Automatica 76 (2017) 222–229

Contents lists available at ScienceDirect

Automatica

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

Brief paper

Unknown time-varying input delay compensation for uncertain nonlinear systems☆

Serhat Obuz, Justin R. Klotz, Rushikesh Kamalapurkar, Warren Dixon

Department of Mechanical and Aerospace Engineering, University of Florida, Gainesville, USA

ARTICLE INFO

Article history:
Received 20 January 2015
Received in revised form
8 April 2016
Accepted 26 August 2016

Keywords:
Input delay
Robust control
Nonlinear control

ABSTRACT

A tracking controller is developed for a class of uncertain nonlinear systems subject to unknown time-varying input delay and additive disturbances. A novel filtered error signal is designed using the past states in a finite integral over a constant estimated delay interval. The maximum tolerable error between unknown time-varying delay and a constant estimate of the delay is determined to establish uniformly ultimately bounded convergence of the tracking error to the origin. The controller development is based on an approach which uses Lyapunov–Krasovskii functionals to analyze the effects of unknown sufficiently slowly time-varying input delays. A stability analysis is provided to prove ultimate boundedness of the tracking error signals. Numerical simulation results illustrate the performance of the developed robust controller.

© 2016 Published by Elsevier Ltd.

1. Introduction

Time delay commonly exists in many engineering applications such as master–slave robots, haptic systems, chemical systems and biological systems. The system dynamics, communication over a network, and sensing with associated sensor processing (e.g., image-based feedback) can induce time delays that can result in decreased performance and loss of stability. Time delays in physical systems are often time-varying. For example, the input delay in neuromuscular electrical stimulation applications often changes with muscle fatigue (Downey, Kamalapurkar, Fischer, & Dixon, 2015; Merad, Downey, Obuz, & Dixon, 2016), communication delays in wireless networks change with the distance between the communicating agents, etc. Motivated by such practical engineering challenges, numerous research efforts have focused on designing controllers to compensate time delay disturbances effects.

Research in recent years has focused on developing controllers that provide stability for systems with delays in the closed-loop dynamics. Smith's pioneering work Smith (1959), Arstein's model reduction (Artstein, 1982), and the finite spectrum approach (Manitius & Olbrot, 1979) have heavily influenced the methods of designing controllers that compensate the effects of delays.

In recent years, research has focused on systems that experience a known delay in the control input. The works in Lozano, Castillo, Garcia, and Dzul (2004), Normey-Rico, Guzman, Dormido, Berenguel, and Camacho (2009) and Roh and Oh (1999) develop robust controllers which compensate for known input time delay for systems with linear plant dynamics. Compensation of input delay disturbances for nonlinear plant dynamics is addressed in prominent works such as Dinh, Fischer, Kamalapurkar, and Dixon (2013), Fischer (2012), Fischer, Dani, Sharma, and Dixon (2011), Fischer, Dani, Sharma, and Dixon (2013), Fischer, Kamalapurkar, Fitz-Coy, and Dixon (2012), Huang and Lewis (2003), Obuz, Tatlicioglu, Cekic, and Dawson (2012), Sharma, Bhasin, Wang, and Dixon (2011) and Teel (1998) for nonlinear plant dynamics affected by external disturbances and in Henson and Seborg (1994), Jankovic (2006) and Mazenc and Bliman (2006) for plant dynamics without external disturbances. However, the controllers in Dinh et al. (2013), Fischer (2012), Fischer et al. (2011), Fischer et al. (2013), Fischer, Kamalapurkar et al. (2012), Henson and Seborg (1994), Huang and Lewis (2003), Jankovic (2006), Mazenc and Bliman (2006), Obuz et al. (2012), Sharma et al. (2011) and Teel (1998), require exact knowledge of the time delay duration. In practice, the duration of an input time delay can be challenging to determine for some applications, therefore, it is necessary to develop new controllers that do not require exact knowledge of the time delay.

Since uncertainty in the delay can lead to unpredictable closed-loop performance (potentially even instabilities), several recent

☆ The material in this paper was not presented at any conference. This paper was recommended for publication in revised form by Associate Editor Hiroshi Ito under the direction of Editor Andrew R. Teel.

E-mail addresses: serhat.obuz@ufl.edu (S. Obuz), jklotz@ufl.edu (J.R. Klotz), rkamalapurkar@ufl.edu (R. Kamalapurkar), wdixon@ufl.edu (W. Dixon).

http://dx.doi.org/10.1016/j.automatica.2016.09.030
0005-1098/© 2016 Published by Elsevier Ltd.

results have been developed which do not assume that the delay is exactly known. Compensation for unknown input delay is investigated in Bresch-Pietri, Chauvin, and Petit (2010, 2011), Bresch-Pietri, Chauvin, and Petit (2012), Bresch-Pietri and Krstic (2009), Choi and Lim (2010), Herrera, Ibeas, Alcantara, Vilanova, and Balaguer (2008), Li, Gu, Zhou, and Xu (2014), Li, Zhou, and Lin (2014), Polyakov, Efimov, Perruquetti, and Richard (2013), Wang, Wu, and Gao (2005) and Wang, Saberi, and Stoorvogel (2013) for systems with exactly known dynamics and Chen and Zheng (2006), Yue (2004), Yue and Han (2005) and Zhang and Li (2006a,b) for systems with uncertain dynamics. However, all of the controllers in Bekiaris-Liberis and Krstic (2013), Bresch-Pietri et al. (2010, 2011), Bresch-Pietri et al. (2012), Bresch-Pietri and Krstic (2009), Chen and Zheng (2006), Choi and Lim (2010), Herrera et al. (2008), Li, Gu et al. (2014), Li, Zhou et al. (2014), Polyakov et al. (2013), Wang et al. (2013), Wang et al. (2005), Yue (2004), Yue and Han (2005) and Zhang and Li (2006a,b) are developed for linear plant dynamics. The works in Balas and Nelson (2011), Bresch-Pietri and Krstic (2014), Mazenc and Niculescu (2011) and Nelson and Balas (2012) develop controllers for plants with nonlinear dynamics and an unknown input delay, but require exact model knowledge of the nonlinear dynamics. The controller designed in Chiu and Chiang (2009) compensates for Takagi–Sugeno fuzzy systems and unknown actuation delay duration by using a memoryless observer and a fuzzy parallel distributed integral compensator for nonlinear, uncertain dynamics. However, the controller in Chiu and Chiang (2009) is designed for output regulation and does not address the output tracking problem. There remains a need for a tracking controller that can compensate for the effects of unknown time-varying input delays for a class of uncertain nonlinear systems.

When uncertain nonlinear dynamics are present, the control design is significantly more challenging than when linear or exactly known nonlinear dynamics are present. For example, in general, if the system states evolve according to linear dynamics, the linear behavior can be exploited to predict the system response over the delay interval. Exact knowledge of the dynamics facilitates the ability to predict the state transition for nonlinear systems. For uncertain nonlinear systems, the state transition is significantly more difficult to predict, especially if the delay interval is also unknown and/or time-varying. Given the difficulty in predicting the state transition, the contribution in this paper (and in Fischer, Kamalapurkar et al., 2012 and Kamalapurkar, Fischer, Obuz, & Dixon, 2016) is to treat the input delay and dynamic uncertainty as a disturbance and develop a robust controller that can compensate for these effects.

Recently, Fischer et al. presented a robust controller for uncertain nonlinear systems with additive disturbances subject to slowly varying input delay in Fischer, Kamalapurkar et al. (2012), where it is assumed that the input delay duration is measurable and the absolute value of the second derivative of the delay is bounded by a known constant. The approach in this study extends our previous work in Fischer, Kamalapurkar et al. (2012) by using a novel filtered error signal to compensate for an unknown slowly varying input delay for uncertain nonlinear systems affected by additive disturbances. In Fischer, Kamalapurkar et al. (2012), a filtered error signal defined as the finite integral of the actuator signals over the delay interval is used to obtain a delay-free expression for the control input in the closed-loop error system. However, the computation of the finite integral requires exact knowledge of the input delay. In this study, a novel filtered error signal is designed using the past states in a finite integral over a constant estimated delay interval to cope with the lack of delay knowledge, which requires a significantly different stability analysis that takes advantage of Lyapunov–Krasovskii functionals. Techniques used in this study provide relaxed requirements of the delay measurement and obviate the need for a bound of the absolute value of the second derivative of the delay. It is assumed that the estimated input delay is selected sufficiently close to the actual time-varying input delay. That is, there are robustness limitations, which can be relaxed with more knowledge about the time-delay. Because it is feasible to obtain lower and upper bounds for the input delay in many applications (Richard, 2003), it is feasible to select a delay estimate in an appropriate range. New sufficient conditions for stability are based on the length of the estimated delay as well as the maximum tolerable error between the actual and estimated input delay. A Lyapunov-based stability analysis is used to prove ultimate boundedness of the error signals. Numerical simulation results demonstrate the performance of the robust controller.

2. Dynamic system

Consider a class of nth-order nonlinear systems

$$\begin{aligned} \dot{x}_i &= x_{i+1}, \quad i = 1, \ldots, n-1, \\ \dot{x}_n &= f(X,t) + d + u(t-\tau), \end{aligned} \tag{1}$$

where $x_i \in \mathbb{R}^m$, $i = 1, \ldots, n$ are the measurable system states, $X = \left[x_1^T,\ x_2^T,\ \ldots,\ x_n^T\right]^T \in \mathbb{R}^{mn}$, $u \in \mathbb{R}^m$ is the control input, $f : \mathbb{R}^{mn} \times [t_0, \infty) \to \mathbb{R}^m$ is an uncertain nonlinear function, $d : [t_0, \infty) \to \mathbb{R}^m$ denotes sufficiently smooth unknown additive disturbance (e.g., unmodeled effects), and $\tau : [t_0, \infty) \to \mathbb{R}$ denotes a time-varying unknown positive time delay,[1] where t_0 is the initial time. Throughout the paper, delayed functions are denoted as

$$h_\tau \triangleq \begin{cases} h(t-\tau) & t-\tau \geq t_0 \\ 0 & t-\tau < t_0. \end{cases}$$

The dynamic model of the system in (1) can be rewritten as

$$x_1^{(n)} = f(X,t) + d + u(t-\tau), \tag{2}$$

where the superscript (n) denotes the nth time derivative. In addition, the dynamic model of the system in (1) satisfies the following assumptions.

Assumption 1. The function f and its first and second partial derivatives are bounded on each subset of their domain of the form $\Xi \times [t_0, \infty)$, where $\Xi \subset \mathbb{R}^{mn}$ is compact and for any given Ξ, the corresponding bounds are known.[2]

Assumption 2 (*Fischer, Kan, & Dixon, 2012*)**.** The nonlinear additive disturbance term and its first time derivative (i.e., $d, \dot{d}$) exist and are bounded by known positive constants.

Assumption 3. The reference trajectory $x_r \in \mathbb{R}^m$ is designed such that the derivatives $x_r^{(i)}$, $\forall i = 0, 1, \ldots, (n+2)$ exist and are bounded by known positive constants.

[1] The developed method can be extended to the case of multiple delays. Assumption 4 can be modified for the case of multiple delays by redefining the delayed input vector and using the maximum input delay instead of the actual delay bound such that $\max\{\tau_1, \tau_2, \ldots, \tau_m\} < \Upsilon$. To obviate the requirement of exact knowledge of the time delay dynamics in the stability analysis and introducing new Lyapunov–Krasovskii functionals for each input delay, the closed-loop dynamics can be revised in terms of $\dot{u}_{\hat{\tau}}$, $(\dot{u}_\tau - \dot{u}_{\hat{\tau}})$ instead of the terms $\dot{u}_{\hat{\tau}}$, $\dot{u}_{\tau}$, : $(\dot{u}_\tau - \dot{u}_{\hat{\tau}})$. In this paper, single time-varying input delay is considered for ease of exposition.

[2] Given a compact set $\Xi \subset \mathbb{R}^{mn}$, the bounds of f, $\frac{\partial f(X,t)}{\partial X}$, $\frac{\partial f(X,t)}{\partial t}$, $\frac{\partial^2 f(X,t)}{\partial^2 X}$, $\frac{\partial^2 f(X,t)}{\partial X \partial t}$, and $\frac{\partial^2 f(X,t)}{\partial^2 t}$ over Ξ are assumed to be known.

Download English Version:

https://daneshyari.com/en/article/5000127

Download Persian Version:

https://daneshyari.com/article/5000127

Daneshyari.com