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Brief paper

Output tracking control of networked control systems via delay compensation controllers[☆]

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ABSTRACT

In this paper, the problem of networked output tracking control is investigated by considering the delay compensations in both the feedback and forward channels in networked control systems. The delayed output measurements are treated as a special output disturbance, and the feedback channel delay is compensated with the aid of an extended functional observer. For the delay in the forward channel, the buffer and packet-based delay compensation approaches are presented, respectively. Then, the stability analysis is performed for the networked closed-loop systems. Finally, a servo motor control system is used to demonstrate the effectiveness of the proposed new design scheme.

1. Introduction

With the growth in computing and networking abilities, more and more networks (e.g., the Internet) have been implemented in distributed control systems, which results in the so-called networked control systems (NCSs). Compared with the traditional feedback control systems, NCSs have advantages in terms of low cost, weight and power requirements reduction, simplicity in installation and maintenance, as well as easy resource sharing, and so on. NCSs receive more and more attention in recent years, research topics on NCSs include modeling, stability analysis, control and filtering design, see for example, Qiu, Feng, and Gao (2010), Vesely, Rosinova, and Quang (2013), Mkondweni and Tzoneva (2014), Yue, Tian, Zhang, and Peng (2009), Xia, Shang, Chen, and Liu (2009), Imer, Yuksel, and Basar (2006), Gao, Liu, and Lam (2009), Zhao, Liu, and Rees (2009a), Zhang, Lam, and Xia (2011), Zhang and Xia (2011), Xia, Fu, and Liu (2011), and the references therein.

Although the network makes it convenient to control large distributed systems, the introduction of limited-capacity network channels into control systems also brings many undesired problems. Among all the problems, the data dropout and the network communication delay are known to be two of the main causes for the performance deterioration or even the instability of the NCSs. Recently, various methods have been presented to handle these two issues or both of them in NCSs, and many control approaches have been established. To mention a few, sampled-data system approaches (Hu, Bai, Shi, & Wu, 2007; Sun, Liu, Wang, & Rees, 2010), stochastic system approaches (Luan, Shi, & Liu, 2011; Nilsson, Bernhardsson, & Wittenmark, 1998), optimal control method (Hu & Zhu, 2003; Lian, Moyne, & Tilbury, 2003), time delay system method (Gao, Chen, & Lam, 2008; Yue, Han, & Lam, 2005), switched system method (Donkers, Heemels, & Nathan, 2011; Sun et al., 2010), robust control method (Zhang & Yu, 2009), and so on.

It is worth mentioning that, in the aforementioned works, the system simply passively accepts the presence of the network communication delay and data dropout, to actively compensate for them, networked predictive control (NPC) strategies are recently proposed in Liu, Mu, Rees, and Chai (2006). The main feature of NPC is to predict the future control inputs of the system and take the corresponding control action according to the current network condition, then the network communication delay and data dropout can be actively compensated. Further studies on NPC methods were made in Liu, Xia, Chen, Rees, and Hu (2007a), Liu, Xia, Chen, Rees, and Hu (2007b), Zhao, Liu, and Rees (2009b),

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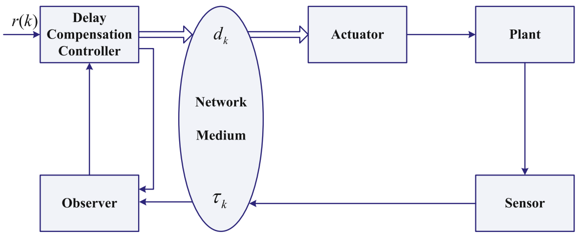

Fig. 1. Block diagram of networked control systems.

Wang, Liu, Wang, Wang, and Rees (2009), Wang, Liu, Wang, Rees, and Zhao (2010), Zhang, Xia, and Shi (2013b), Zhang, Shi, and Xia (2013a), Guo and Li (2010). For example, in Zhao, Liu, and Rees (2008a,b), some NPC approaches are proposed for networked Hammerstein-type systems. In Liu et al. (2007a,b), the state space model based NPC methods was developed for NCSs with feedback channel delay and both forward and feedback channel delays, respectively. In Pin and Parisini (2011), the NPC approach was developed for uncertain constrained nonlinear systems. In Hu, Liu, and Rees (2007), an event-driven NPC method was presented for single input single output (SISO) NCSs.

It should be pointed out that, in most of the existing NPC methods, the predicted control inputs are computed based on the delayed state/output measurements (Guo & Li, 2010; Zhang et al., 2013a,b; Zhao, Kim, & Liu, 2011; Zhao et al., 2009b), which indicates the existing NPC methods are only effective in compensating for the delay in the forward channel of the NCSs, and how to compensate the feedback channel delay is important and interesting. In this paper, we consider the output tracking control problem of NCSs with delay compensations in both the feedback and forward channels. By viewing the delayed output measurement as a special output "disturbance", the feedback channel delay can be compensated with the aid of the proposed extended functional observer. The main contributions of this paper lie in:

1. the delay compensation strategies are proposed to actively compensate the network communication delay in the feedback and forward channels, respectively; and
2. the networked output tracking controllers with delay compensation are designed and the stability analysis is performed for the networked closed-loop systems.

Finally, simulation results on a servo motor control system are given to illustrate the effectiveness of the proposed techniques.

2. Problem formulation

The NCSs structure considered in this paper is shown in Fig. 1,

$$\begin{cases} x(k+1) = Ax(k) + Bu(k) \\ y(k) = Cx(k) \end{cases} \tag{1}$$

where $x(k) \in \mathbb{R}^n$ is the state vector, $u(k) \in \mathbb{R}^m$ is the control input vector, $y(k) \in \mathbb{R}^q$ is the system output vector, $r(k)$ is a bounded reference input, and has constant steady-state value. A, B and C are known constant system matrices with appropriate dimensions. In addition, the following assumptions are made for system (1).

Assumption 1. The pair (A, B) is stabilizable, the pair (A, C) is detectable, and $\begin{bmatrix} A-I_n & B \\ C & 0 \end{bmatrix}$ is of full column rank.

Assumption 2. The time-varying network communication delays τ_k in the feedback channel and d_k in the forward channel are bounded by $\bar{\tau}$ and $\bar{d}$, respectively, where $\bar{\tau}$ and $\bar{d}$ are two positive integers.

Assumption 3. The observer and actuator possess the logical choice capability to guarantee that only the latest data will be used.

Remark 1. In this paper, only network communication delay is considered in both feedback and forward channels. It should be pointed out that, if the data dropout happens in the feedback or forward channel, under Assumption 3, the data dropout can be viewed as a special network communication delay, and merged into τ_k or d_k.

The objective of this paper is to propose the delay compensation schemes to actively compensate the delay occurred in both feedback and forward channels, and to design a controller such that the output $y(k)$ tracks a reference signal $r(k)$.

3. Delay compensation in feedback channel

In this section, we consider the delay compensation problem in the feedback channel. As is shown in Fig. 1, the observer is located at the controller side, and there exists network communication delay τ_k in the feedback channel, thus, at instant k, the corresponding output signal received by the observer is $y_\tau(k) \triangleq y(k-\tau_k)$ rather than $y(k)$. If the system state is not available for the system, we need to introduce an observer to estimate the state. The common and traditional observer is given as

$$\hat{x}(k+1) = A\hat{x}(k) + Bu(k) + L(y_\tau(k) - C\hat{x}(k)). \tag{2}$$

Note that the system output at the observer side can be rewritten in the following form:

$$\begin{aligned} y_\tau(k) &= y(k-\tau_k) = Cx(k-\tau_k) \\ &= Cx(k) + x_f(k) \end{aligned}$$

where $x_f(k) = Cx(k-\tau_k) - Cx(k)$ can be viewed as the "disturbance" induced by the network in the feedback channel. If the observer is chosen as (2), the estimation error $e_x(k) \triangleq x(k) - \hat{x}(k)$ can be determined as

$$\begin{aligned} e_x(k+1) &= x(k+1) - \hat{x}(k+1) \\ &= Ax(k) + Bu(k) \\ &\quad - (A\hat{x}(k) + Bu(k) + L(y_\tau(k) - C\hat{x}(k))) \\ &= Ax(k) - (A\hat{x}(k) + L(Cx(k) + x_f(k) - C\hat{x}(k))) \\ &= (A - LC)e_x(k) - Lx_f(k). \end{aligned} \tag{3}$$

Obviously, the estimation error will be affected unavoidably by the "disturbance" $x_f(k)$ and the observer gain L, and system performance will be degraded inevitably by using the traditional observer (2) for system (1). Motivated by the state observer technique proposed in Fernando and Trinh (2007), Ha, That, Nam, and Trinh (2014), Ha and Trinh (2004), Trinh and Fernando (2012), in the following, the extended functional observer will be designed for system (1) to estimate the state $x(k)$ and the "disturbance" $x_f(k)$ simultaneously.

Now, for the simplicity of presentation, we introduce the following notations:

$$\bar{x}(k) = \begin{bmatrix} x(k) \\ x_f(k) \end{bmatrix} \bar{E} = \begin{bmatrix} I_n & 0_{n\times q} \end{bmatrix},$$
$$\bar{A} = \begin{bmatrix} A & 0_{n\times q} \end{bmatrix}, \qquad \bar{C} = \begin{bmatrix} C & I_q \end{bmatrix}.$$

As a result, system (1) at the observer side can be described in the following extended form:

$$\begin{cases} \bar{E}\bar{x}(k+1) = \bar{A}\bar{x}(k) + Bu(k), \\ y_\tau(k) = \bar{C}\bar{x}(k). \end{cases} \tag{4}$$

Then, the state and "disturbance" estimation problem can be converted into the problem of designing an observer for the