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Finite-time dissipative control for singular T–S fuzzy Markovian jump systems under actuator saturation with partly unknown transition rates[☆]

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ABSTRACT

In this paper, we consider the problem of the static output feedback control for singular T–S fuzzy Markovian jump system with considering the influence of actuator saturation and partly unknown transition probabilities. Sufficient conditions are obtained to guarantee that the closed-loop is not only finite time bounded but also dissipative. The controller gain and the estimation of the domain of attraction can be solved by solving the linear matrix inequalities based optimization problem. Finally, numerical examples are illustrated for the effectiveness of the proposed method.

1. Introduction

Unlike switch systems [1], there exhibit switching between several subsystems. Many dynamical systems subject to random abrupt variations can be modeled by Markovian jump system (MJS), which is a special class of stochastic hybrid systems and initially introduced by Krasovskii and Lidskii [2]. It has been widely investigated in the past decades, and a great number of elegant results have been obtained [3–9]. The singular Markovian jump system (SMJS) has wide application in many engineering systems. Therefore, it is significant to study the problem of singular Markovian system. For example, H_∞ control [5,6] and H_∞ filter [7,8] were demonstrated for a class of singular Markovian jump system. Long et al. [9] discussed stochastic admissibility for a class of singular Markovian jump systems with mode-dependent time delays.

T–S fuzzy system [10–12] has attracted rapidly growing interest in the past decade, owing to its effective application in many industrial production processes, especially singular T–S fuzzy system [13,14]. In [15], Chadli et al. discussed the stability and stabilization for singular uncertain T–S fuzzy, and new sufficient conditions were obtained. Considering the stochastic singular fuzzy system, Zhao et al. [16], designed the H_∞ filter and Li et al. [17] discussed the problem of H_∞ control.

In many practical scenarios, it is questionable and costly to obtain all the precise mode transition information. Thus it is significant and challenging to study the cases when the transition rate matrix (TRM) is partly unknown. Till now, many researchers have paid attention to study SMJS with partly known TRM, for example, stability analysis and controller synthesize were discussed in [17–20]. And in [21], a sliding mode approach was proposed to robust stabilization of Markovian jump linear time-delay systems with generally incomplete transition rates.

In the aforementioned references, the stability analysis and control synthesis on fuzzy system focus on Lyapunov asymptotic stability, which is defined over an infinite time interval. However, in some practical process, the main attention may be related to the behavior of the dynamical systems over a fixed finite-time interval, that is finite time control. Finite time stability admits that the state does not exceed a certain bound during a fixed finite time interval. In many practical engineering applications, the finite time control is of practical significance, such as biochemistry reaction system, communication network system and robot control system. Recently, the study of finite time problem has received increasing attention, see for example [22–24].

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Finite-time dissipative control [25] and passive control [26] were discussed respectively. In [27,28], the problem of finite time H_∞ filtering was solved for a class of discrete-time Markovian jump systems with switching transition probabilities and partly unknown transition probabilities respectively.

On the other hand, in many application systems, actuator saturation is very ubiquitous. It is a physical phenomenon, and sometimes it may result in poor performance of the closed-loop systems. So, it is significant to consider the influence of actuator saturation. Some nonlinear subject to actuator saturation is complex to deal with, owing to the T–S fuzzy model, a class of nonlinear systems under the saturation nonlinearity can be solved handily and effectively [13,29,30]. For multiplicative noised nonlinear systems subject to actuator saturation and H_∞ performance constraints, fuzzy control problem was discussed in [31].

The study of dissipativity theory has captured comprehensive attention, since it is provided by using an output–output description regarding the system energy to study the performance of many nonlinear systems [32]. Using the T–S fuzzy model, many complex nonlinear problem can be simplified [33,34]. In [35], delay-dependent dissipative control for a class of non-linear system via Takagi–Sugeno fuzzy descriptor model with time delay was demonstrated.

In addition, some state variables may be difficult to measure and sometimes have no physical meaning and thus cannot be measured at all. In this situation, the static output feedback control is more suitable for practical application [36]. Based on the LMI technique, static output-feedback was designed for fuzzy power system stabilizers in [37]. However, till now, the design of finite time fuzzy static output feedback controller for singular Markovian jump system subject to actuator saturation and with partly unknown transition probabilities has not been demonstrated.

Motivated by the above discussion, in this paper, for singular fuzzy Markovian jump system with partly unknown TRM and subject to actuator saturation, the problem of finite time dissipative static output feedback control is considered. The contributions can be concluded as follows: (1) sufficient conditions are obtained to ensure the finite time bounded and dissipativity; (2) the static output feedback controller and the estimation of the domain of attraction are solved by LMI-based optimization problems; (3) examples are given to demonstrate the effectiveness of the proposed method; and (4) Fig. 5 plots the estimation of attractions of the three modes.

Notation: Throughout this paper, R^n denotes the n-dimensional Euclidean space, and $\mathrm{R}^{n\times m}$ is the set of real matrices. For $A\in\mathrm{R}^{n\times m}$, $A^{-1}$and A^T denote the matrix inverse and matrix transpose respectively. A^+ denotes the generalized inverse matrix of A. $\lambda(A)$ means the eigenvalue of A. For a real symmetric matrix $A\in\mathrm{R}^{n\times n}$, $A>0(A\geq 0)$ means that A is positive defined (positive semi-defined). $\mathrm{E}\{\cdot\}$ denotes the expectation operator. The symbol $*$ means the symmetric term in a symmetric matrix.

2. Problem formulation

Fix a probability space $(\Omega, F, \mathrm{P}(r_t))$, and consider a class of SMJS, which can be described by the following fuzzy model.

Plant rule i: IF $\varepsilon_1(t)$ is Λ_{i1} and $\varepsilon_2(t)$ is Λ_{i2} …$\varepsilon_p(t)$ is Λ_{ip}, THEN

$$\begin{aligned}
&E\dot{x}(t)=A_i(r_t)x(t)+B_i(r_t)sat(u(t))+B_{\omega i}(r_t)\omega(t),\\
&z(t)=C_i(r_t)x(t)+D_i(r_t)sat(u(t))+D_{\omega i}(r_t)\omega(t),\\
&y(t)=C_{yi}(r_t)x(t),\\
&x(t)=\phi(t),\quad i\in\Re\triangleq\{1,2,\ldots r\},
\end{aligned}\tag{1}$$

where $i\in\Re:=\{1,2\ldots r\}$, r is the number of IF–THEN rules. Λ_{ij} $(i\in\Re, j=1,2,\ldots l)$ are fuzzy sets, $\varepsilon_1(t),\varepsilon_2(t),\ldots,\varepsilon_l(t)$ are premise variables. $x(t)\in\mathrm{R}^n$ is the state vector, $y(t)\in\mathrm{R}^m$ is the measurement output. $E\in\mathrm{R}^n$ with $\mathrm{rank}E=r\leq n$, $\omega(t)\in\mathrm{R}^t$ is the disturbance which belongs to $L_2^t[0,\infty)$, and satisfies

$$\int_0^{\mathrm{T}}\omega^T(t)\omega(t)\leq d^2,\quad d\geq 0,\tag{2}$$

$u(t)\in\mathrm{R}^l$ is the control input, and $sat:\mathrm{R}^l\rightarrow\mathrm{R}^l$ is the standard saturation function defined as follows:

$$sat(u(t))=[sat(u_1(t)),\ldots,sat(u_l(t))]^T,$$

without loss of generality, $sat(u_i(t))=sign(u_i(t))\min\{1,|u_i(t)|\}$. Here the notation of $sat(\cdot)$ is abused to denote the scalar values and the vector valued saturation functions. $\phi(t)\in C_{n,\tau_2}$ is a compatible vector valued initial function. $\{r_t,t\geq 0\}$ is a continuous-time Markovian process with right continuous trajectories taking values in a finite set given by $\mathrm{S}=\{1,2,\ldots,N\}$ with the transition rates matrix (TRM) $\Pi\triangleq\{\pi_{pq}\}$ given by

$$P_r\{r_{t+h}=q|r_t=p\}=\begin{cases}\pi_{pq}h+o(h), & p\neq q\\ 1+\pi_{pq}h+o(h), & p=q\end{cases}$$

where $h>0$, $\lim_{h\to 0}\frac{o(h)}{h}=0$, and $\pi_{pq}\geq 0$, for $q\neq p$, is the transition rate from mode p to q at time $t+h$, which satisfies $\pi_{pp}=-\sum_{q=1,q\neq p}^{N}\pi_{pq}$, for all $p\in\mathrm{S}$.

In this paper, the transition rates or probabilities of the jumping process are considered to be partly accessed. For example, the TRM for system (1) may be expressed as

$$\Pi=\begin{bmatrix}\pi_{11} & \hat{\pi}_{12} & \ldots & \hat{\pi}_{1N}\\ \hat{\pi}_{21} & \hat{\pi}_{22} & \ldots & \pi_{2N}\\ \vdots & \vdots & \ddots & \vdots\\ \hat{\pi}_{N1} & \pi_{N2} & \ldots & \pi_{NN}\end{bmatrix},$$

where $\hat{\pi}_{pq}$ $(p,q\in\mathrm{S})$ represent the inaccessible elements. For notation clarity, $\forall p\in\mathrm{S}$, we denote $\mathrm{S}=\mathrm{S}_k^{(p)}\cup\mathrm{S}_{uk}^{(p)}$ with

$$\begin{aligned}
&\mathrm{S}_k^{(p)}\triangleq\{q|\pi_{pq}\text{ is known for }p\in\mathrm{S}\}\\
&\mathrm{S}_{uk}^{(p)}\triangleq\{q|\pi_{pq}\text{ is unknown for }p\in\mathrm{S}\}
\end{aligned}\tag{3}$$

Moreover, if $\mathrm{S}_k^{(p)}\neq\varnothing$, it can be described as $\mathrm{S}_k^{(p)}=\left\{k_1^{(p)},k_2^{(p)},\ldots,k_{m_p}^{(p)}\right\}$, $m_p\in\mathrm{S}$.

Here $k_q^{(p)}\in\mathrm{Z}^+$, $1\leq k_q^{(p)}\leq N$, $q=1,2,\ldots,m_p$, represents the qth known element for the set $\mathrm{S}_k^{(p)}$ in the TRM. Then we denote $\pi_k^{(p)}=\sum_{q\in\mathrm{S}_k^{(p)}}\pi_{pq}$.

For notional simplicity, in the sequel, for each possible $r_t=p\in\mathrm{S}$, the matrix $A_i(r_t),B_i(r_t),B_{\omega i}(r_t)$, $C_i(r_t),D_i(r_t),D_{\omega i}(r_t)$ are known mode-dependent constant matrices with appropriate dimensions, and they will be denoted by A_{pi},B_{pi} and so on.

Using singleton fuzzifier, product inference, and center-average defuzzifier, the global dynamics of the TS system (1) is described by the convex sum form:

$$\begin{aligned}
&E\dot{x}(t)=\sum_{i=1}^{r}\lambda_i(\varepsilon(t))[A_i(r_t)x(t)+B_i(r_t)sat(u(t))+B_{\omega i}(r_t)\omega(t)],\\
&z(t)=\sum_{i=1}^{r}\lambda_i(\varepsilon(t))[C_i(r_t)x(t)+D_i(r_t)sat(u(t))+D_{\omega i}(r_t)\omega(t)],\\
&y(t)=\sum_{i=1}^{r}\lambda_i(\varepsilon(t))[C_{yi}(r_t)x(t)],\\
&x(t)=\phi(t),\quad i\in\Re\triangleq\{1,2,\ldots,r\},
\end{aligned}\tag{4}$$

where $\varepsilon(t)=[\varepsilon_1(t),\varepsilon_2(t),\ldots,\varepsilon_l(t)]^T$, $\beta_i(\varepsilon(t))=\prod_{j=1}^{p}\Lambda_{ij}(\varepsilon_j(t))$ is the membership function of the system with respect to the ith pant rule.

Let $\lambda_i(\varepsilon(t))=\beta_i(\varepsilon(t))/\sum_{i=1}^{r}\beta_i(\varepsilon(t))$, then $\lambda_i(\varepsilon(t))\geq 0$ and $\sum_{i=1}^{r}\lambda_i(\varepsilon(t))=1$. In the sequel, we denote $\lambda_i(\varepsilon(t))$ by λ_i.