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Brief Papers

Adaptive event-triggered $H\infty$ filtering for T-S fuzzy system with time delay

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ABSTRACT

This paper is concerned with adaptive event-triggered H_∞ filter design for a class of T-S fuzzy systems with time delay. Firstly, an adaptive event-triggered scheme is introduced, which can adaptively adjust the communication threshold to save the limited communication resource. Secondly, a T-S fuzzy model is applied to approximate the nonlinear dynamics of the plant. By using Lyapunov function, sufficient conditions for the existence of the desired filter are established in terms of linear matrix inequalities such that the filtering error dynamics is locally mean square asymptotically stable. Then, the explicit expression is provided for the designed filter parameters. Finally, a simulation example is employed to illustrate the design method.

1. Introduction

Many industrial systems exhibit severe nonlinear characteristics, which usually make the stability analysis and design more difficult [1–3]. On modeling nonlinear behavior, Takagi-Sugeno (T-S) fuzzy models are qualified to represent a class of nonlinear dynamic systems. Much attention has been attracted by T-S fuzzy system, which can be analyzed by many methods of conventional linear systems and described by a family of IF-THEN rules to approximate any continuous functions [4–7]. As is well known, many efforts have been paid to T-S fuzzy system [8–17]. In [15], the paper is concerned with the problem of robust H_∞ control for uncertain T-S fuzzy systems with interval time-varying delay, of which the delay is assumed to be a time-varying function belonging to an interval. In [16], the author investigates the problems of state estimation for nonlinear positive systems based on T-S fuzzy model. The authors in [17] are concerned with event-triggered fuzzy control design for a class of discrete-time nonlinear networked control systems (NCSs) with time-varying communication delays. Specially, the filtering problem have been widely investigated over the past years [18–22]. In [19], reliable H_∞ filter design for a class of T-S fuzzy systems with stochastic sensor faults under an event-triggered scheme has been investigated. In [20], the robust and reliable H_∞ filter design for a class of nonlinear NCSs with random sensor faults via T-S fuzzy model have been investigated. In [22], the authors investigate a combined event-triggered communication scheme and H_∞ fuzzy filter co-design method for a class of nonlinear networked control system.

Compared with the periodic sampling method, the event-triggered scheme could not only reduce the burden of the communication but also preserve the desired properties of the ideal continuous state feedback system, such as stability and convergence. The outstanding application on event-triggered scheme could be found in many literatures [24,23,25–27,29]. For example, in [23], the paper is concerned with the control design problem of event-triggered networked systems with both state and control input quantizations. In [25], authors investigate the reliable control design for networked control system under event-triggered scheme. The author in [26] investigated the event-triggered H_∞ controller design problem for nonlinear networked control systems (NCSs) with time delay and uncertainties. In [27], the problem of event-triggered fuzzy filtering is investigated for a class of NCSs. The authors in [29] proposed a novel event-triggered scheme and constructed a delay system model for the analysis, then they derived the criteria for stability with an H_∞ norm bound and criteria for co-designing both the feedback gain and the trigger parameters. As we all know, the network-induced delays, packet dropouts and disorder are mainly caused by the limited network bandwidth. As communication bandwidth is scarce in a shared communication channel, one obvious problem when considering NCSs is whether there is sufficient communication bandwidth to feedback information to the controller and then

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send the control commands to the actuators and the plants [30,31]. However, the above proposed event-triggered scheme are based on the inequality $e_k^T(t)\Phi e_k(t) > \delta x^T(t_{k+1})\Phi x(t_{k+1})$, where Φ is a symmetric positive definite matrix, δ is a positive constant. Since the trigger parameter is a constant, it cannot adjust the sampling interval dynamically, which can waste the communication resources. Therefore, to mitigate the unnecessary waste of computation and communication resources in the conventional event-triggered scheme while keeping the control performance, the adaptive event-triggered scheme has beenproposed. This is also the motivation of this work.

In this paper, an adaptive event-triggered scheme has been introduced to a T-S fuzzy system with time delay. The adaptive scheme shows an effective way to keep balance for the system control performance and network communication bandwidth burden. An algorithm is presented to find the adaptive threshold instead of a pre-given constant to achieve good performance of the proposed adaptive scheme, which is the challenge of this work. Moreover, the filtering problem for T-S fuzzy system is investigated under the adaptive event-triggered scheme. By using Lyapunov functional approach, a sufficient condition for the existence of the desired filter is established in terms of linear matrix inequalities. Finally, a simulation example is provided to illustrate the effectiveness of the proposed method.

Notation: The superscript "T" represents matrix transposition, $\mathbb{R}^n$ and $\mathbb{R}^{n\times m}$ denote the n-dimensional Euclidean space, and the set of $n\times m$ real matrices; $\|\cdot\|$ represents the Euclidean vector norm or the induced matrix 2-norm as appropriate; I is the identity matrix of appropriate dimension.

$$\begin{bmatrix} A & * \\ B & C \end{bmatrix}$$

denote a symmetric matrix, where $*$ denotes the entries implied by symmetry, for a matrix B and two symmetric matrices A and C. The notation $X>0$ (respectively, $X\geq 0$), for $X\in\mathbb{R}^{n\times n}$ means that the matrix X is real symmetric positive definite (respectively, positive semi-definite).

2. Problem statement and preliminaries

Consider the following nonlinear system represented by the following T-S fuzzy system with r plant rules. Plant rule R^i: IF $\theta_1(t)$ is ${W_1}^i$ and $\cdots$ and $\theta_g(t)$ is ${W_g}^i$, THEN

$$\begin{cases} \dot{x}(t)=A_i x(t)+A_{di}x(t-\tau(t))+A_{\omega i}\omega(t) \\ y(t)=C_i x(t) \\ z(t)=L_i x(t) \end{cases} \tag{1}$$

where r is the number of IF-THEN rules, $\theta_1(t),\theta_2(t),\ldots,\theta_g(t)$ are the premise variables, $x(t)\in\mathbb{R}^n$, $y(t)\in\mathbb{R}^m$ and $z(t)\in\mathbb{R}^p$ are the state vector, output vector and the signal to be estimated, respectively. A_i, A_{di}, $A_{\omega i}$, C_i, L_i are parameter matrices with appropriate dimensions, $\omega(t)\in L_2[0,\infty)$ denotes the exogenous disturbance signal, $\tau(t)$ is a time-varying delay taking values on the interval $[\tau_m,\tau_M]$, where τ_m and τ_M are positive real numbers.

By using center-average defuzzifier, product interference and singleton fuzzifier, the obtained fuzzy system (1) is inferred as follows:

$$\begin{cases} \dot{x}(t)=A(t)x(t)+A_d(t)x(t-\tau(t))+A_\omega(t)\omega(t) \\ y(t)=C(t)x(t) \\ z(t)=L(t)x(t) \end{cases} \tag{2}$$

where $A(t)=\sum_{i=1}^r h_i A_i$, $A_d(t)=\sum_{i=1}^r h_i A_{di}$, $A_\omega(t)=\sum_{i=1}^r h_i A_{\omega i}$, $C(t)=\sum_{i=1}^r h_i C_i$, $L(t)=\sum_{i=1}^r h_i L_i$. h_i is the abbreviation for $h_i(\theta(t))$, $h_i(\theta(t))=\frac{\mu_i(\theta(t))}{\sum_{i=1}^r \mu_i(\theta(t))}$, $\mu_i(\theta(t))=\prod_{j=1}^g W_j^i(\theta_j(t))$, $W_j^i(\theta_j(t))$ is the grade membership value of $\theta_j(t)$ in ${W_j}^i$ and $h_i(\theta(t))$ satisfies $h_i(\theta(t))\geq 0$, $\sum_{i=1}^r h_i(\theta(t))=1$. For notational simplicity, we use h_i to represent $h_i(\theta(t))$.

The purpose of this paper is to design a H_∞ fuzzy filter for system (2), the following time-varying filter structure is proposed:

$$\begin{cases} \dot{x}_f(t)=A_{fi}x_f(t)+B_{fi}\hat{y}(t) \\ z_f(t)=C_{fi}x_f(t) \end{cases} \tag{3}$$

where $x_f(t)\in R^n$ is the filter state vector, $z_f(t)\in R^p$ the estimation of $z(t)$, $\hat{y}(t)$ is the real input of the filter. The matrices $A_{fi}\in R^{n\times n}$, $B_{fi}\in R^{n\times m}$, $C_{fi}\in R^{p\times n}$ are to be determined.

The defuzzified output of (3) is referred by

$$\begin{cases} \dot{x}_f(t)=A_f(t)x_f(t)+B_f(t)\hat{y}(t) \\ z_f(t)=C_f(t)x_f(t) \end{cases} \tag{4}$$

where $A_f(t)=\sum_{i=1}^r h_i A_{fi}$, $B_f(t)=\sum_{i=1}^r h_i B_{fi}$, $C_f(t)=\sum_{i=1}^r h_i C_{fi}$.

Remark 1. In traditional filtering problem, the effect of the communication network can be neglected, thus $\hat{y}(t)=y(t)$. However, in networked control systems, the existence of network-induced delays should be take into account. We have $\hat{y}(t)\neq y(t)$ in this paper.

The sensor sample the measurement output $y(t)$ with the regular sampling period in Fig. 1, which leads to transmit many unnecessary signals, reduce bandwidth utilization and increase consumption of limited energy of wireless sensor nodes because every sampled-signal must be transmitted to a fuzzy filter through a network channel. In order to mitigate the burden of communication and prolong the lifetime of wireless sensor nodes in Fig. 1, an adaptive event generator is attached to the sensor, which is used to determine whether or not the current sampled measurement $y(t)$ should be transmitted. We use kh and $t_k h$ to represent the sampling instants and the triggered instants, respectively, where h is the sampling period. Specifically, once $t_k h$ is transmitted, the next triggered instant is determined by

$$\begin{aligned} t_{k+j}h=t_k h+\min\{nh\,|\,[y(t_{k+j}h)-y(t_k h)]^T\Phi[y(t_{k+j}h)-y(t_k h)] \\ >\delta(t_{k+j}h)y^T(t_{k+j}h)\Phi y(t_{k+j}h)\} \end{aligned} \tag{5}$$

where Φ is a symmetric positive definite matrix, $\delta(t)\in[0.1,0.5]$. nh means the sampling instants between the current transmitted sampling instant t_k and the future transmitted sampling instant t_{k+j}. The trigger parameter $\delta(t)$ in the adaptive event-triggered scheme is not a constant, which presents a differential function

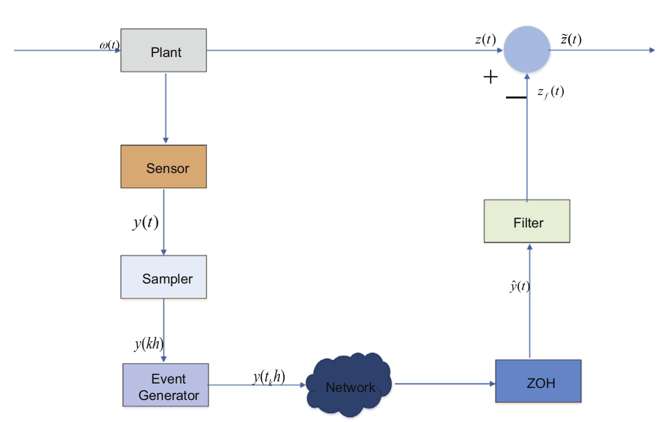

Fig. 1. A typical filtering for networked control system with adaptive event triggered scheme.