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Journal of the Franklin Institute 350 (2013) 129–154

Journal of The Franklin Institute

www.elsevier.com/locate/jfranklin

Output-feedback adaptive fuzzy control for a class of nonlinear systems with input delay and unknown control directions☆

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Received 14 March 2012; received in revised form 29 July 2012; accepted 23 October 2012
Available online 2 November 2012

Abstract

In this paper, an adaptive fuzzy control scheme is proposed for a class of nonlinear systems with input delay, unknown time-varying delays and disturbances via dynamic output-feedback approach. During the controller design procedure, the input delay is dealt with by combining the smoothed dead-zone approach with the integral mean value theorem. Moreover, fuzzy logic systems (FLS) are employed to approximate the unknown continuous functions. The main advantages of this paper are that (1) the output-feedback adaptive fuzzy controller can dispose a class of nonlinear time-varying delay systems with input delay, in which the virtual control coefficients are all unknown and (2) only two parameters need to be adjusted online in controller design procedure, which reduces the online computation burden greatly. It is proven that the proposed control scheme renders the closed-loop system stable in the sense of semiglobal UUB. Finally, simulation results are provided to show the effectiveness of the proposed approach.

1. Introduction

Since adaptive backstepping technique was proposed in [1], lots of extensions on this technique have been reported, for example [15,16] and the references therein, and it has been proven to be a powerful tool for dealing with unmatched and linearly parameterized

☆This work is partially supported by NNSFC (No. 60974139) and partially supported by the Fundamental Research Funds for the Central Universities (No. 72103676).
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0016-0032/$32.00
http://dx.doi.org/10.1016/j.jfranklin.2012.10.010

uncertainties in lower-triangular-structured systems. In order to cope with unmatched and nonlinearly parameterized uncertainties, many approximator-based adaptive backstepping control methods have been developed. For example, adaptive backstepping neural network (NN) control [3] and adaptive backstepping fuzzy control [7,11,12]. Compared with NN, the main advantage of fuzzy system (FS) is that it can combine some experience and knowledge from designers or experts [8]. Therefore, FS as a universal approximator is superior to NN.

If system states are unmeasurable, output-feedback or observer-based control schemes should be utilized in reality. In recent years, several papers have investigated the stabilization of nonlinear systems by using the output-feedback control approach and have obtained some significant results, for example [11,12,31] and the references therein. Tong and Li [11] and Tong et al. [12] developed the adaptive fuzzy output-feedback controllers by designing the linear state observers for SISO uncertain nonlinear systems and MIMO uncertain nonlinear systems, respectively. In [31], the authors also proposed the adaptive fuzzy output-feedback backstepping controller for a class of SISO uncertain nonlinear systems based on K-filters. However, the results in [11,12,31] were obtained under the assumption that the control directions of the nonlinear systems are all known.

In fact, for practical systems the control directions may be unknown. When the signs of control coefficients are unknown, the control problem becomes much more difficult, because in this case, we cannot decide the direction along which the control operates. This control problem had remained open till the early 1980s. The breakthrough solution was originally given for a class of first-order linear systems by introducing the Nussbaum function [24]. Using Nussbaum gain methods, adaptive control was given for the first-order nonlinear systems in [22]. Recently, the results have also been extended to nonlinear systems with general unknown nonlinear functions, rather than the standard assumption of linear-in-the-parameters form made by combining adaptive and fuzzy logic systems parametrization techniques [27]. In recent years, for the systems with unknown control directions, in comparison with the plentiful research results in the state-feedback controls [20,27,28], the study on the output-feedback control for nonlinear systems [15,16,30] received relatively little attention, and many problems still remain open. To the best of our knowledge, most of the output-feedback control schemes have only been investigated for a very special class of nonlinear systems with only one unknown control coefficient, the so-called high-frequency gain. Only in [15,30] the output-feedback adaptive stabilization controllers were designed for nth order nonlinear systems, in which the virtual control coefficients are all unknown constants. However, in [15,30], the authors did not consider the systems with unknown state time-varying delays and input delays.

It is well known that time delays are frequently encountered in real engineering systems, such as electrical networks and hydraulic systems. Due to the effect of time delay, these systems may possess instability, and the control performance of these systems are hardly assured. The stability analysis and control for these time-delay systems attracted a number of researchers over the past years, such as [7,9,10,16,35] and the references therein. However, it is worth noting that in [7,9,10,16,35] authors only investigated the systems with state delays, and the investigation for the systems with input delay have been received some results [13,17,25,32–34]. In [13], a class of uncertain linear time delay systems was discussed. By introducing a state predictor, the original system was converted to a normal system without input delay. The closed-loop system was stabilized by a sliding mode controller. In [17], the problem of the global uniform asymptotic stabilization by bounded