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Nonfragile asynchronous control for fuzzy Markov jump systems with packet dropouts ☆

Yong Xu [a,b], Renquan Lu [a,b,*], Ke-Xia Zhou [a], Zuxin Li [a,c]

[a] School of Automation, Guangdong University of Technology, and Guangdong Key Laboratory of IoT Information Processing, Guangzhou 510006, China.
[b] The Key Lab for IOT and Information Fusion Technology of Zhejiang, the Institute of Information and Control, Hangzhou Dianzi University, Hangzhou 310018, China
[c] School of Engineering, Huzhou University, Huzhou, Zhejiang 313000, China.

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ABSTRACT

In this paper, the problem of passive control for fuzzy Markov jump systems with packet dropouts is studied, where Bernoulli processes are introduced to describe packet dropouts. A nonfragile asynchronous controller is designed not only to overcome the difficulty that the controller is unavailable to the information of the system mode but also to improve the robustness of the controller. Then sufficient condition is established to guarantee that the closed-loop system is mean-square stable and achieves the passivity. The controllers are derived by using the linear matrix inequality approach. Finally, the developed results are illustrated by a numerical example.

1. Introduction

Most of the actual systems are nonlinear, which brings a lot of difficulties to analyze the stability and design the controller. In order to overcome these problems, the T–S fuzzy model has been proposed, where the nonlinear systems are approximated by a set of linear systems [1]. It has become a bridge to connect the nonlinear systems and the linear systems such that some nonlinear systems can be handled by using the linear system methods [2]. In the past three decades, many researchers have studied the T–S fuzzy systems, such as the filter or the controller design for time-delay T–S fuzzy systems [3–5], stabilization and H_∞ performance analysis for networked T–S fuzzy systems [6–8], the fault detection filter design for T–S fuzzy systems [9,10] and so on.

Due to the fact that the random changes of the system structure and the parameters are unavoidable, the hybrid systems have become an important research topic. One of them is Markov jump systems, where a Markov chain is applied to govern the jumping conditions between different modes [11–14]. Recently, researchers have employed the T–S fuzzy approach to deal with discrete-time nonlinear Markov jump systems [15]. In [16], the T–S fuzzy model has be applied to handle the output feedback stabilization for Markov nonlinear systems. In [17], H_∞ control problem has been considered for networked Markov jump nonlinear systems based on T–S fuzzy model. However, for some constraints existing in the real systems, it is hard to obtain the information of the system mode to design the mode-dependent controller. Motivated by [18–20], how to design the asynchronous controller for Markov jump fuzzy systems becomes a critical problem, which has not been fully investigated.

NCS is an important and interesting problem since they possess many advantages, such as flexibility in system implementation, low cost of installation, and facilitating system maintenance [21–26]. However, the characteristic of the shared communication channels of the NCSs always causes packet dropouts, which not only reduce the systems performance, but also lead the systems to be unstable. It has been proved that the systems cannot be stabilized if the packet dropout rate exceeds a threshold [27]. Recently, many results concerning packet dropouts for the fuzzy systems have been proposed. In [28,29], H_∞ filter and H_∞ controller have been designed for the fuzzy systems with packet dropouts, respectively. What we have to point out is that designing the nonfragile controller for the networked T–S fuzzy systems is an important and meaningful problem, especially, in the practical situations.

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* Corresponding author at: School of Automation, Guangdong University of Technology, and Guangdong Key Laboratory of IoT Information Processing, Guangzhou 510006, China.

E-mail addresses: xuyong809@163.com (Y. Xu), rqlu@hdu.edu.cn (R. Lu).

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Passive control has been considered by a number of researchers, since it has been widely applied to deal with NCSs, robotic vehicles, neural networks and so on [30,31]. In [32], the passive output feedback controller has been designed for Markov jump systems with multiple disturbance. In [33], the passive control architecture has been proposed for the NCSs, which was sensitive to the network induced influences. In [34], the robust passive control for the T–S fuzzy systems with randomly occurring uncertainties has been considered. However, the problem of passive control for fuzzy Markov jump systems has not been fully studied yet.

This paper studies the passive control for discrete-time fuzzy Markov jump systems with packet dropouts. Sufficient condition is derived to guarantee that the closed-loop system is mean-square stable and achieves the passive performance. The main contributions of this paper can be summarized as follows:

1. For the existing works of fuzzy Markov jump systems, they assume that the controller is available to the information of the system mode [16,17]. In this paper, the asynchronous controller is firstly designed for Markov jump fuzzy systems, which is less conservative than the mode-independent one [35].
2. For the remote control of the fuzzy systems, the controllers are frequently influenced by the environments which was not considered by [6,9]. In order to improve the robustness of the controller, the nonfragile controller is firstly proposed for fuzzy Markov jump systems.

Notation: In this paper, real numbers, Euclidean space with n dimension, and $n\times m$ real matrices are denoted by $\mathbb{R}$, $\mathbb{R}^n$ and $\mathbb{R}^{n\times m}$, respectively. M^T stands for the transposition of the matrix M. Diagonal matrices are denoted by $diag\{\cdot\}$. For a stochastic variable $\mathbf{x}(k)$, its probability and expectation are denoted by $\mathbb{P}\{\mathbf{x}(k)\}$ and $\mathbb{E}\{\mathbf{x}(k)\}$, respectively. $X>0$ stands for a positive definite matrix. $l_2[0,\infty)$ denotes the space of square summable infinite sequence. The term induced by symmetry is denoted by $*$.

2. Problem formulation

2.1. System description

A nonlinear discrete-time Markov jump system is considered which can be represented by the following T–S Fuzzy model:

Plant Rule i: IF $\varrho_1(k)$ is δ_{i1} and $\varrho_2(k)$ is δ_{i2} and $\cdots$ and $\varrho_p(k)$ is δ_{ip}. THEN

$$\begin{cases}\mathbf{x}(k+1)=A_{i\tau(k)}\mathbf{x}(k)+B_{i\tau(k)}\mathbf{u}(k)+E_{i\tau(k)}\boldsymbol{\nu}(k)\\ \mathbf{z}(k)=C_{i\tau(k)}\mathbf{x}(k)+D_{i\tau(k)}\mathbf{u}(k)+F_{i\tau(k)}\boldsymbol{\nu}(k)\end{cases}\tag{1}$$

where $i\in\Upsilon\triangleq\{1,2,\ldots,r\}$, r is the number of IF–THEN rules, δ_{ij} are the fuzzy sets, and $\varrho_1(k)$, $\varrho_2(k),\ldots,\varrho_p(k)$ are the premise variables. $\mathbf{x}(k)\in\mathbb{R}^n$ is the system state vector, $\mathbf{u}(k)\in\mathbb{R}^m$ is the system input vector, $\mathbf{z}(k)\in\mathbb{R}^q$ is the controlled output. The exogenous disturbance noise $\boldsymbol{\nu}(k)\in\mathbb{R}^l$ belongs to $l_2[0,\infty)$. $A_{i\tau(k)}\in\mathbb{R}^{n\times n}$, $B_{i\tau(k)}\in\mathbb{R}^{n\times m}$, $E_{i\tau(k)}\in\mathbb{R}^{n\times l}$, $C_{i\tau(k)}\in\mathbb{R}^{q\times n}$, $D_{i\tau(k)}\in\mathbb{R}^{q\times m}$, $F_{i\tau(k)}\in\mathbb{R}^{q\times l}$ are known constant real matrices. The subscript $\tau(k)\in\Psi\triangleq\{1,2,\ldots,N\}$ is a Markov chain with the transition probability matrix $\Omega=[\pi_{\sigma\upsilon}]$ given by

$$\mathbb{P}\{\tau(k+1)=\upsilon\,|\,\tau(k)=\sigma\}=\pi_{\sigma\upsilon}$$

where $0\le\pi_{\sigma\upsilon}\le1$, $\forall\sigma,\upsilon\in\Psi$ and $\sum_{\upsilon=1}^{N}\pi_{\sigma\upsilon}=1$, $\forall\sigma\in\Psi$.

Then, the resulting fuzzy Markov jump system can be written as,

$$\begin{cases}\mathbf{x}(k+1)=\sum_{i=1}^{r}h_i(\varrho(k))\{A_{i\tau(k)}\mathbf{x}(k)+B_{i\tau(k)}\mathbf{u}(k)+E_{i\tau(k)}\boldsymbol{\nu}(k)\}\\ \mathbf{z}(k)=\sum_{i=1}^{r}h_i(\varrho(k))\{C_{i\tau(k)}\mathbf{x}(k)+D_{i\tau(k)}\mathbf{u}(k)+F_{i\tau(k)}\boldsymbol{\nu}(k)\}\end{cases}\tag{2}$$

where

$$h_i(\varrho(k))=\frac{\rho_i(\varrho(k))}{\sum_{j=1}^{r}\rho_j(\varrho(k))},\quad \rho_i(\varrho(k))=\prod_{j=1}^{p}\delta_{ij}(\varrho_j(k))$$

with $\delta_{ij}(\varrho_j(k))$ showing the grade of membership of $\varrho_j(k)$ in δ_{ij}. Then, it is not hard to see that $\rho_i(\varrho(k))\ge0,\forall k$, which implies $h_i(\varrho(k))\ge0$, and $\sum_{i=1}^{r}h_i(\varrho(k))=1,\ \forall k$. For the sake of brevity, in the sequel, we use h_i and h_i^+ to represent $h_i(\varrho(k))$ and $h_i(\varrho(k+1))$, respectively.

2.2. Nonfragile asynchronous controller

In this subsection, the following nonfragile asynchronous controller is presented:

Controller Rule i: IF $\varrho_1(k)$ is δ_{i1} and $\varrho_2(k)$ is δ_{i2} and $\cdots$ and $\varrho_p(k)$ is δ_{ip}. THEN

$$\hat{\mathbf{u}}(k)=\overline{K}_{i\theta(k)}\hat{\mathbf{x}}(k)\tag{3}$$

where

$$\overline{K}_{i\theta(k)}=K_{i\theta(k)}+M_{i\theta(k)}\Delta(k)N_{i\theta(k)}\tag{4}$$

with known matrices $M_{i\theta(k)}\in\mathbb{R}^{m\times n}$, and $N_{i\theta(k)}\in\mathbb{R}^{n\times n}$, $\Delta(k)\in\mathbb{R}^{n\times n}$ satisfies $\Delta(k)^T\Delta(k)\le I$. $\hat{\mathbf{x}}(k)\in\mathbb{R}^n$ denotes the controller input, $\hat{\mathbf{u}}(k)\in\mathbb{R}^m$ stands for the controller output, and $K_{i\theta(k)}\in\mathbb{R}^{m\times n}$ are the controller gains which have to be designed. The subscript $\theta(k)\in\Phi\triangleq\{1,2,\ldots,M\}$ is a Markov chain with the transition probability matrix $\Gamma^{\tau(k+1)}=\left[\psi_{\iota\kappa}^{\tau(k+1)}\right]$ given by

$$\mathbb{P}\{\theta(k+1)=\kappa\,|\,\theta(k)=\iota\}=\psi_{\iota\kappa}^{\tau(k+1)}$$

where $0\le\psi_{\iota\kappa}^{\tau(k+1)}\le1,\ \forall\iota,\kappa\in\Phi$ and $\sum_{\kappa=1}^{M}\psi_{\iota\kappa}^{\tau(k+1)}=1,\ \forall\iota\in\Phi$. Then, the form of the controller can be described by

$$\hat{\mathbf{u}}(k)=\sum_{i=1}^{r}h_i\overline{K}_{i\theta(k)}\hat{\mathbf{x}}(k).\tag{5}$$

2.3. Packet dropouts

In networked environments, the controller inputs are no longer equal to the measured states. At the same time, the inputs of the plant are not equivalent to the controller outputs as well, that is

$$\begin{cases}\hat{\mathbf{x}}(k)=\xi_1(k)\mathbf{x}(k)\\ \mathbf{u}(k)=\xi_2(k)\hat{\mathbf{u}}(k)\end{cases}\tag{6}$$

where $\xi_1(k),\xi_2(k)\in\{0,1\}$ are independent Bernoulli processes, which are used to describe packet dropouts. We introduce another process $\zeta(k)$ defined as $\zeta(k)\triangleq\xi_1(k)\xi_2(k)$, where $\zeta(k)=1$ when both $\xi_1(k)=1$ and $\xi_2(k)=1$, and $\zeta(k)=0$, otherwise. A natural assumption on the sequence $\zeta(k)$ is that

$$\begin{cases}\mathbb{P}\{\zeta(k)=1\}=\zeta\\ \mathbb{P}\{\zeta(k)=0\}=1-\zeta.\end{cases}\tag{7}$$

Based on this, we have

$$\mathbf{u}(k)=\zeta(k)\sum_{i=1}^{r}h_i\overline{K}_{i\theta(k)}\mathbf{x}(k).\tag{8}$$