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Exponential stability of Takagi–Sugeno fuzzy systems with impulsive effects and small delays

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This paper deals with the exponential stability of impulsive Takagi–Sugeno fuzzy systems with delay. Impulsive control and delayed fuzzy control are applied to the system, and the criterion on exponential stability expressed in terms of linear matrix inequalities (LMIs) is presented.

Keywords: exponential stability, Takagi–Sugeno fuzzy model, impulsive delay systems, linear matrix inequality

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1. Introduction

In modern science and technology, there exist natural phenomena which are characterized by the fact that their states can be changed instantaneously at a certain moment of time, such as a nanoscale electronic circuit consisting of single-electron tunnelling junctions (SETJs) and the electron tunnelling effects which can cause impulsive changes of charge in SETJ capacitors. Other three typical instances including the population impulsive control system, a mechanical system with impulsive impacts and a financial impulsive control system are addressed in Ref.[1]. At the same time, time delay[2,3] happens frequently in various engineering systems, biological and economical systems where the state change rate depends not only on the current state of the system but also its state at some time in the past. An adequate mathematical model of such phenomena may be described by impulsive delay differential equations and impulsive delay functional differential equations.

Impulsive control is a control paradigm based on impulsive differential equations. Recently, impulsive systems and impulsive control have been studied by many researchers (see Refs.[4–10]). Bainov and Simeonov[4] and Lakshmikantham *et al*[5] have considered the stability of impulsive systems by using Lyapunov functions which are required to be nonincreasing along the whole sequence of switchings. Yang[6] and Li *et al*[7] have presented the concept and principles of impulsive control and obtained some sufficient conditions for a kind of nonlinear systems by using the results in Ref.[5]. However, these proposed stability criteria do not consider the fuzzy system with impulsive delay effects or consider less, which has become a major issue of control systems.

In this paper, we first consider the exponential stability of Takagi–Sugeno (T–S) fuzzy systems with small delays and impulsive effects. It is well known that the T–S fuzzy model provides an effective representation of complex nonlinear systems in terms of fuzzy sets and fuzzy reasoning applied to a set of linear input/output submodels, hence becoming a useful approach to the study of nonlinear systems (see Refs.[11–14]). So we study the nonlinear systems by constructing the T–S fuzzy model and then introduce small delays and an impulsive control law and finally obtain the impulsive delay differential equations based on the T–S fuzzy model. By using the Lyapunov function, we first derive some conditions for the exponential stability of fuzzy delay systems with impulses at fixed times and the results are used to obtain impulsive control laws and design delayed fuzzy controllers for a kind of nonlinear systems.

The rest of this paper is organized as follows. In Section 2, we formulate the impulsive differential equations with small delays and introduce some preliminary definitions which will be used throughout the

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paper. In Section 3, new exponential stability theorem of the impulsive delay T–S fuzzy systems and sufficient conditions are given. Finally in Section 4, we give some conclusions drawn from the present study.

2. Problem formulation

In this section, on the one hand, we utilize the fuzzy system design technique to construct the T–S fuzzy model for a nonlinear system with a control input in order to use the linear matrix inequality (LMI); on the other hand, we introduce delayed state fuzzy control and impulsive control to formulate impulsive delay differential equations based on the T–S fuzzy model.

Consider the following nonlinear system with a control input vector:

$$\dot{\boldsymbol{x}}(t) = \boldsymbol{f}(\boldsymbol{x}(t)) + \boldsymbol{u}(t), \tag{1}$$

where $\boldsymbol{x}(t) \in R^n$ is the state variable, $\boldsymbol{f} \in \mathcal{C}[R^n, R^n]$, $\boldsymbol{u}(t) \in R^n$ is control vector of the system. Utilizing the technique introduced in Ref.[8], we can construct a fuzzy model for Eq.(1) as follows:

Rule i IF $z_1(t)$ is M_{i1}, $\cdots$, and $z_p(t)$ is M_{ip}, THEN $\dot{\boldsymbol{x}}(t) = A_i\boldsymbol{x}(t) + \boldsymbol{u}(t)$,

in which $z_1(t), \cdots, z_p(t)$ are the premise variables, each $M_{ij} (j = 1, 2, \cdots, p)$ is a fuzzy set, and $A_i \in R^{n\times n}$ is a constant matrix.

Utilizing centre-average defuzzifier, the overall fuzzy system is represented as

$$\dot{\boldsymbol{x}}(t) = \sum_{i=1}^{r} h_i(t) A_i \boldsymbol{x}(t) + \boldsymbol{u}(t), \tag{2}$$

where r is the number of fuzzy implications, $h_i(t) = \dfrac{w_i(t)}{\sum_{i=1}^{r} w_i(t)}$, $w_i(t) = \prod_{l=1}^{p} M_{il}(z_l(t))$, and $M_{il}(z_l(t))$ is the grade of membership of $z_l(t)$ in M_{il}. Of course, $h_i(t) \geq 0$ and $\sum_{i=1}^{r} h_i(t) = 1$.

Remark System (2) can exactly represent Eq.(1) in a certain region $W \subset R^n$ which contains the origin. Using the parallel distributed compensation (PDC) design technique, we consider the following delayed state fuzzy control rules:

Control rule i IF $z_1(t)$ is M_{i1}, $\cdots$, and $z_p(t)$ is M_{ip}, THEN $\boldsymbol{u}(t) = F_i\boldsymbol{x}(t - \tau(t))$,

where $\tau(t)$ is small delays satisfying

$$\|\boldsymbol{x}(t - \tau(t))\| \leq \beta\|\boldsymbol{x}(t)\|, \ \beta > 0;$$

$F_i \in R^{m\times n}$ is a constant gain matrix; the controller $\boldsymbol{u}(t)$ is presented as

$$\boldsymbol{u}(t) = \sum_{i=1}^{r} h_i(t) F_i \boldsymbol{x}(t - \tau(t)). \tag{3}$$

Applying expression (3) to system (2), the resulting closed-loop fuzzy system can be represented as

$$\dot{\boldsymbol{x}}(t) = \sum_{i=1}^{r} h_i(t) \left\{A_i\boldsymbol{x}(t) + F_i\boldsymbol{x}(t - \tau(t))\right\}. \tag{4}$$

An impulsive control law of system (4) is given by a sequence $\{t_k, \boldsymbol{U}_k(\boldsymbol{x}(t_k))\}$, where a set of control instants $\{t_k\}, 0 < t_1 < t_2 < \cdots < t_k < \cdots$, $t_k \to \infty$ as $k \to \infty$, and control law $\boldsymbol{U}_k \in \mathcal{C}[R^n, R^n]$ denotes the incremental change of the state at time t_k. Thus the impulsive differential equation with small delays is given by

$$\begin{aligned}
&\dot{\boldsymbol{x}}(t) = \sum_{i=1}^{r} h_i(t) \left\{A_i\boldsymbol{x}(t) + F_i\boldsymbol{x}(t - \tau(t))\right\}, \\
&\forall t \geq 0, \quad t \neq t_k, \\
&\Delta\boldsymbol{x}(t)|_{t=t_k} = \boldsymbol{U}_k(\boldsymbol{x}(t)) = \boldsymbol{B}\boldsymbol{x}(t), t = t_k, \ k \in N, \\
&\boldsymbol{x}(t_0^+) = x_0, \ t_0 \geq 0,
\end{aligned} \tag{5}$$

where $\boldsymbol{B}$ is an $n \times n$ constant matrix, $\Delta\boldsymbol{x}(t)|_{t=t_k} = \boldsymbol{x}(t_k^+) - \boldsymbol{x}(t_k^-)$, $\boldsymbol{x}(t_k^+) = \lim\limits_{t\to t_k^+} \boldsymbol{x}(t)$, $\boldsymbol{x}(t_k^-) = \lim\limits_{t\to t_k^-} \boldsymbol{x}(t), k \in N$.

Remarks

1) The controller (3) is delayed state control in the framework of T–S fuzzy system. At the same time, the control law $\boldsymbol{U}_k(\boldsymbol{x}(t))$ is something related to the concept of 'input' in other control methods.

2) Given a constant matrix F_i, the problem of impulsive T–S fuzzy systems with small delays is to find an impulsive control law such that system (5) is stable. This situation belongs to the impulsive control of fuzzy system.

3) If the impulsive control law $\boldsymbol{U}_k(\boldsymbol{x}(t))$ is given, the problem of impulsive T–S fuzzy systems with small delays is to design delayed fuzzy controllers. This situation belongs to the delayed state fuzzy control of impulsive system.

4) If there exist the impulsive control law $\boldsymbol{U}_k(\boldsymbol{x}(t))$ and constant matrix F_i to be determined later, such that system (5) is stable, that is the hybrid control including impulsive control and delayed fuzzy control which are applied to the nonlinear system.

In this paper, we consider the exponential stability of T–S fuzzy system with impulsive effects and small delays, i.e. we find both the constant matrix

F_i to design the delayed fuzzy controller and an impulsive control matrix $\boldsymbol{B}$ to design the impulsive controller, such that system (5) is stable. In a word, this is a hybrid impulsive and switched controller.

We also need the following definitions, which play an important role in analysing the exponential stability of impulsive delay differential systems based on the fuzzy T–S model.

Definition 1 Let $V : R_+ \to R_+$. The right upper derivative of $V(\boldsymbol{x}(t))$ is defined as

$$D^+V(\boldsymbol{x}(t)) = \limsup_{s\to 0^+} \frac{1}{s}[V(\boldsymbol{x}(t+s)) - V(\boldsymbol{x}(t))].$$

Definition 2 Let $\boldsymbol{x}(t, t_0, \boldsymbol{x}_0)$ be any solution to system (5), and $\boldsymbol{x}(\boldsymbol{t_0}) = \boldsymbol{x}_0 \in W$. System (5) is said to be globally exponentially stable if for any scalar $\delta > 0$, there exist scalars $\gamma > 0$ and $k(\delta) > 0$, when $\|\boldsymbol{x}_0\| < \delta$, such that

$$\|\boldsymbol{x}(t, t_0, \boldsymbol{x}_0)\| \le k(\delta)\exp(-\gamma(t - t_0)),\ \forall t \ge t_0 \ge 0.$$

Definition 3 If there exists a constant gain matrix F_i such that system (4) is asymptotically stable, system (5) is said to be asymptotically stabilized by delayed state fuzzy controller (3).

Definition 4[15] If there exists an impulsive control law $\{t_k, \boldsymbol{U}_k(\boldsymbol{x}(t_k))\}$ such that system (5) is stable, system (4) is said to be impulsively stabilizable.

Definition 5 If there exist an impulsive control law $\{t_k, \boldsymbol{U}_k(\boldsymbol{x}(t_k))\}$ and a constant gain matrix F_i, such that system (5) is stable, system (1) is said to be stabilized by an impulsive control law and a delayed fuzzy controller.

3. Main results

In this section, we discuss exponential stability criteria for T–S fuzzy systems with impulsive effects and small delays.

Theorem 1 Let $n \times n$ matrix $\boldsymbol{P}$ be symmetric and positive definite, and $\lambda_{\min}(P) > 0$ and $\lambda_{\max}(P) > 0$ that are, respectively, the smallest and the largest eigenvalues of $\boldsymbol{P}$. Let $M_i = PF_i$. λ is the largest eigenvalue of the matrix

$$\boldsymbol{P}^{-1}(\boldsymbol{I} + \boldsymbol{B})^{\mathrm{T}}\boldsymbol{P}(\boldsymbol{I} + \boldsymbol{B}),$$

where $\boldsymbol{I}$ is the identity matrix, $(\boldsymbol{I} + \boldsymbol{B})^{\mathrm{T}}$ is the transpose of $(\boldsymbol{I} + \boldsymbol{B})$, and λ satisfies

$$\lambda^k \le \exp(-\rho(t-t_0)),\ t \ge t_0 \ge 0, \quad k = \max\{i | t_i < t\},$$

then system (5) will be globally exponentially stable if there exist matrices $\boldsymbol{F}_i$, $\boldsymbol{B}$, and scalars α, ρ, and for any $t \ge 0$ the following two conditions hold:

$$\theta = \frac{\alpha + \beta^2}{\lambda_{\min}(\boldsymbol{P})} < \rho, \tag{6}$$

$$\begin{bmatrix} \alpha\boldsymbol{I} - \boldsymbol{P}A_i - A_i^{\mathrm{T}}\boldsymbol{P} & M_i \\ M_i^{\mathrm{T}} & -\boldsymbol{I} \end{bmatrix} < 0,\ i = 1, \cdots, r. \tag{7}$$

Proof Construct the Lyapunov function $V(\boldsymbol{x}(t)) = \boldsymbol{x}^{\mathrm{T}}(t)\boldsymbol{P}\boldsymbol{x}(t)$. It yields

$$\lambda_{\min}(\boldsymbol{P})\|\boldsymbol{x}(t)\|^2 \le V(\boldsymbol{x}(t)) \le \lambda_{\max}(\boldsymbol{P})\|\boldsymbol{x}(t)\|^2. \tag{8}$$

When $t \ne t_k$ and $k \in N$, the right-hand upper derivative of $V(\boldsymbol{x}(t))$ is

$$\begin{aligned} D^+V(\boldsymbol{x}(t)) =& \dot{\boldsymbol{x}}^{\mathrm{T}}(t)\boldsymbol{P}\boldsymbol{x}(t) + \boldsymbol{x}^{\mathrm{T}}(t)\boldsymbol{P}\dot{\boldsymbol{x}}(t) \\ =& \sum\nolimits_{i=1}^{r} h_i(t)\left\{\boldsymbol{x}^{\mathrm{T}}(t)(\boldsymbol{P}A_i + A_i^{\mathrm{T}}\boldsymbol{P})\boldsymbol{x}(t) + 2\boldsymbol{x}^{\mathrm{T}}(t-\tau(t))\boldsymbol{F}_i^{\mathrm{T}}\boldsymbol{P}\boldsymbol{x}(t)\right\} \\ \le& \sum\nolimits_{i=1}^{r} h_i(t)\left\{\boldsymbol{x}^{\mathrm{T}}(t)(\boldsymbol{P}A_i + A_i^{\mathrm{T}}\boldsymbol{P})\boldsymbol{x}(t) + \boldsymbol{x}^{\mathrm{T}}(t-\tau(t))\boldsymbol{x}(t-\tau(t)) + \boldsymbol{x}^{\mathrm{T}}(t)\boldsymbol{P}\boldsymbol{F}_i\boldsymbol{F}_i^{\mathrm{T}}\boldsymbol{P}\boldsymbol{x}(t)\right\} \\ =& \sum\nolimits_{i=1}^{r} h_i(t)\left\{\boldsymbol{x}^{\mathrm{T}}(t)(\boldsymbol{P}A_i + A_i^{\mathrm{T}}\boldsymbol{P} + \boldsymbol{P}\boldsymbol{F}_i\boldsymbol{F}_i^{\mathrm{T}}\boldsymbol{P})\boldsymbol{x}(t) + \boldsymbol{x}^{\mathrm{T}}(t-\tau(t))\boldsymbol{x}(t-\tau(t))\right\}. \end{aligned}$$

Since matrix (7), by the Schur complement, is equivalent to

$$\boldsymbol{P}A_i + A_i^{\mathrm{T}}\boldsymbol{P} + M_iM_i^{\mathrm{T}} - \alpha\boldsymbol{I} < 0 \Leftrightarrow \boldsymbol{P}A_i + A_i^{\mathrm{T}}\boldsymbol{P} + \boldsymbol{P}\boldsymbol{F}_i\boldsymbol{F}_i^{\mathrm{T}}\boldsymbol{P} < \alpha\boldsymbol{I},\quad i = 1, \cdots, r,$$

and $\|\boldsymbol{x}(t-\tau(t))\| \le \beta\|\boldsymbol{x}(t)\|$, it follows from inequalities (6) and (8) that

$$D^+V(\boldsymbol{x}(t)) < (\alpha + \beta^2)\boldsymbol{x}^{\mathrm{T}}(t)\boldsymbol{x}(t) = (\alpha + \beta^2)\|\boldsymbol{x}(t)\|^2 \le \theta V(\boldsymbol{x}(t)),\ t \in (t_{k-1}, t_k), k \in N. \tag{9}$$

When $t = t_k$, we have

$$\begin{aligned}V\left(\boldsymbol{x}(t_k^+)\right)=&\left[\boldsymbol{x}(t_k)+B(\boldsymbol{x}(t_k))\right]^{\mathrm{T}}\boldsymbol{P}\left[\boldsymbol{x}(t_k)+\boldsymbol{B}(\boldsymbol{x}(t_k))\right]\\=&\boldsymbol{x}^{\mathrm{T}}(t_k)\left[\boldsymbol{I}+\boldsymbol{B}\right]^{\mathrm{T}}\boldsymbol{P}\left[\boldsymbol{I}+\boldsymbol{B}\right]\boldsymbol{x}(t_k)\\=&\boldsymbol{x}^{\mathrm{T}}(t_k)\boldsymbol{P}\boldsymbol{P}^{-1}\left[\boldsymbol{I}+\boldsymbol{B}\right]^{\mathrm{T}}\boldsymbol{P}\left[\boldsymbol{I}+\boldsymbol{B}\right]\boldsymbol{x}(t_k)\\\leq&\lambda\boldsymbol{x}^{\mathrm{T}}(t_k)\boldsymbol{P}\boldsymbol{x}(t_k)\\=&\lambda V(\boldsymbol{x}(t_k)).\end{aligned}\tag{10}$$

According to expressions (9) and (10), we shall show that

$$\begin{aligned}&V(\boldsymbol{x}(t))\leq V(\boldsymbol{x}_0)\lambda^k\exp(\theta(t-t_0)),\\&k=\max\{i|t_i<t\},\quad t\geq t_0\geq 0.\end{aligned}\tag{11}$$

To do this, we shall consider all regions of t in detail. The following situations are considered.
If $t_0<t\leq t_1$, we have

$$\begin{aligned}V(\boldsymbol{x}(t))\leq&V(\boldsymbol{x}(t_0^+))\exp(\theta(t-t_0^+))\\=&V(\boldsymbol{x}_0)\exp(\theta(t-t_0)),\\V(\boldsymbol{x}(t_1))\leq&V(\boldsymbol{x}_0)\exp(\theta(t_1-t_0));\end{aligned}$$

when $t_1<t\leq t_2$, we obtain

$$\begin{aligned}V(\boldsymbol{x}(t))\leq&V(\boldsymbol{x}(t_1^+))\exp(\theta(t-t_1^+))\\\leq&V(\boldsymbol{x}_0)\lambda\exp(\theta(t-t_0)),\\V(\boldsymbol{x}(t_2))\leq&V(\boldsymbol{x}_0)\lambda\exp(\theta(t_2-t_0));\end{aligned}$$

when $t_2<t\leq t_3$, we obtain

$$\begin{aligned}V(\boldsymbol{x}(t))\leq&V(\boldsymbol{x}(t_2^+))\exp(\theta(t-t_2^+))\\\leq&V(\boldsymbol{x}_0)\lambda\lambda\exp(\theta(t-t_0))\\=&V(\boldsymbol{x}_0)\lambda^2\exp(\theta(t-t_0)),\\V(\boldsymbol{x}(t_3))\leq&V(\boldsymbol{x}_0)\lambda^2\exp(\theta(t_3-t_0));\end{aligned}$$

generally, when $t_{k-1}<t\leq t_k$, for $k\in N$, we have

$$\begin{aligned}V(\boldsymbol{x}(t))\leq&V(\boldsymbol{x}(t_{k-1}^+))\exp(\theta(t-t_{k-1}^+))\\\leq&V(\boldsymbol{x}_0)\underbrace{\lambda\cdots\lambda}_{k-1}\exp(\theta(t-t_0))\\=&V(\boldsymbol{x}_0)\lambda^{k-1}\exp(\theta(t-t_0));\end{aligned}$$

when $t_k<t\leq t_{k+1}$, for $k\in N$, we have

$$\begin{aligned}V(\boldsymbol{x}(t))\leq&V(\boldsymbol{x}(t_k^+))\exp(\theta(t-t_k^+))\\\leq&V(\boldsymbol{x}_0)\underbrace{\lambda\cdots\lambda}_{k}\exp(\theta(t-t_0))\\=&V(\boldsymbol{x}_0)\lambda^k\exp(\theta(t-t_0)).\end{aligned}$$

Therefore, inequality (11) holds. QED.

Applying $\lambda^k\leq\exp(-\rho(t-t_0))$ to inequality (11), and letting $\upsilon=\dfrac{\rho-\theta}{2}>0$, we can obtain

$$\begin{aligned}V(\boldsymbol{x}(t))\leq&V(\boldsymbol{x}_0)\lambda^k\exp(\theta(t-t_0))\\\leq&V(\boldsymbol{x}_0)\exp(-\rho(t-t_0))\exp(\theta(t-t_0))\\=&V(\boldsymbol{x}_0)\exp(-2\upsilon(t-t_0)),\ t\geq t_0\geq 0.\end{aligned}$$

Arbitrarily choose a scalar $\delta>0$ and a vector $\boldsymbol{x}_0\in W$ such that $\|\boldsymbol{x}_0\|<\delta$, according to inequality (8), we can obtain

$$\begin{aligned}\lambda_{\min}(\boldsymbol{P})\|\boldsymbol{x}(t)\|^2\leq&V(\boldsymbol{x}(t))\\\leq&\lambda_{\max}(\boldsymbol{P})\|\boldsymbol{x}_0\|^2\exp(-2\upsilon(t-t_0))\\\leq&\lambda_{\max}(\boldsymbol{P})\delta^2\exp(-2\upsilon(t-t_0)),\\&t\geq t_0\geq 0.\end{aligned}$$

Let $k(\delta)=\sqrt{\dfrac{\lambda_{\max}(\boldsymbol{P})}{\lambda_{\min}(\boldsymbol{P})}}\delta$, such that $k(\delta)>0$, then

$$\begin{aligned}\|\boldsymbol{x}(t)\|\leq&\sqrt{\frac{\lambda_{\max}(\boldsymbol{P})}{\lambda_{\min}(\boldsymbol{P})}}\delta\exp\left(-\upsilon(t-t_0)\right)\\=&k(\delta)\exp\left(-\upsilon(t-t_0)\right),\quad t\geq t_0\geq 0.\end{aligned}$$

According to definition 2, system (5) is globally exponentially stable. QED.

Remark: If system (5) is globally exponentially stable, system (4) is globally exponentially stabilized by the impulsive control matrix $\boldsymbol{B}$ and constant gain matrix $\boldsymbol{F}_i$, that is, system (1) is said to be stabilized with an exponential decay rate by the hybrid impulsive and switched controller.

4. Conclusions

We have proposed exponential stabilization criteria for T–S fuzzy systems with impulsive effects and small delays. To our knowledge, this is the first study of the stability and stabilization of T–S fuzzy systems with impulsive effects and delayed state feedback. In the future work we shall focus on similar topics among the fuzzy systems, impulsive control systems and some delay differential equations.

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