Information Sciences 328 (2016) 206–221

Contents lists available at ScienceDirect

Information Sciences

journal homepage: www.elsevier.com/locate/ins

Pre-specified performance based model reduction for time-varying delay systems in fuzzy framework☆

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ARTICLE INFO

Article history:
Received 22 January 2015
Revised 3 August 2015
Accepted 21 August 2015
Available online 28 August 2015

Keywords:
T-S fuzzy systems
Model reduction
Time-varying delay
Projection approach

ABSTRACT

This paper attempts to provide a new solution to the model approximation problem for dynamic systems with time-varying delays under the fuzzy framework. For a given high-order system, our focus is on the construction of a reduced-order model, which approximates the original one in a prescribed error performance level and guarantees the asymptotic stability of the corresponding error system. Based on the reciprocally convex technique, a less conservative stability condition is established for the dynamic error system with a given error performance index. Furthermore, the reduced-order model is eventually obtained by applying the projection approach, which converts the model approximation into a sequential minimization problem subject to linear matrix inequality constraints by employing the cone complementary linearization algorithm. Finally, two numerical examples are provided to illustrate the effectiveness of the proposed method.

1. Introduction

The vast majority physical systems and processes carry rather complicated high-order mathematical models, which impose significant challenge for the corresponding control design and stability analysis. Finding a suitable lower-order model to approximate the high-order one without introducing significant errors is a highly desirable solution to simplify the original high-order system. Therefore, how to simplify these models with respect to certain pre-specified criteria attracts much attention. In the past decades, a large number of results regarding the arduous problem of model approximation have been presented, such as the energy-to-energy approach [29], the H_2 approach [35], the energy-to-peak approach [15], and the Hankel-norm approach [10]. More recently, the linear matrix inequality technique has been employed to tackle the model approximation problem for different kinds of systems, including time-delay systems [20,21], Markovian jump systems [16], and stochastic systems [24]. However, for continuous-time Takagi–Sugeno (T-S) fuzzy systems with time-varying delays, limited results have been reported for the model reduction problem with a prescribed error performance, which motivates this work.

☆ This work was partially supported by the National Key Basic Research Program (973), China (2012CB215202, 2014CB249200), the National Natural Science Foundation of China (61403048 and 61134001), the Fundamental Research Funds for the Central Universities (106112015CDJXY170001,CDJZR175501), and the Basic and Frontier Research Project of Chongqing (cstc2015jcyjA40005, cstc2014jcyjA90005).

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http://dx.doi.org/10.1016/j.ins.2015.08.031
0020-0255/

As we all know, nonlinear which is frequently resulted from modeling of many systems and processes in the real word, is severely difficult to analyze and synthesize by applying the conventional theory and approach. Consequently, considerable attention has been paid to develop an effective technique to approximate this class of nonlinear systems. With the advent of fuzzy modeling [26], it has been proved that the complex nonlinear system can be approximated to any accuracy by the T-S fuzzy system, which is described by a family of IF-THEN rules to express local input-output relations of the nonlinear systems, and eventually realized by smoothly blending these local linear models together through the membership functions. Thus, the research for T-S fuzzy systems has captured growing concern and a large quantity of results have been reported. To mention a few, the stability analysis and stabilization are studied in [17,30,31,34]; the filtering problem is investigated in [5,33]; fault detection is reported in [4,6,32].

On the other hand, the time delay, which is generally considered as one of primary sources to trigger poor performance, oscillation and even instability [1,2,7,11–14], invariably appears in many engineering systems, interaction networks, chemical processes and other areas. Therefore, the study of time-delay systems has exerted a tremendous fascination on researchers, and various approaches to develop delay-dependent conditions for time-delay systems have been proposed. For example, the delay partitioning approach introduced in [36], divides the time delay into several segments uniformly to handle the integral term concerning time delays. The relaxed matrix method presented in [28], is provided to express the relationships among the terms of the system equation to augment extra terms in favor of the derivation of Lyapunov–Krasovskii functional. The reciprocally convex approach proposed in [22], can solve the inversely weighted convex combination of quadratic terms resulted from the integral term of quadratic quantities bounded by time delays. The input-output technique investigated in [23], which employs the scaled small-gain theorem to deal with time delays, is another effective method. In this work, the reciprocally convex technique is extended to tackle the Lyapunov–Krasovskii functional, which is proved to be not only less complexity in the calculation but also less conservatism in stability analysis for T-S fuzzy systems with time-vary delays.

Motivated by the significance of model approximation in theoretical and practical engineering areas, in this work, we investigate the model reduction for a class of delayed nonlinear systems, which can be modeled as T-S fuzzy systems with time-varying delays. So far, the problem of model approximation for T-S fuzzy systems has made reasonable progress, such as the model approximation for discrete-time T-S fuzzy delayed systems studied in [25], and the model approximation for T-S fuzzy stochastic systems developed in [24]. However, to the best of the authors' knowledge, few works have been addressed on model approximation for the continuous-time T-S fuzzy time-varying delay system.

In this paper, the problem of model approximation is investigated for the continuous-time T-S fuzzy system with time-varying delays. For a given stable high-order system, our attention is focus on the construction of a lower-order model, which approximates the original system with an accuracy that satisfies a given error performance requirement. First, we utilize the reciprocally convex approach to develop an asymptotic stability condition for the T-S fuzzy time-varying delay system. Based on this, a new model approximation is proposed by employing the projection approach, which casts the reduced-order model into a sequential minimization problem subject to linear matrix inequality constraints by the cone complementary linearization algorithm [9]. Finally, two numerical examples are given to demonstrate the effectiveness of the proposed technique.

The main contributions of this paper are summarized as follows.

1. To further tackle the conservatism generated by time-varying delays, the reciprocally convex approach is employed to amplify the results of the negative integral terms of quadratic quantities, instead of immediately ignoring the negative integral terms of quadratic quantities. The effectiveness of this proposed technique is shown via the detailed example compared with the existing results.
2. For the time-varying delay system in T-S fuzzy framework, the problem of model approximation has been solved by a sequential minimization technique subject to linear matrix inequality constraints by employing the cone complementary linearization algorithm.
3. Based on the stability condition obtained, our constructed reduced-order model can approximate the original system well under the pre-specified error performance.

The rest of this paper is organized as follows. The problem formulation and some preliminaries are described in Section 2. In Section 3, the system performance analysis is developed. The model approximation technique is provided in Section 4. Section 5 presents two numerical examples to illustrate the effectiveness of the proposed approach. Our conclusions are given in Section 6.

Notations: The superscript "T" stands for matrix transposition, $\mathbb{R}^n$ denotes the n-dimensional Euclidean space, the notation $P > 0(\geq 0)$ means that P is real symmetric and positive definite (semidefinite), I and 0 represent the identity matrix and zero matrix, respectively, diag$(\dots)$ stands for a block-diagonal matrix. $L_2[0, \infty)$ denotes the signals that are square integrable over $[0, \infty)$. For a matrix $U \in \mathbb{R}^{m\times n}$ with rank k, we denote $U^{\perp}$ as the orthogonal complement, which is defined as a (possibly nonunique) $(m-k)\times m$ matrix with rank $(m-k)$, such that $U^{\perp}U = 0$. We denote U^{+} as the Moore–Penrose inverse of U, and U_L and U_R are any full rank factors of U, that is, $U_L U_R = U$. In symmetric block matrices, we use a star ($\star$) to represent a term that is induced by symmetry. Matrices, if their dimensions are not precisely stated, are assumed to be compatible for algebraic operations.

2. Problem formulation and preliminaries

In this paper, we consider a class of nonlinear systems which can be described by the following continuous-time T-S fuzzy delayed model.