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Fuzzy control design of nonlinear systems under unreliable communication links: A systematic homogenous polynomial approach

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ABSTRACT

In this study, we propose a systematic homogenous polynomial approach for fuzzy control design of discrete-time Takagi-Sugeno fuzzy systems under unreliable communication links. A novel delayed fuzzy control scheme, which is homogenous polynomially parameter-dependent on both the current normalized fuzzy weighting function and the one-step-past normalized fuzzy weighting function, is designed to accomplish the assignment of relaxed control synthesis. In contrast to the existing methods, the closed-loop controlled system is stochastically stable in the mean square sense with less conservative stabilization conditions. Finally, simulation results are provided to verify the advantage and the effectiveness of the proposed approach.

1. Introduction

As stated in [27,28], fuzzy models and fuzzy modeling dwell upon a concept of information granules, i.e., fuzzy sets. Meanwhile, fuzzy sets form a blueprint of any fuzzy model and contribute to the key features of fuzzy models, e.g., their interpretability. During the past several decades, there has been a growing interest in the Takagi-Sugeno (T-S) fuzzy model [34]. The model acts as a pivotal mechanism and bridges the gap between linear control theory and complex nonlinear systems. Recently, many researchers have devoted their interest into control synthesis of T-S fuzzy systems, and thus a great number of results have been reported, see [2,8,25,39] and the references therein. In particular, an important result was given in [14] and the so-called non-parallel distributed compensation(non-PDC) control law was applied for the first time. Note that the non-PDC control law plays an important role in reducing the conservatism of control synthesis of T-S fuzzy systems, thus its extended versions have been widely and deeply investigated, see [3,5,19,24] and the related references therein.

Recently, the famous homogenous polynomially parameter-dependent (HPPD) solutions [26] have been widely applied in robust stability analysis of linear parameter-varying (LPV) dynamic systems. Due to the fact that the LPV dynamic system is somewhat similar to the T-S fuzzy system, researchers generalize fuzzy Lyapunov functions to the HPPD Lyapunov functions, and thus more information of the normalized fuzzy weighting functions can be involved in the process of control synthesis [4,20,21,33,36–38,40]. From a functional point of view, the above results aren't merely simple extensions of the HPPD

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solutions to LPV dynamic systems. Unlike LPV dynamic systems, an important feature of the T-S fuzzy system is that its normalized fuzzy weighting functions are measurable on-line, and thus it provides a chance to further reduce the conservatism if one can make full use of this feature. In other words, one has to be aware that further investigations in this area should be addressed for investigators in fuzzy theory.

On the other hand, all the above literature concerning T-S fuzzy control systems, a common assumption is that the communication between the physical plant and controller is perfect, i.e., the signals transmitted from the plant always arrive at the controller without any information losses. Obviously, such assumption is not always true in practice [12,13]. For instance, due to the unreliability of the network links, a networked control system(NCS) typically exhibits significant communication delays [16,17] and data loss across the network [6], which receives considerable research attention on how to control synthesis of systems with related considerations of network-induced delay constraints and the data loss issue. Recently, the problem of communication delay distribution dependent networked control for a class of T-S fuzzy system has been investigated in [29,31,32], the problem of networked control of a class of T-S fuzzy systems with stochastic sensor faults has been studied in [30], sampled-data fuzzy control design approach for T-S model-based fuzzy networked systems has been proposed in [11,18], and H_∞ fuzzy control and filtering for systems with random packet losses have been addressed in [7,9,10,22,23]. In particular, in order to reduce the conservatism under the quadratic framework, the basis-dependent Lyapunov function has been applied in [9]. However, it is difficult to obtain LMI-based conditions for the controller design via the basis-dependent framework, unless additional overdesign is introduced. As an alternative, the authors in [9] have presented a controller design procedure based on the cone complementarity linearization (CCL) algorithm.

In this paper, we make an attempt to address the problem of control synthesis of discrete-time T-S fuzzy systems under unreliable communication links via a systematic homogenous polynomial approach. Using the stochastic model given in [9], the communication links between the plant and controller are assumed to be imperfect (i.e., data packet dropouts occur intermittently), and stochastic variables satisfying the Bernoulli random binary distribution are applied to model the unreliable communication links. More attention will be focused on the design of new fuzzy control schemes such that the closed-loop system is stochastically stable with less conservatism. In brief, there are two essential contributions in this paper and those along with well-motivating factors all together bring forward a certain facet of originality.

(1) A novel delayed fuzzy controller is designed to accomplish the assignment of control synthesis, i.e., the stochastic stability in the mean square of closed-loop system with less conservative stabilization conditions than those existing ones. It is worth mentioning that it is homogenous polynomially parameter-dependent on both the current-time normalized fuzzy weighting functions and the one-step-past normalized fuzzy weighting functions. Compared with the existing results in [9], more additional decision variables can be introduced, and consequently more flexibility is generated to further reduce the conservatism of control synthesis.

(2) A new matrix transformation, which presents an efficient approach to convert the control synthesis into LMI-based conditions, is developed to overcome the obstacle occurred in [9]. As a result, less conservative stabilization conditions could be obtained in terms of linear matrix inequalities(LMIs), which can be easily solved via standard numerical software, in other words, the problem of control synthesis of discrete-time T-S fuzzy systems under unreliable communication links can been derived by means of LMIs instead of using the CCL algorithm.

This study is organized as follows: In Section 2, the problem under consideration is addressed. In Section 3, a systematic homogenous polynomial approach is developed. In Section 4, experimental results are reported to show the applicability of the developed theoretical result. Finally, Section 5 concludes this paper.

Notations. $\mathbb{Z}_+$ stands for the set of positive integers, $\mathbb{R}$ stands for the set of real numbers, $\mathbb{N}$ represents the natural numbers set {0, 1, 2, ...}, and $p!$ represents factorial, i.e., $p! = p(p-1)(p-2)\cdots(2)(1)$ for $p \in \mathbb{N}$ with $0! = 1$. For a matrix P, $\min(P)$ (respectively, $\max(P)$) means the smallest (respectively, largest) eigenvalue of P. $\mathrm{He}(M)$ is defined as $\mathrm{He}(M) = M + M^T$ and M^{-T} stands for $(M^{-1})^T$ if the matrix M is nonsingular. $E(x)$ and $E(x|y)$ will, respectively, mean expectation of x and expectation of x conditional on y. Matrices, if their dimensions are not explicitly stated, are assumed to be compatible for algebraic operations.

2. Problem formulation and preliminaries

2.1. Nonlinear physical plant under unreliable communication links

According to the fuzzy modeling method given in [34], a class of discrete-time nonlinear 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 $t \in \mathbb{N}$, $x(t) \in \mathbb{R}^{n_1}$ is the state vector, $u(t) \in \mathbb{R}^{n_2}$ is the control input, and $z(t) = (z_1(t), z_2(t), \ldots, z_p(t))^T$ is the premise variable of the underlying T-S fuzzy model, $F_1^i, F_1^i, \ldots, F_p^i$ are fuzzy sets that are formed in the space of input variables $z_1(t), z_2(t), \ldots, z_p(t)$. In particular, fuzzy sets/membership functions form a blueprint of any fuzzy model and contribute to the key features of fuzzy models such as their interpretability [28]. When a process is simple, most present models have been built based only on operators experience and knowledge, such as those in [3,8,36]. When a process is complex, there

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