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Multi-instant fuzzy control design of nonlinear networked systems with data packet dropouts

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ABSTRACT

In this study, the so-called multi-instant fuzzy control design is discussed for a class of nonlinear networked systems with unreliable communication channels. Different from most existing results in the references, we aim to design a new multi-instant fuzzy controller such that the variation information between two fore-and-aft normalized fuzzy weighting functions is considered in the process of control design. Based on the above effort, a class of slack variable technique that is fit for the multi-instant case with higher efficiency as well is applied by extending some key matrix transform results. Finally, some simulation results are employed to illustrate the superiority of the proposed approach.

1. Introduction

During the past several decades, the Takagi–Sugeno (T–S) fuzzy model [1] has attracted great attention because of its theoretical and practical significance in coping with the analysis/synthesis problems of nonlinear systems. Under the parallel distribution compensation framework, the well-developed linear system theory can be easily extended to control designs of nonlinear systems. As a result, a rich body of important methods have been reported in the literature. To mention a few as follows, the stability analysis of continuous/discrete-time T–S fuzzy systems in [2–5], the filtering designs in [6–9] while the fault detection problems in [10,11], model reduction problems in [12,13], state/output-feedback control designs in [14–16], fuzzy control designs of hyperbolic PDE systems in [17,18], and fuzzy adaptive neural network tracking control designs in [19–24]. For more details on the same or similar topics, see the above literature and the references therein. Even though the underlying approaches are promising, they are still somewhat conservative and leave plenty of room for further improvement in the future.

On another related frontier research area, it should be noted that all the aforementioned results are valid under an implicit assumption that the signals that exist in the underlying T–S fuzzy control systems can be directly feedback to the destination nodes (e.g., the controller node or the actuator note) without involving either time delays or packet losses [25]. Actually, the above assumption is difficult to be ensured in a spatially distributed control system where data transmission is transferred through a communication network [26]. As far as the network-induced delay is concerned, fruitful results have been derived in recent years, such as, fuzzy model-based robust networked control [27], decentralized networked control of networked teleoperation system with time-varying delay [29,30], communication delay distribution dependent-type networked control designs [28,31,32], etc. Unfortunately, the communication between the physical plant and controller is unhealthy, e.g., the signals transmitted from the plant always arrive at the controller with some information losses [33]. In view of such related problems, a lot of featured results concerning NCSs were reported (see for example, [34–37] and references therein). To mention a few here, the basis-dependent Lyapunov function has been applied in [25,38,39] with the purpose of reducing the conservatism that comes from the previous usage of the common Lyapunov function. Anyway, employing the so-called basis-dependent technique and its extensions, it is impossible to obtain design conditions in terms of linear matrix inequalities (LMIs) in [25,38]. As an alternative, a bank of LMI-based results have been given in [39]. Nevertheless, its complexity (the number of LMI constraints and slack variables) is, of course, higher and this leads to much more computational burden with actual LMI solvers. As this limitation still exists, how to derive more efficient LMI-based design conditions becomes an interesting problem and this fact motivates us to carry the following study.

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Motivated by the aforementioned analysis, the problem of relaxed control design of discrete-time T–S fuzzy control systems under unreliable communication channels is studied in this paper. The key contributions of this study are summarized as: different from the most results in the literature, we aim to design a new multi-instant fuzzy controller such that the variation information between two fore-and-aft normalized fuzzy weighting functions is considered in the process of control design. Based on the above effort, a class of slack variable technique that is fit for the multi-instant case with higher efficiency as well is applied by extending some key matrix transform results. Finally, some simulation results will be employed to illustrate the superiority of the proposed results.

The rest of this paper is organized as follows. Section 2 gives preliminaries and problem descriptions. In Section 3, the main result is derived. The simulation study is given in Section 4 and followed by Section 5 which concludes this study.

2. Preliminaries and problem descriptions

As described in [38], the framework of nonlinear networked systems with unreliable communication channels is illustrated by Fig. 1, where the physical plant is represented based on the T–S fuzzy model. Usually, the unreliable communications include both the up-channel (from controller to physical plant) and the down-channel (from physical plant to controller) [38]. Employing the fuzzy modeling method given by [1], a set of T–S fuzzy rules is applied to represent the nonlinear control system:

Plant rule i: IF $z_1(t)$ is ${F_1}^i$, and $z_2(t)$ is ${F_2}^i$, …, and $z_p(t)$ is ${F_p}^i$, THEN

$$x(t+1)=A_i x(t)+B_i u(t),\quad i\in\{1,2,\ldots,r\}$$

where $x(t)\in\mathbb{R}^{n_1}$ stands for the system state vector, $u(t)\in\mathbb{R}^{n_2}$ stands for the control input vector, $z(t)=(z_1(t),\ldots,z_p(t))^T$ represents the fuzzy premise variables vector.

Afterwards, the overall T–S fuzzy model can be inferred as follows:

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

where $h_i(z(t))$ denotes the ith normalized fuzzy weighting function.

In nature, the actual data loss in the communication channels is produced along two directions, i.e., one is from the sensor to the controller, and the other one is from the controller to the actuator. In other words, the measurement value of the plant is no longer equivalent to the input value of the controller, and the output value of the controller is no longer equivalent to the input value of the plant [38]. In general, the data loss phenomena are modeled by employing the Bernoulli distributed white sequence like in [38]

$$x(t+1)=\sum_{i=1}^{r} h_i(z(t))(A_i x(t)+e(t)B_i u(t))$$

$$=\sum_{i=1}^{r} h_i(z(t))(A_i x(t)+(\bar{e}+\tilde{e}(t))B_i u(t)),\tag{2}$$

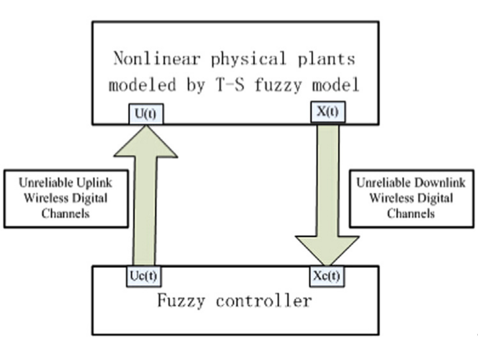

Fig. 1. Framework of networked systems with unreliable communication links.

and we have $\{e(t)\}$ belongs to a Bernoulli distributed white sequence, $E(e(t))=\bar{e}$, $\tilde{e}(t)=e(t)-\bar{e}$, $E(\tilde{e}(t))=0$, $E(\tilde{e}(t)\tilde{e}(t))\ =\bar{e}(1-\bar{e})$.

Next, an existing definition is introduced here which is borrowed from [38].

Definition 1 (*Gao et al.* [38]). For any initial condition $x(0)$, the closed-loop system (2) is considered to be stochastically stable in the mean square if, there exists one positive definite matrix W such that the following inequality is satisfied:

$$E\left\{\sum_{j=0}^{\infty}|x(j)|^2\,|\,x(0)\right\}<x^T(0)Wx(0).\tag{3}$$

Specially, a bank of required definitions about homogeneous polynomials are offered in detail, which are borrowed from [15] and the references therein.

Firstly, one defines the set Δ_r as $\Delta_r=\{\alpha\in\mathbb{R}^r;\ \sum_{i=1}^{r}\alpha_i=1;\alpha\geq 0\}$. Then, one defines $\alpha_1^{k_1}\alpha_2^{k_2}\cdots\alpha_r^{k_r}$, $\alpha\in\Delta_r, k_i\in\mathbb{Z}_+$, $i=1,2,\ldots,r$ as the monomials, $k=k_1k_2\cdots k_r$. $P_k\in\mathbb{R}^{n\times n}$, $\forall k\in\mathcal{K}(g)$ are a set of matrix-valued coefficients. $\mathcal{K}(g)$ denotes the set of r-tuples collected by all possible combinations of nonnegative integers $k_i, i=1,2,\ldots,r$, such that $k_1+k_2+\cdots+k_r=g$. Mathematically, we can define $k\geq k'$ if $k_i\geq k'_i, (i=1,\ldots,r)$ for two r-tuples k and k'. The conventional operations of summation, $k+k'$, and subtraction, $k-k'$ (whenever $k\geq k'$), are defined as componentwise. For $k\in\mathcal{K}(g)$, one defines $\mathcal{A}(k)=\{i\,|\,k_i\geq 1, i\in\{1,\ldots,r\}\}$. Another two key definitions of the coefficient $\pi(k)$ and a r-tuple $\chi_i\in\mathcal{K}(1)$ are provided as follows:

$$\pi(k)=(k_1!)\times\cdots\times(k_r!),\quad \chi_i=0\cdots0\underbrace{1}_{i-\text{th}}0\cdots0.\tag{4}$$

Then, the authors use the same abbreviations as in [39] in the rest of the paper:

$$\begin{cases} h_i(t)=h_i(z(t)), \quad h(t)=[h_1(t),\ldots,h_r(t)]^T,\\ h^k=h_1(t)^{k_1}h_2(t)^{k_2}\cdots h_r(t)^{k_r}, \quad h_i(t-j)=h_i(z(t-j)),\\ h(t-j)=[h_1(t-j), \quad h_2(t-j),\ldots,h_r(t-j)]^T,\\ h(t-j)^k=h_1(t-j)^{k_1}h_2(t-j)^{k_2}\cdots h_r(t-j)^{k_r}. \end{cases}$$

Lemma 1 (*Xie et al.* [39]). *For two symmetric matrices $P>0$ and P_+, the inequality*

$$\begin{bmatrix}A_1^T A_2^T\end{bmatrix}\begin{bmatrix}P_+ & 0\\ 0 & P_+\end{bmatrix}\begin{bmatrix}A_1\\ A_2\end{bmatrix}-P<0$$

always holds in true, if there is a matrix G such that the following inequality is satisfied:

$$\begin{bmatrix}P & (*) & (*)\\ GA_1 & G+G^{\mathrm{T}}-P_+ & (*)\\ GA_2 & 0 & G+G^{\mathrm{T}}-P_+\end{bmatrix}>0.$$

Property 1 (*Xie et al.* [15]). *Based on the above definitions about homogeneous matrix polynomials, the following equality evidently holds in true*:

$$\sum_{\left(\substack{k\in\mathcal{K}(g),i\in\mathcal{A}(k),\ j\in\mathcal{A}(k),\\ k-\chi_i-\chi_j\geq 0,i\in\{1,\ldots,m+1\}}\right)} h(t)^k E^{ij}_{(k-\chi_i-\chi_j)}=\sum_{\left(\substack{k\in\mathcal{K}(g-2),1\leq i\leq r,\\ 1\leq j\leq r}\right)} h(t)^k h_i(t)h_j(t)E^{ij}_k,\tag{5}$$

and the value of g is a positive integer with $g>2$.

3. Main results

Different from the recent result in the literature [39], we aim to design a lighter multi-instant fuzzy controller and to find a way