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Relaxed fuzzy control synthesis of nonlinear networked systems under unreliable communication links

Xiang-Peng Xie[a,*], Dong Yue[a], Chen Peng[b]

[a] Institute of Advanced Technology, Nanjing University of Posts and Telecommunications, Nanjing 210003, PR China
[b] School of Mechatronic Engineering and Automation, Shanghai University, 200072, PR China

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ABSTRACT

This paper proposes relaxed conditions for control synthesis of discrete-time Takagi–Sugeno fuzzy control systems under unreliable communication links. To widen the applicability of the fuzzy control approach under network environments, a novel fuzzy controller, which is homogenous polynomially parameter-dependent on both the current-time normalized fuzzy weighting functions and the multi-steps-past normalized fuzzy weighting functions, is provided to make much more use of the information of the underlying system. Moreover, a new kind of slack variable approach is also developed and thus the algebraic properties of these multi-instant normalized fuzzy weighting functions are collected into some augmented matrices. As a result, the conservatism of control synthesis of discrete-time Takagi–Sugeno fuzzy control systems under unreliable communication links can be significantly reduced. Two illustrative examples are presented to demonstrate the effectiveness of the theoretical development.

1. Introduction

In the real world, most of physical control systems are naturally nonlinear, and the inherent nonlinearity makes the problem of control design very hard. In the past several decades, the so-called Takagi–Sugeno (T–S) fuzzy model given in [1] has been acted as an effective tool in dealing with a variety of complex nonlinear problems, e.g., cluster-centric fuzzy modeling [2], fuzzy periodic oscillations [3] and fuzzy speed estimation [4]. In particular, the famous parallel distribution compensation (PDC) control scheme, which shares the same structure of the associated T–S fuzzy model, has been widely applied in control design and fruitful related results have been developed such as those in [5–8]. In order to reduce the conservatism, lots of relaxed methods via the so-called non-parallel distributed compensation(non-PDC) have attracted a rapidly growing interest in the existing literature, see [9–12] and those references therein. Recently, the so-called homogenous polynomially parameter-dependent solutions have been successfully applied to the problem of control synthesis of T–S fuzzy systems [13–15]. In particular, a slack variable technique has been developed by using the homogenous polynomial approach in [14], and the algebraic properties of the current-time normalized fuzzy weighting functions have been collected into a sets of united collection matrices to increase the convergent rate of reducing the conservatism of stabilization conditions. However, there are some limitations existing in the underlying result: (a) some additional equality constraints must be satisfied in [14] and it results in an introduction of conservatism, (b) the underlying result is only parameter-dependent on the current-time normalized fuzzy weighting functions. Therefore, further studies in this area should be investigated with the purpose of overcoming the above two drawbacks.

With the rapid development of computer and industrial network technologies, networked control systems (NCS) have drawn much attention due to their great advantages over traditional point-to-point control systems [16]. However, the utilization of NCS has also bring us with some challenges [17]. Indeed, the network-induced delay and data packet dropout are two challenging ones. The issue of NCS analysis/control synthesis with network-induced delay has been well investigated in the last decade and fruitful results have been obtained for T–S networked control systems with time-delays, e.g., H_∞ design [18,20,21], guaranteed cost networked control [19], decentralized networked control [23], communication delay distribution dependent networked control [22,24,25], networked cascade control [26], H_∞ filtering for nonlinear discrete-time systems subject to quantization and packet dropouts [27], etc. On the other hand, in almost all the above literature, it has been assumed that the communication between the physical plant and controller is in health, i.e., the signals transmitted from the plant always reach the controller without any information losses. However, there is always a nonzero probability that either measurements or control inputs may be lost during the process of transmission [28]. Based on the PDC technique, the problems of networked control with random packet losses were investigated in [29–33], respectively. Recently, the issue of nonlinear networked control design via Type-2 fuzzy model has also been an interesting topic and two important results have been given in [34,35]. To reduce the conservatism in the quadratic framework, both the non-PDC technique and the basis-dependent Lyapunov function were applied in [36]. However, it is difficult to derive LMI-based conditions under the non-PDC and basis-dependent framework, unless additional overdesign is implemented. As an alternative, the authors in [36] proposed a controller design method with the help of the cone complementarity linearization (CCL) algorithm, which inevitably introduced some conservatism as a tradeoff. As far as this problem is considered, how to obtain relaxed stabilization conditions is still very challenging, which motivates us to carry the current study.

* Corresponding author at: Institute of Advanced Technology, Nanjing University of Posts and Telecommunications, Nanjing 210003, PR China. Tel.: +86 02585866931.
E-mail addresses: xiexiangpeng1953@163.com (X.-P. Xie), medongy@vip.163.com (D. Yue), c.peng@shu.edu.cn (C. Peng).

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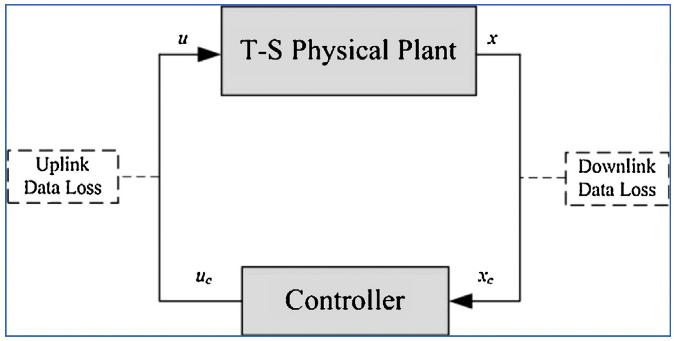

Fig. 1. Framework of T–S fuzzy control system with unreliable communication links.

The main purpose of this paper is to propose relaxed conditions for control synthesis of discrete-time T–S fuzzy control systems under unreliable communication links. More attentions are focused on designing a new fuzzy controllers such that the closed-loop system is stochastically stable with less conservatism than the existing one in the literature. The main contributions of this paper can be summarized as follows:

(1) A novel fuzzy controller, which is homogenous polynomially parameter-dependent on both the current normalized fuzzy weighting functions and the multi-steps-past normalized fuzzy weighting functions, is provided to make much more use of the information of the nonlinear networked systems.
(2) In order to overcome the obstacle faced in [36], i.e., it is difficult to derive LMI-based conditions under the non-PDC and basis-dependent framework, a kind of matrix transformation is proposed to act as an efficient tool to convert the underlying problem into solving LMI-based optimization problem. Then, the problem of control synthesis can be derived in terms of LMIs instead of the conservative CCL algorithm.
(3) A new kind of slack variable approach is also developed and thus the algebraic properties of these multi-instant normalized fuzzy weighting functions are collected into some augmented matrices. As a result, the conservatism of control synthesis of discrete-time T–S fuzzy control systems under unreliable communication links can be significantly reduced.

Notations. Throughout the paper, the notations are fairly standard. In particular, $\mathbb{Z}_+$ denotes the set of positive integers, $\mathbb{R}$ represents the set of real numbers, and $n!$ represents factorial, i.e., $n! = n \times (n-1) \cdots \times 1$ for $n \in \mathbb{N}$ and one has $0! = 1$. He(E) is defined as $\text{He}(E) = E + E^T$ and E^{-T} stands for $(E^{-1})^T$ if the matrix E is nonsingular. $E(x)$ and $E(x|y)$ will, respectively, denote expectation of x and expectation of x conditional on y.

2. Preliminaries

2.1. Discrete-time T–S fuzzy control systems under unreliable communication links

The control synthesis problem with unreliable communication links is shown in Fig. 1, where its physical plant is described by a T–S fuzzy model, and the unreliable communications include both the uplink (between controller and physical plant) and the downlink (between physical plant and controller). By using the fuzzy modeling approach proposed in [1], a class of discrete-time nonlinear control system can be described by a set of T–S fuzzy rules as follows:

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

Then, the overall T–S fuzzy model is inferred as:

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

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

Because of the possible data loss in the communication links from both the sensor to the controller and the controller to the actuator, 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. As given in [36], the data loss phenomena can be modeled as follows:

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

where $\{e(t)\}$ is a Bernoulli process with $E(e(t)) = \bar{e}$, $E(\tilde{e}(t)) = 0$ and $E(\tilde{e}(t)\tilde{e}(t)) = \bar{e}(1-\bar{e})$.

Definition 1. [[36]] The closed-loop system (2) is said to be stochastically stable in the mean square if, for any initial condition $x(0)$, there exists a finite matrix $W > 0$ such that:

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