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Fuzzy impulsive control for uncertain nonlinear systems with guaranteed cost

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Received 8 July 2014; received in revised form 10 May 2015; accepted 29 September 2015

Abstract

In this paper, a guaranteed cost fuzzy impulsive control (GCFIC) problem is addressed for uncertain continuous-time nonlinear systems which can be represented by the Takagi–Sugeno (T–S) fuzzy model with parametric uncertainties. Based on the T–S fuzzy model, a novel time-varying Lyapunov function is initially constructed to derive the existence condition of guaranteed cost fuzzy impulsive controllers, which cannot only exponentially stabilize the uncertain fuzzy system, but also provide an upper bound on the quadratic cost function. Then, two procedures for designing suboptimal guaranteed cost fuzzy impulsive controllers are given in the sense of minimizing an upper bound of the cost function: one casts the controller design into a parameter-dependent linear matrix inequality (LMI) optimization problem and the other casts the controller design into a sequential minimization problem subject to LMI constraints by using the cone complementary linearization (CCL) algorithm. Finally, an example is presented to illustrate the effectiveness of the proposed method.

Keywords: Fuzzy control; Guaranteed cost control; Impulsive control; Uncertain nonlinear systems; Linear matrix inequality (LMI); Cone complementarity linearization (CCL)

1. Introduction

The past few years have witnessed rapidly growing interest in fuzzy control of nonlinear systems. In particular, the so-called Takagi–Sugeno (T–S) fuzzy model has been widely employed for the control design of nonlinear systems (see, e.g., [1,2], and the references therein for a survey of recent development). Fuzzy logic theory enables us to utilize qualitative, linguistic information about a highly complex nonlinear system to decompose the task of modeling and control design into a group of easier local tasks. At the same time, it also provides the mechanism to blend these local tasks together to yield the overall model and control design. It can provide an effective solution to the modeling and control of plants that are complex, uncertain, and ill-defined.

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http://dx.doi.org/10.1016/j.fss.2015.09.026
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Impulsive dynamical systems are a class of hybrid systems composed of continuous ordinary differential equations with instantaneous state jumps at discrete instants, which provide a natural framework for mathematical modeling of many real world evolutionary processes where the states undergo abrupt changes at certain instants. During the past decades, impulsive control has been also gaining considerable attention in many science and engineering fields [3–7], because it can provide an efficient way to deal with the plants which cannot endure continuous control inputs. Using the impulsive control technique, the continuous-time systems can be stabilized from only small control impulses generated by samples of the state variables at discrete time instants. The stability properties of impulsive systems have been intensively studied in [8–12] and the references therein. Recently, the T–S fuzzy model based control technique combined with the impulsive control approach has been applied to deal with the stabilization and synchronization of chaotic dynamical systems, and many important results have been developed, e.g., [13–19]. However, it is noted that the existing fuzzy impulsive control methods are based on the use of the time-invariant Lyapunov function, which may neglect the hybrid structure characteristic of impulsive systems and thus the resulting stability and stabilization conditions may be conservative. Moreover, the knowledge of membership functions in the above mentioned results is not considered, which seems to have room for improvement. More recently, some nice results on impulsive control by the time-varying Lyapunov function have been reported in [20–22]. But, these works did not consider the performance of impulsive systems.

Guaranteed cost control for uncertain continuous-time systems has been extensively studied in the past decade [23–31]. The underlying objective is to design a control system that is not only robust stable but also guarantees an upper bound of quadratic performance for all admissible parameter uncertainties. We note that all of the above works are based on the assumption that the control inputs of the system are continuous. However, because of the applications of digital actuators, the inputs of many control systems are only available at discrete instants. Recently, the analysis and design of guaranteed cost control for uncertain continuous-time systems via sampling information involve mainly two approaches. In the first approach, the guaranteed cost controller is designed by updating the inputs in a sample-and-hold fashion [32]. The second one is the so-called guaranteed cost impulsive control approach i.e., the controller is designed by updating the inputs only at discrete instants of time. Compared with continuous-time control, the advantage of impulsive control lies in that the transmission of the stabilization information from the plant to the impulsive controller at discrete time instants can drastically save the bandwidth of networks and communication cost. In [33], some sufficient conditions for the existence of a guaranteed cost control law for a class of uncertain linear impulsive switched systems are given. But, it is worth pointing out that the guaranteed cost controller design in [33] is still considered with the assumption that the control inputs are continuous. Furthermore, to the best of our knowledge, little attention has been paid towards guaranteed cost impulsive control for uncertain nonlinear systems.

This paper deals with the problem of guaranteed cost fuzzy impulsive control (GCFIC) for uncertain nonlinear systems, which can be represented by a T–S fuzzy model with parameter uncertainties. A novel time-varying Lyapunov function is firstly constructed to explore the hybrid characteristic of the closed-loop fuzzy impulsive system. Then, using this Lyapunov function, a sufficient condition for the existence of guaranteed cost fuzzy impulsive controllers is derived, which cannot only guarantee that the closed-loop fuzzy system is exponentially stable, but also provide an upper bound of the given quadratic cost function. Furthermore, two procedures for designing suboptimal guaranteed cost fuzzy impulsive control laws are given in the sense of minimizing an upper bound of the guaranteed cost: one transforms the controller design into a parameter-dependent linear matrix inequality (LMI) optimization problem and the other utilizes the cone complementarity linearization (CCL) method to cast the controller design into a sequential minimization problem subject to LMI constraints. Finally, the proposed design method is successfully applied to the control of mass–spring–damper system.

The main contribution and novelty of this paper are summarized as follows: (i) A novel time-varying Lyapunov function is introduced to the uncertain fuzzy impulsive systems, and the GCFIC problem is considered; (ii) Some less conservative results are obtained for the uncertain fuzzy impulsive systems based on the time-varying Lyapunov approach, and two LMI-based procedures are proposed for designing the desired guaranteed cost fuzzy impulsive controllers.

The rest of this paper is organized as follows. The problem formulation is presented in Section 2. In Section 3, the GCFIC design is proposed for uncertain fuzzy systems. In Section 4, a simulation example is given to illustrate the effectiveness of the proposed method. Finally, concluding remarks are given in Section 5.

Notations: Throughout this paper, if not explicitly stated, matrices are assumed to have compatible dimensions. $\mathbb{N}^+$ is the set of positive integers. $\mathbb{R}$, $\mathbb{R}^+$ denote the set of real and nonnegative real numbers, respectively. $\mathbb{R}^n$,

Please cite this article in press as: Z.-P. Wang and H.-N. Wu, Fuzzy impulsive control for uncertain nonlinear systems with guaranteed cost, Fuzzy Sets and Systems (2015), http://dx.doi.org/10.1016/j.fss.2015.09.026