Automatica 93 (2018) 444–453

Contents lists available at ScienceDirect

Automatica

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

Brief paper

Adaptive tracking control for nonlinear time-varying delay systems with full state constraints and unknown control coefficients☆

Dongjuan Li [a], Dapeng Li [b,*]

[a] School of Chemical and Environmental Engineering, Liaoning University of Technology, Jinzhou, Liaoning, 121001, China
[b] School of Electrical Engineering, Liaoning University of Technology, Jinzhou, Liaoning, 121001, China

ARTICLE INFO

Article history:
Received 14 August 2017
Received in revised form 25 December 2017
Accepted 23 February 2018

Keywords:
Barrier Lyapunov functions
Nussbaum gain control
Adaptive control
Lyapunov–Krasovskii functional
Nonlinear systems with time-delay

ABSTRACT

This paper proposes an adaptive tracking control approach for a class of nonlinear state-constrained and time-varying delay systems with unknown time-varying control coefficients. As far as we know, there is no control method for such systems at present. To stabilize such a class of systems, the neural networks and a backstepping technique are utilized to structure an adaptive tracking controller. The Nussbaum gain technique is utilized to solve the problem of unknown time-varying control coefficients, and the Lyapunov–Krasovskii functionals (LKFs) are employed to eliminate the effect of unknown time-varying delays. In addition, the states are guaranteed to remain within their constraint sets based on the Barrier Lyapunov functions (BLFs). Finally, it can be proved that all signals in the closed-loop systems are bounded, the state constraints are never violated and the tracking errors fluctuate within the predetermined compact range around the zero. The simulation results are provided to illustrate the effectiveness of the proposed control strategy.

1. Introduction

In recent years, the control design and stability analysis for the uncertain nonlinear systems have attracted much attention due to theoretical challenge and application demand (Krstic, Kanellakopoulos, & Kokotovic, 1994, 1995). As the universal approximators, the neural networks (Chen, Hua, & Ge, 2014; Wen, Chen, Liu, & Liu, 2017) or the fuzzy logic systems (Boulkroune, Hamel, Azar, & Vaidyanathan, 2016; Chen, Ren, & Du, 2016; Lai et al., 2017; Liu & Tong, 2017) have been involved in the adaptive tracking control strategies to approximate the unknown functions. Subsequently, the numerous notable studies based on the neural networks (NNs) and the fuzzy logic systems (FLSs) have been presented for uncertain nonlinear systems (Arefi, Zarei, & Karimi, 2014; Dong, Zhao, Karimi, & Shi, 2013; Liu, Gao, Tong, & Chen, 2016; Liu & Tong, 2016; Na, Herrmann, & Zhang, 2017; Niu, Karimi, Wang, & Liu, 2017; Yoo, 2013; Zhao, Pawlus, Karimi, & Robbersmyr, 2014). Several adaptive output feedback control methods in Na, Chen, Herrmann, Burke, and Brace (2017), Wei, Qiu, and Karimi (2017), Yoo (2016b) and adaptive state feedback control methods in Liu, Yin, Gao, Alsaadi, and Hayat (2015), Na, Chen, Ren, and Guo (2014) and Rathinasamy, Karimi, Joby, and Santra (2017) were presented for uncertain nonlinear systems based on the NNs or the FLSs. But it is noteworthy that the restriction of constraint problem is not taken into account in the above research.

Due to the application demand, such as safety specifications and physical stoppages in the practical engineering systems, the constraint problem has been paid more and more attention. The BLFs become the main tools to guarantee that the tracking errors never violated the predetermined range. The BLFs were first proposed for the strict-feedback nonlinear system with constant output constraint in Tee, Ge, and Tay (2009). In He and Ge (2015) and Li and Li (2015), based on the BLFs, the output constraint problems were solved by the proposed adaptive control approaches for the flexible beam systems and the continuous stirred tank reactor. In addition, other noteworthy control methods-based the BLFs for handling the output constraint problem for nonstrict-feedback nonlinear systems in Li, Bai, Wang, Zhou, and Wang (2017) and strict-feedback nonlinear systems in Liu, Lai, Zhang, and Chen (2015). By combining the backstepping technique and BLFs, several adaptive controller designs were studied for dealing with partial state constraints in Tee and Ge (2011) and state constraints in He, Chen, and Yin (2016), Kim and Yoo (2014), Liu, Gong, Tong, Chen, and Li (2018), Liu, Lu et al. (2018), Liu, Tong, Chen, and Li (2017) and Tee and Ge (2012). The authors in Liu, Lu, and Tong

☆ This work was supported in part by the National Natural Science Foundation of China under Grants 61603164, 61622303, 61473139, 61773188, the Program for Liaoning Innovative Research Team in University under Grant LT2016006, and the Program for Distinguished Professor of Liaoning Province. The material in this paper was not presented at any conference. This paper was recommended for publication in revised form by Associate Editor Shuzhi Sam Ge under the direction of Editor Miroslav Krstic.
* Corresponding author.
E-mail addresses: ldjuan@126.com (D. Li), li_dapengsir@163.com (D. Li).

https://doi.org/10.1016/j.automatica.2018.03.063

(2017), Liu, Lu, Li, and Tong (2017) and Tee, Ren, and Ge (2011) have further developed the adaptive tracking controller designs for various nonlinear systems with time-varying constraints. But the time delay is to effect another performance source of real systems, which is not considered in the above studies.

Obviously, the time delay often occurs in many engineering systems, and it is a source of severe system performance degradation and even causes system instability. An adaptive control design was given in Bresch-Pietri and Krstic (2009, 2014) for the systems with the unknown delay value and unknown parameters. The compensation design for nonlinear systems with input and state delays was specified in Bekiaris-Liberis and Krstic (2012, 2013). The LKF is an effective tool for handling the stability problem of nonlinear systems with time delays in Yoo (2016a) and Yoo, Park, and Choi (2007). Based on the LKF and the NNs, several adaptive tracking controller designs were developed for nonlinear systems with unknown constant time delays in Karimi (2011), Karimi and Gao (2010), Li, Li, and Feng (2016), Wang, Chen, Liu, and Shi (2008), Wang, Chen, and Shi (2008), Wang, Liu, Liu, and Karimi (2015), Yoo (2017) and Zhao, Yang, Karimi, and Zhu (2016). As the existence of constant time delays, the time-varying delays have been further studied by structuring the adaptive NN controllers based on novel LKFs and a backstepping technique (Boulkroune, M'Saad, & Farza, 2011; Li, Li, Wang, & Chen, 2015; Yoo & Park, 2009). The noteworthy adaptive control methods to eliminate the effect of time delays were presented for nonlinear state-constrained systems in Li and Li (2017), Li, Liu, Tong, Chen, and Li (2018) and Wu, Wu, Luo, and Guan (2012), MIMO nonlinear systems in Chen, Liu, Liu, and Lin (2009), Ge and Tee (2007) and Zhang and Ge (2007). Based on above mentioned descriptions, there exists a main limitation, i.e., the signs of the control gain must be known. It is obvious that the known signs of the control gain are a special case in practical application.

For unknown signs of the control gain, the adaptive tracking control problem of such systems becomes more complex and general. As the effective tool for dealing with unknown signs of the control gain, the Nussbaum gain technique was first given in Nussbaum (1983). Subsequently, the Nussbaum gain technique has been widely employed for handling the challenge of unknown signs of the control gain. By employing the Nussbaum gain technique, an observer-based fuzzy adaptive controller is structured to solve the stability problem of nonlinear systems with uncertain control coefficients in Boulkroune and M'saad (2012). An adaptive compensation control approach was framed in Wang, Wang, Liu, and Tong (2017) and Wang, Wen, and Lin (2017) for SISO nonlinear systems with unknown control gain. The robust adaptive control method was proposed for nonlinear strict-feedback systems with time-varying control gain in Ge and Wang (2002, 2003). Several adaptive control methods were framed to solve the stability problem of the unknown control coefficients for MIMO nonlinear systems in Shi, Luo, and Li (2017), the nonlinear time-delay systems in Boulkroune, Tadjine, M'Saad, and Farza (2010) and Wang, Chen, Liu, Liu, and Zhang (2008), and state-constrained systems in Liu and Tong (2017). The urgent problem is that how to control and stabilize nonlinear state-constrained and time-varying delay systems with unknown time-varying control coefficients.

This paper will present an adaptive control approach to solve the stability problem of a class of nonlinear state-constrained systems with unknown time-varying delays and control gain coefficients. To the best of our knowledge, such a class of systems was first studied at present. The key contributions of this paper are summarized as follows: (i) Based on the employment of BLFs and a backstepping technique, an adaptive tracking controller is structured to guarantee that the states always remain in constrained set; (ii) The Nussbaum gain technique is employed to deal with the challenge of the unknown time-varying control coefficients; (iii) The LKFs and the NNs are utilized to eliminate the effect of the unknown time-varying delays. Finally, by using the Lyapunov stability analysis, it can be proved that all the signals in the closed-loop systems are bounded, all the state constraints are never violated and the tracking errors are within the small neighborhood of the origin. The feasibility of proposed control method is validated by employing the simulation results.

2. System descriptions

We consider a class of SISO unknown nonlinear state-constrained systems with time-delays as follows:

$$\begin{cases} \dot{x}_i(t) = g_i(\bar{x}_i(t))\, x_{i+1}(t) + f_i(\bar{x}_i(t)) \\ \qquad\quad + h_i(\bar{x}_i(t-\tau_i(t))) + d_i(x,t) \\ \dot{x}_n(t) = g_n(x(t))\, u(t) + f_n(x(t)) \\ \qquad\quad + h_n(x(t-\tau_n(t))) + d_n(x,t) \\ y(t) = x_1(t) \end{cases} \tag{1}$$

where $x_n = [x_1, \ldots, x_n]^T \in R^n$ and $\bar{x}_i = [x_1, \ldots, x_i]^T \in R^i$, $i = 1, 2, \ldots, n-1$ stand for the system states; $u \in R$ and $y \in R$ denote the control input and output, respectively; there exists a constant k_{c_i}, which is the upper bound of x_i, i.e., $|x_i| \le k_{c_i}$; $f_i(\cdot)$ and $h_i(\cdot)$ stand for unknown and smooth functions; $g_i(\cdot)$ represents unknown time-varying piecewise continuous function; $d_i(\cdot)$ stands for the external disturbance uncertainty; $\tau_i(t)$ denotes the unknown time-varying delay to satisfy $0 < \tau_i(t) \le \tau_{\max}$ and $\dot{\tau}_i(t) \le \tau \le 1$ with $\tau_{\max}$ and τ being known constants.

The control objective is that an adaptive neural control controller is structured to guarantee the boundedness of all closed-loop systems signals, the system output $y(t)$ follows the desired reference signal $y_d(t)$, the tracking errors converge to a small neighborhood about zero, and all the state constrains are never violated.

Assumption 1 (*Tee & Ge, 2011*)**.** For any constant k_{c_1}, there are the positive constants $A_0, A_1, \ldots, A_n$, the desired trajectory $y_d(t)$ satisfies $|y_d(t)| \le A_0 \le k_{c_1}$, and its time derivatives $y_d^j(t)$ satisfy $\left|y_d^j(t)\right| \le A_j, j = 1, 2, \ldots, n$.

Assumption 2 (*Tee & Ge, 2011*)**.** There is the positive function $\rho_i(\bar{x}_i(t))$ such that the external disturbance $d_i(x,t)$ satisfied $|d_i(x,t)| \le \rho_i(\bar{x}_i(t))$.

Assumption 3 (*Zhang & Ge, 2007*)**.** The signs of the unknown functions $g_i(\bar{x}_i)$, $i = 1, \ldots, n$ are unknown and $g_i(\bar{x}_i) \ne 0$, there exist the constants $\underline{g}_i$ and $\bar{g}_i$, such that $0 \le \underline{g}_i \le |g_i(\bar{x}_i)| \le \bar{g}_i$.

Remark 1. The stability problem of nonlinear constrained systems has been solved in the past under the assumption that the sign of control gain is known. In this brief paper, an adaptive controller was proposed for nonlinear systems with unknown time-varying delays and full state constraints without a priori knowledge of control coefficients due to the increasing complexity of the engineering environment.

Definition 1 (*Nussbaum, 1983*)**.** The continuous function $N(\zeta)$ is called a Nussbaum-type function when it has the properties $\lim_{\gamma\to+\infty} \sup \frac{1}{\gamma}\int_0^{\gamma} N(\zeta)\, d\zeta = +\infty$ and $\lim_{\gamma\to-\infty} \inf \frac{1}{\gamma}\int_0^{\gamma} N(\zeta)\, d\zeta = -\infty$.