2005 American Control Conference
June 8-10, 2005. Portland, OR, USA

Design of Robust Networked Predictive Control Systems

Junxia Mu, G. P. Liu and David Rees

Abstract – **Random communication time delay highly degrades the control performance of networked control systems. The paper addresses the problem by presenting a novel control technique using a modified Model Predictive Control (MPC) and a modified Smith predictor. By using MPC, future control sequences are generated to compensate for the forward communication time delay when control signals are delayed or missed. Using the Smith predictor, the backward time delay can also be compensated for. The design of a filter is used to improve the robustness of the networked control system. To illustrate the improvement in control performance using the proposed method, simulation results are presented to show that the method is superior to the standard GPC and networked predictive control.**

I. Introduction

With the development of network technology, the Internet has provided a powerful tool for distance collaborative work. It can be potentially used in many applications, such as traffic control, tele-operation, tele-surgery, space exploration and so on. Although Internet-based control system is quite new and some theories are still in its infancy, there has been increased interest in these developments in recent years. This kind of control systems provides a convenient way of remote monitoring and control of plants that are located all over the world. More and more researchers are working in this area. Some of them have produced promising results using small-scale experiments [1,2] and web-based control laboratories for long distance learning [3,4].

It is well known that networked control systems are very difficult to control due to the random network communication time delay caused by the routes of the data transmission and network traffic congestion [5]. This can produce wrong command order, even lost command packets, thus highly degrading the control performance of controlled systems. Conventional control methods are not suitable for this kind of systems. There is however an advantage in networked control systems, which is that a set of control sequences can be packed and transmitted from one location to another location at the same time through a network channel. Liu *et al*. [6] proposed a Networked Predictive Control (NPC) method to deal with these random communication time delay problems. In order to improve the control performance of the NPC scheme proposed by Liu *et al*. [6], a modified MPC is proposed to compensate for the forward time delay and a modified Smith predictor is recommended for the backward time delay. To improve system robustness of the proposed method to overcome model uncertainties, a low pass filter is used. Simulation results are presented to show the improvement in the control performance using the proposed Robust Networked Predictive Control (RNPC) method.

J. X. Mu, G. P. Liu and D. Rees are with School of Electronics, University of Glamorgan, Pontypridd, CF37 1DL, Wales, UK (phone: +44-1443-482817; fax: +44-1443-482541; email: jmu@glam.ac.uk; gpliu@glam.ac.uk; drees@glam.ac.uk).

II. Robust Networked Predictive Control

In this paper, a modified Generalised Predictive Control (GPC) [7] is used for the design of the networked predictive control system shown in Fig. 1. The controller and plant are connected by the Internet, which causes random communication time delay and occasional data packet misses. In order to compensate for the random forward time delay, the networked predictive controller can be configured as follows. During normal operation without communication time delay, only the first predicted control signal at each sampling instant is applied to the plant, the remaining predicted control signals are just discarded. However, when the networked control system is subject to communication time delay and data packet failure, the control signal generated on the remote side is delayed or missed in its transmission to the plant side. In this case, the predicted control input from the last available sequence can be safely applied to the plant to compensate for these time delays. In order to compensate for a time delay in the backward channel, a modified Smith predictor is used.

To improve the robustness of the networked control system, a low pass unitary gain filter is used to filter the error produced between the delayed plant output measurement and its delayed open-loop model output. The proposed RNPC has several advantages. The design of the filter is very simple and takes both disturbance rejection and robustness requirements into account. This strategy consists of two steps. Firstly, choose the GPC parameters to obtain an optimal control performance for the nominal case without model uncertainties. Secondly compute the output prediction using the open-loop model, which is corrected by adding the filtered error signal between the delayed plant output measurement and the output of the delayed open-loop model.

Consider a single-input and single-out with d+1 step time delay plant, $(G_n + \Delta G_u)z^{-d}$, modelled by $G_n z^{-d}$.

$$G_n = \frac{B(z^{-1})z^{-1}}{A(z^{-1})} \tag{1}$$

$$\begin{aligned} A(z^{-1}) &= 1 + a_1 z^{-1} + \cdots + a_{n_a} z^{-n_a} \\ B(z^{-1}) &= b_0 + b_1 z^{-1} + \cdots + b_{n_b} z^{-n_b} \end{aligned} \tag{2}$$

where $\Delta G_u z^{-d}$ is unconstructed model uncertainties. n_a and n_b define the maximum number of the input and output lag terms respectively. In GPC, the control trajectory can be found by minimising the following function:

$$J(t,U(t)) = \sum_{k=N_1}^{N_2} [r(t+k) - \bar{y}(t+k)]^2 + \rho \sum_{k=1}^{N_u} [\Delta u(t+k-1)]^2 \tag{3}$$

with respect to N_u future control inputs and subject to the control constraints, namely

$$U(t) = [u(t) \quad \cdots \quad u(t+N_u-1)]^T \tag{4}$$

$$\Delta u(t+k) = 0,\ N_u \le k \le N_2 - d - 1 \tag{5}$$

where N_1 denotes the minimum prediction horizon, N_2 the maximum prediction horizon, N_u the control horizon, ρ the weight factor and $\Delta = 1 - z^{-1}$. In order to derive a predictor, the following Diophantine equation is used

$$\Delta A(z^{-1}) E_k(z^{-1}) + z^{-k} F_k(z^{-1}) = 1 \tag{6}$$

where the polynomial $E_k(z^{-1})$ is of order k-1 and $F_k(z^{-1})$ is of order n_a.

Each open-loop prediction is corrected by adding the filtered error signal between the fixed time delayed (f) plant output measurement and the output of the delayed (d+f) open-loop model using a low-pass unitary gain filter given in Eq. (8).

$$\begin{aligned} &\bar{y}(t+d-i) \\ &= \hat{y}(t+d-i) + T(z)\big(y(t-f-i) - \hat{y}(t-f-i)\big) \end{aligned} \tag{7}$$

$$T(z) = \frac{1-\alpha}{1-\alpha z^{-1}} \tag{8}$$

Using the Diophantine equation (6) and the prediction in Eq. (7), a future k-step ahead prediction is obtained.

$$\begin{aligned} &\hat{y}(t+d+k) = \overline{G}_k(z^{-1})\Delta u(t+k-1) \\ &+ z^k \left[G_k(z^{-1}) - \overline{G}_k(z^{-1})\right] \Delta u(t-1) + F_k(z^{-1})\bar{y}(t+d) \end{aligned} \tag{9}$$

for $1 \le k \le N_2 - d$

$$\begin{aligned} G_k(z^{-1}) &= E_k(z^{-1})B(z^{-1}) \\ &= g_0 + g_1 z^{-1} + \cdots + g_{k-1+n_b} z^{1-k-n_b} \\ \overline{G}_k(z^{-1}) &= g_0 + g_1 z^{-1} + \cdots + g_{k-1} z^{1-k} \end{aligned} \tag{10}$$

Therefore, the future predicted control sequence can be determined by the following equation [6].

$$\begin{aligned} &\begin{bmatrix} u(t|t) \\ u(t+1|t) \\ \vdots \\ u(t+N_u-1|t) \end{bmatrix} = \begin{bmatrix} 1 \\ 1 \\ \vdots \\ 1 \end{bmatrix} u(t-1|t-1) \\ &+ \begin{bmatrix} H_1 \\ H_2 \\ \vdots \\ H_{N_u} \end{bmatrix} \big(R(t) - G(z^{-1})\Delta u(t-1|t-1) - F(z^{-1})\bar{y}(t+d)\big) \end{aligned} \tag{11}$$

where $u(t+i|t)$ is the i-th step ahead control prediction at time t, $\Delta u(t$-1$|t$-1) is the first predicted control input at time t-1, and the matrix H is

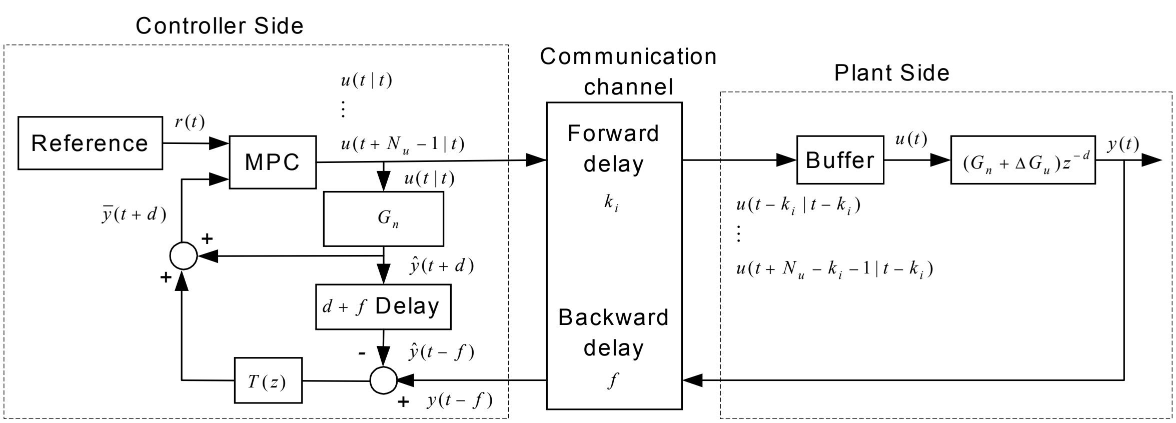

Fig. 1. The robust networked predictive control system.

$$\begin{bmatrix} H_1 \\ H_2 \\ \vdots \\ H_{N_u} \end{bmatrix} = \begin{bmatrix} 1 & 0 & \cdots & 0 \\ 1 & 1 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 1 & 1 & \cdots & 1 \end{bmatrix} \left(\Gamma^T \Gamma + \rho I_{N_u \times N_u}\right)^{-1} \Gamma^T \quad (12)$$

$$\in \Re^{N_u \times (N_2 - d)}$$

$$\Gamma = \begin{bmatrix} g_0 & 0 & \cdots & 0 \\ g_1 & g_0 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ g_{N_2-d-1} & g_{N_2-d-2} & \cdots & g_{N_2-d-N_u} \end{bmatrix}_{(N_2-d)\times N_u} \quad (13)$$

$$R(t) = \left[r(t+d+1) \quad r(t+d+2) \quad \cdots \quad r(t+N_2)\right] \quad (14)$$

$$G(z^{-1}) = \begin{bmatrix} \left(G_1(z^{-1}) - \overline{G}_1(z^{-1})\right)z \\ \left(G_2(z^{-1}) - \overline{G}_2(z^{-1})\right)z^2 \\ \cdots \\ \left(G_{N_2-d}(z^{-1}) - \overline{G}_{N_2-d}(z^{-1})\right)z^{N_2-d} \end{bmatrix} \quad (15)$$

$$F(z^{-1}) = \left[F_1(z^{-1}) \quad F_2(z^{-1}) \quad \cdots \quad F_{N_2-d}(z^{-1})\right]^T \quad (16)$$

In order to compensate for the network communication time delay in the forward channel, which is assumed no greater than the set of the predicted control sequence, a network control predictor is proposed. It is assumed that all predicted control sequences at the current time are packed and sent to the plant. Then the networked delay compensator chooses the control value from the latest control sequences available on the plant side. For example if the following predictive control sequences are received on the plant side:

$$\begin{bmatrix} u(t-k_1|t-k_1) \\ u(t-k_1+1|t-k_1) \\ \vdots \\ u(t|t-k_1) \\ \vdots \\ u(t+N_u-k_1-1|t-k_1) \end{bmatrix}, \begin{bmatrix} u(t-k_2|t-k_2) \\ u(t-k_2+1|t-k_2) \\ \vdots \\ u(t|t-k_2) \\ \vdots \\ u(t+N_u-k_2-1|t-k_2) \end{bmatrix}, \ldots, \begin{bmatrix} u(t-k_l|t-k_l) \\ u(t-k_l+1|t-k_l) \\ \vdots \\ u(t|t-k_l) \\ \vdots \\ u(t+N_u-k_l-1|t-k_l) \end{bmatrix} \quad (17)$$

where the control values $u(t|t-k_i)$ for i= 1, 2,..., l, are available on the plant side. The control input of the plant at time t is chosen from the latest control sequences as follows:

$$u(t) = u(t|t - \min\{k_1, k_2, \cdots, k_l\}) \quad (18)$$

Thus the networked predictive control scheme can be implemented in the following steps:

(1) Design the MPC parameters (N_1, N_2, N_u and ρ) to obtain the desired control performance without the networked communication time delay and model uncertainties.

(2) Use the same MPC parameters, the predicted control sequence in Eq. (11) is obtained, based on past inputs, past outputs and the future references.

(3) Transmit this control prediction sequence to the plant side through the communication channel.

(4) Choose the control input in the buffer in accordance with Eq. (18).

III. Robustness Analysis of Networked Predictive Control System

In order to study the robustness of the proposed RNPC, unstructured uncertainties are considered. The reason for using unstructured uncertainties is that in most industrial systems, the high frequency structure of the system is usually not known, thus low-order models are often used to represent the complex dynamics. This results in some unmodelled dynamics and the unstructured uncertainty model seems to be a better way to quantify this kind of uncertainties [8]. Also due to the forward and backward time delay compensators, there is a difference between the plant and its model. These can also be considered as unmodelled uncertainties. It is clear from Eq. (11) that the first prediction is obtained

$$\begin{aligned} u(t|t) &= u(t-1|t-1) + H_1 R(t) \\ &- H_1 G(z^{-1})\Delta u(t-1|t-1) - H_1 F(z^{-1})\overline{y}(t+d) \end{aligned} \quad (19)$$

which gives

$$u(t|t) = \frac{H_1 R(t) - H_1 F(z^{-1})\overline{y}(t+d)}{(1 + H_1 G(z^{-1}) z^{-1})\Delta} \quad (20)$$

Using Eq. (11) and Eq. (20), the k_i-step ahead control prediction at time t- k_i is expressed by

$$\begin{aligned} u(t|t-k_i) &= u(t-k_i-1|t-k_i-1) + H_{k_i+1} R(t-k_i) \\ &- H_{k_i+1} G(z^{-1})\Delta u(t-k_i-1|t-k_i-1) \\ &- H_{k_i+1} F(z^{-1})\overline{y}(t-k_i+d) \\ &= \left(1 - H_{k_i+1} G(z^{-1})\Delta\right) z^{-1} u(t-k_i|t-k_i) \\ &+ H_{k_i+1} R(t-k_i) - H_{k_i+1} F(z^{-1})\overline{y}(t-k_i+d) \end{aligned} \quad (21)$$

$$u(t|t-k_i) = \frac{\left(H_1 z^{-1} + H_{k_i+1}\Delta\right)\left(R(t-k_i) - F(z^{-1})\overline{y}(t-k_i+d)\right)}{(1 + H_1 G(z^{-1}) z^{-1})\Delta} \quad (22)$$

From Eq. (20) and Eq. (22), there is a proportional relationship between $u(t|t-k_i)$ and $u(t|t)$, which can be stated as

$$\frac{u(t|t-k_i)}{u(t|t)} = D_i(z) = \frac{\left(H_1 z^{-1} + H_{k_i+1}\Delta\right) z^{-k_i}}{H_1} \tag{23}$$

The difference of input signals between the plant and model can be stated as follows:

$$u(t|t-k_i) - u(t|t) = \frac{\left(H_1(z^{-k_i-1}-1) + H_{k_i+1}\Delta z^{-k_i}\right)\left(R(t) - F(z^{-1})\bar{y}(t+d)\right)}{(1 + H_1 G(z^{-1})z^{-1})\Delta} \tag{24}$$

In order to simplify the robustness analysis of the networked predictive control system, let $H_1 = [h_{11} \quad h_{12} \quad \cdots \quad h_{1(N_2-d)}]$ and use the first predicted control increment obtained from Eq. (19). This is shown below

$$\Delta u(t|t) = H_1 \begin{bmatrix} r(t+d+1) \\ r(t+d+2) \\ \vdots \\ r(t+N_2) \end{bmatrix} - H_1 G(z^{-1})\Delta u(t-1|t-1) - H_1 F(z^{-1})\bar{y}(t+d) \tag{25}$$

where it can be seen that the robust networked predictive control can be simplified to the controller $C(z)$ in Eq. (26) and reference filter $W(z)$ in Eq. (27) for the nominal case without model uncertainties. However for the non-nominal case, there is an additional controller $D_i(z)$ included and each open-loop prediction is corrected by adding the filtered error signal between the delayed output measurement and the delayed open-loop model output. This is shown in Fig. 2.

$$C(z) = \frac{H_1 F(z^{-1})}{(1-z^{-1})(1 + H_1 G(z^{-1})z^{-1})} \tag{26}$$

$$W(z) = \frac{\sum_{i=1}^{N_2} h_{1i} z^{i+d}}{H_1 F(z^{-1})} \tag{27}$$

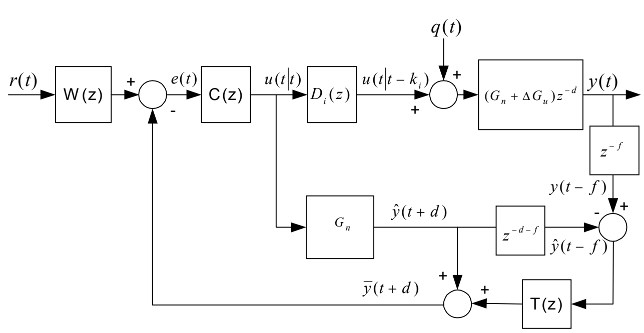

Fig. 2. Equivalent structure of the robust networked predictive control.

To analysis the system robustness, assume that the disturbance $q(t) = 0$ and that $G_n z^{-d}$ gives the transfer function of the linear system in its nominal case. Unstructured uncertainties are represented by $\Delta G_u z^{-d}$, thus yielding

$$\bar{G} = (G_n + \Delta G_u)z^{-d} = \frac{L}{Q} = \frac{(l_0 + l_1 z^{-1} + \cdots + l_{m_b} z^{m_b})}{1 + q_1 z^{-1} + \cdots + q_{m_a} z^{m_a}} z^{-d} \tag{28}$$

The transfer function from $u(t|t)$ to $\bar{y}(t+d)$ can be expressed as

$$\frac{\bar{y}(t+d)}{u(t|t)} = G_n + T(z)\left(z^{-d-f} \sum_{i=0}^{m_b} \frac{l_i D_i(z) z^{-i}}{Q} - G_n z^{-d-f} \right) = G_n + T(z) z^{-d-f} \left(\sum_{i=0}^{m_b} \frac{l_i}{Q} \frac{\left(H_1 z^{-1} + H_{k_i+1}\Delta\right) z^{-k_i-i}}{H_1} - G_n \right) \tag{29}$$

The first part of the above equation is the system transfer function for the nominal case. The second part is related to the forward and backward time delay, and the model uncertainties. These can be combined as total system uncertainties by:

$$\delta = z^{-f} \left(\sum_{i=0}^{m_b} \frac{l_i}{Q} \frac{\left(H_1 z^{-1} + H_{k_i+1}\Delta\right) z^{-k_i-i}}{H_1} - G_n \right) \tag{30}$$

Using the small gain theory [9], the normal $|\bullet|$ bound uncertainty region is derived to maintain closed-loop stability and is defined as follows:

$$\left| T(z) z^{-d} \delta \right| \left| \frac{C(z)}{1 + C(z)G_n(z)} \right| < 1, \quad \forall \omega \in (0, \pi), \; z = e^{j\omega} \tag{31}$$

So

$$|\delta| < \Delta P = \left| \frac{1 + C(z)G_n(z)}{C(z)T(z)} \right|, \quad \forall \omega \in (0, \pi), \; z = e^{j\omega} \tag{32}$$

It can be seen that if the uncertainties caused by the forward and backward time delay, and unmodelled dynamics are within a norm boundary in Eq. (32), the system is stable. The model uncertainties have an inverse relationship to the uncertainties caused by the forward and backward time delay.

The nominal control performance of the system is not modified by including the filter *T*. When the plant and its model are exactly the same and no forward and backward time delay, then the error signal between the plant and its model is zero. So the filter *T* has no effect on the control performance of the closed system. However the disturbance rejection is affected by including the filter. To estimate the effect of the filter on the disturbance rejection performance, consider the closed-loop transfer function between the disturbance $q(t)$ and the control input $u(t|t-k_i)$. In general, in order to achieve good performance for the disturbance rejection, $|u/q|$ should be close to one over the system bandwidth.

$$\left|\frac{u}{q}(z)\right| = \left|\frac{C(z)D_i(z)G_n(z)z^{-d-f}T(z)}{1+C(z)G_n(z)}\right|$$
$$= \left|\frac{C(z)D_i(z)G_n(z)T(z)}{1+C(z)G_n(z)}\right| = 1,\ \forall\omega < \omega_0, z = e^{j\omega} \tag{33}$$

where ω_0 is the desired bandwidth of the closed loop system. The percentage of the uncertainty norm boundary is calculated as follow:

$$\gamma P = \frac{\Delta P}{\left|G_n z^{-d}\right|} = \left|\frac{1+C(z)G_n(z)}{C(z)G_n(z)T(z)}\right| = \frac{|D_i(z)|}{|u/q(z)|},\ z = e^{j\omega} \tag{34}$$

Eq. (34) clearly shows that the high disturbance rejection performance leads to low robustness. So there is a need to make a compromise between disturbance rejection and robustness. In general, the unstructured model uncertainties are dominant at high frequencies, therefore T must be chosen to increase the value of γP at these high frequencies and maintain the unitary gain of u/q for the frequencies below the desired bandwidth ω_0. So T must be chosen to have unitary gain at d.c. and to be a low pass filter.

IV. Simulation Examples

To illustrate the properties of the proposed robust networked predictive control method, a discrete model of a DC motor speed control system with a sampling time 0.12s, gives the following transfer function

$$G(z) = \frac{0.009201z^{-1} + 0.005709z^{-2}}{1 - 1.088z^{-1} + 0.2369z^{-2}} \tag{35}$$

The GPC controller is set to N_1 =1, N_2 =20, N_u =20 and ρ =0.1 for the best control performance when there is no model uncertainties and no time-delay in both forward and backward channels. The response is shown in Fig. 3(a). For a 5-step fixed backward time delay, the system can deal with a maximum 3-step fixed forward time delay using NPC proposed by Liu *et al.* [6]. Using the standard GPC without delay compensator, the system is unstable even for 0-step forward time. However, using the RNPC method with the filter setting, $\alpha = 0.9$, the system is still stable for a 19-step forward time delay. This is shown in Fig. 3(b).

5% denominator parameter uncertainties yield the transfer function in Eq. (36). For a 5-step fixed backward time delay, using NPC, the system can cope with a 3-step fixed forward time delay. However using RNPC the forward time delay can be increased to a 10-step fixed time delay and the system is still stable. This is shown in Fig. 4, where the system is stable using RNPC for a 10-step fixed forward and a 5-step fixed backward time delay. However using NPC, the system is unstable.

$$G(z) = \frac{0.009201z^{-1} + 0.005709z^{-2}}{1 - 1.1424z^{-1} + 0.2487z^{-2}} \tag{36}$$

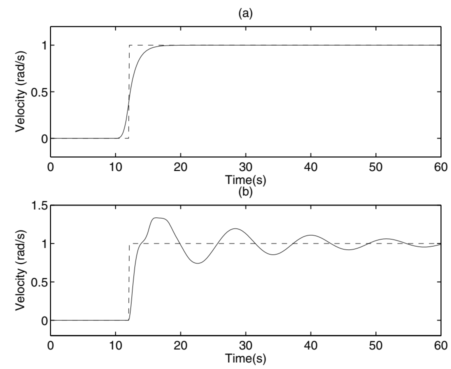

Fig. 3. Step responses. (a) no model uncertainty and time delay, (b) a 19-step fixed forward and 5-step fixed backward time delay using RNPC. Reference (dashed), system output (solid).

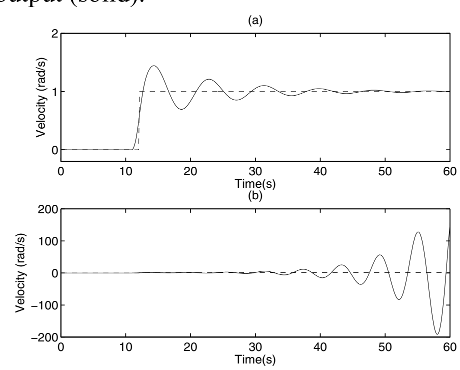

Fig. 4. Step responses for a 10-step fixed forward and 5-step fixed backward time delay with 5% denominator parameter uncertainties. (a) RNPC, (b) NPC. Reference (dashed), system output (solid).

If there exists unmodelled dynamics, such as Eq. (37),

$$G(z) = \frac{0.01z^{-1} - 0.009007z^{-2}}{1 - 0.006738z^{-1}} \tag{37}$$

the control performance is improved using RNPC compared with NPC (Fig. 5). This is based on a comparison between a 5-step fixed backward and a 10-step fixed forward time delay for the case of RNPC, with a 5-step fixed backward and 2-step fixed forward time delay for NPC. These were the limiting values in the case of RNPC and NPC to ensure stability.

If the system has unmodelled dynamics in Eq. (37) and a 2-step fixed time delay uncertainty in both channels, the control performance is still superior using RNPC. This is shown in Fig. 6 where the system can cope with a 8-step fixed forward time delay for a 5-step fixed backward time delay using RNPC. However using NPC, even with no forward time delay, the system is still unstable.

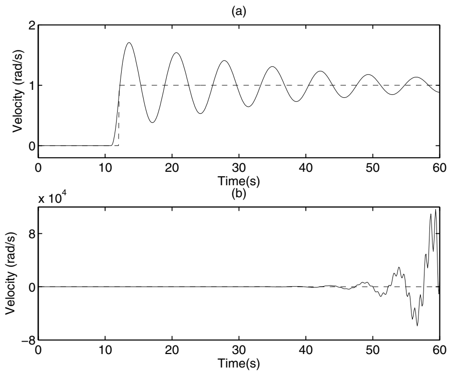

Fig. 5. Step responses for a 10-step fixed forward and 5-step fixed backward time delay with unmodelled dynamics. (a) RNPC, (b)NPC. Reference (dashed), system output (solid).

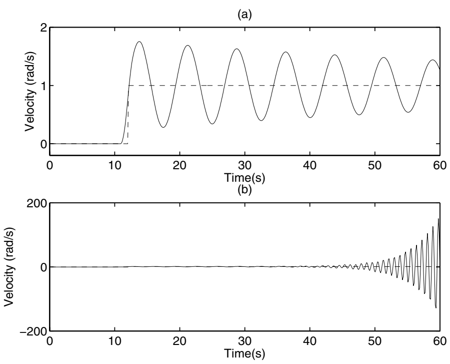

Fig. 6. Step responses for a 5-step fixed backward time delay with unmodelled dynamics and a 2-step fixed time delay uncertainty in both channels. (a) RNPC with a 8-step forward time delay, (b) NPC with a 0-step forward time delay. Reference (dashed), system output (solid).

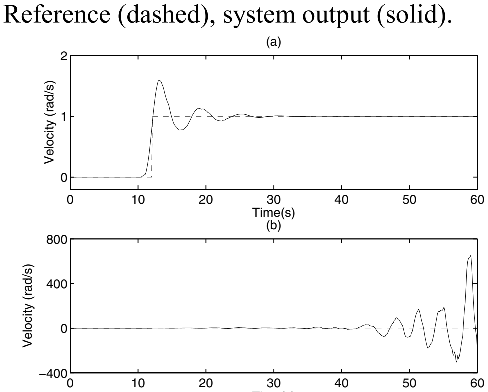

Fig. 7. Step responses for a 8-step random forward and a 5-step fixed backward time delay with unmodelled dynamics and a 2-step random time delay uncertainty in both channels. (a) RNPC, (b)NPC. Reference (dashed), system output (solid).

Fig. 7 gives the performance in the case of time delay and model uncertainties for a 8-step random time delay in the forward channel and a 5-step fixed time delay in the backward channel. The system uncertainties are as follows: (a) a 2-step random time delay in both channels. (b) unmodelled dynamics shown in Eq. (37). Using RNPC, the system is stable. However it is unstable using NPC.

In conclusion, RNPC has a superior control performance to NPC for parameter uncertainties, unmodelled dynamics and time delay uncertainties for both fixed and random time delay in the forward channel and fixed time delay in the backward channel.

V. Conclusions

This paper has presented a method to improve the robustness of networked control systems subject to random transmission time delay. This is achieved by using a modified MPC, which can generate future input signals applied to the system when the input signal is delayed or missed in the forward communication channel. Using a Smith predictor, the time delay in the backward channel can also be compensated for. Using this structure, the robustness of the networked control system can also be improved using a low pass transfer function to filter the error signal between the delayed plant output measurement and the delayed open-loop model output. The uncertainty norm boundary has been obtained. If the system uncertainties along with uncertainties caused by the forward and backward time delay are within its norm boundary, the system is stable. Simulation results show that the proposed robust networked predictive control method has dramatically improved the control performance compared with the standard GPC and the NPC method proposed by Liu. *et al*. [6].

References

[1] A. Halley and P. Gauld, "Integration where Java meets process control", *Control and Instrumentation*, vol. 31, 1999, pp.57-58.

[2] S. H. Yang and X. Chen, "Dealing with time delay and data loss for internet-based control systems", *4th IFAC Workshop on Time Delay Systems*, Rocquencourt, France, 2003.

[3] J. W. Overstreet and A. Tzes, "An internet-based real-time control engineering laboratory", *IEEE Control System Magazine*, vol. 19, 1999, pp.19-34.

[4] C. C. Ko, B. M. Chen, J. Chen, Y. Zhuang and K. C. Tan, "Development of a web-based laboratory for control experiments on a coupled tank apparatus", *IEEE Transactions on Education*, vol. 44, 2001, pp.76-86.

[5] R. C. Luo and T. M. Chen, "Development of a multibehaviour-based mobile robot for remote supervisory control through the Internet", *IEEE Transaction on Mechatronics*, vol. 5, 2000, pp.376-385.

[6] G. P. Liu, J. X. Mu and D Rees, "Networked predictive control of systems with random communication delay", *UKACC2004 International Conference on Control*, Bath, UK, 2004.

[7] D. W. Clarke, C. Mothadi and P. S. Tuffs, "Generalised predictive control – Part I. The basic algorithm", *Automatica*, vol. 23, 1987, pp.137-148.

[8] J. G. Owen and G. Zames, "Robust h-infinity disturbance minimization by duality", *System and Control Letters*, vol. 19, 1992, pp.255-263.

[9] M. Morari and E. Zafiriou. *Robust Process Control*. Printice Hall, Englewood Cliffs, NJ; 1989.