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Brief paper

Input delay compensation for neutral type time-delay systems[☆]

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ABSTRACT

In this contribution we investigate the input delay compensation for neutral type time-delay systems with both state and input delays. A nested predictor is established to predict the future states such that the input delay that can be arbitrarily large yet bounded are compensated completely. It is shown that the compensated closed-loop system in the presence of input delay possesses the same characteristic equation as the closed-loop system in the absence of input delay. An implementation scheme by adding input filters is also proposed. Under an additional assumption, explicit nested predictor feedback controllers involving only 1-fold integrals are established. A numerical example is carried out to support the obtained theoretical results.

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1. Introduction

Analysis and design of time-delay control systems modeled by functional differential equations have received considerable attention on both control and applied mathematics communities. This is because, on the one hand, time-delay systems have very wide applications in engineering practice such as chemical process control, machining, combustion systems, energy systems and networked systems (Chen & Zheng, 2011; Fridman, 2010; Gu & Niculescu, 2000; Lam, Xu, Ho, & Zou, 2012; Wang & Cheng, 2016; Zhang, Ren, & Li, 2016; Zhang, Zhang, & Wang, 2016; Zhou, Huang, Tian, & Liao, 2016), and, on the other hand, time-delay systems belong to infinite dimensional control systems that are mathematically challenging (Hale, 1977; Krstic, 2009; Michiels & Niculescu, 2007). There have been plenty of results available in the literature dealing with the analysis and design of time-delay systems from various aspects. Particularly, some classical control problems for delay-free control systems such as robust control (Han, 2004), H_∞ control, observer design (Cacace, Germani, & Manes, 2014), and optimal control (Cacace, Conte, & Germani, 2016; Zhang, Li, Xu, & Fu, 2015) have been extended to time-delay systems properly. The neutral type time-delay systems have also been well studied in the literature (Han, 2004; Kharitonov, 2005; O'Connor & Tarn, 1983; Wang & Zhong, 2007). In recent years with the development of technique of linear matrix inequalities (LMIs), many problems for time-delay systems can be solved quite efficiently with the help of the Lyapunov–Krasovskii stability theory (see Fridman, 2010; Huang & Sun, 2016; Lam et al., 2012; Michiels & Niculescu, 2007; Xu, Lam, & Yang, 2001 and the references therein).

Generally, the time-delay that is relatively small is not a problem in both theory and in practical applications since the controllers designed without considering the time-delay generally possess certain robustness with respect to small time-delays (Krstic, 2010a). However, if the time-delay is relatively large, it is no longer ignorable in the controller design stage and should be properly taken into consideration. A particular approach developed for this issue is the Smith predictor, which aims to compensate completely the time-delay effect so that the closed-loop system acts like a delay-free system (Smith, 1959). Since the Smith predictor works only for asymptotically stable systems, a new approach named predictor feedback was latterly built to compensate arbitrarily large yet bounded input delays without requiring the asymptotic stability of the open-loop system (Manitius & Olbrot, 1979). The predictor feedback has received renewed interest in recent years (see, for example, Jankovic, 2009, 2010; Karafyllis, 2011; Krstic, 2009; Zhou, Lin, & Duan, 2012 and the references therein). One of the novel idea is to model the input delay dynamics as a partial differential equation (PDE) of transport type. This work was initialized by Krstic (2009) and has been extended in many aspects (Bekiaris-Liberis & Krstic, 2010; Karafyllis, 2011; Krstic, 2010b). The merit of this approach is

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that Lyapunov–Krasovskii functionals can be easily constructed and explicit stability estimates can be derived for the closed-loop system. Moreover, by this approach, it is possible to consider more complicated time-delays such as time-varying and/or state-dependent time delays (Bekiaris-Liberis, 2014; Bekiaris-Liberis & Krstic, 2010, 2012).

Very recently, motivated by the existing design of predictor feedback for linear systems with input delays (Artstein, 1982; Krstic, 2009; Manitius & Olbrot, 1979), we have considered in Zhou (2014) a new problem of compensating long input time delays for linear systems with both input and state delays. Different from the existing work which aims to compensate all the time delays so that the resulting closed-loop system is delay-free, we are only concerned with the compensation of the input delay. It turns out that, no matter how large the input delay is, as long as the open-loop system without input delay can be stabilized, a stabilizing predictor feedback can be constructed nestedly for the considered time-delay systems. The nested predictor feedback proposed in Zhou (2014) can be easily implemented in computer. An alternative solution to the same problem by adding integrators has been recently established in Zhou (2015). It is interesting to notice that the same problem was independently investigated in Kharitonov (2014) where a completely different approach was built by using the fundamental matrix functions for the open-loop time-delay system. A different solution to such a problem was later provided in Yoon and Lin (2014, 2015). The approach in Kharitonov (2014) was then extended in Kharitonov (2015) to neutral type time-delay systems. The resulting controllers by using this approach are in quite neat forms, however, are implicit since they require in addition the fundamental matrix functions which needs extra computations.

The aim of the present paper is to complete the study of the nested predictor feedback in Zhou (2014) by revisiting the input delay compensation problem for neutral type time-delay systems. The first contribution of this paper is that we can show that the nested predictor feedback proposed in Zhou (2014) for retarded type time-delay systems can be successfully extended to the neutral type case and a numerical implementation scheme can also be established. By noting that the nested predictor feedback controllers involve multiple integrals, another contribution of this paper is to provide explicit nested predictor feedback controllers containing only 1-fold integrals under an additional assumption. The extension of the nested predictor feedback in Zhou (2014) to the neutral type time-delay system is nontrivial since the latter system contains three different time-delay components that should be carefully treated in the subsequent developments, and, moreover, explicit nested predictor feedback controllers are proposed. Compared with the fundamental matrix functions based approach developed in Kharitonov (2015), our nested predictor feedback approach proposed in this paper possesses some advantages. Firstly, the nested predictor feedback uses only the system coefficients and is thus easy to implement. Secondly, the neutral type time-delay system considered in this paper has different delays in the time-derivative vector and the state vector, whereas these two delays are assumed to be the same in Kharitonov (2015). Finally, we are able to provide explicit controllers under an additional assumption (which is satisfied by all the numerical examples in Kharitonov (2015)) while the controllers in Kharitonov (2015) are implicit as they require the fundamental matrix functions of the open-loop time-delay system.

This paper is organized as follows: The input delay compensation by using nested predictor and implementation by adding input filters are given in Section 2. In Section 3, we will present the explicit nested predictor. A numerical example will be carried out to support the theoretical results in Section 4. Finally, Section 5 concludes the paper.

2. Input delay compensation by nested predictor

2.1. Problem formulation

We consider the following neutral type time-delay system with both state and input delays

$$\frac{\mathrm{d}}{\mathrm{d}t}\left[x(t)-Dx(t-h)\right]=Ax(t)+A_rx(t-r)+Bu(t-R), \tag{1}$$

where $A, A_r, D \in \mathbf{R}^{n\times n}$ and $B \in \mathbf{R}^{n\times m}$ are constant matrices, $h > 0$ and $r > 0$ are state delays, and $R > 0$ is the input delay. In this paper we are interested in the design of stabilizing controllers for this class of systems. To this end, we first give some assumptions as follows.

Assumption 1. The matrix D is Schur stable, namely, $|\lambda_i(D)| < 1, i \in \mathbf{I}[1,n] \triangleq \{1,2,\ldots,n\}$, where $\lambda_i(D)$ denotes the ith eigenvalue of D.

We mention that the above assumption is necessary for the existence of a stabilizing controller that does not use the time-derivative term $\dot{x}(t)$ (see, for example, O'Connor & Tarn, 1983; Pepe & Karafyllis, 2013). Hereafter, we denote

$$y(t)=x(t)-Dx(t-h),\quad t\geq 0. \tag{2}$$

Assumption 2. The neutral type time-delay system

$$\dot{y}(t)=Ax(t)+A_rx(t-r)+Bu(t), \tag{3}$$

which corresponds to system (1) without input delay, can be stabilized by the following state feedback controller

$$u(t)=Kx(t)+K_rx(t-r), \tag{4}$$

where $K \in \mathbf{R}^{m\times n}$ and $K_r \in \mathbf{R}^{m\times n}$ are some feedback gains, namely, the closed-loop system

$$\dot{y}(t)=(A+BK)x(t)+(A_r+BK_r)x(t-r), \tag{5}$$

is asymptotically stable.

Regarding the design of the matrices K and K_r in Assumption 2, we give the following lemma. The proof is quite similar to that in Wang and Zhong (2007) and is omitted.

Lemma 1. *There exist two matrices K and K_r such that the state feedback controller (4) stabilizes system (3) if there exist matrices $P_1 > 0, S > 0, Q > 0, M > 0, Z = \begin{bmatrix} Z_{11} & Z_{12} \\ * & Z_{22}\end{bmatrix} > 0$, and matrices P, G and G_r such that*

$$\begin{bmatrix} \Pi_1 & \Pi_2 & A_rP^{\mathrm{T}}+BG_r+Z_{12}^{\mathrm{T}} & DP^{\mathrm{T}} \\ * & \Pi_3 & A_rP^{\mathrm{T}}+BG_r & DP^{\mathrm{T}} \\ * & * & rZ_{11}-Z_{12}-Z_{12}^{\mathrm{T}}-Q & 0 \\ * & * & * & -M \end{bmatrix}<0, \qquad Z_{22}-S<0, \tag{6}$$

where $\Pi_1 = AP^{\mathrm{T}}+BG+PA^{\mathrm{T}}+G^{\mathrm{T}}B^{\mathrm{T}}+Q$, $\Pi_2 = P_1-P^{\mathrm{T}}+PA^{\mathrm{T}}+G^{\mathrm{T}}B^{\mathrm{T}}$, and $\Pi_3 = rS-P-P^{\mathrm{T}}+M$. Moreover, two feedback gains can be obtained as

$$K=G\left(P^{-1}\right)^{\mathrm{T}},\qquad K_r=G_r\left(P^{-1}\right)^{\mathrm{T}}. \tag{7}$$

The problem to be solved can be stated as follows.

Problem 1. Let Assumptions 1–2 be satisfied. Design a linear controller $u(t)=F(x_t)+G(u_t)$, where F and G are some linear operators, for the neutral type time-delay system (1) such that the closed-loop system possesses the same characteristic equation as system (5).

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