

Guaranteed Cost Control for Networked Control Systems Based on an Improved Predictive Control Method

Rui Wang, Guo-Ping Liu, Wei Wang, David Rees, and Yunbo B. Zhao

Abstract—This brief deals with the problem of guaranteed cost control for a class of uncertain networked control systems with time-varying delay. An improved predictive controller design strategy is proposed to compensate for the delay and data dropout in both the forward and backward channels to achieve the desired control performance. The varying controller gains which are designed to vary with delays can lead to less conservative results. Meanwhile, an algorithm involving a convex optimization problem is presented to achieve a suboptimal guaranteed cost. Furthermore, a numerical simulation and a practical experiment are given to illustrate the effectiveness of the proposed method.

Index Terms—Guaranteed cost control, linear matrix inequalities (LMIs), networked control system (NCS), predictive control, switched systems.

I. INTRODUCTION

IN RECENT years, considerable attention has been paid to networked control systems (NCSs) in which the control loops are closed via a communication network [1]–[8]. There are many advantages to NCSs, such as reduced system wiring, facilitated system maintenance, and increased systems flexibility.

However, due to the insertion of communication channels, this brings many challenging problems such as network-induced delay, data packet dropout, etc. These issues are detrimental to the performance of the system and can make the system unstable. There are a number of design methods that have been proposed to deal with this problem [9]–[13]. For example, in [9], the optimal stochastic control method deals with the effects of random network delays in NCS as a linear quadratic Gaussian problem. The H_∞ control problem has been studied in [12] for a class of NCSs, taking account of the effects of both the network-induced delay and data dropout, based on Lyapunov–Krasovskii method. However, in these control methods, the system just passively accepts the presence of the delay in the network rather

than actively compensating for it. In order to overcome the negative impact of the network delay on system stability and performance, a networked predictive control (NPC) scheme which is an active control strategy is proposed in [14]–[17]. This includes a control prediction generator (CPG) at the controller side and a network delay compensator (NDC) at the actuator side, and it is shown to be an effective method of addressing this problem. However, in these publications a fixed controller gain was used, and the controller gain design problem was not considered. This results in a significant conservative design because the controller gain does not reflect the range of possible delays in the network. Thus, a new technique needs to be developed to address this issue.

In designing a controller for a real plant, it is invariably necessary to design a control system which not only is stable but also possesses a strong robust performance. One way to deal with this is the so-called guaranteed cost control approach proposed by Chang and Peng [18]. This addresses the robust performance problem and has the advantage of providing an upper bound on a given performance index guaranteeing that system performance degradation incurred by uncertainty is less than this bound. Many results have appeared on this topic [19]–[24]. For NCSs, it is important to design a guaranteed cost controller such that the NCSs are stable and satisfy a performance index.

In this brief, we are concerned with the design problem of guaranteed cost controller for a class of uncertain NCSs by employing the modified compensation scheme. Network delay and data dropout are considered in both forward and feedback channels. An improved predictive controller scheme in which the controller gain varies with the delays in both the channels is proposed to make the corresponding closed-loop system asymptotically stable for all admissible uncertainties. In contrast with some existing references which are based on the fixed controller gain approach, these varying feedback controller gains can lead to less conservative results. Moreover, an iterative algorithm involving convex-optimization is presented to design the desired controllers with a suboptimal guaranteed cost.

This brief is organized as follows. In Section II, preliminaries and problem formulations are introduced. Section III gives the sufficient condition of guaranteed cost control and the algorithm of controller design. Section IV provides two examples to show the effectiveness of the proposed method. Conclusions are summarized in Section V.

II. SYSTEM DESCRIPTION AND PRELIMINARIES

In this brief, $*$ denotes the symmetric block in one symmetric matrix. I denotes the identity matrix of an appropriate dimension. The trace of a matrix is denoted by $tr(\cdot)$.

The NCS system structure considered in this brief is shown in Fig. 1, where f_t and k_t are the backward and forward channel

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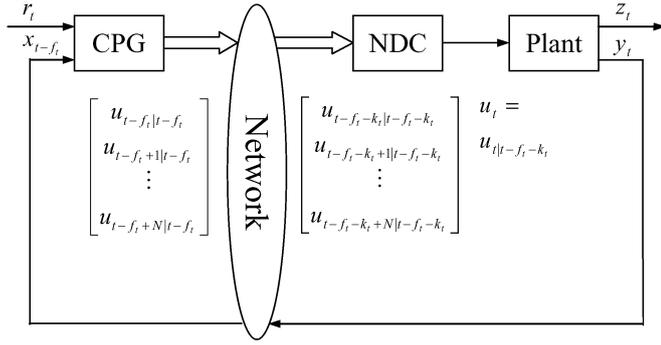


Fig. 1. NPC system structure.

delays, respectively. The plant is modelled in the following discrete-time state space form:

$$x_{t+1} = (A + \Delta A)x_t + Bu_t \quad y_t = Cx_t \quad (1)$$

where $x_t \in R^n$, $u_t \in R^m$, and $y_t \in R^p$ denote the state vector, control input and controlled output, respectively; A , B , and C are known constant matrices with appropriate dimensions. ΔA is real-valued matrix representing time-varying parameter uncertainties, and has the following form:

$$\Delta A = DF_tE$$

where D, E are known constant matrices of appropriate dimensions, F_t is an unknown matrix function satisfying

$$F_t^T F_t \leq I.$$

$r_t \in R^n$ is the reference input. Without loss of generality, r_t is assumed to be zero throughout this brief.

In order to measure the network delay, a time stamp signal is transmitted together with the control predictions [25]. Although computer communication networks may not have this capability, time-triggered protocols (e.g., Flexray) would probably be able to support a time-delay measurement.

The guaranteed cost function associated with system (1) is given by

$$J = \sum_{t=0}^{+\infty} (x_t^T Q x_t + u_t^T R u_t) \quad (2)$$

where Q and R are positive definite weighted matrices.

Associated with the cost function (2), the guaranteed cost controller is defined as follows.

Definition 1: Consider the uncertain system (1) and cost function (2). If there exists a control law u_t^* and a positive scalar J^* such that for all admissible uncertainties, the closed-loop system is asymptotically stable and the value of the cost function (2) satisfies $J \leq J^*$, then J^* is said to be a guaranteed cost and u_t^* is said to be a guaranteed cost control law.

The following assumptions are adopted.

Assumption 1: The upper bounds of the time-varying network delays k_t in the forward channel and the feedback

channel f_t are not greater than N_1 and N_2 , respectively, where N_1 and N_2 are positive integers, i.e., $k_t \in \{0, 1, \dots, N_1\}$, $f_t \in \{0, 1, \dots, N_2\}$, where $t = 0, 1, 2, \dots$, denotes the sampling instant.

Assumption 2: The number of consecutive data dropouts in the forward channel and the feedback channel are less than L_1 and L_2 , respectively, both of which are positive integers. So the upper bound number of consecutive data dropouts and network delay is equal to $N = N_1 + N_2 + L_1 + L_2$.

III. GUARANTEED COST CONTROL USING PREDICTIVE CONTROLLER FOR NCSs

A. Prediction of Future Control Sequence

If the state vector x is not available, the state observer is designed as

$$\hat{x}_{t+1} = A\hat{x}_t + Bu_t + L(y_t - C\hat{x}_t) \quad (3)$$

where $\hat{x}_t \in R^n$ is the observed state and $u_t \in R^m$ is the input of the observer at time t , respectively, L is the observer gain to be designed later.

For the system without time delay, the controller is designed as follows:

$$u_t = K_0 \hat{x}_t \quad (4)$$

where $K_0 \in R^{m \times n}$ is the control gain matrix to be determined.

When there are time-varying delay and data dropout in the feedback channel, the predictive controller from time $t - f_t + 1$ to t is constructed as

$$\begin{aligned} u_{t-f_t+1|t-f_t} &= K_1 \hat{x}_{t-f_t} \\ u_{t-f_t+2|t-f_t} &= K_2 \hat{x}_{t-f_t} \\ &\vdots \\ u_{t|t-f_t} &= K_{f_t} \hat{x}_{t-f_t} \end{aligned}$$

where $f_t = 0, 1, \dots, N_2 + L_2$.

When time-varying delay and data dropout happen in the forward channel, the predictive controller from $t + 1$ to $t + k_t$ is constructed as

$$\begin{aligned} u_{t+1|t-f_t} &= K_{f_t+1} \hat{x}_{t-f_t} \\ u_{t+2|t-f_t} &= K_{f_t+2} \hat{x}_{t-f_t} \\ &\vdots \\ u_{t+k_t|t-f_t} &= K_{f_t+k_t} \hat{x}_{t-f_t} \end{aligned}$$

where $k_t = 0, 1, \dots, N_1 + L_1$.

Thus, the state feedback controller can be given as

$$u_{t|t-f_t-k_t} = K_{f_t+k_t} \hat{x}_{t-f_t-k_t}, \quad f_t + k_t = 0, 1, \dots, N. \quad (5)$$

Therefore observer (3) can be written as

$$\hat{x}_{t+1} = (A - LC)\hat{x}_t + BK_i \hat{x}_{t-i} + LCx_t, \quad i = 0, 1, \dots, N. \quad (6)$$

The closed-loop system of system (1) can be written as

$$\begin{aligned} x_{t+1} &= (A + \Delta A)x_t + Bu_{t-i} \\ &= (A + \Delta A)x_t + BK_i \hat{x}_{t-i}, \quad i = 0, 1, \dots, N. \end{aligned} \quad (7)$$

Combining (5)–(7) gives the augmented switched system

$$X_{t+1} = \Lambda_i X_t \quad (8)$$

where

$$\begin{aligned} X_t &= [x_t^T, x_{t-1}^T, \dots, x_{t-i}^T, x_{t-i-1}^T, \dots, x_{t-N}^T, \\ &\quad \hat{x}_t^T, \hat{x}_{t-1}^T, \dots, \hat{x}_{t-i}^T, \dots, \hat{x}_{t-N-1}^T, \hat{x}_{t-N}^T]^T \\ \Lambda_i &= \begin{bmatrix} \hat{\Pi} & \Xi_i \\ \Psi & \Gamma_i \end{bmatrix} \end{aligned}$$

with

$$\begin{aligned} \hat{\Pi} &= \begin{bmatrix} A + \Delta A & 0_{n \times Nn} \\ I_{Nn} & 0_{Nn \times n} \end{bmatrix} \\ \Xi_i &= \begin{bmatrix} 0_{n \times in} & BK_i & 0_{n \times (N-i)n} \\ 0_{(N+1)n \times in} & 0_{(N+1)n \times n} & 0_{(N+1)n \times (N-i)n} \end{bmatrix} \\ \Psi &= \begin{bmatrix} LC & 0_{n \times Nn} \\ 0_{Nn \times n} & 0_{Nn \times Nn} \end{bmatrix} \\ \Gamma_i &= \begin{bmatrix} A - LC & 0_{n \times (i-1)n} & BK_i & 0_{n \times (N-i)n} \\ I_n & I_{(i-1)n} & I_{(N-i)n} & 0_{Nn \times n} \end{bmatrix}. \end{aligned}$$

B. Sufficient Conditions for Guaranteed Cost Control

Theorem 1: Consider system (8) and the cost function (2). If there exist positive definite matrix $P > 0$ such that the following matrix inequalities:

$$\Lambda_i^T P \Lambda_i - P + \bar{Q} + \bar{R} < 0 \quad (9)$$

hold, where

$$\begin{aligned} \bar{R} &= \begin{bmatrix} K_i^T R K_i & 0_{n \times (2N+1)n} \\ 0_{(2N+1)n \times (2N+2)n} & \end{bmatrix} \\ \bar{Q} &= \begin{bmatrix} Q & 0_{n \times (2N+1)n} \\ 0_{(2N+1)n \times (2N+2)n} & \end{bmatrix} \end{aligned}$$

then system (8) with the controllers (5) is asymptotically stable and the cost function (2) satisfies the following bound:

$$J \leq X_0^T P X_0. \quad (10)$$

Proof: This is given in the Appendix.

Theorem 1 provides sufficient conditions for guaranteed cost controller design. However, inequalities (9) are not in the form of LMIs if the controller gains are to be determined. We will give LMIs conditions for determining the controller gains in the next subsection.

C. Design of Guaranteed Cost Controller

In the following, Theorem 1 is extended to design the controller gains K_i for system (8).

Theorem 2: Consider system (8) and the cost function (2). If there exist positive definite matrix $P > 0$ such that the following matrix inequalities:

$$\begin{bmatrix} -P + \bar{Q} + \bar{E}^T \bar{E} & \bar{A}_i^T & \bar{I}^T K_i^T \\ * & \bar{D} \bar{D}^T - P^{-1} & 0 \\ * & * & -R^{-1} \end{bmatrix} < 0 \quad (11)$$

hold, where

$$\begin{aligned} \bar{I} &= [I \ 0 \ \dots \ 0] \\ \bar{D} &= [D^T \ 0 \ \dots \ 0]^T \\ \bar{E} &= [E \ 0 \ \dots \ 0] \\ \bar{A}_i &= \begin{bmatrix} \Pi & \Xi_i \\ \Psi & \Gamma_i \end{bmatrix} \end{aligned}$$

where

$$\Pi = \begin{bmatrix} A & 0_{n \times Nn} \\ I_{Nn} & 0_{Nn \times n} \end{bmatrix}$$

and Ξ_i, Ψ, Γ_i are defined in (8). Then system (8) with the controllers (5) is asymptotically stable and the cost function (2) satisfies (10).

Proof: This is given in the Appendix.

Remark 1: The conditions for the guaranteed cost controller synthesis problem in Theorem 2 are difficult to solve because \bar{A}_i contain K_i and L . In the following, we separate K_i and L from \bar{A}_i in order to solve the controller gain K_i and L using LMI control toolbox.

Define matrices

$$\begin{aligned} B_1 &= \begin{bmatrix} B \\ 0_{(2N+1)n \times m} \end{bmatrix} \\ B_2 &= \begin{bmatrix} 0_{(N+1)n \times m} \\ B \\ 0_{Nn \times m} \end{bmatrix} \\ \tilde{I} &= \begin{bmatrix} 0_{(N+1)n \times n} \\ I_n \\ 0_{Nn \times n} \end{bmatrix} \\ \bar{C} &= [C \ 0_{p \times Nn} \ -C \ 0_{p \times Nn}] \\ I_0 &= [0_{n \times (N+1)n} \ I_n \ 0_{n \times Nn}] \\ I_1 &= [0_{n \times (N+2)n} \ I_n \ 0_{n \times (N-1)n}] \dots \\ I_i &= [0_{n \times (N+i+1)n} \ I_n \ 0_{n \times (N-i)n}] \\ \tilde{A} &= \begin{bmatrix} \Pi & 0_{(N+1)n \times (N+1)n} \\ 0_{(N+1)n \times (N+1)n} & \Pi \end{bmatrix} \end{aligned}$$

where Π is defined in Theorem 2.

Then \bar{A}_i can be written as

$$\bar{A}_i = \tilde{A} + B_1 K_i I_i + \tilde{I} L \bar{C} + B_2 K_i I_i. \quad (12)$$

It follows from (11) and (12) that (See equation at bottom of page)

$$\begin{bmatrix} -P + \bar{Q} + \bar{E}^T \bar{E} & (\tilde{A} + B_1 K_i I_i + \tilde{I} L \bar{C} + B_2 K_i I_i)^T & \bar{I}^T K_i^T \\ * & \bar{D} \bar{D}^T - P^{-1} & 0 \\ * & * & -R^{-1} \end{bmatrix} < 0 \quad (13)$$

In view of the above, we can now obtain the following theorem.

Theorem 3: Consider system (8) and the cost function (2). If there exist positive definite matrix $P > 0$ such that the matrix inequalities (13) hold, then system (8) with the controllers (5) is asymptotically stable and the cost function (2) satisfies (10).

Remark 2: It is noted that condition (13) are not LMIs conditions because of the terms P and P^{-1} . However, by using a cone complementary linearization algorithm proposed in [26], the original non-convex optimization problem can be converted to a LMI-based minimization problem, and by applying a related iterative algorithm, the suboptimal guaranteed cost can be obtained.

First, by replacing the term P^{-1} in (13) by W , we get

$$\begin{bmatrix} -P + \bar{Q} + \bar{E}^T \bar{E} & (\tilde{A} + B_1 K_i I_i + \tilde{L} \bar{C} + B_2 K_i I_i)^T & \bar{I}^T K_i^T \\ * & \bar{D} \bar{D}^T - W & 0 \\ * & * & -R^{-1} \end{bmatrix} < 0 \quad (14)$$

Then, inequalities (13) are transformed into LMIs (14), and the minimization problem involving LMIs constraints can be formulated as follows:

minimize trace (PW)

subject to (14)

$$\begin{bmatrix} P & I \\ I & W \end{bmatrix} \geq 0 \quad (15)$$

$$\begin{bmatrix} -\gamma & X_0^T \\ X_0 & -W \end{bmatrix} < 0. \quad (16)$$

D. Algorithm

We give the following iterative algorithm to solve the aforementioned nonlinear problem. Note that here we use (13) as a stopping criterion in the iterative algorithm in the following procedure since it is numerically very difficult in practice to obtain the optimal solution, and thus only the suboptimal guaranteed cost can be obtained within a specified number of iterations.

- Step 1) Choose a sufficiently large initial γ such that there exists a feasible solution to LMIs conditions in (14)–(16).
- Step 2) Find a feasible solution P, W, K_i, L satisfying LMIs in (14)–(16). Set $k = 0$.
- Step 3) Solve the following LMIs problem for the variables P, W :

$$\begin{aligned} & \text{minimize trace } (P_k W + P W_k) \\ & \text{subject to LMIs in (14)–(16).} \end{aligned}$$

- Step 4) If condition (13) is satisfied, then return to Step 2) after decreasing γ to some extent. If conditions (14)–(16) are not satisfied within a specified number of iterations, then exit. Otherwise, set $k = k + 1$, $P_{k+1} = P, W_{k+1} = W$ and go to Step 3).

Remark 3: In our papers [14]–[17], state feedback $u_t = K \hat{x}_{t-i}$ is used, where K is fixed and it is given for the case where there is no delay or data packet dropout in both channels. Compared with this, the proposed approach in this brief relaxes

this requirement by designing multiple controller gains which can vary with time delay. Thus this approach is more appropriate for practical systems.

Remark 4: There exist various types of networked control systems with uncertainties in practice, e.g., fieldbus control systems, which are widely used in industrial process control. It is important to ensure a closed-loop networked control system can achieve the required performance even though there are uncertainties or modelling errors in the system. The proposed control strategy and derived results in this brief provide an effective way of solving this issue.

IV. SIMULATION AND EXPERIMENT

In this section, numerical and experimental examples are considered to illustrate the effectiveness of the proposed design approach to NCSs.

A. Numerical Simulation

Example 1: Consider an open-loop unstable uncertain discrete system in the form of (1) with the following system matrices:

$$A = \begin{bmatrix} 1.01 & 0.2710 & -0.4880 \\ 0.4820 & 0.1 & 0.24 \\ 0.0020 & 0.3681 & 0.7070 \end{bmatrix}$$

$$B = \begin{bmatrix} 5 & 5 \\ 3 & -2 \\ 5 & 4 \end{bmatrix}$$

$$C = \begin{bmatrix} 1 & 2 & 3 \\ 4 & 3 & 1 \end{bmatrix}$$

$$D = E = 0.01I$$

and $F_t = \sin t$. Choosing positive definite weighted matrices $R = 0.1I, Q = 0.02I$.

It is assumed that the upper bounds of the network delays k_t in the forward channel is not greater than 1 and the feedback channel f_t are all not greater than 2. We now apply our Algorithm to this example. The maximum iteration number is chosen to be 40, and the final value for γ is 0.8818. For this value of γ , we obtain

$$K_0 = \begin{bmatrix} 0.0058 & -0.0078 & -0.0382 \\ -0.0263 & -0.0106 & 0.0335 \end{bmatrix}$$

$$K_1 = \begin{bmatrix} 0.0038 & -0.0105 & -0.0244 \\ -0.0296 & 0.0003 & 0.0262 \end{bmatrix}$$

$$K_2 = \begin{bmatrix} 0.0001 & -0.0092 & -0.0203 \\ -0.0282 & 0.0009 & 0.0295 \end{bmatrix}$$

$$K_3 = \begin{bmatrix} -0.0020 & -0.0135 & -0.0260 \\ -0.0294 & 0.0071 & 0.0464 \end{bmatrix}$$

$$L = \begin{bmatrix} -0.1916 & 0.1500 \\ -0.0382 & 0.0442 \\ 0.1341 & -0.0794 \end{bmatrix}.$$

We assume the initial conditions for the three state-variables is $[0.5 \ 0.5 \ 0.5]^T$. The observer state trajectories of the system are shown in Fig. 2. Output trajectories of the system are shown

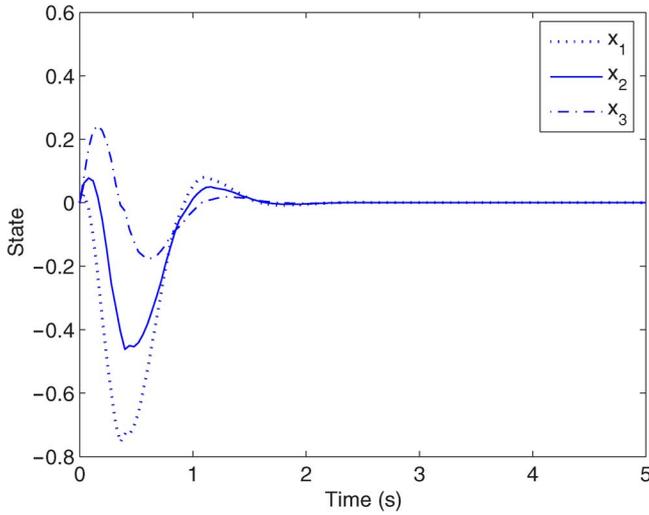


Fig. 2. Observer states of the system in example 1.

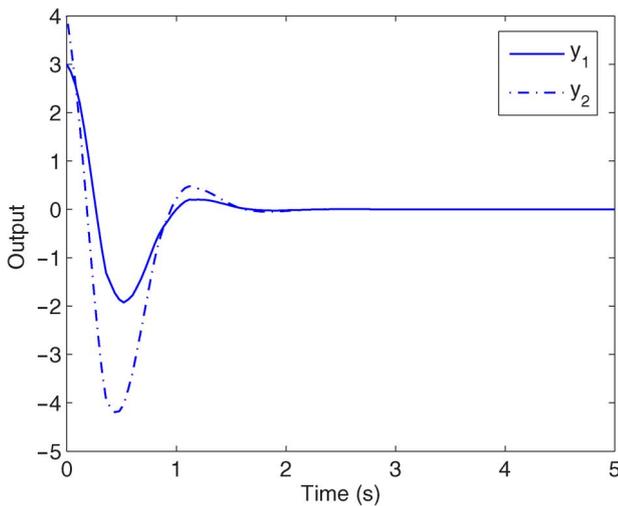


Fig. 3. Output of the system in example 1.

in Fig. 3. It can be readily seen that the system is stable and has a good performance.

Compared with our previous paper [17], the approach in this brief is an improved contributed for the following three reasons. First, the varying controller gains are easy to design while the fixed controller gain in [17] needs to be selected in advance. Secondly, the proposed approach can solve the minor guaranteed cost bound while this bound can not be solved by employing the method in [17]. Thirdly, by using the method in this brief, it only takes 2 s to reach a steady-state response, while in [17] it takes approximately 100 s to achieve.

B. Practical Experiment

Example 2: In this example, an internet-based test is used to verify the effectiveness of the approach presented in this brief.

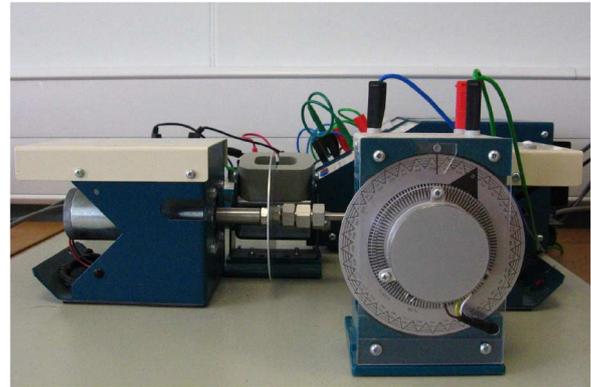


Fig. 4. DC servo plant in the University of Glamorgan.



Fig. 5. Network controller in the Chinese Academy of Sciences.

This test rig consists of a plant (DC servo system, see Fig. 4) which is located in the University of Glamorgan, Pontypridd, U.K., and a remote controller which is located in the Institute of Automation, Chinese Academy of Sciences, Beijing, China (see Fig. 5). The plant and the controller are connected via the Internet, whose IP addresses are 193.63.131.219 and 159.226.20.109, respectively. A web-based laboratory is also available at <http://www.ncslab.net/to> to implement experiments online.

The DC servo system is identified in [17] to be a third-order system and is described by the following state-space system matrices:

$$A = \begin{bmatrix} 1.12 & 0.213 & -0.335 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix}$$

$$B = \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix}$$

$$C = [0.0541 \ 0.1150 \ 0.0001].$$

The parameter uncertainties matrices are given by $D = E = 0.01I$ and $F_t = sint$, and the performance index is given by (2) with positive definite weighted matrices $R = 0.1$, $Q = 0.02I$. The maximum network delay was measured to be 0.32 s and

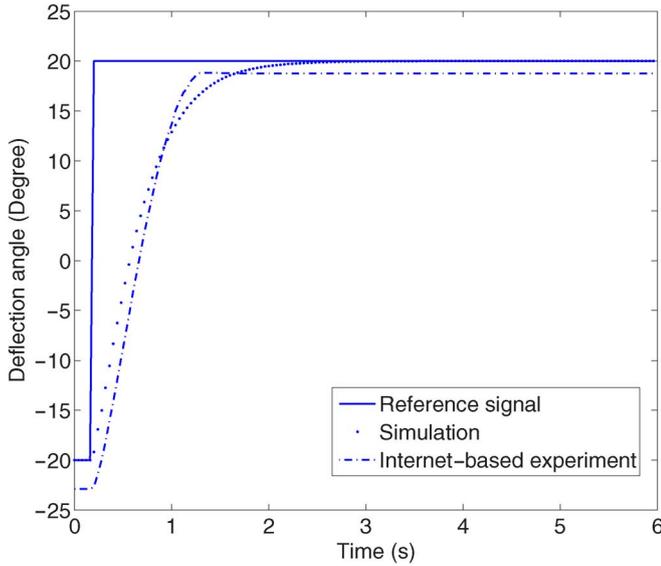


Fig. 6. Comparison between simulation and experimental results of linear networked control system.

the sampling period was 0.04 s. So, the upper bound $N = 8$. By apply our Algorithm to this example, we obtain

$$\begin{aligned}
 K_0 &= [-0.0469 \ 0.0007 \ 0.0003] \\
 K_1 &= [-0.0056 \ -0.0171 \ -0.0114] \\
 K_2 &= [-0.0136 \ -0.0135 \ -0.0053] \\
 K_3 &= [-0.0116 \ -0.0123 \ -0.0056] \\
 K_4 &= [-0.0113 \ -0.0111 \ -0.0062] \\
 K_5 &= [-0.0087 \ -0.0107 \ -0.0075] \\
 K_6 &= [-0.0096 \ -0.0091 \ -0.0070] \\
 K_7 &= [-0.0076 \ -0.0121 \ -0.0055] \\
 K_8 &= [-0.0094 \ -0.0106 \ -0.0071] \\
 L &= [5.1685 \ 3.6030 \ 5.3620]^T
 \end{aligned}$$

and the suboptimal guaranteed cost bound $\gamma = 19.7827$.

The comparison between the simulation and experimental results is illustrated in Fig. 6, which shows that the NPC method is valid in practice. It is seen however that there is a small error between the simulation and experimental results. Several possible reasons may contribute to this error [15]: 1) the identified model for the DC servo system may not be accurate enough; 2) the dead zone of the DC servo plant has not been considered; and 3) the measurement of the network-induced delays is not fully accurate in practice.

V. CONCLUSION

The problem of guaranteed cost control for a class of uncertain NCSs has been investigated in this brief. An improved predictive controller scheme in which the controller gain varies with the delays in both channels is presented to make the corresponding closed-loop system asymptotically stable for all admissible uncertainties. Furthermore, a numerical algorithm involving a convex optimization problem is presented to minimize a specific cost bound for a quadratic performance index. Finally,

a numerical simulation and a practical experiment have successfully demonstrated the effectiveness of the networked predictive control scheme proposed in this brief.

APPENDIX

Proof of Theorem 1: Define the common Lyapunov functions as

$$V_t = X_t^T P X_t \quad (17)$$

where P is positive definite matrix satisfying matrix inequalities (9).

Along the trajectory of system (8), for Lyapunov function (17), we have

$$\begin{aligned}
 \Delta V &= V_{t+1} - V_t \\
 &= X_t^T (\Lambda_i^T P \Lambda_i - P) X_t \\
 &< -X_t^T (\bar{Q} + \bar{R}) X_t < 0.
 \end{aligned}$$

Thus system (8) is asymptotically stable under arbitrary switching.

In the following, we show that the closed-loop system satisfies the performance upper bound:

$$\begin{aligned}
 J &= \sum_{t=0}^{+\infty} (x_t^T Q x_t + u_t^T R u_t) \\
 &= \sum_{t=0}^{+\infty} [X_t^T (\bar{Q} + \bar{R}) X_t + \Delta V_t - \Delta V_t] \\
 &\leq V(0) = X_0^T P X_0.
 \end{aligned}$$

This completes the proof.

Proof of Theorem 2: In view of $\bar{R} = \bar{I}^T K_i^T R K_i \bar{I}$, and according to Schur complement Lemma, inequalities (9) are equivalent to the following matrix inequalities:

$$\begin{bmatrix} -P + \bar{Q} & \Lambda_i^T & \bar{I}^T K_i^T \\ * & -P^{-1} & 0 \\ * & * & -R^{-1} \end{bmatrix} < 0.$$

Obviously, it holds that

$$\begin{bmatrix} -P + \bar{Q} & \bar{A}_i^T & \bar{I}^T K_i^T \\ * & -P^{-1} & 0 \\ * & * & -R^{-1} \end{bmatrix} + \begin{bmatrix} 0 & \Delta \bar{A}^T & 0 \\ \Delta \bar{A} & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} < 0 \quad (18)$$

where $\Delta \bar{A} = \bar{D} F(t) \bar{E}$.

Note that

$$\begin{aligned}
 \begin{bmatrix} 0 & \Delta \bar{A}^T & 0 \\ \Delta \bar{A} & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} &= \begin{bmatrix} \bar{E}^T \\ 0 \\ 0 \end{bmatrix} F^T(t) [0 \ \bar{D}^T \ 0] \\
 &\quad + \begin{bmatrix} 0 \\ \bar{D} \\ 0 \end{bmatrix} F(t) [\bar{E} \ 0 \ 0] \\
 &\leq \begin{bmatrix} \bar{E}^T \\ 0 \\ 0 \end{bmatrix} [\bar{E} \ 0 \ 0] + \begin{bmatrix} 0 \\ \bar{D} \\ 0 \end{bmatrix} [0 \ \bar{D}^T \ 0] \\
 &= \begin{bmatrix} \bar{E}^T \bar{E} & 0 & 0 \\ 0 & \bar{D} \bar{D}^T & 0 \\ 0 & 0 & 0 \end{bmatrix}. \quad (19)
 \end{aligned}$$

Combining (18) and (19) yields (11). This completes the proof.

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1. Guaranteed cost control for networked control systems based on an improved predictive control method

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Abstract: This brief deals with the problem of guaranteed cost control for a class of uncertain networked control systems with time-varying delay. An improved predictive controller design strategy is proposed to compensate for the delay and data dropout in both the forward and backward channels to achieve the desired control performance. The varying controller gains which are designed to vary with delays can lead to less conservative results. Meanwhile, an algorithm involving a convex optimization problem is presented to achieve a suboptimal guaranteed cost. Furthermore, a numerical simulation and a practical experiment are given to illustrate the effectiveness of the proposed method. © 2010 IEEE.

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