2017 International Symposium on Nonlinear Theory and Its Applications,
NOLTA2017, Cancun, Mexico, December 4-7, 2017

Networked Motion Control with Tamper Detection Observer and Smith Predictor

Jin Hoshino†, Takahiro Funakoshi†, Kenta Yamada†, and Ryogo Kubo†

†Department of Electronics and Electrical Engineering, Keio University
3–14–1 Hiyoshi, Kohoku-ku, Yokohama-shi, Kanagawa 223–8522, Japan
Email: hoshino.jin@kbl.elec.keio.ac.jp, funakoshi.takahiro@kbl.elec.keio.ac.jp
yamada.kenta@kbl.elec.keio.ac.jp, kubo@elec.keio.ac.jp

Abstract—The tamper detection observer (TDO) has been proposed to achieve safe and secure operation of networked motion control systems with redundant feedback paths. However, the conventional TDO does not consider the transmission delays of communication networks, which degrade the performance and stability of the system. This paper proposes time-delay compensation methods of a networked motion control system using the TDO. The proposed system includes the Smith predictor, which is one of the popular time-delay compensation techniques. Three time-delay models in the Smith predictor, i.e., minimum, maximum, and average time-delay models, are proposed for the redundant feedback paths with different transmission delays. The proposed methods using the three models are compared by simulations.

1. Introduction

By the development of motion control technology and the Internet, networked control systems (NCSs) are being widely deployed in many areas. The NCSs are not only utilized in the industrial field, such as factory automation and power plant control [1], but also in consumer electronics devices. The NCSs can achieve cost-effective and flexible control of multiple actuators over the Internet. At the same time, the stability of the NCS can be deteriorated by the network elements, such as network delays and packet losses. There are many studies on compensation techniques of time delays and information losses to improve the stability of the NCSs [2, 3]. The Smith predictor using a constant time-delay model is one of the most popular time-delay compensation techniques [4].

Currently, one of the most attractive topics in the NCSs is cybersecurity. The number of incidents targeting NCSs are increasing rapidly. In 2010, the first cyberattack on an NCS was confirmed, and the target was a nuclear power plant. Car factories, pipe lines, and power plants have been also the targets of cyberattacks. The areas of cyberattacks are still increasing, and there are the reports of cars and planes being targeted [5]. Losing control in the NCSs means posing a great risk to nations, economies and citizens since they are utilized mostly in critical infrastructure [6]. Therefore, gaining a safe and secure NCSs has become a top priority issue and there are many studies against the cyberattacks [7].

Current cybersecurities for NCSs have been handled with information technology (IT), i.e., confidentiality, integrity, and availability. However, the priorities for network security and control system security are different, which makes it difficult to provide safe control only with the IT. We have proposed a tamper detection observer (TDO) to provide safe and secure operation of networked motion control systems in [8]. The networked motion control system with the TDO is comprised of a controller, communication networks with redundant feedback paths, and an electric motor. The TDO can detect tampering, which is one of the most critical cyberattacks to NCSs, and select correct feedback signals. Although the TDO was able to detect and compensate the effects of tampering, we have not studied the effects of network delays in the redundant feedback paths.

This paper proposes time-delay compensation methods of networked motion control systems with the TDO to achieve safe and secure operation of the system. All the proposed system utilizes the Smith predictor. Normal NCSs have only one feedback path, and the artificial delay model in the Smith predictor is set as the sum of the forward and feedback path delays. However, the NCSs with the TDO has redundant feedback paths with different time delays. The proposed system includes three kinds of time-delay models in the Smith predictor, i.e., minimum, maximum, and average time-delay models. The proposed methods using the three models are compared by simulations.

This paper is organized as follows. The following section presents a conventional networked motion control system and a disturbance observer (DOB) for robust motion control. Section 3 describes a tamper detection technique using the TDO. Section 4 explains the Smith predictor and the proposed time-delay compensation methods. Simulation results are shown in Section 5. Finally, our conclusion is described in Section 6.

2. Networked Motion Control

This section presents a networked motion control system using the DOB.

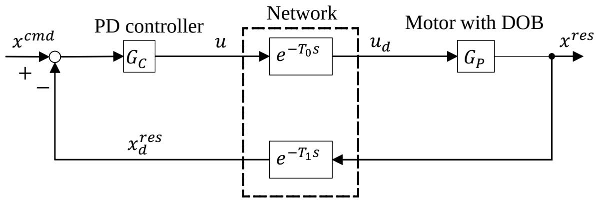


Figure 1: Block diagram of networked motion control system.

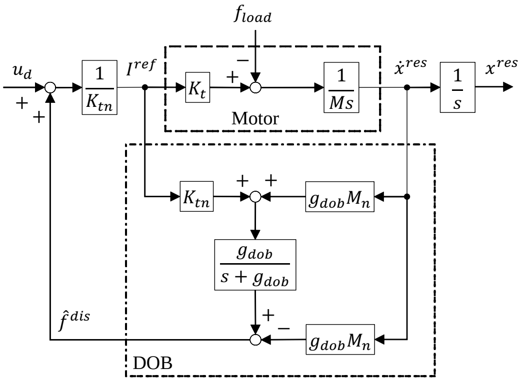


Figure 2: Block diagram of DOB.

2.1. System Configuration

The block diagram of a networked motion control system is shown in Fig. 1. The system is comprised of a proportional-derivative (PD) controller, an electric motor, and network elements whose time delays are T_0 and T_1. In addition, x^{cmd}, x^{res}, x_d^{res}, u, u_d, and s denote the position command, position response, delayed position response, reference, delayed reference, and Laplace operator, respectively.

2.2. DOB

The block diagram of the DOB is shown in Fig. 2. The DOB is implemented to compensate disturbances such as load torque and external torque. In Fig. 2, f_{load}, M and K_t are the load torque, the moment of inertia, and torque constant, respectively. The subscript n stands for a nominal value.

The disturbance torque f^{dis} is esitimated by the DOB as (1) and (2)

$$\hat{f}^{dis} = \frac{g_{dob}}{s+g_{dob}} f^{dis}, \tag{1}$$

$$f^{dis} = f_{load} + \Delta M \ddot{x}^{res} + \Delta K_t I^{ref}, \tag{2}$$

where $\Delta M = M - M_n$, $\Delta K = K_{tn} - K_t$, g_{dob}, and I^{ref} are the modeling errors of M and K_t, the cut-off frequency of a low-pass filter (LPF) and reference current, respectively.

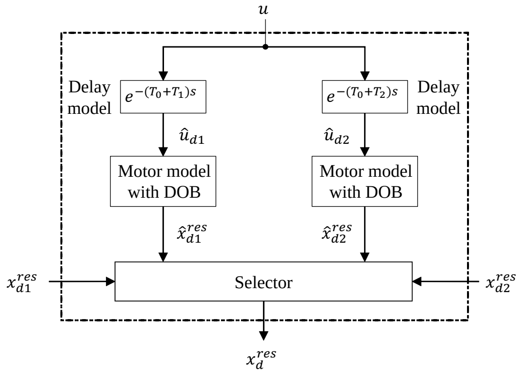


Figure 3: Internal structure of TDO.

The disturbance f^{dis} is added to the system through a high-pass filter (HPF) by implementing the DOB.

3. TDO-based Tamper Detection

This section describes the TDO-based tamper detection technique. The internal structure of the TDO, which is implemented on the controller side, is shown in Fig. 3. We consider the feedback paths are divided into two paths. In Fig. 3, x_{d1}^{res} and x_{d2}^{res} are the delayed responses on feedback paths 1 and 2, respectively. In addition, T_1 and T_2 are time delays of feedback paths 1 and 2, respectively.

The reference u is input to the delay models of the virtual redundant feedback paths, i.e., paths 1 and 2, on the controller side. The delayed references are defined as $\hat{u}_{d1}$ and $\hat{u}_{d2}$. The delayed references are then input to the motor model with the DOB to gain the estimated responses $\hat{x}_{d1}$ and $\hat{x}_{d2}$. If tampering is injected on path 1, x_{d1}^{res} is not equal to $\hat{x}_{d1}^{res}$. If tampering is injected on path 2, x_{d2}^{res} is not equal to $\hat{x}_{d2}^{res}$. The selector decides the correct response used in the controller, x_d^{res} as (3)

$$x_d^{res} = \begin{cases} x_{d1}^{res} & \text{if } |x_{d1}^{res} - \hat{x}_{d1}^{res}| < |x_{d2}^{res} - \hat{x}_{d2}^{res}| \\ x_{d2}^{res} & \text{if } |x_{d1}^{res} - \hat{x}_{d1}^{res}| \geq |x_{d2}^{res} - \hat{x}_{d2}^{res}| \end{cases}. \tag{3}$$

4. Proposed Time-Delay Compensation

This section describes the Smith predictor and proposes three kinds of time-delay models in the Smith predictor for the networked motion control systems with redundant feedback paths.

4.1. Smith Predictor

The block diagram of the proposed networked motion control system with the TDO and Smith predictor is shown in Fig. 4. In Fig. 4, $\hat{T}_s$ is the estimated round-trip time (RTT) delay, and G_C, G_P, and $\hat{G}_P$ are the transfer functions of the controller, actual plant, and plant model, respectively.

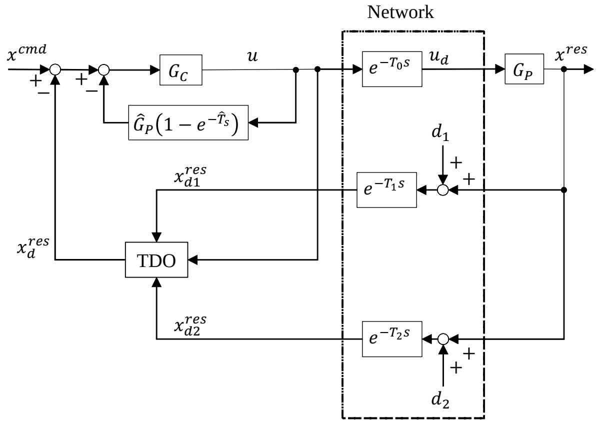


Figure 4: Block diagram of NCS with Smith predictor.

The transfer function of the networked motion control system without the Smith predictor shown in Fig. 1 is calculated as (4)

$$\frac{x^{res}}{x_{cmd}} = \frac{G_C G_P e^{-T_0 s}}{1 + G_C G_P e^{-(T_0+T_1)s}}. \tag{4}$$

Leaving the delay elements in the denominator does not only affect the stability of the system, but also makes it difficult to design the controller. The transfer function of the networked motion control system with the Smith predictor is calculated as (5)

$$\frac{x^{res}}{x_{cmd}} = \frac{G_C G_P e^{-T_0 s}}{1 + G_C \hat{G}_P - G_C \hat{G}_P e^{-\hat{T}s} + G_C G_P e^{-(T_0+T_k)s}}, \tag{5}$$

where T_k ($k = 1,\ 2$) is the transmission delay of the selected path, i.e., path 1 or 2 .

When the conditions (6)–(8) are satisfied, (5) is equivalent to (9).

$$\hat{G}_P = G_P \tag{6}$$

$$\hat{T} = T_0 + T_1 \tag{7}$$

$$\hat{T} = T_0 + T_2 \tag{8}$$

$$\frac{x^{res}}{x_{cmd}} = \frac{G_C G_P e^{-T_0 s}}{1 + G_C G_P} \tag{9}$$

Therefore, it is able to remove the time-delay element from the denominator by using the Smith predictor, when the redundant feedback paths have the same trasmission delay, $T_1 = T_2$. In real networked motion control systems with the TDO, however, the redundant feedback paths have different transmission delays.

4.2. Design of Time-Delay Models

In the networked motion control systems with the TDO, the time-delay model in the Smith predictor must be determined in consideration of different transmission delays of the redundant feedback paths. This paper proposes three kinds of time-delay models, i.e., the minimum, maximum, and average time-delay models.

Table 1: Simulation parameters.

Cut-off frequency of pseudo-differential g_{pd}	100 rad/s
Cut-off frequency of DOB g_{dob}	100 rad/s
Transmission delay on the forward path T_0	10 ms
Transmission delay on feedback path 1 T_1	60 ms
Transmission delay on feedback path 2 T_2	40 ms
Sampling period	1 ms

The first method utilizes the minimum time-delay model. This method designs $\hat{T}$ as the sum of T_0 and the minimum transmission delay of the feedback paths, T_{min} as (10)

$$\hat{T} = T_0 + T_{min}. \tag{10}$$

The second method utilizes the maximum time-delay model. This method designs $\hat{T}$ as the sum of T_0 and the maximum transmission delay of the feedback paths, T_{max} as (11)

$$\hat{T} = T_0 + T_{max}. \tag{11}$$

The third method utilizes the average time-delay model. This method designs $\hat{T}$ as the sum of T_0 and the average time delay of the feedback paths as (12)

$$\hat{T} = T_0 + \frac{T_{min} + T_{max}}{2}. \tag{12}$$

5. Simulation

This section shows the simulation results of the the proposed time-delay compensation methods using the TDO and Smith predictor.

5.1. Setup

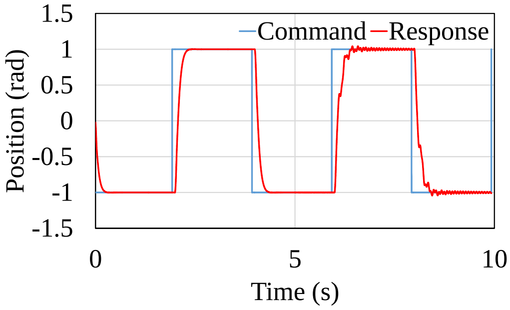
Simulations were performed to compare the three time-delay compensation methods, i.e., the minimum, maximum, and average time-delay models in the Smith predictor, for the networked motion control systems with the TDO. The transfer function of the PD controller G_C was set as (13)

$$G_C = 0.0166(400 + 40s). \tag{13}$$

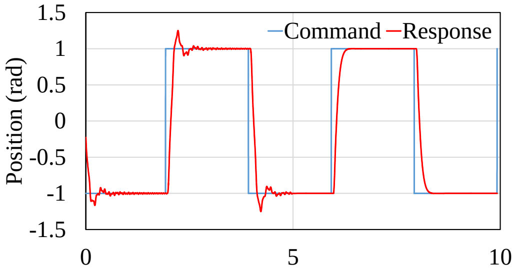
The transfer function of the real plant $G_{P,r}$ was set as (14)

$$G_{P,r} = \frac{1.53}{0.0254s^2 + s}. \tag{14}$$

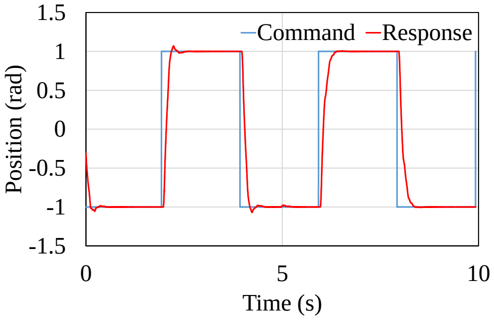
The other parameters for the simulations were set as Table 1. In the simulations, at 5 s, the tampering signal d_2 was injected on path 2 as an 800-Hz sinusoidal wave, while d_1 was not injected on path 1.



(a) Minimum time-delay model



(b) Maximum time-delay model



(c) Average time-delay model

Figure 5: Simulation results.

5.2. Results

The simulation results are shown in Fig. 5. Path 2 was selected because of the smaller transmission delay when the tampering signal was not injected. On the other hand, path 1 was selected when the tampering signal was injected on path 2.

As shown in Figs. 5(a) and (b), the response was converged to the command without oscillations when the time-delay model was equal to the actual time delay. However, when the time-delay model was not equal to the actual transmission delay, the effects of the time delay was seen as oscillations in both the minimum and maximum time-delay models. As shown in Fig. 5(c), the average time-delay model did not generate excessive oscillations even if the tampering signal was injected, and both tampering signals and time delay effects were compensated.

6. Conclusion

This paper proposed three kinds of time-delay models in the Smith predictor, i.e., the minimum, maximum, and average time-delay models, for the networked motion control systems with the TDO. Simulation results showed that the average time-delay model outperformed the minimum and maximum time-delay models.

Acknowledgment

This research was supported in part by JSPS KAKENHI Grant Number 16K16049, Kenjiro Takayanagi Foundation, and SECOM Science and Technology Foundation.

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