The Butterfly-Shaped Feedback Loop in Networked Control Systems for the Unknown Delay Compensation

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***Abstract*—Available model-based networked control system (NCS) design approaches are basically formulated from the known system model and the information of the networked-induced delay time. Because the delay in remote control systems is significant and time-varied as commercial networks involved, available model-based NCS design approaches may thus become impractical. The increase of time delay due to the limited communication bandwidth usually induces data dropout to make NCS design even more difficult. In this paper, the scheme of the perfect delay compensation (PDC) is proposed by introducing the butterfly-shaped inner feedback loop in NCS to deal with the unknown network-induced time delay. Furthermore, analytical results indicate that the controller obtained in general control systems can be directly implemented on NCS with the proposed PDC scheme. Both simulation and experimental results were successfully carried out on an ac servo motor at a distance of 15 km through Ethernet to maintain a stable remote control system.**

***Index Terms*—Butterfly element, delay compensation, implementation, networked control systems (NCS), network-induced delay.**

I. Introduction

IN THE EARLY stage of the network development, networked control systems (NCS) technologies were mainly designed for industrial applications. Industrial buses such as Profibus, DeviceNet, Modbus, and CAN have been employed mainly in engineering to render convenient implementation and systematic maintenance. Nowadays, networks have been widely used in our daily life and business market through the Internet, such as asynchronous transfer mode (ATM) network, integrated services for digital network (ISDN), Token-Ring network, Wi-Fi, WiMAX, and Ethernet. In other words, the remote control to efficiently convey the control technology to any corner of the earth now becomes feasible only if the control target can be reached by the Internet or Wireless communications. Eventually, to realize remote control systems, the real-time NCS can be constructed with the integration of the commercial network and the industrial bus for real applications such as monitoring, diagnosis, adjustment, and control operation now becomes feasible. However, the network-induced time delay mainly from the commercial networks may seriously degrade control performance and stability of NCS.

When all actuators, sensors, and controllers are interconnected in NCS, quality of the communication is thus unavoidably reduced; therefore, a lower system sampling rate is usually suggested to prevent the serious data dropout owing to the limited network bandwidth of NCS. In general, the time delay and the data dropout are two major factors greatly affecting performance and stability of NCS [1]. As commercial networks involved in NCS, the delay usually presents in different forms, either constant, bounded, stochastic, random, or unpredictable, and also depends on the network protocol, hardware, and the number of end users. Therefore, integration of the industrial bus with the commercial network as NCS for remote control systems easily results in instability due to the unpredictable time delay. The abovementioned challenges have widely attracted researchers in recent NCS studies on time delay and packet loss [2]–[5]. The issue about packet disorder and time-varying transmission intervals was further discussed [6] and the tradeoff between distributed NCS security and its real-time performance was also investigated [7].

To determine a suitable sampling period for NCS, the key components of delay were identified [8]. An extensive research on the network-delay model with both forward and feedback delays was proposed by Nilsson [9]; moreover, the corresponding NCS can be suitably modeled as a Markov chain process [10]. Due to the variation of the time delay in NCS, the robust Smith predictor was implemented [11]. On the other hand, an observer-based predictor was designed to compensate for the distributed delays [12]. Robust methods and state feedback design were also obtained under the assumption that the varied delay is relatively small compared with its sampling time [13], [14]. Practically, those results are suitable only for NCS connected through the Intranet within a limited distance or environment. In other words, formulating the NCS as a switched system to discuss the asymptotical stability for a known time-delay model has also been investigated [15], [16]. A switched Ethernet network has been proposed to overcome the effect of network load under

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the varying network delay and packet loss conditions [17]. A packet-based control framework was proposed with a known upper bound of the time delay [18], [19], and an optimized communication sequence for a known range of time delay has been calculated to obtain robust closed-loop control performance [20].

As the Internet is adopted in remote control systems, the time delay usually varies depending on the number of user nodes and communication data loads. In general, the time delay in NCS is relatively larger compared with the sampling time of general control systems. It is challenging for the NCS design that even the serious time delay can be properly taken care to maintain its stability and performance. However, the model-based NCS design is apparently inadequate to be applied to remote control systems including the commercial network, because the model-based NCS design is sensitive to the modeling error mainly from the varied time delay.

A gain scheduler middleware that adjusts controller gains externally at the controller output was proposed by Tipsuwan and Chow [21], and the current network traffic condition was measured in real time using the round-time trip (RTT). Similarly, the adaptive Smith predictor approach was proposed to greatly simplify the problem on varying time delays of NCS for industrial applications with the online measured delay [22], [23]. To deal with the unknown network-induced delay in NCS, the model-based communication disturbance observer (CDOB) has been proposed to assume the delay as the disturbance to be estimated and eliminated [24]. Moreover, a passive control architecture with the known system model has been presented to guarantee stability of NCS in the presence of unknown time delay [25]. To compensate for the unknown but constant time delay, the scattering transformation was proposed with both the known system model and the available controller in the feedback loop of NCS [26]; however, the design procedure of the scattering transformation is not straightforward and the design results are sensitive to modeling error.

Despite the number of extensive studies in NCS during the last decade, robust and effective compensation for unknown network-induced time delays remains an open question. In the present paper, the perfect delay compensation (PDC) with two modified butterfly elements embedded in the feedback loop is proposed to deal with the unknown and varied delay without considering the system model. Analytical results indicate that as the variation of the time delay decays, formulation of the NCS with the PDC is thus greatly simplified as a general control system with a pure delay. In practice, both simulation and experiments performed on a remote control system with a CAN-bus ac servo motor from 15 km away through the Ethernet. Successful results indicate that the present NCS with the proposed PDC is feasible and reliable to render satisfactory stability and performance, even with the time-varied delay through the commercial network Ethernet [27]. In addition, both successful simulation and experimental results for the multiple-in-multiple-out (MIMO) NCS are further provided in this paper to prove the direct networking of the proposed PDC scheme. Therefore, the well-designed or well-tuned controller, obtained in general control systems without networking, can be directly implemented on NCS with the proposed PDC scheme.

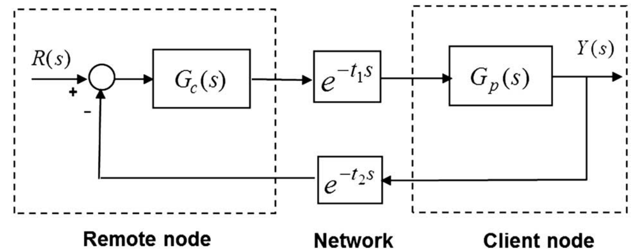

Fig. 1. Block diagram of the general NCS with the constant network delay.

II. Model-Based NCS Design for the Time Delay

Most NCS are designed with the model-based approach. Without the network, $G_p(s)$ and $G_c(s)$ denote the transfer functions of the plant and the controller, respectively, and the controller $G_c(s)$ is designed with concerns of stability, performance, and robustness to meet all specifications of general control systems as

$$M_o(s) = \frac{G_c(s) \cdot G_p(s)}{1 + G_c(s) \cdot G_p(s)}. \tag{1}$$

With the well-designed or well-tuned controller $G_c(s)$, the desired control system dynamics $M_o(s)$ is thus obtained. With the network realization of system (1) as shown in Fig. 1, its delay time due to the network can be modeled as t_1 and t_2 in the forward and feedback directions, and $R(s)$ and $Y(s)$ are the command and the output of the NCS, respectively. If both the forward and feedback networked-induced delays are assumed as constant, the more complicated transfer function from the input R to the output Y is obtained due to the delays as

$$G_{\text{NCS}}(s) = \frac{Y(s)}{R(s)} = \frac{G_c(s)G_p(s)e^{-t_1 s}}{1 + G_c(s)G_p(s)e^{-(t_1+t_2)s}}. \tag{2}$$

A. General Structure With Known Models

Most NCS design approaches were proposed with the known system model and the assumed constant network-induced time delay. Traditionally, the constant delay of processes can be handled by applying the Smith predictor by eliminating the time-delay effect from its closed control loop. Recently, the unknown delay effect has been effectively eliminated with practical approaches proposed as the adaptive Smith predictor [23] and CDOB [24]. The adaptive Smith predictor requires both an accurate system model and the online measured time delay, thereby increasing the cost of implementation and consuming more bandwidth of the network transmission. Although the CDOB does not need information of the time delay, which is regarded as the disturbance, it still requires the system model in NCS design.

B. Feedback Loop of Scattering Transformation [26]

It is interesting to include well-designed elements to the feedback loop in NCS to cope with the time-delay problem. As shown in Fig. 2, the transfer function of the LTI closed-loop

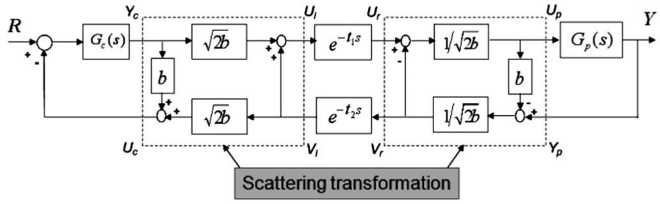

Fig. 2. NCS with scattering transformation [26].

system with scattering transformation is obtained with a suitable parameter b as [26]

$$G_{\text{NCS}}(s) = \frac{G_c(s)G_p(s)}{1+G_c(s)G_p(s)} \times \frac{2e^{-t_1 s}}{K(s)(1-e^{-(t_1+t_2)s}) + (1+e^{-(t_1+t_2)s})} \quad (3)$$

where $K(s) = \frac{1}{b}\frac{b^2 G_c(s)+G_p(s)}{1+G_c(s)G_p(s)}$.

Ideally, if $K(s) = 1$ holds with the parameter b, the closed-loop NCS system simply becomes a desirable closed-loop system $M_o(s)$ with a pure forward delay time t_1 as [26]

$$G_{\text{NCS}}(s) = \frac{Y(s)}{R(s)} = \frac{G_c(s)G_p(s)e^{-t_1 s}}{1+G_c(s)G_p(s)} = M_o(s)e^{-t_1 s}. \quad (4)$$

However, it is difficult to achieve $K(s) = 1$ for all s, and the uncertainty of the model will thus also degrade performance of NCS with the scattering transformation.

All the aforementioned model-based methods require accurate system models for NCS design; in addition, some of those methods require the constant time-delay model. These requirements are impractical in real applications because the delay in a commercial network is unavoidably varied, even it is slowly changed. Therefore, it is desired to develop other elements in the feedback loop of NCS to simplify the design and implementation procedures, and to effectively compensate for the varied network-induced delay without the effect of modeling error.

III. Model-Free PDC

The network time delay varies due to the network loads, scheduling, number of nodes, and protocols. Assumptions of a constant delay time at a fixed level is not practical in NCS design, and specification of an upper bound of the delay time leads to over-conservative results in most cases [24], [26]. In this paper, the proposed model-free PDC scheme including butterfly elements is intuitively developed to effectively deal with the unknown delay in NCS feedback loop. All analysis, simulation, and experiments will be provided to prove the proposed PDC scheme.

To simplify the derivation of PDC in NCS, the constant time delay is considered to provide analysis for LTI systems, and the controller is connected to the plant located in the client node. The modified butterfly and anti-butterfly elements in the proposed PDC scheme are implemented in both sides of the network as shown in Fig. 3(a) [27]. Note that both butterfly elements are realized without knowing either the network delay information or the models of the plant or controller. The output equations of the modified butterfly element can be obtained as

$$U_p(s) = U_r(s) + Y_p(s); \quad Y_r(s) = -U_p(s) - Y_p(s). \quad (5)$$

The transfer function from the input U_r to the output Y_r is given as

$$\frac{Y_r(s)}{U_r(s)} = \frac{-U_p(s) - Y_p(s)}{U_p(s) - Y_p(s)} = \frac{G_c(s)G_p(s) - 1}{G_c(s)G_p(s) + 1} \quad (6)$$

where $\frac{Y_p(s)}{U_p(s)} = -G_c(s)G_p(s)$.

The signal flow of the PDC structure is characterized by considering the relationship between the modified butterfly and the anti-butterfly elements. As shown in Fig. 3(a), the open-loop transfer function between the input U_c and the output Y_c on the left of the element can be expressed as [28]

$$\frac{Y_c(s)}{U_c(s)} = \frac{(1+G_c(s)G_p(s)) - (G_c(s)G_p(s)-1)e^{-(t_1+t_2)s}}{(1+G_c(s)G_p(s)) + (G_c(s)G_p(s)-1)e^{-(t_1+t_2)s}}. \quad (7)$$

Moreover, the forward loop of the NCS from R to Y_c is expressed as

$$\frac{Y_c(s)}{R(s)} = \frac{(1+G_c(s)G_p(s)) - (G_c(s)G_p(s)-1)e^{-(t_1+t_2)s}}{2(1+G_c(s)G_p(s))}. \quad (8)$$

Combining (7) with (8) yields

$$U_c(s) = R(s) - Y_c(s) \quad (9)$$

$$(-U_p(s) - Y_p(s))e^{-t_2 s} + U_c(s) = Y_c(s). \quad (10)$$

By integrating (8) and (9) into (10), the transfer function of the closed-loop system of the NCS with the PDC scheme can be directly obtained as

$$G_{\text{NCS}}(s) = \frac{Y(s)}{R(s)} = \frac{G_c(s)G_p(s)e^{-t_1 s}}{1+G_c(s)G_p(s)} = M_o(s)e^{-t_1 s}. \quad (11)$$

The present NCS with PDC in (11) simply consists of only two parts: 1) the desirable transfer function of the system $M_o(s)$ without the delay time and 2) the pure time delay t_1. The formulation of PDC indicates that the present NCS with the PDC scheme is greatly simplified compared with the original NCS in (2). Moreover, if the controller is realized on another far side of the network, the equivalent PDC can be obtained as shown in Fig. 3(b) and only extra simple computation is required [27].

Note that in (11), the NCS dynamics is the same as the desirable system $M_o(s)$ of the original control system without networking, and only a pure forward delay term t_1 is cascaded. In other words, stability of the original system is now fully preserved under PDC implementation regardless of the network-induced time delay t_1 and t_2. With the proposed PDC scheme, the input/output signal is passive in both sides of the network, especially in transient and time-varying delay cases. The effect of constant time delay on stability of the NCS is thus eliminated. Therefore, the controller, which is well-designed or well-tuned

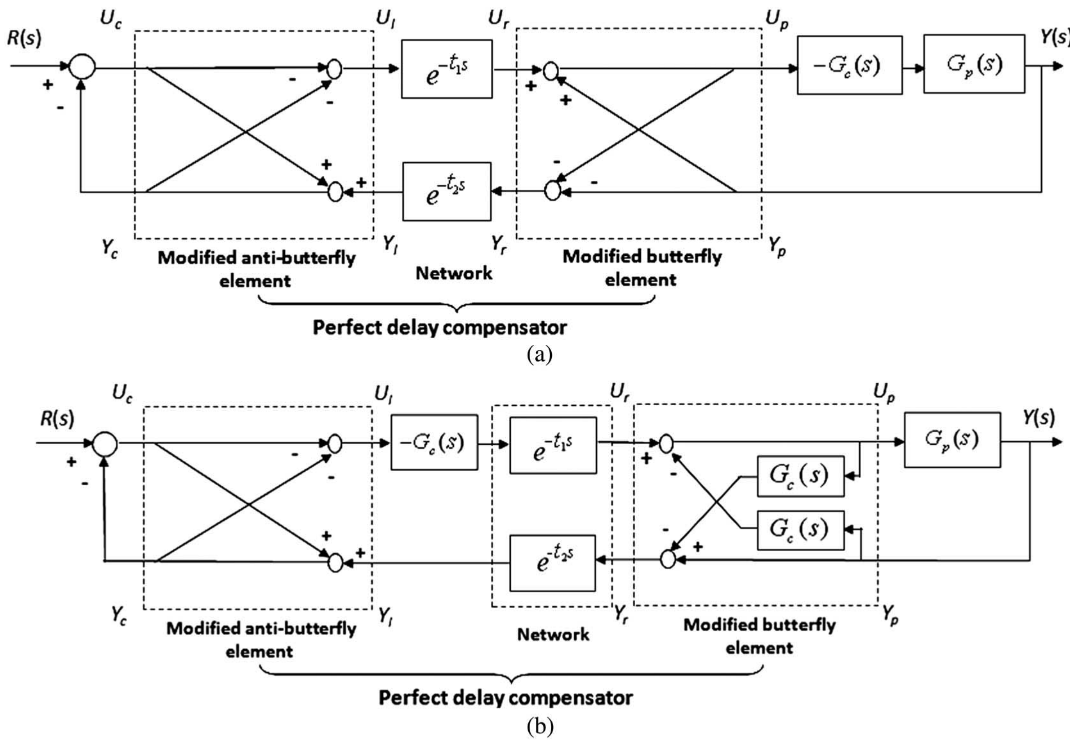

Fig. 3. (a) Structure with PDC in the proposed NCS and (b) the equivalent PDC with different controller location. Note: √ is an advantage or good characteristic and X is a disadvantage or bad characteristic.

from a general control system, can be directly implemented in NCS with the proposed PDC scheme. Furthermore, as the time delay changes slowly compared with the sampling time, the proposed PDC can be still effective in NCS to deal with the delay effect. In addition to simulation with serious constant and time-varied delays in this paper, successful experiments with the sampling time 20 ms were also provided for the NCS through Ethernet with the measured RTT ranged from 50 to 700 ms.

IV. Simulation Results

Example 1: PDC for NCS With Serious Delay

To verify the proposed PDC under both the constant delay and the time-varied delay, assume both equal forward and feedback time delays $t_1 = t_2 = (\mathrm{RTT}/2)$ in the present NCS and with the plant $G_p(s) = 73/s(s + 10.15)$ and the lead-lag controller $G_c(s) = 1.3981(s + 9.9114)/(s + 9.1558)$ [26] with the sampling time 1 ms. The original design for the control system without the network led to a rise time of 145.5 ms and a 19.3% overshoot without steady-state error, as shown in Fig. 4(b). In the case of a constant delay time 400 ms (assuming $t_1 = t_2 = 200$ ms) as shown in Fig. 4(a), the parameter b in the scattering transformation was set to 0.6203 as provided by [26] and performance of the NCS with the scattering transformation had a slower response (rise time = 254.8 ms) but less overshoot (5.4%), and a nonzero steady-state error (0.013) also as shown in Fig. 4(b). This was because $K(s)$ in the scattering transformation was not equal to the unit throughout the whole frequency range. On the other hand, the NCS with the PDC presented the same system performance as the original design, with the exception of the appearance of an additional pure delay of 200 ms, as shown in Fig. 4(c).

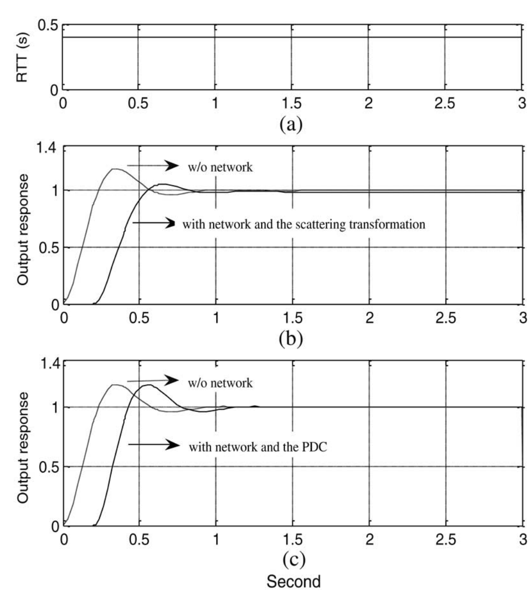

Fig. 4. Simulation results with (a) the constant time delay ($\mathrm{RTT} = 400$ ms); (b) the scattering transformation; and (c) the PDC scheme.

With similar conditions in the time-varying delay case shown in Fig. 5(a), the online measured time-delay RTT was adopted and results show that the system response presents significant overshoot by applying the scattering transformation, as shown in Fig. 5(b). However, the PDC still renders a consistent performance similar to that of the original system without networking

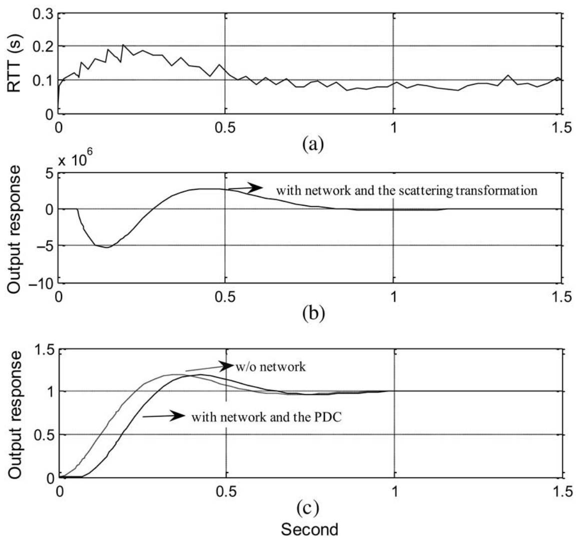

Fig. 5. Simulation results with (a) the time-varying delay; (b) NCS with scattering transformation; and (c) NCS with the PDC.

except for the pure network-induced time delay, as shown in Fig. 5(c).

Example 2: Direct Networking for MIMO NSC With PDC In general, controller design procedures for MIMO systems are inherently complicated. Furthermore, MIMO NCSs are extremely difficult to be realized if the network-induced time delay is significant. Since the controller of the present NCS with PDC is obtained as the model-free approach, an unstable two-input-two-output batch reactor realized with the NCS is verified here with the linearized model in [28] as

$$\dot{x} = \begin{bmatrix} 1.38 & -0.2077 & 6.715 & -5.676 \\ -0.5814 & -4.29 & 0 & 0.675 \\ 1.067 & 4.273 & -6.6654 & 5.893 \\ 0.048 & 4.273 & 1.343 & -2.104 \end{bmatrix} x + \begin{bmatrix} 0 & 0 \\ 5.679 & 0 \\ 1.136 & -3.146 \\ 1.136 & 0 \end{bmatrix} u$$

$$y = \begin{bmatrix} 1 & 0 & 1 & -1 \\ 0 & 1 & 0 & 0 \end{bmatrix} x.$$

It leads to the transfer function of the plant as shown at the bottom of the page.

To achieve zero steady-state tracking error, the controller with a desirable sensitivity function was obtained in [28] as

$$\boldsymbol{G}_c(s) = \begin{bmatrix} 0 & \frac{2s+2}{s} \\ \frac{-5s-8}{s} & 0 \end{bmatrix}.$$

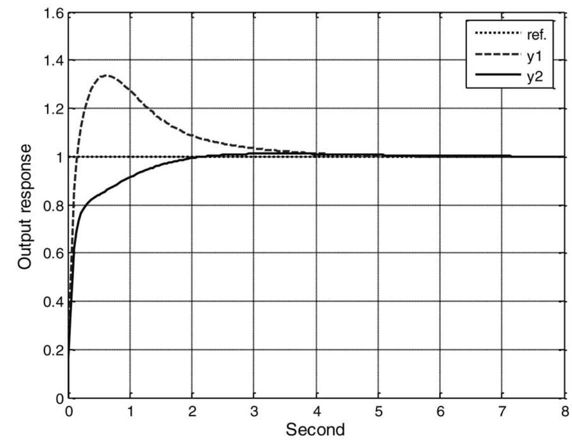

Fig. 6. Step responses without the network [28].

Note that the controller was designed for a general control system without the network, and satisfactory step responses for the two outputs are shown in Fig. 6.

By introducing the forward and feedback time delays as $T_1 = T_2 = (\mathrm{RTT}/2) = 80\ \mathrm{ms}$ for NCS, simulation results show that the NCS system response tends to be slightly damped, as shown in Fig. 7(a). Theoretically, as the delay time increases, the maximum allowable transfer interval $\mathrm{RTT} = 120\ \mathrm{ms}$ [28]. The results show that the step response becomes unstable under such conditions, as shown in Fig. 7(b). As the PDC was applied to the NCS, significantly improved performance was then obtained as shown in Fig. 8. Note that performance of NCS in Fig. 8 is exactly the same as performance in its general control system as shown in Fig. 6, except the pure time delay 120 ms.

V. Experiments on the Remote Control System

To implement the proposed NCS with the PDC scheme, the structure with both CAN bus and Ethernet was adopted for the present experiments, as shown in Fig. 9. Computer networking used in the transport layer protocols of the Internet protocol suite is generally adopted as the transmission control protocol (TCP) or the user datagram protocol (UDP). Typically, UDP is suitable for real-time NCS but the loss of data must be compensated. On the other hand, TCP avoids the loss of data at a price of inevitable time delay in NCS applications. In this paper, TCP was adopted for guaranteed eventual delivery of packets. The remote node was provided with the reference command, and the client node comprised an ac servo motor and a position loop controller. The remote node and the client node communicated with each other through the Ethernet with a distance of 15 km [22].

The proposed PDC was tested on both 1) the Intranet in a local area with a relatively lower and constant delay time and 2) the Internet with a distance of 15 km and its delay time is significantly varied. The PI controller was tuned as $k_p = 0.0002$ and $k_i = 0.0000001$ with a 20-ms sampling time implemented on the

$$\boldsymbol{G}_p(s) = \frac{\begin{bmatrix} 29.23s + 263.4 & -(3.146s^3 + 32.67s^2 + 89.83s + 31.81) \\ 5.679s^3 + 42.67s^2 - 68.83s - 106.8 & 9.43s + 15.15 \end{bmatrix}}{s^4 + 11.67s^3 + 15.75s^2 - 88.29s + 5.514}.$$

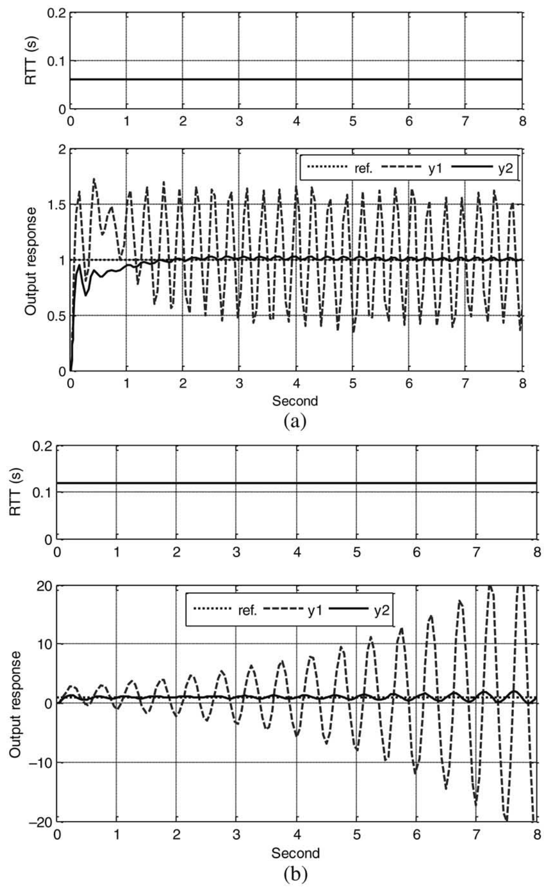

Fig. 7. Simulation results of NCS with a constant time delay. (a) $\mathrm{RTT} = 80$ ms and (b) $\mathrm{RTT} = 120$ ms.

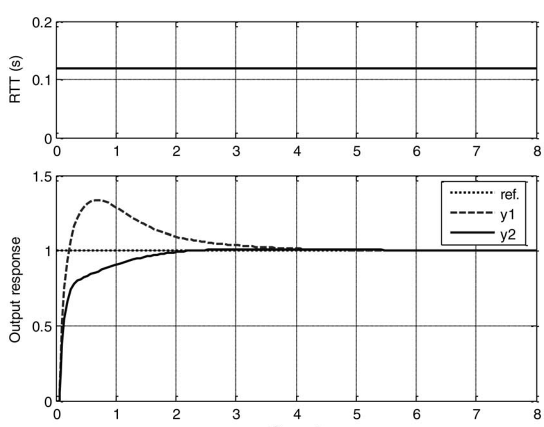

Fig. 8. Simulation results with PDC in NCS with the constant time delay $\mathrm{RTT} = 120$ ms.

TI TMS320F2812 DSP microcontroller with CAN bus. The client node included the gateway for communication between the Ethernet network and the CAN bus. The proposed NCS with PDC was based on a combination of both the time-driven task in the client node and the event-driven task in the remote node (Fig. 10). At the beginning of each sampling period, the time-driven sensor node transmitted sampling data to the remote node; when vacant sampling occurred, the previous data were held. When more than two data messages arrived at the same sampling

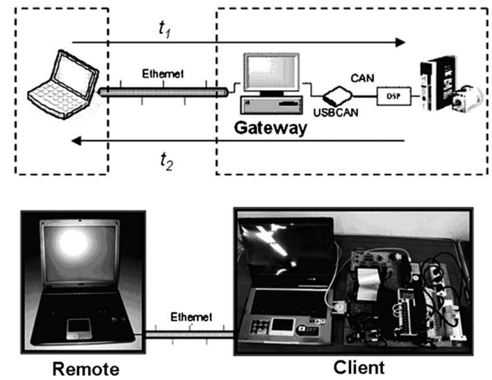

Fig. 9. Experimental setup.

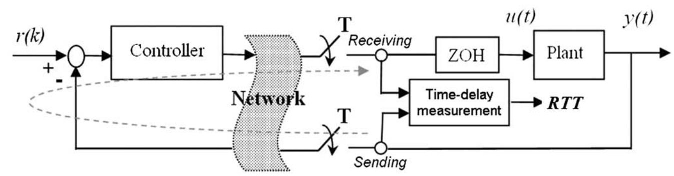

Fig. 10. Block diagram of NCS with the measured RTT.

period, the message rejection mode was adopted, and only the most recent data message was adopted and all the previous data were discarded [21]. To obtain the network-induced time delay in real environments, a real-time measured RTT of the delay time was adopted in this paper with all counters, indices, and delays. Moreover, the resolution of the counter was set at 1 ms with the following definitions:

S_c: sending counter;

R_c: receiving counter;

N: number of packets;

i: index of a sequence number, $i = 1, 2, \ldots, N$; and

$\mathrm{RTT}[i]$: round-trip delay time measurement of the ith packet, using counters and $i = 1, 2, \ldots, N$

$$\mathrm{RTT}[i] = S_c[i] - R_c[i]. \tag{12}$$

Example 3: Remote Control of the ac Servo Motor

Experimental results indicate that in the Intranet of NCS, the time-delay measurement was relatively at a constant level as shown in Fig. 11(a). The delay of Internet as shown in Fig. 11(b) is time-varied according to its variable operating conditions such as congestion and channel quality. Because the negligible delay time RTT was relatively small in Intranet only around 10–20 ms as shown in Fig. 12, control performance of its NCS is acceptable even without PDC. Fig. 13 shows that for the Intranet with an artificial delay time around 235 ms, the NCS system response became unstable if the PDC was not applied. However, with the proposed PDC, stability of NCS was greatly improved and desirable control performance was obtained as shown in Fig. 14. Furthermore, if the delay time of the Internet significantly varied between 50 and 700 ms, the proposed PDC still effectively and reliably rendered satisfactory performance as shown in Fig. 15.

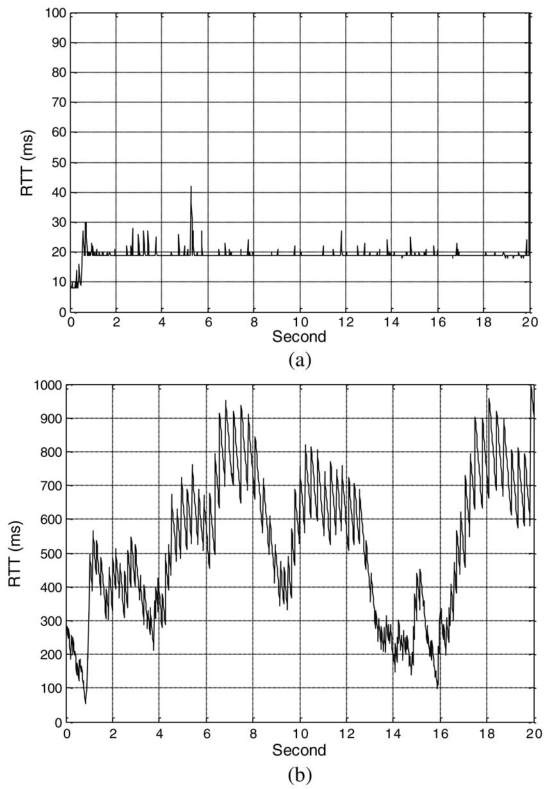

Fig. 11. Time-delay measurement in (a) Intranet with less and varied delay, and (b) Internet with larger and varied delay.

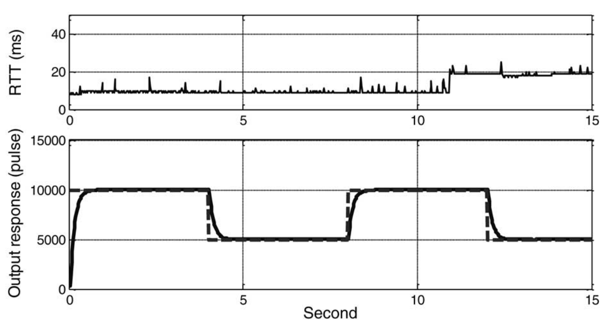

Fig. 12. Output response of the NCS without PDC in Intranet (time delay: 10–20 ms).

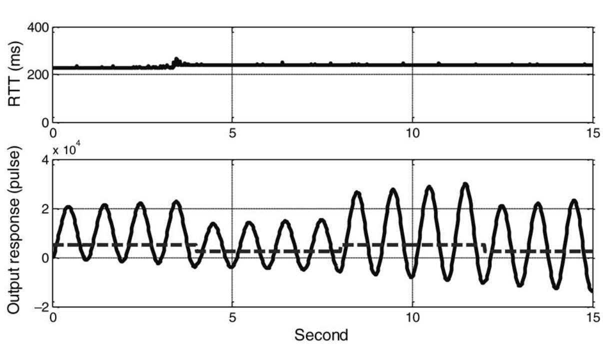

Fig. 13. Output response of the NCS without PDC in Intranet (artificial serious but constant time delay: around 235 ms).

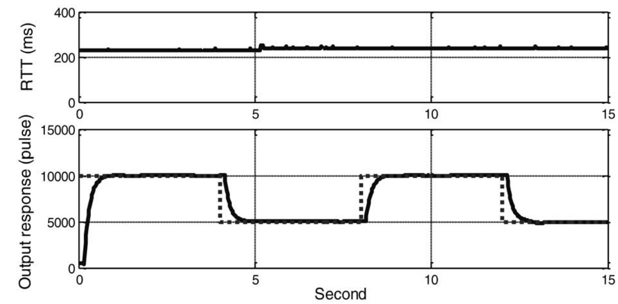

Fig. 14. Output response of the NCS with PDC in Internet (time delay: around 235 ms).

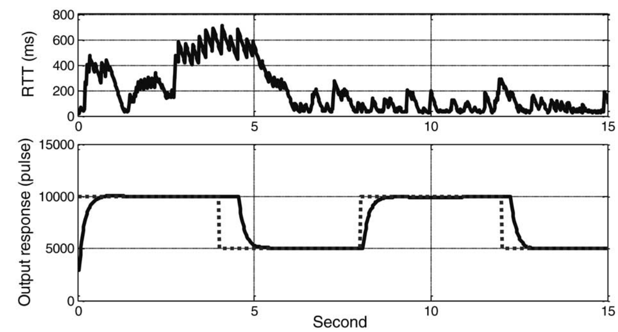

Fig. 15. Output response of the NCS with PDC in Internet with a significantly varied time delay (varied time delay: 50–700 ms).

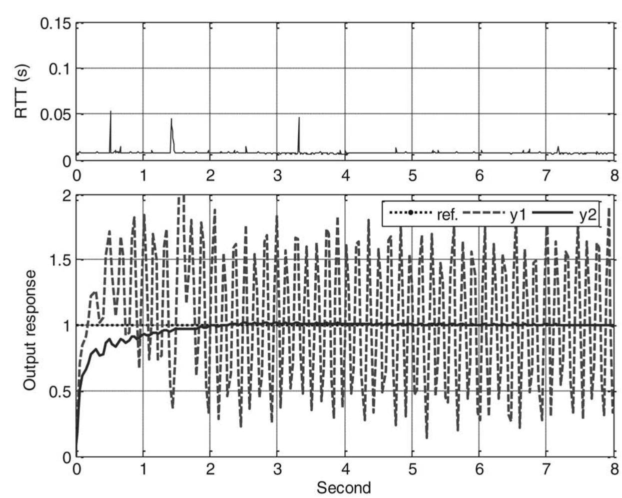

Fig. 16. Experimental results without PDC under a minor delay (varied from 6 to 52 ms, average 15.91 ms).

Example 4: Experimental Verification of MIMO NSC

Experiments with setup as shown in Fig. 9 were also applied to the remote-controlled MIMO plant as in *Example 2*, except the motor was replaced by the DSP board to generate output data according to the same linearized model. Even with a minor time delay (6–52 ms) induced from the network, experimental results indicate that the MIMO controller originally designed without networking was not suitable as shown in Fig. 16.

Moreover, by applying the proposed PDC with the same controller, its performance has been greatly restored as shown in Fig. 17. Furthermore, even under a serious and varied

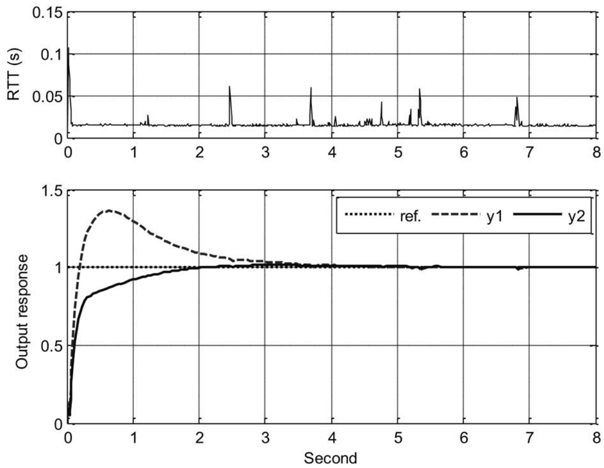

Fig. 17. Experimental results with PDC under a minor delay (varied from 14 to 107 ms, average 19.51 ms).

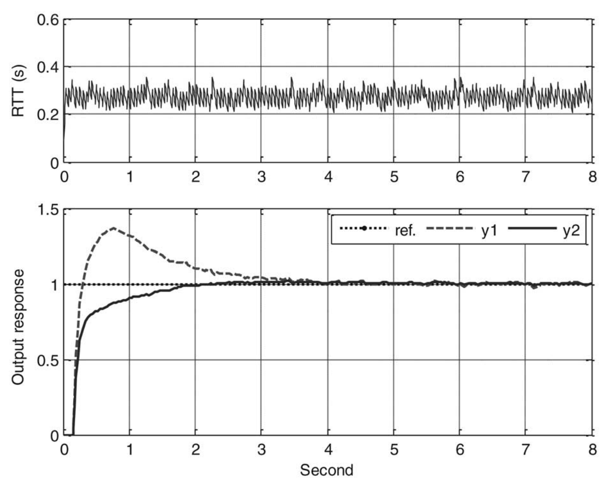

Fig. 18. Experimental results with PDC under a major delay (varied from 210 to 356 ms, average 278.34 ms).

network-induced delay (210–356 ms), satisfactory results have been obtained, as shown in Fig. 18. Results indicate that the proposed PDC is applicable to the NCS even with varied time delay in practice.

VI. Conclusion

Generally, NCS is difficult to be modeled and analyzed because of its serious time-delay effect on both feedforward and feedback network connections. In the linear modeling, the delay components result in exponential elements intermingled with other linear elements and thus, NCS eventually leads to the nonlinear model design. By introducing the butterfly inner feedback loop as the PDC, this study successfully deals with the network-induced delay. Thus, the controllers obtained in general control systems without networking can be directly realized on NCS. Moreover, the proposed PDC can be easily implemented on NCS together with the available controller obtained in general control systems.

Simulation results on both SISO and MIMO systems have proven that the proposed PDC is effective on NCS implementation to deal with the significant network-induced time delay. Although the PDC is originally formulated with a constant network-induced time delay, its stability and performance of NCS with time-varied delay will become stable as the transition of the time delay decays or the delay of NCS is slowly changed. Successful experiments on a remote control system with an ac servo motor from a 15-km distance have also firmly proven the feasibility and reliability of the proposed PDC in practice. By comparing the proposed PDC to other available NCS model-based design approaches [23]–[26], the proposed PDC renders the most satisfactory performance in all design cost, control performance, and robustness [27]. Note that it is almost impossible to realize the MIMO system on NCS before. Furthermore, the well-designed notch filter was successfully realized on its NCS implementation with PDC for vibration suppression to prove the direct networking of the proposed PDC [29]. The direct networking function of the proposed PDC has also been proven through experiments.

The proposed PDC has been applied to NCS when all data are received and the network-induced delay is assumed to be constant. Furthermore, the PDC has also been successfully applied to real NCS through the Ethernet with the time-varied delay in different levels, as shown in Figs. 15–18. Results indicate that the proposed PDC in NCS is robust to the time delay in practice. However, when the delay is more serious with transmission jam or the delay variation becomes significant in wireless networks, the dropout effect will also become significant and the sampling time must be increased to maintain a stable NCS and thus, performance of NCS will also be degraded [30]. Under such circumstances, estimation of the missing message should be concerned with the proposed PDC to simultaneously deal with both the time delay effect and the dropout effect.

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