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Robust fuzzy-scheduling control for nonlinear systems subject to actuator saturation via delta operator approach

Hongjiu Yang [a], Xuan Li [a], Zhixin Liu [a,*], Ling Zhao [b]

[a] Institute of Electrical Engineering, Yanshan University, Qinhuangdao 066004, China
[b] Hebei Provincial Key Laboratory of Heavy Fluid Power Transmission and Control, College of Mechanical Engineering, Yanshan University, Qinhuangdao 066004, China

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ABSTRACT

This paper focuses on robust fuzzy-scheduling control for nonlinear systems with actuation saturation via delta operator approach. A class of T–S fuzzy delta operator systems is extended to describe nonlinear systems subject to actuator saturation and linear fractional uncertainty. Moreover, a set invariance condition is established for T–S fuzzy delta operator systems. Based on the set invariance condition, an optimization approach is proposed to estimate the domain of attraction for the T–S fuzzy delta operator systems. The domain of attraction is arbitrarily close to a null controllable region by the designed PDC control law or non-PDC control law. Furthermore, the non-PDC control law is proposed by using fuzzy weighting-dependent Lyapunov function. The effectiveness of the developed techniques is shown through a numerical example.

1. Introduction

Many real-world physical processes are generally characterized by the presence of nonlinearity, complexity and uncertainty. However, there are little systematic mathematical tools available to help find necessary and sufficient conditions on guaranteeing system stability and performance [1–4], hence it is difficult to control a nonlinear systems. During the last two decades, fuzzy technique has been widely used in nonlinear system modeling especially for systems with incomplete plant information [5–8]. It has been shown that T–S fuzzy technology gives an effective way to represent complex nonlinear systems by some simple local linear dynamic systems with their linguistic description, please refer to [9–12] and the references therein. For T–S fuzzy discrete-time systems with time-varying delays, both controller and filter have been designed in [13,14], respectively. Some relaxed stabilization conditions for discrete-time two-dimension T–S fuzzy systems have been given in [15]. For a class of continuous-time T–S fuzzy systems, a state feedback controller has been designed in finite frequency domain [16]. By non-PDC control laws derived, constrained infinite-horizon model predictive control for fuzzy discrete-time systems has been investigated in [17]. Although many researchers have studied the control problems for nonlinear systems, there are also a lot of space to be improved on T–S fuzzy systems with PDC or non-PDC control scheme, such as combining with time delay, uncertain parameter, actuator saturation, and high sampling condition.

Due to the inherent physical limitations of the devices, actuator saturation is very ubiquitous in all practical control systems [18]. Ignoring saturation can lead to performance degradation and even instability of closed-loop systems [19].

* Corresponding author. Tel.: +86 13933671941.
E-mail addresses: yanghongjiu@ysu.edu.cn (H. Yang), lixuancc@126.com (X. Li), lzxauto@ysu.edu.cn (Z. Liu), zhaoling84@ysu.edu.cn (L. Zhao).

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T–S fuzzy models with actuator saturation and norm-bounded uncertainty have been used to describe the nonlinear systems subject to actuator saturation in [20]. An overhead crane model has been described by a class of T–S fuzzy systems with input delay and actuator saturation in [21]. An anti-windup fuzzy control approach for uncertain nonlinear time-delay systems with actuator saturations has been presented in [22]. A problem of fuzzy tracking control has been dealt with for a class of nonlinear time-delay systems subject to actuator saturation [23]. However, combining with PDC and non-PDC in T–S fuzzy systems subject to actuator saturation remains as an open research area.

In recent years, high-speed signal transmission has become common, due to advances in technology that allow rapid signal processing and storage of the large quantities of associated data. However, there exists the problem of crowding poles within the boundary of stability circle in normal shift operating systems at small sampling interval, which usually results in the difficulties of truncation and round-off errors [24]. Delta operator based implementations has gained interest due to their excellent finite word length performance under fast sampling [25,26]. Therefore, there are a number of results on delta operator systems, see for examples [27–29], and the references therein. Stabilization of networked control systems with nonuniform random sampling periods has been investigated in [30]. By delta operator approach, a stability problem for high frequency networked control systems has been considered in [31]. Analysis and synthesis on delta operator systems have been discussed in [32]. A robust H_∞ control problem for a class of T–S fuzzy systems with time delays by using delta operator approach has been studied in [33]. However, to the best of our knowledge, there have been few papers on robust fuzzy-scheduling control for nonlinear systems with actuation saturation via delta operator approach, which motivates us to make an effort in this paper.

In this paper, we consider the problem of robust fuzzy-scheduling control for nonlinear systems with actuation saturation via delta operator approach. A set invariance condition in the T–S fuzzy delta operator system will be established. Both PDC and non-PDC control laws are designed, such that the domain of attraction for the closed-loop T–S fuzzy delta operator system will be arbitrarily close to a null controllable region. Finally, a numerical example is provided to illustrate the effectiveness of the proposed design techniques.

This paper is organized as follows. In Section 2, the problem statement of T–S fuzzy delta operator systems with actuator saturation is formulated. Section 3 covers the design of both PDC and non-PDC controller for the T–S fuzzy delta operator systems. In Section 4, we present numerical simulation results. Conclusions are given in Section 5.

The main contributions of this paper are summarized as below:

i. A new kind of robust fuzzy-scheduling controller design methods is proposed for nonlinear systems with actuation saturation via delta operator approach.
ii. The fuzzy PDC control law is designed such that the domain of attraction of T–S fuzzy delta operator systems is close to a null controllable region.
iii. The fuzzy non-PDC control law which has better control effect than the PDC control law is also proposed by weighting-dependent Lyapunov function.

Notation: Throughout this paper, R^n denotes the n-dimensional Euclidean space; the notation $X > Y$ ($X \geqslant Y$) means that the matrix $X - Y$ is positive definite ($X - Y$ is semi-positive definite, respectively); And $P > 0$ means that P is symmetric and positive-define; I is the identity matrix of appropriate dimension; For any matrix A, A^T denotes the transpose of matrix A, A^{-1} denotes the inverse of matrix A; The shorthand $diag\{M_1, M_2, \dots, M_r\}$ denotes a block diagonal matrix with diagonal blocks being the matrices $M_1, M_2, \dots, M_r$. The symmetric terms in a symmetric matrix are denoted by $*$.

2. Problem statement and preliminaries

2.1. Problem statement

In this paper, we consider the following nonlinear system:

$$\dot{x}(t) = f(x(t), v(t)) \tag{1}$$

where $x(t) \in R^n$ is the state variable, $v(t) \in R^m$ is the control input, $f(\cdot)$ is sufficiently smooth in $x(t)$ and affine in $v(t)$. The control input $v(t)$ is subject to actuator saturation. That is,

$$v(t) = sat(u(t))$$

in which the function sat: $R^m \to R^m$ is the standard saturation function. It is defined as

$$sat(u) = [sat(u_1), sat(u_2), \dots, sat(u_m)]^T$$

where

$$sat(u_i) = sgn(u_i)\min\{1, |u_i|\}$$

As in [20], the nonlinear system (1) is represented by T–S fuzzy model composed of a set of fuzzy implications, and each implication is expressed by a linear system model. The ith rule of this T–S fuzzy model is of the following form.