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Event-triggered reliable control for fuzzy Markovian jump systems with mismatched membership functions ☆

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ABSTRACT

The problem of event-triggered reliable control for fuzzy Markovian jump system (FMJS) with mismatched membership functions (MMFs) is addressed. Based on the mode-dependent reliable control and event-triggered communication scheme, the stability conditions and control design procedure are formulated. More precisely, a general actuator-failure is designed such that the FMJS is reliable in the sense of stochastically stable and reduce the utilization of network resources. Furthermore, the improved MMFs are introduced to reduce the conservativeness of obtained results. Finally, simulation results indicate the effectiveness of the proposed methodology.

1. Introduction

It is well known that sudden variations may involved in the practical systems, for example, sudden environmental changes and component failures. There systems can be represented as Markovian jump systems (MJSs) and the random jumps of MJSs are determined by a finite Markov process. Therefore, MJSs have been received an enormous number of attentions in the application of practical systems, such as engineering, economic and communication systems [1–3]. Many significant results about MJSs have been reported with the assumption that all the information on mode transitions are completely known. For instance the discrete-time case [4,5,40], and the continuous-time one [6,7]. However, it is difficult to precisely estimate all the transition probabilities (TPs) of a Markov chain. To relax the above assumption, the focus has been moved to the MJSs with partly unknown transition probabilities (PUTPs). A series of results have been devoted to the PUTPs for MJSs on stability analysis [8,9], stabilization [10,11], H_∞ control [12,13,40], distributed filtering [14,15], H_∞ filtering [16] and references therein.

It is well recognized that most complex industrial engineering and manufacturing process are nonlinear, Takagi–Sugeno (T–S) fuzzy modeling technique is a common method that allows describing a nonlinear system [17]. Up to now, many important results on the T–S fuzzy systems have been extensively investigated [18–21,38-39]. To obtain a constant positive definite matrix of quadratic Lyapunov function, the conventional Lyapunov function techniques have been introduced and many valuable results have been achieved [22,23]. It is worth mentioning that, the fuzzy controller considered in [22,23] with the aid of premise variables measurement. However, the aforementioned condition is impossible in the real network environment. The communication delays always exist in the data transmission from plant to controller, MMFs are neglected in [23]. In order to overcome the drawback of MMFs, asynchronous premises methods are proposed in [24–26] and less conservative criteria are obtained. It should be mentioned that, the controllers obtained in [27–29] are linear. The properties of MMFs are not fully considered in the previous studies about FMJSs with PUTPs.

On the other hand, the event-triggered technique is an efficient way to govern whether the sampling signals should be sent out, which has received widespread attentions. Compared with time-driven transmission framework, the event-triggered method can save the utilization of network bandwidth. For continuous-time systems, the event-triggered scheme (ETS) has been considered in [30–32]. However, the ETS has received little attention for discrete-time systems [33], not mentioned to the reliable

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controller. The performance of the controlled system can be ensured with the aid of the reliable controller against possible sensor failures and actuator [34–36]. It is important to design the ETS reliable control for discrete-time FMJSs.

Motivated by the above discussion, the event-triggered reliable control for a class of FMJS with MMFs is considered in this paper. The ETS is introduced to determine whether the newly sampled data should be sent out. Both the ETS and the actuator failure model are mode-dependent and characterized by the discrete-time Markov chain. A novel reliable controller is designed by using actuator faults and limited networked resources. Finally, an example is presented to demonstrate the effectiveness of the event-trigged reliable control scheme.

The paper is organized as follows: The notation and background is presented in Section 2. The main result is formulated in Section 3. In Section 4, the proposed method is simulated. Finally, the concluding remarks are considered in Section 5.

Notations: The notations throughout the paper are fairly standard. $\mathcal{R}^n$ represents the n dimensional Euclidean space, and $R^{m\times n}$ denotes the set of all $m\times n$ real matrices, $*$ stands the elements below the main diagonal of a symmetric block matrix. $\lambda_M(\cdot)$ and $\lambda_m(\cdot)$ represent the largest and smallest eigenvalue of given square matrix, respectively. diag$\{\ldots\}$ denotes the block diagonal matrix.

2. Notation and background

2.1. Physical plant

Consider a class of discrete-time T–S FMJSs. For each mode, the fuzzy model is described as follows.

Plant Rule I: IF $\varpi_1(k)$ is M_{i1}, $\varpi_2(k)$ is M_{i2}, …, and $\varpi_p(k)$ is M_{ip}, THEN

$$\begin{cases} x(k+1)=A_{i,r_k}x(k)+B_{i,r_k}u(k)+B^{w}_{i,r_k}\omega(k)\\ z(k)=C_{i,r_k}x(k)+D_{i,r_k}\omega(k)\end{cases}\tag{1}$$

where $i\in\mathcal{M}=\{1,2,\ldots,m\}$, and m is the number of IF-THEN rules; $\varpi_1(k)$, $\varpi_2(k),\ldots,\varpi_p(k)$ are the premise variables, and p is the number of these premise variables; $M_{ij}(j=1,2,\ldots,p)$ is the fuzzy set; $x_k\in\mathcal{R}^{n_x}$, $u(k)\in\mathcal{R}^{n_u}$, $z(k)\in\mathcal{R}^{n_z}$ and are plant state, control input, controlled output, respectively. $\omega(k)\in\mathcal{R}^{n_w}$ is the exogenous disturbance. $\{r_k,k\ge 0\}$ is a discrete-time Markov process taking values in a finite set $N=\{1,2,\ldots,N\}$ with mode TPs $\Pr(r(k+1)=q|r(k)=p)=\pi_{pq}$, where $\pi_{pq}\ge 0$, $\forall p,q\in\mathcal{N}$ and $\sum_{q=1}^{N}\pi_{pq}=1$; A_{i,r_k}, B_{i,r_k}, B^{w}_{i,r_k}, C_{i,r_k} and D^{w}_{i,r_k}, which are known real-valued matrix functions of the r_k, are real and constant. It is assumed that the premised variables do not depend on the input variables $u(k)$ explicitly.

By adopting a center-average defuzzifier, product-fuzzy inference, and a singleton fuzzifier, the global model of the discrete-time FMJS with time delays can be expressed as follows:

$$\begin{cases} x(k+1)=\sum_{i=1}^{s}h_i(\varpi(k))\left\{A_{i,r_k}x(k)+B_{i,r_k}u(k)+B^{w}_{i,r_k}\omega(k)\right\}\\ z(k)=\sum_{i=1}^{s}h_i(\varpi(k))\{C_{i,r_k}x(k)+D_{i,r_k}\omega(k)\}\end{cases}\tag{2}$$

where

$$\varpi(k)=[\varpi_1(k)\ \ \varpi_2(k)\ \ \cdots\ \ \varpi_p(k)],\quad h_i(\varpi(k))=\frac{\theta_i(\varpi(k))}{\sum_{i=1}^{s}\theta_i(\varpi(k))},$$

$$\theta_i(\varpi(k))=\prod_{j=1}^{p}M_{ij}(\varpi_j(k))$$

In (2), $h_i(\varpi(k))$ is the fuzzy basis function, and $M_{ij}(\varpi_j(k))$ is the grade of membership of $\varpi_j(k)$ in M_{ij}. Then, it can be seen that

$$\theta_i(\varpi(k))\ge 0,\quad i\in\mathcal{M},\quad\text{and}\quad\sum_{i=1}^{s}\theta_i(\varpi(k))>0$$

for all k. Therefore, we have

$$h_i(\varpi(k))\ge 0,\quad i\in\mathcal{M},\quad\text{and}\quad\sum_{i=1}^{s}h_i(\varpi(k))=1.$$

In this paper, the transition rates or probabilities of the jumping process are considered to be partly accessed. The transition probability matrix is defined by

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

where $\hat{\pi}_{pq}(p,q\in\mathcal{N})$ represents the inaccessible elements. For notation clarity, $\forall p\in\mathcal{N}$, we denote $\mathcal{N}=\mathcal{N}^p_k\cup\mathcal{N}^p_{uk}$ with

$\mathcal{N}^p_k=\{q|\pi_{pq}$ is known for $p\in\mathcal{N}\}$, $\mathcal{N}^p_{uk}=\{q|\pi_{pq}$ is unknown for $p\in\mathcal{N}\}$.

If $\mathcal{N}^p_k\ne\varnothing$, it can be described as

$$\mathcal{N}^p_k=\{\mathcal{K}_1,\mathcal{K}_2,\ldots,\mathcal{K}_{s_p},\},\quad\forall 1\le s_p\le N,$$

where $\mathcal{K}^p_s$ represents the jump mode q corresponding to known element located in the ith element of matrix Π.

Moreover, we denote $\pi^{+}_p=\sum_{q\in\mathcal{N}^p_k}\pi_{pq}$ in the following discussion.

2.2. Reliable control

When the actuators experience failures, we use $u^F(k)$ to describe the control signal sent from actuators and the control input of actuator fault can therefore be described as follows:

$$u^F(k)=\alpha_{r_k}u(k)\tag{3}$$

where α_{r_k} is the actuator fault matrix with

$$\begin{cases}\alpha_{r_k}=\mathrm{diag}\{\alpha_{1r_k},\ldots,\alpha_{n_g r_k}\}, & \underline{\alpha}_{r_k}\le\alpha_{r_k}\le\overline{\alpha}_{r_k},\\ \underline{\alpha}_{r_k}=\mathrm{diag}\left\{\underline{\alpha}_{1r_k},\ldots,\underline{\alpha}_{n_g r_k}\right\}\ge 0, & \overline{\alpha}_{r_k}=\mathrm{diag}\{\overline{\alpha}_{1r_k},\ldots,\overline{\alpha}_{r_k n_g}\}\le I\end{cases}\tag{4}$$

and the variables $\alpha_{ir_k}(i=1,2,\ldots,n_g)$ quantify the failures of the actuators. $\underline{\alpha}_{ir_k}$ and $\overline{\alpha}_{ir_k}$ serve as the lower and the upper bounds on α_{ir_k}, respectively.

Defining

$$\begin{aligned}\hat{\alpha}_{r_k}&=\mathrm{diag}\left\{\frac{\underline{\alpha}_{1r_k}+\overline{\alpha}_{1r_k}}{2},\ldots,\frac{\underline{\alpha}_{n_g r_k}+\overline{\alpha}_{n_g r_k}}{2}\right\}\\ \tilde{\alpha}_{r_k}&=\mathrm{diag}\left\{\frac{-\underline{\alpha}_{1r_k}+\overline{\alpha}_{1r_k}}{2},\ldots,\frac{-\underline{\alpha}_{n_g r_k}+\overline{\alpha}_{n_g r_k}}{2}\right\}\end{aligned}\tag{5}$$

the matrix α_{r_k} can be rewritten as

$$\alpha_{r_k}=\hat{\alpha}_{r_k}+\Delta_\alpha(k)=\hat{\alpha}_{r_k}+\mathrm{diag}\{\varrho_1(k),\ldots,\varrho_{n_g}(k)\}\tag{6}$$

where $\varrho_l(k)\ (l=1,2,\ldots,n_g)$ are certain scalars satisfying $|\varrho_l(k)|\le\frac{-\underline{\alpha}_{lr_k}+\overline{\alpha}_{lr_k}}{2}$.

Remark 1. It is reasonable that the actuator fault in current research is characterized by the discrete-time Markov chain r_k. The $r_k=p$ represents the r_kth fault mode and $p\in\mathcal{N}=\{1,2,\ldots,N\}$. If $N=1$, there exists only one fault mode is explicitly depicted in