliding mode control law is designed to keep the state trajectories on the sliding surface in a finite time.

**Theorem 4.1.** For T-S fuzzy systems (2), if the SMC law is designed as (16), the system state trajectories can be guaranteed to reach the sliding surface in a finite time.

\[ u(t) = -Kx(t) - [c(B_i + B_{di})]^{-1}[hS + \epsilon\|S\|^a S] \quad (16) \]

where \( c, h, \epsilon, a \) are positive constants, \( a \in (0, 1) \).

**Proof.** Selecting Lyapunov function
\[ V(s(t), t) = \frac{1}{2}S^T(t)S(t) \quad (17) \]

From (7) and (16), we have
\[
V(\dot{S}(t), t) = \frac{1}{2}S^T(t)S(t) \\
= \frac{1}{2}S^T(t)[C \sum_{i=1}^{r} h_i(z(t))[(B_i + B_{di})Kx(t)(B_i + B_{di})u(t)]] \\
= - \frac{1}{2}S^T(t)C \sum_{i=1}^{r} h_i(z(t))c(hS + \epsilon\|S\|^a S) \\
\leq - \frac{1}{2}\|S(t)\| \sum_{i=1}^{r} h_i(z(t))\|C\|(2c\|S(t)\|) \\
\leq - c\|S(t)\|^2 < 0
\]

So the conclusion is proved. Combining theorem 3.1, we can know that \( S(t) = 0 \).

5. Numerical simulation. To further illustrate the effectiveness of our theory. In this paper, we give the following examples:

Consider the following T-S fuzzy time-delay system:
\[ \dot{x}(t) = \sum_{i=1}^{2} h_i(z(t))(A_ix(t) + A_{di}x(t-\tau) + B_iu(t) + B_{di}u(t-\tau) + f_i(x, t)) \]

The parameters of the system model are selected as follows:
\[ A_1 = \begin{bmatrix} 1 & 2 \\ -2 & 1 \end{bmatrix}, \quad A_2 = \begin{bmatrix} 2 & 4 \\ 2 & 1 \end{bmatrix}, \quad A_{d1} = \begin{bmatrix} -2 & 0 \\ 0 & 4 \end{bmatrix}, \quad A_{d2} = \begin{bmatrix} 2 & 0 \\ 0 & 4 \end{bmatrix}, \]

\[ B_{d1} = \begin{bmatrix} 1 \\ 0 \end{bmatrix}, \quad B_{d2} = \begin{bmatrix} 1 \\ 0 \end{bmatrix}, \quad B_1 = \begin{bmatrix} 1 \\ 2 \end{bmatrix}, \quad B_2 = \begin{bmatrix} 1 \\ 2 \end{bmatrix}, \]

\[ f_i(x, t) = \sin(x_1(t)), \quad i = 1, 2 \]

We select \( K_1 = 1, K_2 = 0, M_1 = \frac{\|\sin(x_1(t))\|}{\|x(t)\|} \) and the membership function is selected as follows:

\[ h_1(z) = \frac{1 - \sin(x_1(t))}{2}, \quad h_2(z) = \frac{1 + \sin(x_1(t))}{2}, \quad \text{with} \quad z = x_1(t). \]

In the SMC law (16), we select \( \varepsilon = 0.05, h = 0.1, a = 0.2 \).

By solving linear matrix inequality (10), we get

\[ C = \begin{bmatrix} 1 & 0 \end{bmatrix}, \quad \Gamma = \begin{bmatrix} 1.2471 & 3.2593 \end{bmatrix}, \]

The simulation results are shown in the Figure1-6.

**Figure 1.** Trajectory of state \( x_1(t) \) before adding controller

**Figure 2.** Trajectory of state \( x_2(t) \) before adding controller
Figure 3. Control input signal

Figure 4. Trajectory of state $x_1(t)$ after adding controller

Figure 5. Trajectory of state $x_2(t)$ after adding controller
6. Conclusion. In this paper, the design method of sliding surface and sliding mode control law are given for uncertain input delay T-S fuzzy systems, and a sufficient condition for the asymptotic stability of sliding mode is also introduced. We can see that the method in this paper has a good control effect for the case of both delay terms and nonlinear uncertainties which do not meet the matching conditions. Simulation results show that the method is effective and easy to implement.

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Received May 2019; Final revision August 2019.

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