Paper:

Event-Triggered Predictive Control for Networked Systems Using Allowable Time Delays

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Abstract. In this paper, an event-triggered networked predictive control (NPC) method is proposed for a networked control system with random network delays, packet disorders and packet dropouts in the feedback and forward channels, which makes full use of the allowable time delay of the system. In this method, these random communication constraints are uniformly treated as time delay. Then the controller is designed by the time-delay state feedback control law, and the event-triggered NPC method is used to actively compensate for the part of the network delay that exceeds the allowable time delay. In addition, the introduction of an event-triggered mechanism reduces the communication load and saves network resources. A necessary and sufficient stability condition is derived for the resulting closed-loop system, which is independent of random time delays and related to the allowable time delay. Finally, the effectiveness of the proposed method is verified by simulation results.

Keywords: Networked control systems (NCSs), networked predictive control, event-triggered mechanism, random communication constraints, allowable time delay

1. Introduction

With the development of various networking technologies, networked control systems (NCSs) have been widely used in many fields, such as aircraft engine systems [1], smart vehicles [2], remote surgical robots [3], and smart power grids [4], because of their unique advantages compared with traditional point-to-point control systems. However, due to the introduction of communication networks, random communication constraints such as network delays, packet dropouts and disorder inevitably occur. Many scholars have carried out extensive studies on how to mitigate negative effects of random communication constraints.

Among various methods to deal with communication constraints [5], networked predictive control (NPC) methods have received widespread attention because it can actively compensate for communication constraints [6]-[8]. The main idea is to obtain a limited number of future control commands in the controller based on the model of the controlled plant and transmit them to the actuator in a data packet together with the current control command, and then a suitable future control command is selected in the actuator and applied to the plant according to the real-time network delay. In addition, due to limited network resources, event-triggered control methods have also received increasing attention in recent years. In [9], an adaptive event-triggered dynamic output predictive control strategy was presented, which could greatly reduce the data transmission times with an acceptable control performance. In [10], the output-based predictive control problem for NCSs with communication delays was investigated by utilizing an event-triggered mechanism in order to save limited network resources.

On the other hand, it is found that the system can still remain stable under a certain allowable delay through some observations on the research work of time-delay systems [11]-[20]. For example, in [11], the problem of robust stability of uncertain interval time-varying time-delay systems was studied, and the maximum allowable upper bound of interval time-varying time-delays that guarantees the asymptotic stability of the NCS was given. In [13], by increasing the maximum allowable upper bound of time delays and reducing the number of decision variables, the stability analysis for a continuous linear system with two additive time-varying delays was proposed. In [16], a certain time delay was introduced to a system which cannot be stable without time delay but can be stable with proper time delay so as to achieve a satisfactory H_∞ control performance. The aforementioned observations motivate the study in this paper.

In this paper, for a class of NCSs that are still stable with appropriate time delay in the control loop, an event-triggered networked predictive control method is presented, where two-channel communication constraints such as network delays, packet disorders and packet dropouts are considered. The main contributions are summarized as follows.

i) An event-triggered NPC method is proposed, which makes full use of the time delay allowed by the system and also actively compensates for the additional network delay.

ii) A necessary and sufficient closed-loop stability condition is obtained, which is not related to random time delays, and simulation results are given to illustrate the effectiveness of the proposed method.

The rest of this paper is organized as follows. Section 2 introduces the control scheme design. The stability analysis for the resulting closed-loop system is presented in Section 3. Numerical simulation is performed in Section 4 to verify the proposed method. Section 5 concludes this paper.

Notation: The notations used throughout this paper are fairly standard. $\mathbb{R}^n$ and $\mathbb{R}^{n\times m}$ denote the n-dimensional Euclidean space and the set of $n\times m$ real matrices, respectively. I_n and $0_{n\times m}$ are an n-dimensional identity matrix and an $n\times m$ zero matrix, respectively. The diag$\{\cdots\}$ represents a block-diagonal matrix.

2. Control Scheme Design

The controlled plant is described by the following discrete-time linear system:

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

where $x(k)\in\mathbb{R}^n$ is the system state, $u(k)\in\mathbb{R}^m$ is the control input, and $y(k)\in\mathbb{R}^q$ is the system output; A, B and C are matrices with compatible dimensions.

When there exist communication networks in the control loop of system (1), random network delays, packet disorders and packet dropouts in the feedback and forward channels are inevitable, which are converted into the corresponding total time delays τ_k^{sc} and τ_k^{ca}, respectively, by using a similar method in [5]. In order to compensate for them and make full use of the allowable time delay of the system, a new event-triggered NPC method is presented as shown in Fig. 1, which includes an event-triggered unit in the sensor, a predictive controller in the controller, and a network delay compensator in the actuator.

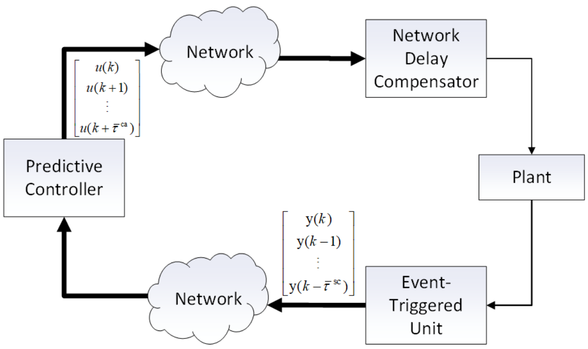

Fig. 1. An NPC system.

To implement the proposed NPC method, the following assumptions are necessary.

Assumption 1: The pair (A,C) is observable, and the pair (A,B) is controllable.

Assumption 2: The controller, actuator and sensor are synchronous, and all data packets are transmitted together with the corresponding timestamps.

Assumption 3: The time delays in the feedback and forward channels are upper-bounded by $\bar{\tau}^{sc}$ and $\bar{\tau}^{ca}$, respectively, i.e., $\tau_k^{sc}\le\bar{\tau}^{sc}$ and $\tau_k^{ca}\le\bar{\tau}^{ca}$, where $\bar{\tau}^{sc}\ge 0$ and $\bar{\tau}^{ca}\ge 0$ are integers.

2.1. Event-Triggered Unit

In order to reduce the communication load and save network resources, an event-triggered unit is designed in the sensor to monitor the system output $y(k)$ and send a feedback data packet to the controller if the following condition is satisfied:

$$\big(y(k)-\bar{y}(k-1)\big)^2>\lambda\bar{y}(k-1)^2, \tag{2}$$

where $\lambda\ge 0$ is the event-triggered coefficient to be determined, and

$$\begin{cases} \bar{y}(k)=y(k), \text{ if (2) is satisfied} \\ \bar{y}(k)=\bar{y}(k-1), \text{ otherwise.} \end{cases} \tag{3}$$

By using the processing way of communication constraints in [5], the event-triggered mechanism would introduce additional time delays in the feedback channel, which are upper-bounded by $\bar{\tau}^e$, where $\bar{\tau}^e\ge 0$ is an integer. As a result, the total time delays in the feedback channel have a new upper bound, i.e., $\tau_k^{sc}\le\bar{\tau}^{sc}+\bar{\tau}^e$.

If the event-triggered condition (2) is satisfied, the following feedback data and the corresponding timestamp k are sent to the controller:

$$Y(k)=\{y(k),y(k-1),y(k-2)\cdots,y(k-\bar{\tau}^{sc}-\bar{\tau}^e),k\}. \tag{4}$$

Remark 1: If the event-triggered condition (2) is not satisfied at several consecutive time instants, no data packets will be sent to the controller, which thus will induce additional time delays in the feedback channel. It can be seen from (4) that the length of $Y(k)$ is related to these additional time delays. Hence, consecutive non-triggered time instants are upper-bounded by $\bar{\tau}^e$ in this paper. That is, even if the condition (2) is not satisfied at more than $\bar{\tau}^e$ consecutive time instants, it will be triggered at the $\bar{\tau}^e+1$-th time instant, and the feedback data packet $Y(k)$ will be transmitted to the controller.

2.2. Predictive Controller

According to the characteristics of system (1), if there no communication networks in the control loop, the acceptable state feedback controller is supposed to be

$$u(k)=-K\hat{x}(k-\tau_D|k-\tau_D-1), \tag{5}$$

where K is the controller gain to be determined, $\tau_D\ge 0$ is the allowable time delay of the system, and $\hat{x}(k)$ is the estimate of the system state $x(k)$ calculated by the following state observer:

$$\begin{aligned}\hat{x}(k+1|k)=&A\hat{x}(k|k-1)+Bu(k)\\&+L\big(y(k)-C\hat{x}(k|k-1)\big),\end{aligned} \tag{6}$$

where L is the observer gain to be determined.

Due to the presence of the time delay τ_k^{sc} in the feedback channel, the following feedback data packet is available in the controller at time k:

$$Y(k-\tau_k^{sc}) = \{y(k-\tau_k^{sc}), y(k-\tau_k^{sc}-1), y(k-\tau_k^{sc}-2), \cdots, y(k-\tau_k^{sc}-\bar{\tau}^{sc}-\bar{\tau}^{e}), k-\tau_k^{sc}\}. \quad (7)$$

If the time delay τ_k^{sc} is constant, using the delayed system output in (7), the state observer (6) becomes

$$\begin{aligned}&\hat{x}(k-\tau_k^{sc}+1|k-\tau_k^{sc})\\ =&A\hat{x}(k-\tau_k^{sc}|k-\tau_k^{sc}-1)+Bu(k-\tau_k^{sc})\\ &+L\big(y(k-\tau_k^{sc})-C\hat{x}(k-\tau_k^{sc}|k-\tau_k^{sc}-1)\big).\end{aligned} \quad (8)$$

In practice, however, the time delay τ_k^{sc} is generally random, and packet disorders and dropouts are inevitable. In this paper, only the latest data packet is adopted in the controller. Thus, if no newer data packet is received at time k, the state observer (6) will not be updated, i.e.,

$$\hat{x}(k-\tau_k^{sc}|k-\tau_k^{sc}-1) = \hat{x}(k-1-\tau_{k-1}^{sc}|k-2-\tau_{k-1}^{sc}). \quad (9)$$

If a newer data packet arrives at the controller at time k, to eliminate the adverse effect of packet disorders and dropouts, the state observer (6) will be performed one or more times by using the data packet $Y(k-\tau_k^{sc})$, i.e.,

$$\begin{aligned}&\hat{x}(k-\tau_{k-1}^{sc}+i-1|k-\tau_{k-1}^{sc}+i-2)\\ &=A\hat{x}(k-\tau_{k-1}^{sc}+i-2|k-\tau_{k-1}^{sc}+i-3)\\ &\quad+Bu(k-\tau_{k-1}^{sc}+i-2)\\ &\quad+LC\tilde{x}(k-\tau_{k-1}^{sc}+i-2|k-\tau_{k-1}^{sc}+i-3),\end{aligned} \quad (10)$$

for $i=1,2,\cdots,\tau_{k-1}^{sc}+1-\tau_k^{sc}$, where $\tilde{x}(k)=x(k)-\hat{x}(k|k-1)$.

It is noted that the time delay τ_D is the allowable time delay in the control law (5). Although the time delay in the feedback channel is random and unpredictable, it can be real-time calculated by using the timestamp technique in the controller. According to the relationship between τ_D and τ_k^{sc}, the following two cases are considered to compensate for the time delays in the feedback and forward channels.

Case 1: $\tau_k^{sc} \le \tau_D$

In this case, the estimate and predictions of the system state are calculated, respectively, by

$$\begin{aligned}&\hat{x}(k-\tau_D|k-\tau_D-1)\\ &=A\hat{x}(k-\tau_D-1|k-\tau_D-2)+Bu(k-\tau_D-1)\\ &\quad+LC\tilde{x}(k-\tau_D-1),\end{aligned} \quad (11)$$

$$\begin{aligned}&\hat{x}(k-\tau_D+i|k-\tau_D-1)\\ &=A\hat{x}(k-\tau_D+i-1|k-\tau_D-1)+Bu(k-\tau_D+i-1).\end{aligned} \quad (12)$$

for $i=1,2,\cdots,\bar{\tau}^{ca}$. Using the control law (5), the future control command is calculated as

$$u(k+\bar{\tau}^{ca}) = -K\hat{x}(k-\tau_D+\bar{\tau}^{ca}|k-\tau_D-1). \quad (13)$$

Case 2: $\tau_k^{sc} > \tau_D$

In this case, the state estimate $\hat{x}(k-\tau_D|k-\tau_D-1)$ cannot be obtained, and the latest state estimate calculated by using (10) is $\hat{x}(k-\tau_k^{sc}|k-\tau_k^{sc}-1)$. Then based on it, the predictions of the system state up to time $k+\bar{\tau}^{ca}$ are calculated as

$$\begin{aligned}&\hat{x}(k-\tau_k^{sc}+i|k-\tau_k^{sc}-1)\\ =&A\hat{x}(k-\tau_k^{sc}+i-1|k-\tau_k^{sc})+Bu(k-\tau_k^{sc}+i-1),\end{aligned} \quad (14)$$

for $i=1,2,\cdots,\bar{\tau}^{ca}+\tau_k^{sc}-\tau_D$. Using the control law (5), the future control command is computed as

$$u(k+\bar{\tau}^{ca}) = -K\hat{x}(k-\tau_D+\bar{\tau}^{ca}|k-\tau_k^{sc}-1). \quad (15)$$

For the above Case 1 or Case 2, the following control command sequence and its timestamp k are available in the controller:

$$U(k) = \{u(k), u(k+1), u(k+2)\cdots, u(k+\bar{\tau}^{ca}), k\}. \quad (16)$$

which is transmitted in a packet to the network delay compensator at each time instant.

2.3. Network Delay Compensator

In the actuator, a network delay compensator is designed to choose an appropriate control signal from the latest control command sequence received by the actuator at each time instant according to the real-time delay in the forward channel. Suppose that at time k, the forward channel delay is τ_k^{ca}, and thus the control command sequence $U_{k-\tau_k^{ca}}$ is available in the actuator. In order to compensate for the forward channel delay and the corresponding feedback channel delay, the following control signal is chosen to drive the plant at time k:

$$\begin{aligned}u(k) &= U_{k-\tau_k^{ca}}\{\tau_k^{ca}\}\\ &= \begin{cases} -K\hat{x}(k-\tau_D|k-\bar{\tau}^{ca}-\tau_D-1), & \text{if } \tau_k^{sc}\le\tau_D\\ -K\hat{x}(k-\tau_D|k-\bar{\tau}^{ca}-\tau_{k-\bar{\tau}^{ca}}^{sc}-1), & \text{otherwise,}\end{cases}\end{aligned} \quad (17)$$

where $U_{k-\tau_k^{ca}}\{\tau_k^{ca}\}$ denotes the $(\tau_k^{ca}+1)$-th element of the control command sequence $U_{k-\tau_k^{ca}}$.

3. Stability Analysis

In this section, the stability of the resulting closed-loop NPC system is analyzed.

Firstly, the stability of the corresponding local control system (LCS) is analyzed, i.e., there are no communication networks in the control loop. Subtracting (6) from (1) yields

$$\tilde{x}(k+1) = (A-LC)\tilde{x}(k), \quad (18)$$

Substituting (5) into (1) gives

$$\begin{aligned}x(k+1) &= Ax(k)-BK\hat{x}(k-\tau_D|k-\tau_D-1)\\ &= Ax(k)-BKx(k-\tau_D)+BK\tilde{x}(k-\tau_D).\end{aligned} \quad (19)$$

By combining (18) and (19), we have

$$X(k+1) = FX(k), \tag{20}$$

where

$$X(k) = \begin{bmatrix} x(k) \\ x(k-1) \\ \vdots \\ x(k-\tau_D) \\ \tilde{x}(k-\tau_D) \end{bmatrix} \in \mathbb{R}^{(\tau_D+2)n},$$

$$F = \begin{bmatrix} \Phi & \Psi \\ 0_{n\times(\tau_D+1)n} & A-LC \end{bmatrix}.$$

with

$$\Phi = \begin{bmatrix} A & 0_{(\tau_D-1)n\times n} & -BK \\ & I_{\tau_D n} & 0_{\tau_D n\times n} \end{bmatrix}, \Psi = \begin{bmatrix} BK \\ 0_{\tau_D n\times n} \end{bmatrix}.$$

Obviously, the closed-loop system is stable if and only if the matrix F is Schur stable. Hence, the following theorem is obtained.

Theorem 1: The closed-loop LCS (20) is stable if and only if the eigenvalues of matrices Φ and $A-LC$ are within the unit circle.

When there exist random communication constraints in the control loop of system (1), the corresponding closed-loop stability analysis is given as follows.

The control signal applied to the plant at time k can be rewritten as

$$\begin{aligned} u(k) &= -K\hat{x}(k-\tau_D|k-\bar{\tau}^{ca}-\max\{\tau_D,\tau^{sc}_{k-\bar{\tau}^{ca}}\}-1) \\ &= -K\hat{x}(k-\tau_D|k-\tau_k-1), \end{aligned} \tag{21}$$

where $\tau_k \triangleq \bar{\tau}^{ca}+\max\{\tau_D,\tau^{sc}_{k-\bar{\tau}^{ca}}\} \in [\tau_D,\bar{\tau}]$ with $\bar{\tau} = \bar{\tau}^{ca}+\max\{\tau_D,\bar{\tau}^{sc}\}$. Thus, it is obtained from (12) and (14) that

$$\begin{aligned} &\hat{x}(k-\tau_D|k-\tau_k-1) \\ &= A\hat{x}(k-\tau_D-1|k-\tau_k-1)+Bu(k-\tau_D-1). \end{aligned} \tag{22}$$

Define $\tilde{x}(k-\tau_D|k-\tau_k-1) \triangleq x(k-\tau_D)-\hat{x}(k-\tau_D|k-\tau_k-1)$, and by subtracting (22) from (1), we get

$$\begin{aligned} &\tilde{x}(k-\tau_D|k-\tau_k-1) \\ &= A\tilde{x}(k-\tau_D-1|k-\tau_k-1) \\ &= A^{\tau_k-\tau_D}\tilde{x}(k-\tau_k). \end{aligned} \tag{23}$$

By substituting (21) into (1) and then using (23), we obtain

$$\begin{aligned} x(k+1) &= Ax(k)-BK\hat{x}(k-\tau_D|k-\tau_k-1) \\ &= Ax(k)-BKx(k-\tau_D) \\ &\quad +BK\tilde{x}(k-\tau_D|k-\tau_k-1) \\ &= Ax(k)-BKx(k-\tau_D)+BKA^{\tau_k-\tau_D}\tilde{x}(k-\tau_k) \end{aligned} \tag{24}$$

Combining (18) and (24) leads to

$$X'(k+1) = H(\tau_k)X'(k) \tag{25}$$

where

$$X'(k) = \begin{bmatrix} x(k) \\ x(k-1) \\ \vdots \\ x(k-\tau_D) \\ \tilde{x}(k-\tau_D) \\ \tilde{x}(k-\tau_D-1) \\ \vdots \\ \tilde{x}(k-\bar{\tau}) \end{bmatrix} \in \mathbb{R}^{(\bar{\tau}+2)n},$$

$$H(\tau_k) = \begin{bmatrix} \Phi & \Upsilon(\tau_k) \\ 0_{(\bar{\tau}-\tau_D+1)n\times(\tau_D+1)n} & \Gamma \end{bmatrix}.$$

with

$$\Upsilon(\tau_k) = \begin{cases} \begin{bmatrix} BK & 0_{n\times(\bar{\tau}-\tau_D)n} \\ 0_{\tau_D n\times(\bar{\tau}-\tau_D+1)n} & \end{bmatrix}, & \text{if } \tau_k = \tau_D \\ \begin{bmatrix} 0_{n\times(\tau_k-\tau_D)n} & -BKA^{\tau_k-\tau_D} & 0_{n\times(\bar{\tau}-\tau_k)n} \\ & 0_{\tau_D n\times(\bar{\tau}-\tau_D+1)n} & \end{bmatrix}, & \text{otherwise,} \end{cases}$$

$$\Gamma = \mathrm{diag}\{A-LC \ \cdots \ A-LC\} \in \mathbb{R}^{(\bar{\tau}-\tau_D+1)n\times(\bar{\tau}-\tau_D+1)n}.$$

It can be seen from (25) that although the closed-loop system is time-varying, its stability condition is the same as that for the LCS, because the system matrix $H(\tau_k)$ is a time-varying block upper triangular matrix. Therefore, we have the following theorem.

Theorem 2: The closed-loop NPC system (25) is stable if and only if the eigenvalues of matrices Φ and $A-LC$ are within the unit circle.

4. Simulation Results

In order to verify the effectiveness of the method proposed in this paper, the following system is considered for the sampling time $\mathrm{T} = 0.01\mathrm{s}$:

$$\begin{cases} x(k+1) = \begin{bmatrix} 1 & 0.1 \\ 0 & 0.999 \end{bmatrix} x(k) + \begin{bmatrix} 0 \\ 0.001 \end{bmatrix} u(k) \\ y(k) = [1 \quad 0]x(k). \end{cases} \tag{26}$$

The random time delays in the feedback and forward channels are $\tau^{sc}_k \in [1,10]$ and $\tau^{ca}_k \in [1,10]$, as shown in Figs. 2 and 3, respectively. The allowable time delay $\tau_D = 3$. The observer and controller gains are chosen to be $L = \begin{bmatrix} 0.2 & 0.798 \end{bmatrix}^{\mathrm{T}}$ and $K = \begin{bmatrix} 37.5 & 115 \end{bmatrix}$, respectively. Then the following three cases are considered for simulation.

Case 1: The local control system (LCS) with the allowable time delay τ_D, i.e., the control law (5) is used. In this case, the time delays in the feedback and forward channels are $\tau^{sc}_k = 0$ and $\tau^{ca}_k = 0$, respectively. The simulation

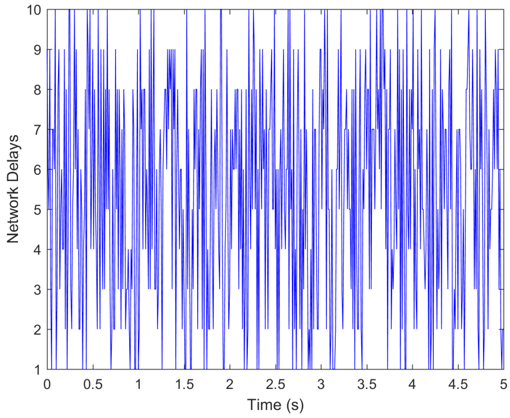

Fig. 2. Random network delays in the feedback channel.

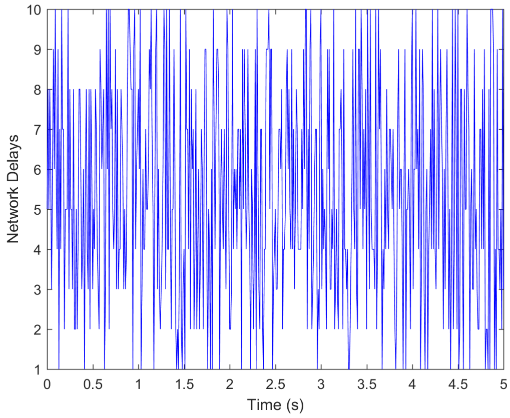

Fig. 3. Random network delays in the forward channel.

result is shown in Fig. 4, which indicates that the LCS is still stable when the time-delay control law (5) is used with allowable time delay $\tau_D = 3$.

Case 2: The NCS without network delay compensation, i.e., the following control law is applied:

$$u(k) = -K\hat{x}(k-\tau_k|k-\tau_k-1). \tag{27}$$

The simulation result is shown in Fig. 5. Obviously, with network delay compensation, random time delays $\tau_k^{sc} \in [1,10]$ and $\tau_k^{ca} \in [1,10]$ make the closed-loop NCS unstable.

Case 3: The NPC system with the proposed method. In this case, random time delays shown in Figs. 2 and 3 are considered, and the control law (17) is used. When the event-triggered parameter is chosen to be $\lambda = 0.2$, the simulation result is shown in Fig. 6. It can be seen that the closed-loop NPC system is stable, and further, the output response is almost the same as that of the LCS shown in Fig. 4. That is, random time delays are divided into two parts. One part is used by the time-delay control law (5), and the other part is effectively compensated by the proposed NPC method. Hence, the effectiveness of the proposed NPC method is verified.

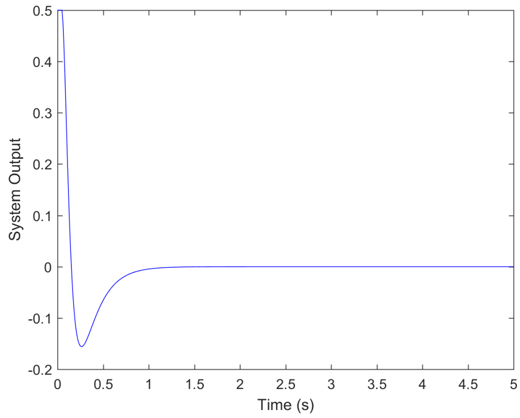

Fig. 4. Simulation result of the LCS.

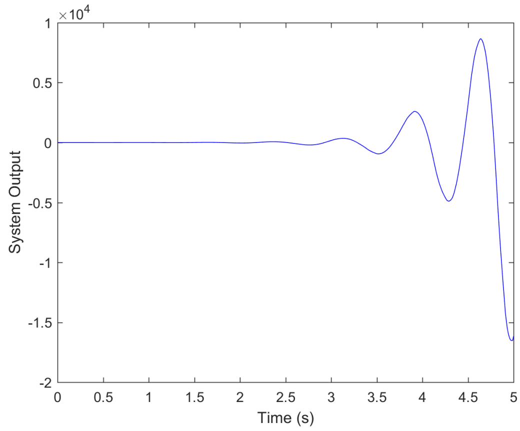

Fig. 5. Simulation result of the NCS without compensation.

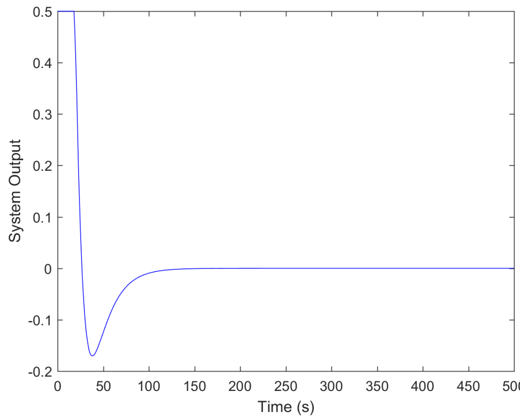

Fig. 6. Simulation result of the proposed NPC method.

5. Conclusion

In this paper, an event-triggered NPC method is proposed for an NCS with random communication constraints in two channels, which makes full use of the allowable time delay of the system. It has the following two advantages: 1) the event-triggered mode can significantly save network resources, and 2) the usage of the allowable time delay can reduce computational burden. Then, the stability condition of the resulting closed-loop system is derived, which is independent of random time delays and related to the allowable time delay. Finally, the effectiveness of the proposed method is demonstrated by simulation results given in this paper.

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