Proceedings of the 17th World Congress
The International Federation of Automatic Control
Seoul, Korea, July 6-11, 2008

State-Space Model Based Generalized Predictive Control for Networked Control Systems

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Abstract: This paper is concerned with generalized predictive control based on state-space model for networked control systems. Both the network-induced time delay and packet loss are taken into account. The networked predictive controller design is discussed with respect to three network cases, which are related to packet loss, network-induced delay, and both packet loss and network-induced delay, respectively. Simulation and experiment results show the effectiveness of our networked predictive control algorithms.

1. INTRODUCTION

Recently the research for networked control systems (NCSs) has attracted much attention. One of the main problems in NCSs is to compensate for the influence of network-induced time delay and packet dropout, which have been proved to seriously degrade the system performance and even lead to unstability. For network-induced time delay compensation problem, please refer to Zhang, Shi, Chen & Huang (2005), Yang, Wang, Huang & Gani (2006), Hu, Bai, Shi and Wu (2007) and Lam, Gao & Wang (2007), Zhang & Li (2007), Mercangoz & Doyle III (2007), Liu, Mu, Rees & Chai (2006). For packet loss compensation problem, please refer to Imer, Yuksel & Basar (2006), Gupta, Hassibi & Murray (2007), Huang & Dey (2007), Xiong & Lam (2007), Hu & Yam (2007). It is seen from the above-mentioned literatures that model predictive control has not been intensively studied, especially for the case of packet loss.

In this paper, we consider generalized predictive control based on state-space model for networked control systems with both the network-induced time delay and packet loss. The networked predictive controller design is concerned in three network cases, which are related to packet loss, constant network-induced time delay and both random packet loss and random network-induced time delay, respectively. Furthermore, simulation and experiment results are given to show the effectiveness of our controller design method.

2. PROBLEM FORMULATION

The controlled plant is modelled by a linear discrete-time system

$$x_o(t+1) = A_o x_o(t) + B_o u(t) + B_{o,\omega}\omega_o(t) + B_{o,v} v_o(t)\,, \qquad (1)$$

$$y(t) = C_o x_o(t) + \omega_o(t)\,, \qquad (2)$$

where $t \in Z_+$ is the time step, $x_o(t) \in R^n$ and $u(t) \in R^m$ are respectively the plant state and control input. $v_o(t)$ and $\omega_o(t)$ are respectively the plant disturbance and measurement noise. A_o , B_o , $B_{o,v}$ and C_o are constant matrices of appropriate dimensions. We assumed that $v_o(t)$ and $\omega_o(t)$ are white, Gaussian, and zero-mean noises with covariance matrices Q_{v_o} and Q_{ω_o} , respectively, and are independent each other. The initial condition x_0 is assumed to be independent of $v_o(t)$ and to have mean zero and covariance matrix Q_0 .

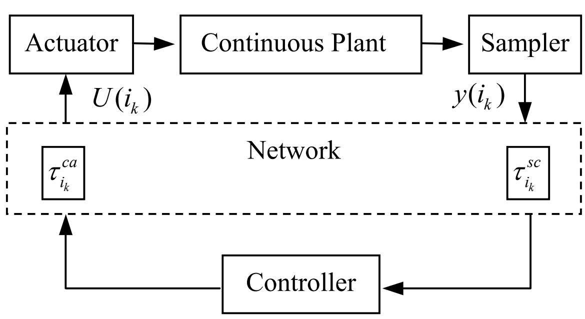

Fig. 1 The structure of networked control systems

The framework of the NCS considered in this paper is shown in Fig. 1. Networks exist between sampler and controller, and between controller and actuator. The sampler is time-driven, the controller and actuator are event-driven and the data are transmitted in a single packet at each time step. Let $\Phi \triangleq \{i_k, k = 1,2\cdots\}$, a subsequence of $\{1,2,3,\cdots\}$, denote the sequence of sampling instants of successful data transmissions from the sampler to the actuator and $s \triangleq \max_{i_k \in \Phi}(i_{k+1} - i_k)$ be the maximum packet-loss upper bound. Let $\tau_{i_k}^{sc}$ and $\tau_{i_k}^{sc}$ denote the network-induced time delays between sampler and controller and between controller and actuator, respectively. We model the two transmission delays as input delays. With (1)-(2), the controlled plant from the view of controller can be modelled for the internal $t \in [i_k + \tau_{i_k}, i_{k+1} + \tau_{i_{k+1}})$ as

$$x_o(t+1) = A_o x_o(t) + B_o u(t - \tau_{i_k}^{ca} - \tau_{i_k}^{sc}) + B_{o,\omega}\omega_o(t) + B_{o,v} v_o(t), \tag{3}$$

$$y(t) = C_o x_o(t) + \omega_o(t), \tag{4}$$

where $\tau_{i_k} = \tau_{i_k}^{sc} + \tau_{i_k}^{ca}$.

The networked controller is a generalized predictive controller based on an equivalent incremental state-space model. The incremental state-space model of (3)-(4) can be given as

$$x(t+1) = Ax(t) + B\Delta u(t - \tau_{i_k}^{ca} - \tau_{i_k}^{sc}) + B_\omega \omega(t) + B_v v(t), \tag{5}$$

$$y(t) = Cx(t) + \omega(t), \tag{6}$$

where

$$x(t) = \begin{bmatrix} y(t-1) \\ \Delta x_o(t) \end{bmatrix}, \Delta x_o(t) = x_o(t) - x_o(t-1),$$

$$\Delta u(t) = u(t) - u(t-1), v(t) = v_o(t) - v_o(t-1),$$

$$\omega(t) = \omega_o(t) - \omega_o(t-1),\ A = \begin{bmatrix} I & C_o \\ 0 & A_o \end{bmatrix},\ B = \begin{bmatrix} 0 \\ B_o \end{bmatrix},$$

$$B_\omega = \begin{bmatrix} I \\ B_{o,\omega} \end{bmatrix}, B_v = \begin{bmatrix} 0 \\ B_{o,v} \end{bmatrix}, C = [I \quad C_o].$$

At every instant $t = i_k + \tau_{i_k}^{sc}$, a new control increment vector $\Delta U(i_k)$ is produced, which can be given as follow:

$$\Delta U(i_k) = f_c(x(i_k), \Delta u(i_k - \tau_{i_k}^{ca} - \tau_{i_k}^{sc}), \cdots, \Delta u(i_k - 1)), \tag{7}$$

where $f_c(\bullet)$ means that $\Delta U(i_k)$ is a function of $x(i_k)$, $\Delta u(i_k - \tau_{i_k}^{ca} - \tau_{i_k}^{sc})$, $\cdots$, $\Delta u(i_k - 1)$.

Since this generalized predictive control (GPC) algorithm depends on the state $x(i_k)$ of the incremental model and the available feedback is the output $y(i_k)$ of the original plant, it is necessary to estimate the state $x(i_k)$ using $y(i_k)$ and the incremental state-space model. In this paper, the optimal estimation of $x(i_k)$ is not discussed in detail, which can be achieved with the method proposed by Gupta, Hassibi & Murray (2007).

The control vector $U(i_k)$ sent from controller to actuator is given as follow:

$$U(i_k) = \begin{bmatrix} u(i_k - 1) \\ u(i_k - 1) \\ \vdots \\ u(i_k - 1) \end{bmatrix} + M_c \Delta U(i_k), \tag{8}$$

where

$$M_c \in R^{(N_u \times m) \times (N_u \times m)} = \begin{bmatrix} I_m & & & \\ I_m & I_m & & \\ & & \ddots & \\ I_m & I_m & \cdots & I_m \end{bmatrix},\ I_m \in R^{m \times m}.$$

For the time interval $t \in [i_k + \tau_{i_k} + 1, i_{k+1} + \tau_{i_{k+1}}]$, the elements of $U(i_k)$ act in sequence on the controlled plant, which can be given from the view of controller as follow:

$$x_o(i_k + 1 + l) = A_o x_o(i_k + l) + B_o u(i_k + l - \tau_{i_k}) + B_{o,\omega}\omega_o(i_k + l) + B_{o,v} v_o(i_k + l),$$

$$y(i_{k+1} + \tau_{i_{k+1}}) = C_o x_o(i_{k+1} + \tau_{i_{k+1}}) + \omega_o(i_{k+1} + \tau_{i_{k+1}}),$$

where $l \in \{0\} \bigcup \mathbb{Z}_+$ and $0 \le l \le i_{k+1} + \tau_{i_{k+1}} - (i_k + \tau_{i_k})$.

3. NETWORKED PREDICTIVE CONTROLLER DESIGN

In this section the networked predictive controller design is discussed in three cases for clarity. The three cases are on the compensation of the influences of the random packet loss, the constant network-induced delay, and both the random packet loss and random network-induced delay, respectively.

3.1 Case of random packet loss

For the NCS considered in this case, it is assumed that there exist the packet losses and every packet sent is free of the transmission delay, i.e. $\tau_{i_k} = 0$. To compensate for the influence of packet losses in the NCS, the controller creates a control increment vector $\Delta U(i_k) = [\Delta u^{\mathrm{T}}(i_k), \Delta u^{\mathrm{T}}(i_k + 1), \cdots, \Delta u^{\mathrm{T}}(i_k + N_u - 1)]^{\mathrm{T}}$ of length $N_u > s$ using the received feedback packet, which is sampled at instant i_k, and then the produced control vector $U(i_k) = [u^{\mathrm{T}}(i_k), u^{\mathrm{T}}(i_k + 1), \cdots, u^{\mathrm{T}}(i_k + N_u - 1)]^{\mathrm{T}}$ is sent to actuator in a single packet. In the time interval $[i_k + 1, i_{k+1}]$, the controls $u(l)$ $(i_k \le l \le i_{k+1} - 1)$ are successively imposed on the controlled continuous plant.

The cost function in this case is given as follow

$$J(i_k, \Delta U(i_k)) = E\{\sum_{j=1}^{N} (y(i_k + j | k) - w(i_k + j))^2 + \sum_{j=1}^{N_u} \lambda_j (\Delta u(i_k - 1 + j))^2\}, \tag{9}$$

where $w(t)$ is reference locus, N is the maximal step length of prediction, $s \le N_u \le N$ is the step length of predictive control, λ_j $(j=1, \cdots, N_u)$ are the weights of control increments.

With the incremental model (5)-(6), we obtain the $j>0$ step forward prediction

$$y(k+j\mid k)=CA^j x(k)+\sum_{i=1}^{j} CA^{j-i}B\Delta u(k+i-1)$$
$$+\sum_{i=1}^{j} CA^{j-i}B_v v(k+i-1)+\sum_{i=1}^{j} CA^{j-i}B_\omega \omega(k+i-1)+\omega(k+j).$$

From the equation above, it is seen that the third and fourth terms at the right hand are respectively the white plant noises at the instant k and its' future instants, and the white measurement noise at instant $k+j$. So the optimal prediction of $y(k+j\mid k)$ is given as

$$\hat{y}(k+j\mid k)=E[y(k+j\mid k)]$$
$$=CA^j E[x(k)]+\sum_{i=1}^{j} CA^{j-i}B\Delta u(k+i-1), \tag{10}$$

where $E\{\bullet\}$ denotes the mathematical expectation. For the output feedback case, $E[x(k)]$ can be estimated by Kalman filter. For every feedback sampled at i_k, we obtain from (10) that

$$\hat{y}(i_k+j\mid i_k)=E[y(i_k+j\mid i_k)]$$
$$=CA^j E[x(i_k)]+\sum_{i=1}^{j} CA^{j-i}B\Delta u(i_k+i-1). \tag{11}$$

Let

$$\hat{Y}(i_k+1)=[\hat{y}^{\mathrm{T}}(i_k+1\mid i_k),\cdots,\hat{y}^{\mathrm{T}}(i_k+N\mid i_k)]^{\mathrm{T}},$$
$$\Delta U(i_k)=[\Delta u^{\mathrm{T}}(i_k),\cdots,\Delta u^{\mathrm{T}}(i_k+N_u-1)]^{\mathrm{T}},$$

$$G=\begin{bmatrix} CB & & & 0 \\ CAB & CB & & \\ \vdots & & \ddots & \\ CA^{N_u-1}B & CA^{N_u-2}B & \cdots & CB \\ \vdots & & & \vdots \\ CA^{N-1}B & CA^{N-2}B & \cdots & CA^{N-N_u}B \end{bmatrix}_{N\times N_u},$$

$$F(i_k+1)=\begin{bmatrix} CA \\ CA^2 \\ \vdots \\ CA^N \end{bmatrix} E[x(i_k)].$$

Then we obtain from (10) the following optimal prediction in a vector form

$$\hat{Y}(i_k+1)=G\Delta U(i_k)+F(i_k+1) \tag{11}$$

Let

$$\lambda=diag[\lambda_1 \quad \lambda_2 \quad \cdots \quad \lambda_{N_u}],$$
$$W(i_k+1)=[w^{\mathrm{T}}(i_k+1),\cdots,w^{\mathrm{T}}(i_k+N)]^{\mathrm{T}},$$
$$Y(i_k+1)=[y^{\mathrm{T}}(i_k+1\mid i_k),\cdots,\ y^{\mathrm{T}}(i_k+N\mid i_k)]^{\mathrm{T}}.$$

The cost function (9) can be given in the following vector form

$$J\left(i_k,\Delta U(i_k)\right)=E\{[Y(i_k+1)-W(i_k+1)]^{\mathrm{T}}$$
$$\bullet[Y(i_k+1)-W(i_k+1)]+\Delta U^{\mathrm{T}}(i_k)\Delta U(i_k)\} \tag{12}$$

Substituting (11) into (12) and letting $\dfrac{\partial J(i_k,\Delta U(i_k))}{\partial \Delta U(i_k)}=0$, (7) is further given as follow:

$$\Delta U(i_k)=(G^{\mathrm{T}}G+\lambda I)^{-1}G^{\mathrm{T}}(W(i_k+1)-F(i_k+1)) \tag{13}$$

With (13) and (8), the control sequence for the case of packet loss is obtained.

3.2 Case of constant network-induced time delay

For the NCS considered in this case, it is assumed that there exist no packet loss, and every packet sent experiences some constant network-induced time delay, i.e. $\tau_{i_k}=\tau=\tau^{sc}+\tau^{ca}$. It is noted that $i_k=k$ in this case. To compensate for the influence of the constant delay, the controller creates a control increment vector $\Delta U(i_k)=[\Delta u^{\mathrm{T}}(i_k),\Delta u^{\mathrm{T}}(i_k+1),\cdots,$ $\Delta u^{\mathrm{T}}(i_k+N_u-1)]^{\mathrm{T}}$ of length $N_u>s$ using the received feedback packet sampled at instant i_k, and then produces a control vector $U(i_k)=[u^{\mathrm{T}}(i_k),u^{\mathrm{T}}(i_k+1),\cdots,u^{\mathrm{T}}(i_k+N_u-1)$ $]^{\mathrm{T}}$, which is sent from controller to actuator in a single packet. For $i_k+1=i_{k+1}$ in this case, only the control $u(i_k)$ is imposed on the controlled continuous plant in the time interval $[i_k+1,i_{k+1}]$.

The cost function in this case is given as follow

$$J(i_k,\Delta U(i_k))=E\{\sum_{j=N_0}^{N}(y(i_k+j\mid k)-w(i_k+j))^2$$
$$+\sum_{j=1}^{N_u}\lambda_j(\Delta u(i_k-1+j))^2\}, \tag{14}$$

where $w(t)$ is reference locus, $N_0\geq\tau_{i_k}+1$ and $N\geq N_0$ $+N_u$ are respectively the minimal and maximal step length of prediction, $s\leq N_u\leq N$ is the step length of predictive control, $\lambda_j(j=1,\cdots,N_u)$ are the weights of control increments.

In this case, the $j>0$ step forward prediction is different from that of the case of packet loss, which is given as follow:

$$y(k+j\mid k)$$
$$=CA^j x(k)+\sum_{i=1}^{j} CA^{j-i}B\Delta u(k+i-1-\tau^{ca}-\tau^{sc})$$

$$
\begin{aligned}
&+\sum_{i=1}^{j} CA^{j-i}B_v v(k+i-1) \\
&+\sum_{i=1}^{j} CA^{j-i}B_\omega \omega(k+i-1)+\omega(k+j) \\
&= CA^j x(k) + \sum_{i=1}^{\tau^{ca}+\tau^{sc}} CA^{j-i}B\Delta u(k+i-1-\tau^{ca}-\tau^{sc}) \\
&+ \sum_{i=1}^{j-\tau^{ca}-\tau^{sc}} CA^{j-i-\tau^{ca}-\tau^{sc}}B\Delta u(k+i-1) + \sum_{i=1}^{j} CA^{j-i}B_v v(k+i-1) \\
&+\sum_{i=1}^{j} CA^{j-i}B_\omega \omega(k+i-1)+\omega(k+j).
\end{aligned}
\tag{15}
$$

It is seen from (15) that $y(k+j\,|\,k)$ depends on both the determined control increments $\Delta u(k-1)$, $\cdots$, $\Delta u(k-\tau^{sc}-\tau^{ca})$ and the future ones $\Delta u(k)$, $\cdots$, $\Delta u(k+j)$. Then the optimal prediction of $y(k+j\,|\,k)$ is given as follow:

$$
\begin{aligned}
&\hat{y}(k+j\,|\,k) = E[y(k+j\,|\,k)] \\
&= CA^j E[x(k)] + \sum_{i=1}^{\tau^{ca}+\tau^{sc}} CA^{j-i}B\Delta u(k+i-1-\tau^{ca}-\tau^{sc}) \\
&+ \sum_{i=1}^{j-\tau^{ca}-\tau^{sc}} CA^{j-i-\tau^{ca}-\tau^{sc}}B\Delta u(k+i-1).
\end{aligned}
\tag{16}
$$

Define

$\hat{Y}(i_k+N_0) = [\hat{y}^{\mathrm{T}}(i_k+N_0\,|\,i_k),\cdots,\hat{y}^{\mathrm{T}}(i_k+N\,|\,i_k)]^{\mathrm{T}}$,

$\Delta U(i_k) = [\Delta u^{\mathrm{T}}(i_k),\cdots,\Delta u^{\mathrm{T}}(i_k+N_u-1)]^{\mathrm{T}}$,

$$
G = \begin{bmatrix}
CB & & & 0 \\
CAB & CB & & \\
\vdots & & \ddots & \\
CA^{N_u-1}B & CA^{N_u-2}B & \cdots & CB \\
\vdots & & & \vdots \\
CA^{N-N_0}B & CA^{N-N_0-1}B & \cdots & CA^{N-N_0-N_u+1}B
\end{bmatrix}_{(N-N_0+1)\times N_u},
$$

$\Delta U_d(i_k) = [\Delta u^{\mathrm{T}}(i_k-N_0+1),\cdots,\Delta u^{\mathrm{T}}(i_k-1)]^{\mathrm{T}}$,

$$
F(i_k+N_0) = \begin{bmatrix} CA^{N_0} \\ CA^{N_0+1} \\ \vdots \\ CA^{N} \end{bmatrix} E[x(i_k)]
+ \begin{bmatrix}
CA^{N_0-1}B & CA^{N_0-2}B & \cdots & CAB \\
CA^{N_0}B & CA^{N_0-1}B & \cdots & CA^2B \\
\vdots & & & \vdots \\
CA^{N-1}B & CA^{N-2}B & \cdots & CA^{N-N_0+1}B
\end{bmatrix} \Delta U_d(i_k).
$$

Then we have from (16) that

$\hat{Y}(i_k+N_0) = G\Delta U(i_k) + F(i_k+N_0)$.

Similarly, (7) is further given as follow:

$$
\Delta U(i_k) = (G^{\mathrm{T}}G+\lambda I)^{-1}G^{\mathrm{T}}(W(i_k+N_0)-F(i_k+N_0)) , \tag{17}
$$

where

$\lambda = diag[\lambda_1 \quad \lambda_2 \quad \cdots \quad \lambda_{N_u}]$,

$W(i_k+N_0) = [w^{\mathrm{T}}(i_k+N_0),\cdots,w^{\mathrm{T}}(i_k+N)]^{\mathrm{T}}$.

With (17) and (8), the control sequence for the case of network-induced time delay is obtained.

3.3 Case of both packet loss and random network-induced time delay

For the NCS considered in this case, it is assumed that there simultaneously exist random packet loss and random network-induced time delay. For every feedback sampled at i_k , the controller produces the related $\Delta U(i_k)$ and $U(i_k)$. Because of the random network-induce time delay, $\Delta U(i_k)$ and $U(i_k)$ are same to those of the case of constant network-induced time delay. In the time interval $[i_k+\tau_{i_k}+1$, $i_{k+1}+\tau_{i_{k+1}}]$, to compensate for the influence of the packet loss, the controls $u(l)$ $(i_k \le l \le i_{k+1}-1)$ are successively imposed on the controlled continuous plant.

4. SIMULATIONS

The considered discrete-time state-space model is identified from a practical circuit system. This circuit system is a first-order inertial loop. The model is given as follow:

$$
\begin{aligned}
x_o(t+1) &= A_o x_o(t) + B_o u(t) + B_{o,\omega}\omega_o(t) \\
y(t) &= C_o x_o(t) + \omega_o(t)
\end{aligned},
$$

where $A_o = 0.9672$, $B_o = 0.06557$, $B_{o,\omega} = 0.9672$, $C_o = 1$. Then the equivalent incremental state-space model is given as follow:

$$
\begin{aligned}
x(t+1) &= Ax(t) + B\Delta u(t) + B_\omega \omega(t) \\
y(t) &= Cx(t) + \omega(t)
\end{aligned},
$$

where

$A = \begin{bmatrix} 1 & 1 \\ 0 & 0.9672 \end{bmatrix}$, $B = \begin{bmatrix} 0 \\ 0.06557 \end{bmatrix}$, $B_\omega = \begin{bmatrix} 1 \\ 0.9672 \end{bmatrix}$,

$C = [1 \quad 1]$.

The noise $\omega(t)$ is assumed to be zero-mean and white.

For the networked generalized predictive control algorithm, the set point is 4, $N-N_0+1=13$, $N_u=9$, and the weights $\lambda_i(i=1,\cdots,N_u)$ are set to be 0.1. In the following fig. 2~7, the solid line denotes the output signal and the dotted the control signal.

4.1 Case of constant packet loss

Fig. 2 is the simulation results for the case of packet loss. The sub figures from the top to the bottom are related to the cases with packet loss 0, 2, 5 and 8, respectively, for every interval

$[i_k, i_{k+1}]$. It is seen that the controls are different for different numbers of packet loss, and more packet loss leads to the bigger variance of control sequence.

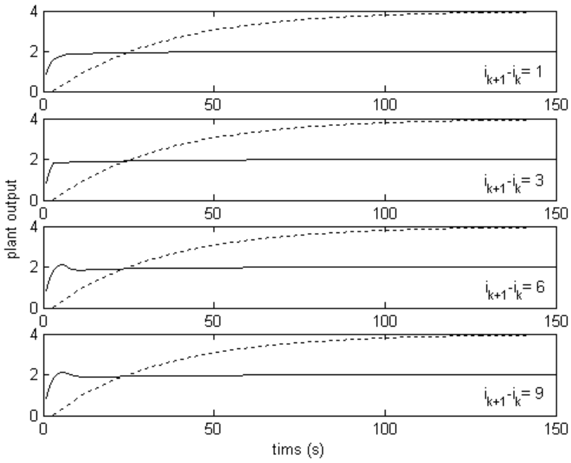

Fig. 2. The simulation results for the case of packet loss

4.2 Case of constant network-induced time delay

Fig. 3 is the simulation results for the case of constant network-induced time delay. The delays of three sub figures from the top to the bottom are 0, 10 and 20, respectively. It is seen that the three controls are same to each other though the transmission delays are different. Because of the transmission delay, every output response is shifted ahead by the size of delay.

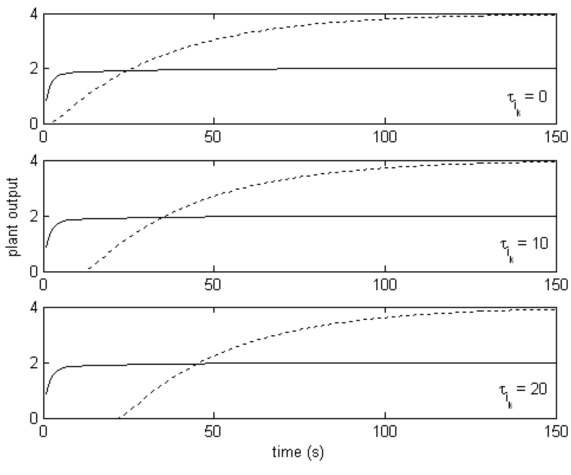

Fig. 3. The simulation results for the case of constant network-induced time delay

4.3 Case of packet loss and network-induced time delay

Fig. 4 is the simulation results for the case of both packet loss and network-induced time delay. The network-induced time delay is 20. The numbers of packet loss from the top to the bottom are 0, 2, 5 and 8, respectively, for every interval $[i_k, i_{k+1}]$. The controls are different each other with respect to packet loss and the output responses are just shifted ahead with the steps of the transmission delay.

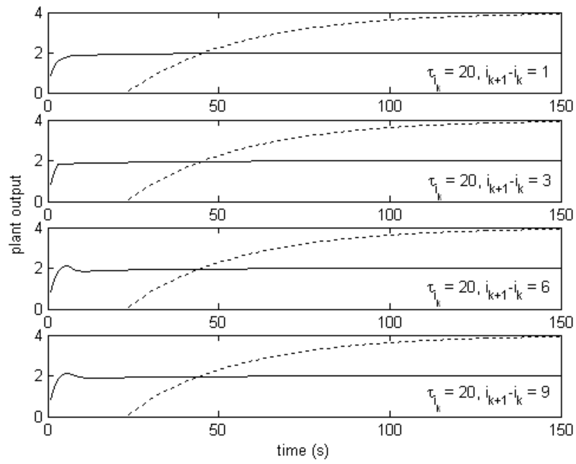

Fig. 4. The simulation results for the case of both packet loss and network-induced time delay

5. EXPERIMENTS

In this section, we apply the networked predictive control algorithm on the practical circuit system to verify its' effectiveness. The predictive control algorithm is implemented in a networked controller board (NCB), and the sampler and actuator are located at a networked implemented board (NIB). For more information of the boards, refer to Liu, Mu, Rees & Chai (2006).

5.1 Case of packet loss

Fig. 5 is the experimental results of the case of packet loss. It is seen that the step response is very similar to that of the simulation results of Fig. 2.

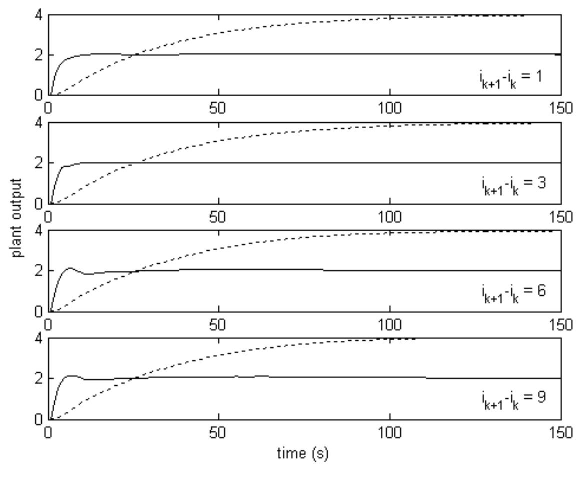

Fig. 5. The experimental results of the case of packet loss

5.2 Case of constant network-induced delay

Fig. 6 is the experimental results of the case of constant network-induced time delay. It is seen that the step response is very similar to that of simulation results of Fig. 3.

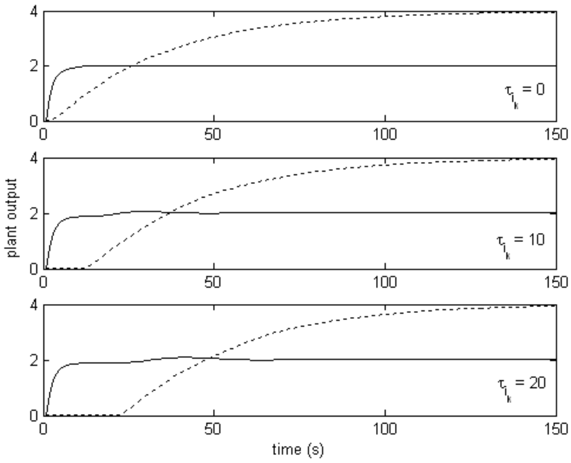

Fig. 6. The experimental results of the case of constant network-induced time delay

53. Case of both packet loss and network-induced delay

Fig. 7 is the experimental results of the case of both packet loss and network-induced time delay. It is seen that the step response is very similar to that of the simulation results of Fig. 4.

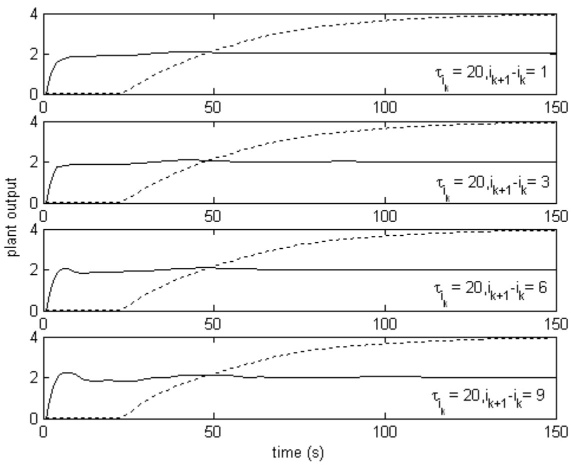

Fig. 7. The experimental results of the case of both packet loss and network-induced time delay

6. CONCLUSIONS

This paper has presented a networked predictive controller design method for NCS subject to packet loss and network-induced time delay. To compensate for the influence of packet loss in NCS, when the networked controller receives a networked feedback, it creates a control sequence and sends it to actuator. The elements of the control sequence successively act on the plant till a new control sequence is available for actuator. To compensate for the influence of network-induced time delay, the controller uses the forward output prediction to construct the future response. By minimizing the cost function with a minimal prediction step related to network-induced time delay, a control sequence is computed to counteract the influence of network-induced time delay. The simulation and experiment results have shown the effectiveness of our networked predictive controller design method.

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