國立交通大學

電控工程研究所

博 士 論 文

網路控制系統之時間延遲補償設計

Networked Control Systems Design with the Time Delay Compensation

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摘 要

近年來隨著網路的興起，即時的網路控制成為一種趨勢，在工業上的應用也越來越多，其可以很便利達成系統性的維護。然而，將控制系統網路化之後，也帶來了幾個缺點，例如：在共享的有限網路資源，隨著使用者數目的增減而造成變化極大的時間延遲，此問題輕則明顯降低系統效能，重則使整個系統產生不穩定的情形。

根據網路協定、節點數和軟硬體條件，網路的時間延遲特性可能是固定或是有界的，甚至是隨機和不可預測的。因此，針對處理實際網路的重大的時間延遲變化，本論文提出兩種網路控制系統(NCS)之時間延遲補償的方法。第一個方法是發展即時的時間延遲估測，透過量測實際網路環境中兩個節點封包往返的時間(RTT)，可估測網路控制系統的時間延遲，並應用於三個方面：（1）發展適應性史密斯預估控制，可針對重大的時間延遲變化作處理；（2）強健性的網路控制系統設計，可對付具有局部時間延遲變化與外部干擾的 NCS；及（3）多重取樣週期的設計，可針對無線網路的壅塞問題作解決。上述所提之方法均已成功地實現於一交流伺服馬達的遠端控制系統。

此外，第二個解決時間延遲的方法，是提出時間延遲完全補償策略(PDC)，能有效處理網路所引起時間延遲的影響，既不需要系統的模型也不用已知時間

延遲的資訊。網路控制系統能等效為原來的閉迴路系統串接一單純的時間延遲。因此，當引用 PDC 在設計網路控制系統時，不需考慮對網路時間延遲的影響，只需將所設計的控制系統直接實現於網路上即可。最後，實驗結果透過十五公里的 Internet 網路連線，進一步證明 SISO 和 MIMO 控制系統，都可經由所提出的 PDC 直接施行網路化，在實際網路環境保持其系統閉迴路的特性。

關鍵詞：網路控制系統、網路時間延遲、即時時間延遲估測、多重取樣週期的設計、時間延遲完全補償、網路化

Networked Control Systems Design with the Time Delay Compensation

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ABSTRACT

Real-time network control applications have increasingly gained attentions due to the rapid development of data communication network technologies. Network systems can be conveniently and systematically maintained in industrial applications. The networked control system (NCS), which simply interconnects all sensors, actuators, and controllers through the network, is promising in the future development of industrial technologies with low integration cost. However, NCS also leads to unavoidable problems in time delays that seriously degrade control performance and stability. The characteristics of network-induced delays may be in constant, bounded, random, or unpredictable natures depending on the network protocols, nodes, software, and hardware. In this study, there are two approaches proposed for NCS design under significantly varied time delays. In the first approach, on-line estimation of the delay time is developed by processing the on-line measurement of the round-trip time (RTT) between two nodes in real network environments. Three related controllers are thus developed: (1) the adaptive Smith predictor control scheme for significantly varied time delay, (2) the robust NCS design for bounded variation of time delay and disturbance, and (3) the multi-rate design under the condition of wireless network congestion.

The second approach is proposed as the model-free perfect delay compensation (PDC) scheme. This scheme effectively deals with network-induced delays requiring neither the delay time information nor the plant model. NCS with PDC is thus simply equivalent to the original closed-loop system with an additional pure time delay and it is designed without concerning the network. Therefore, the well-designed controller can be directly implemented on a network and its stability can be guaranteed without being affected by the varied time delay. The proposed approaches have been successfully applied to remote control systems under significantly time-varying delay to control an AC servo motor. Provided experimental results have further proven that both SISO and MIMO systems can be directly implemented in networking systems by including the proposed PDC to maintain its original feedback-loop characteristics.

Keywords: Networked control system (NCS), network-induced delay, on-line delay estimation, multi-rate sampling, perfect delay compensation (PDC), MIMO NCS, direct networking

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Chapter 1

Introduction

Real-time network control applications are increasingly gaining attentions on account of the rapid development of network technologies with data communication through the Internet. Networked control systems (NCS) have become more popular because they can be easily maintained in industrial applications with a convenient and systematic manner. Their future applications are promising, encompassing a spectrum as wide as in space exploration, hazardous environments, factory automation, remote diagnostics and troubleshooting, remote mobile robots, aircraft, automobiles, manufacturing plant monitoring, nursing homes, and tele-operations, etc. However, network-induced time delay is unavoidable in NCS, and stability is still highly concerned in NCS design. Moreover, as the number of nodes increases when all sensors, actuators, and controllers are interconnected within a network, real-time NCS performance is seriously degraded by the time delay effect and becomes unstable due to the limited network bandwidth. Therefore, controllers obtained from general design without considering the network are not suitable for NCS implementation and have to be redesigned or modified to minimize the time delay effect which mainly causes the time delay and data dropout.

1.1 General review

Many researchers have been working on NCS during the past decades. The effect of integrated communication and control problems were discussed by Halevi and Ray (1988) and Liou and Ray (1991). Recent research topics and challenges in NCS have attracted attentions mainly on (1) control of networks in the protocol, (2) control over networks in the application layer, and (3) multi-agent systems (Tatikonda and Mitter, 2004; Baillieul and Antsaklis, 2007; Hespanha et al., 2007; Zampieri, 2008; Gupta and Chow, 2010). The main issues regarding NCS design can be categorized into two types: (a) the time delay and (b) the data dropout. Transmission control protocol (TCP) is a reliable stream delivery service that it guarantees transmission of a data stream sent from one node to another node without duplication or data loss but TCP also plays the major role of network-induced delays.

NCS performance will be degraded if a lower sampling rate is adopted owing to the limited network bandwidth. On the other hand, a faster sampling rate is more desirable in the sampled-data system to improve its performance. However, it also increases the network load, which it in turn results in a longer transmission delay. Thus, finding a suitable sampling rate to tolerate the network-induced delay and to achieve desirable system performances are crucial in NCS design. Lian et al. (2002) identified several key components of the time delay in order to determine an acceptable working range of sampling periods for NCS design.

On the other hand, some approaches have been proposed to improve communication protocols and eliminate competition for the shared network medium. Although some approaches allow each node on the network to transmit and receive data according to a predetermined schedule, for example, redesigning the protocols enhances transmission technology and provides guaranteed quality of service (QoS) for real-time requirements (Soucek and Sauter, 2004; Grenier and Navet, 2008), consumers can only access network resources in the application layer of the open system interconnection (OSI) model, and these protocols are not easily modified according to users' requirements to improve NCS performance in real applications.

Recent research about the time delay of NCS mainly focused on modeling, stability, and controller design. In modeling techniques, some methodologies have been developed such as the Markov chain (Nilsson, 1998), probability distribution (Lian et al., 2002), a communication model for TCP (Chen et al., 2007), and the Takagi–Sugeno (T–S) model in network-induced delays (Zhang et al., 2007). In stability analysis, a necessary and sufficient condition ensuring a stable NCS was presented with random delays in less than one sampling period only (Yue et al., 2004; Zhang et al., 2005; Dritsas and Tzes, 2009). An asymptotically stable problem with a certain time-bound varying delay is solved by using Lyapunov functions (Zhang et al., 2001; Zhivoglyadov and Middleton, 2003). The maximum allowable delay bound (MADB) was proposed for NCS stability analysis (Kim et al., 2003). Basically, the induced network delay varies according to the network load, the scheduling policy, the number of nodes, and the different protocols. The network-induced time delay with time-varying characteristics makes modeling and stability analysis for NCS more difficult. Thus, studies in network delays mainly for the controller design are crucial in NCS design.

1.2 Model-based NCS control design

Many NCS controller design methods have been proposed to deal with network-induced delays. Most available approaches are based on the model-based design to alleviate the network time delay effect. Available approaches can be categorized as shown in Table 1.1. Among these NCS control design methods, only two methods are designed without information of the time delay. Classification of major approaches in NCS control design and details are discussed below.

Table 1.1 Classification of major approaches in NCS control design

	Time Delay	**Constraint**	**Methods**
Model-based NCS design	Known delay	Constant delay time	1. Smith predictor (Peng et al., 2004)
		Time-varying delay < sampling time	1. State feedback controller (Tang et al., 2008) 2. H_∞ robust controller (Gao and Chen, 2008)
		Bounded time-varying delay > sampling time	1. Model predictor control (Zhao et al., 2009) 2. Gain scheduler middleware (Tipsuwan and Chow, 2004) 3. Switched system approach (Xie et al., 2008) 4. Fuzzy controller (Lee et al., 2003) 5. Optimal controller (Li et al., 2009)
	Unknown delay	Constant	1. CDOB (Natori and Ohnishi, 2008) 2. Scattering transformation (Matiakis et al., 2009)
		Time-varying delay	1. CDOB (Natori et al., 2008)

(1) The known network-induced delay

The popular time delay compensation scheme, known as the Smith predictor, was also proposed to deal with a constant delay time for NCS (Peng et al., 2004). Robust control and state feedback are achieved with the general assumption that the varied delay is relatively small compared with its sampling time (Gao and Chen, 2008; Tang et al., 2008). If the delay is longer than one sampling period, it may result in difficulties in dealing with vacant sampling and message rejection in the real-time NCS. Thus, robust NCS design results are only suitable for NCS with a small time-varying delay only.

Different techniques for the bounded-delay cases were proposed such as predictive control, switched system, optimal design, and gain scheduler middleware (Zhao et al., 2009; Xie et al., 2008; Li et al., 2009; Tipsuwan and Chow, 2004). Model predictor control (MPC) was also proposed with a sequence of control signals to be sent to compensate for irregular communication error with a known limitation of time delay (Yang, 2007; Zhao et al., 2009). The switched system was proposed to study asymptotical stability for a large system with a known time delay model (Zhai et al., 2002; Xie et al., 2008). For estimating the distribution of time delay, the algorithm of the optimal stabilizing gain was used (Li et al., 2009). In real NCS implementation over the Internet, the time delay which usually varies depending on the number of user nodes and communication data loads is relatively large compared with the sampling time. Thus, the design and implementation of NCS become more complicated in real applications.

Tipsuwan and Chow (2004) proposed the use of a gain scheduler middleware (GSM) to adjust the NCS controller gain, maintain control performance, and stabilize the system with respect to the real-time network traffic conditions with the measured probing packet RTT. The GSM design adopting a known upper-bounded delay also avoids the high gain controller as well as the input saturation. However, most of the abovementioned research results are limited to the time delays in constant, less time-varying, or bounded natures, which are not true in real network environments. The time delay induced during the transmission over the communication network becomes more unpredictable because the network time delay significantly varies due to the varied loads, scheduling, number of nodes, and protocols. The NCS design results generally obtained from a nominal model with a known delay time thus become invalid for real NCS applications.

(2) The unknown network-induced delay

Recently, the communication disturbance observer (CDOB) (Natori and Ohnishi, 2008) and the scattering transformation with a known system model (Matiakis et al., 2009) have been proposed to effectively compensate for unknown constant time delays in NCS. Although CDOB can be extensively applied to conditions with the time-varying delay, and undesirable performance with oscillation and noise are still present in the CDOB output in practice. On the other hand, the scattering transformation with a known system model is also not applicable to real NCS with varied time delays (Matiakis et al., 2009). Moreover, these newly developed NCS design approaches still require an accurate system model in the design procedure.

Network-induced time delays may be constant, bounded, stochastic, random, or unpredictable depending on the network protocol and hardware. Therefore, network-induced delays have different natures especially in a shared Internet with a huge number of network users at the same time. Although some methods have been proposed to eliminate the time delay effect from its closed control loop in NCS design, the design results obtained are usually based on a system model with known and bounded delay information. Therefore, those model-based methodologies are usually not applicable to real networks with significantly varied time delays.

1.3 Problem statement

Although many methods have been proposed to design controllers for NCS with network-induced delays in the past two decades, some critical issues still exist as follows:

(1) Network-induced delay is unpredictable, especially in a shared Internet with a huge number of user nodes.

(2) Network time delay significantly varies due to network loads, scheduling, number of nodes, and protocols.

(3) Most NCS control designs are based on the nominal system model. However, modeling error and disturbance exist in real environments.

(4) Owing to the limited bandwidth of wireless networks, wireless NCS easily becomes unstable because of transmission congestion.

(5) Implementing well-designed controllers directly on NCS with satisfactory stability without being bothered by the network-induced delay is desirable.

(6) Since SISO NCS is a challenging task, designing a stable MIMO NCS is even more difficult due to the significant degradation of phase lag as a result of network-induced time delay. In other words, traditional control design methods unavoidably face an intrinsic barrier in the MIMO NCS control design.

1.4 Proposed approach

In this dissertation, two approaches for NCS design are proposed.

(1) The on-line delay estimator for NCS

The delay is estimated by processing the on-line measurement of the round-trip time (RTT) between two nodes in real network environments. Its applications can be applied to three aspects in this dissertation as follows:

(a) The adaptive Smith predictor control scheme is developed by directly applying the estimated time delay for varied network-induced time delay, particularly in commercial Internet.

(b) By considering the network-delay variation in the phase and the external disturbance in the gain, the robust control design of the quantitative feedback theory (QFT) is integrated with the adaptive Smith predictor to achieve the robust NCS design.

(c) In wireless NCS with serious network traffic jam, a multi-rate design method is obtained based on the on-line-measured RTT to switch the sampling time and to avoid the network traffic jam.

(2) The model-free perfect delay compensation (PDC) scheme

PDC with modified butterfly elements is proposed to effectively deal with network-induced delays requiring neither the delay time information nor the plant model. The NCS design results with the model-free PDC is equivalent to the closed-loop control system design with an additional pure time delay only. Thus, the NCS design is greatly simplified and is effective in both SISO and MIMO systems. In summary, the traditional control design results can be directly implemented on networking systems by including the proposed PDC scheme to maintain its original feedback-loop characteristics with an additional pure time delay.

1.5 Contributions

All analytical and experimental results of this dissertation lead to the following contributions:

(1) The on-line estimated time delay RTT is adopted in the adaptive Smith predictor to cope with the significantly varied network-induced delay.

(2) The robust NCS design is proposed in real concerns to render better control responses against the time delay variation and external disturbance.

(3) A multi-rate design method is proposed to avoid the network traffic jam with wireless communication and stabilize the NCS.

(4) The developed PDC in NCS efficiently deals with unknown and varied network-induced delays, even without the time delay or the system model.

(5) With the proposed PDC elements, well-designed controllers can be directly realized in NCS for both SISO and MIMO cases.

1.6 Contents overview

This dissertation is organized as follows: the on-line time delay estimation design is presented in Chapter 2. Chapter 3 introduces the robust NCS design with the implementation of RTT. Chapter 4 presents the RTT technique and multi-rate design applied to wireless NCS with unpredictable delay. In Chapter 5, the model-free PDC scheme is introduced for SISO control systems. Chapter 6 describes the proposed PDC for MIMO control systems. Finally, conclusions and recommendations for further research are provided in Chapter 7.

Chapter 2

On-line Time-delay Estimation Design

In real applications, a remote control system is generally an integration of a commercial network for message transmission and an industrial network to control the remote hardware through a communication gateway. As the delay in a commercial network Ethernet is significantly time varying depending on the number of end users, the delay is estimated in this study by processing the on-line measurement of RTT between the application layers of the remote node and the client node. This research proposes a remote NCS structure by implementing the on-line time delay estimator with an adaptive Smith predictor because the induced time delay in NCS degrades its stability and performance. The adaptive Smith predictor scheme is developed by directly applying the estimated time delay to deal with network-induced delays. NCS is thus simplified as the desirable closed-loop system with an additional pure time delay. To prove the feasibility of the proposed remote control system, the developed design has been applied to an AC 400 *W* servo motor tested in 15 *Km* distance. Experimental results indicate that significantly improved stability and motion accuracy can be reliably achieved by applying the proposed approach.

2.1 Introduction

Due to the rapid development of data communication network technologies in the Internet, real-time network control applications have increasingly gained attentions. These applications include tele-operations, remote mobile robots, and factory automation, which are organized by wiring connections among control system devices through network resources. The popularity of network control applications is obvious because they can be conveniently and systematically maintained in an industry (Kaplan, 2001). NCS is one of the newly developed technologies in modern industrial applications. It has potential applications by simply interconnecting all sensors, actuators, and controllers through networks (Lian et al., 2001). The introduction of network technologies provides easy maintenance and expandability for control system design. However, it also leads to problems of time delay, data dropout, and package collision. Network scheduling has been studied to cope with these problems. Another concern is that NCS performance may become unstable because network delay is stochastic in nature and it is difficult to directly apply linear delay-time system analysis. The total network-induced delay, both in the controller and the actuator, may present a bound or random format depending on the network protocols, which may seriously degrade NCS performance.

Recently, the use of NCS to deal with band-limited channels, time delays, and packet loss has been widely studied mainly for the improvement of communication protocols and controller design (Baillieul and Antsaklis, 2007; Hespanha et al., 2007; Zampieri, 2008). With proper communication protocols, the enhancement of transmission technology provides guaranteed quality of service (QoS) for real-time applications (Grenier and Navet, 2008). A sufficient condition ensuring robust stability of NCS was presented by Chen et al. (2007). Tatikonda et al. (2004) formulated a linear discrete-time control problem with a noiseless digital communication link, and provided the role of information patterns and control policy knowledge. Zai et al. (2002) used an average dwell time for discrete switched systems to obtain conditions where the stability of NCS is guaranteed. Network-induced delay is one of the most important issues of NCS. Different methodologies have been proposed to deal with the delay effect within the process control loop. Considering both known and constant process delays with noise, a minimum variance control law (Jain and Lakshminarayanan, 2005) and a step-by-step tuning procedure (Goradia et al., 2005) were developed separately to obtain achievable PI performance for linear SISO time delay processes. Furthermore, extension of the abovementioned approaches was then developed to the MIMO system (Jain and Lakshminarayanan, 2007). A solution of the minimum variance control law for linear time-variant processes has been derived in a transfer function form (Huang, 2002). Lian et al. (2002) identified several components of the time delay of network protocols and control dynamics and they determined an acceptable working range of the sampling period in NCS. The feedback gain of a memoryless controller and the maximum allowable delay can be derived by solving a set of linear matrix inequalities (Yue et al. 2004). A design method of time-delayed control systems based on the concept of network disturbance and communication disturbance observer (CDOB) without the knowledge of the delay-time model was also proposed (Natori and Ohnishi, 2008).

Most of the abovementioned research results are limited to constant delays or less time-varying delays, which are not true in real network environments. In this research, time-based time delay analysis of NCS is provided to explain how it affects network systems. By applying the proposed adaptive Smith predictor based on the on-line time delay estimation, satisfactory control performance of NCS can be obtained even as the time delay increases significantly over integrated commercial and industrial networks. The proposed NCS has been applied to a remote control system for an AC 400 *W* servo motor tested in 15 *Km* distance to verify the proposed design.

2.2 NCS and time-delay measurement

The general NCS in the closed-loop model is shown in Fig. 2.1, where t_1 and t_2 are the time delays induced in the network structure for the controller-to-actuator direction and the sensor-to-controller direction, respectively. Basically, the induced network delay varies according to the network load, scheduling policies, number of nodes, and different protocols. Network delay systems are also different from general linear time delay systems, where there is an assumption that the delay on the former is constant or bounded. NCS with time-varying characteristics makes modeling and design more difficult. The total time delay can be categorized into three classes based on the parts where they occur: (1) the client node, (2) the network channel, and (3) the remote node. Time delay at the client node is mainly in the preprocessing time, which is the sum of the computation, encoding, waiting, total queuing, and blocking time. Network time delay includes the total transmission time of a message and its propagation delay, which depends on the message size, data rate, and length of the network cable. Time delay at the remote node is mainly in the post-processing time, as shown in Fig. 2.1.

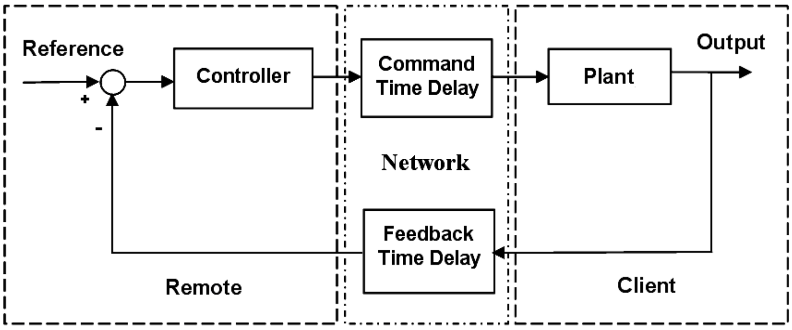


Fig. 2.1 The NCS block diagram

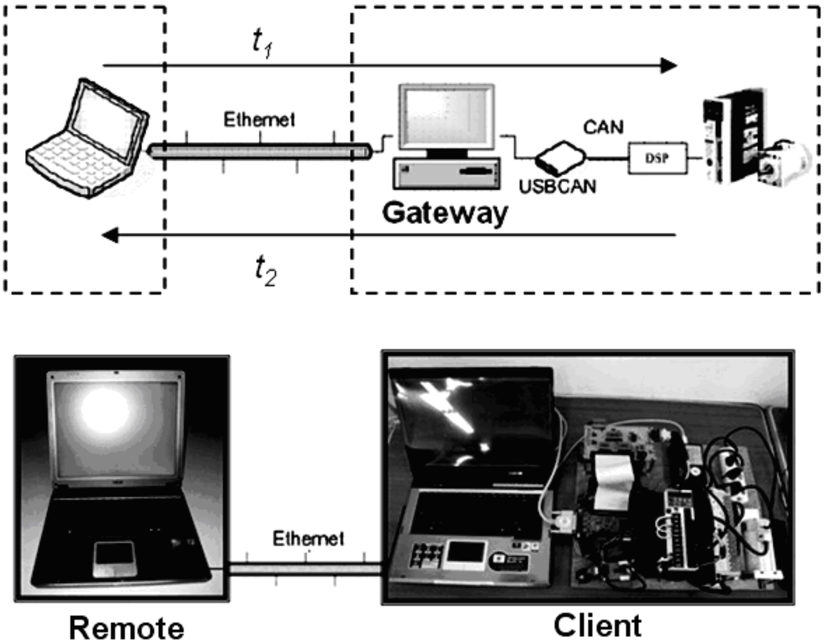


Fig. 2.2 The experimental setup

Figure 2.2 shows the structure of the present remote NCS which includes the controller in the remote node and the client for the remote-controlled device or plant. The client and the remote nodes communicate with each other from a distance through the Ethernet network. The client consists of two parts in the present experimental setup. The first part is the gateway. This is implemented in a computer with USBCAN, which is designed to communicate between the Ethernet network and the CAN bus. The second part is the local servo motor controller implemented on TI TMS320F2812 DSP with a speed-control mode. The data communication protocol adopts the TCP to construct the position loop for the remote control (Cheng et al., 2007). As shown in Fig. 2.2, the communication network can be modeled as the time delay on the forward-command direction for actuators (t_1) and on the feedback direction for sensors (t_2). Therefore, the network time delay includes both the total transmission time of a message and the transformation time of the package from CAN to Ethernet data. The total time delay (RTT) can be expressed as $t_p = t_1 + t_2$ (Fig. 2.2).

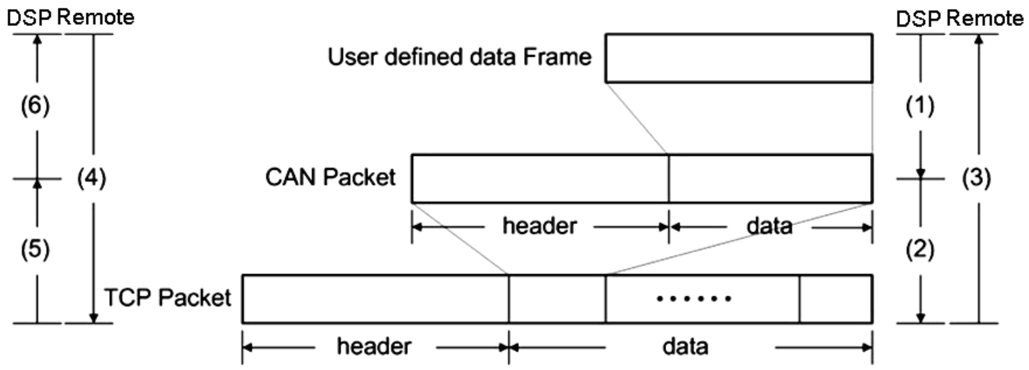
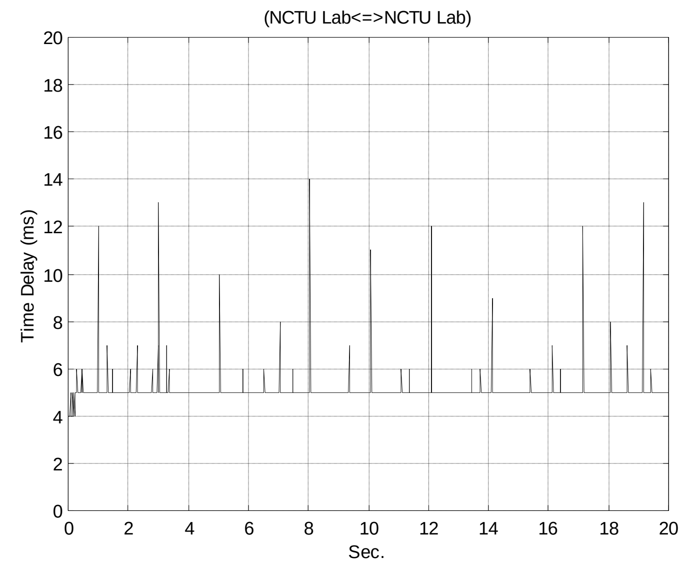


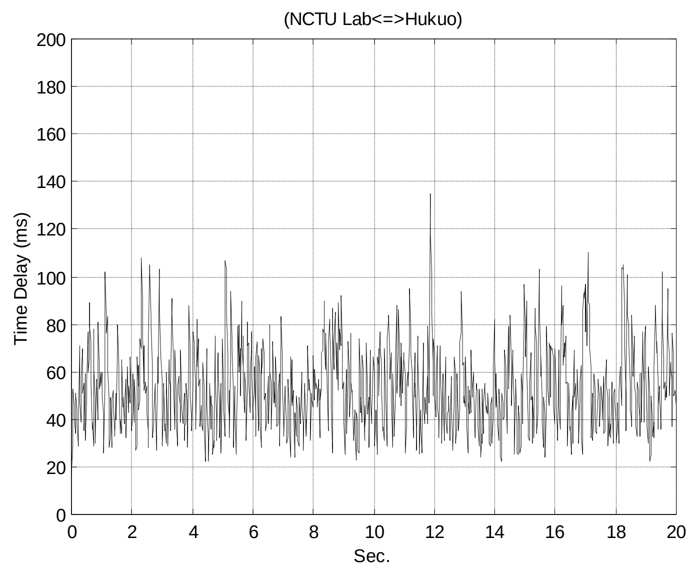
Fig. 2.3 The package transition diagram

These two protocols, Ethernet and CAN, cannot communicate with each other directly. Thus, message packages have to be processed through a gateway**,** as shown in Fig. 2.2. When data are transmitted to the remote node from the local hardware DSP, the type and the transmission data in a data frame should be set up in advance (Fig. 2.3). These data are then included into the CAN package and transmitted to the gateway through the CAN network, as indicated in step 1 of Fig. 2.3. After the gateway has received the package from the CAN network, the data of the CAN package will be included in the Ethernet package and the Ethernet network may thus transmit the package directly (step 2 in Fig. 2.3). When the remote node has received the package from the Ethernet network, part of the CAN package will be extracted from the Ethernet package and the data defined by users can be further obtained. In the end, the data frame will be analyzed and transmitted (step 3 of Fig. 2.3). By following the procedure (1) ➔(2) ➔(3), the message of the local DSP can be transmitted to a remote node. On the contrary, when data are transmitted to the remote node from the DSP, both transmission data in the data frame should be set up in the CAN package. The CAN message is then included in the Ethernet package and part of the data will be transmitted to the gateway through the Ethernet network (step 4 of Fig. 2.3). After the gateway receives the package from the Ethernet network, the data from the CAN package will be extracted from the Ethernet package. The CAN network will be utilized to transmit this package to DSP (step 5 of Fig. 2.3). After DSP receives the package from the CAN network, the data frame in the CAN package will be extracted. This is step 6 in following the procedure (4) →(5) →(6) shown in Fig. 2.3.

The network time delay for the present experiments includes the following cases: (1) NCTU Laboratory⇔ NCTU Laboratory and (2) NCTU Laboratory⇔ Hukuo (the two places are 15 *Km* apart). The computer used for this network transmission has the following specifications: Intel® Pentium CPU 1.60 *GHz*, 496 *MB* of RAM, Realtek RTL8139/810x Family Fast Ethernet NIC Network Card, and Windows XP Professional Version 2002 OS with SP2. The local area network (LAN) is used with the time delay between the application layer of the client and remote nodes. In addition, the RTT measurement is crucial in obtaining accurate delay measurements periodically. Technically, the Windows Forms Timer component in the operating system is single threaded and is limited to an accuracy of 55 *ms*. A higher resolution performance counter of the DSP timer with an accuracy of 1 *ms* is used to measure network delay between the remote and the client nodes. We measured the time delay from two different clients within the NCTU Laboratory, and from two different clients located each in the NCTU Laboratory and Hukuo, separately, as shown in Fig. 2.4 (a) and (b). The delay time in the integrated Ethernet and the CAN Bus within a 20 *ms* sampling period was measured, as shown in Fig. 2.4. Only a very small time delay (around 3–15 *ms*) was recorded because the transmission speed of the intranet was at 100 *Mbps* and there was only a relatively short route within the NCTU Laboratory. From the NCTU Laboratory to Hukuo, the delay time increases because the transmission procedure takes more routes and switches. Experimental results as shown in Fig. 2.4 indicate that the application environment greatly affects the induced delay time in NCS. Moreover, as distance increases, the delay time of a network increases as more nodes are involved.



(a)



(b)

Fig. 2.4 Measured Internet delays (a) NCTU Lab - NCTU Lab and (b) NCTU Lab - Hukuo

2.3 Adaptive Smith predictor

The communication network can be modeled as the time delay on the forward-command direction for the actuator and on the feedback direction for the sensor as shown below:

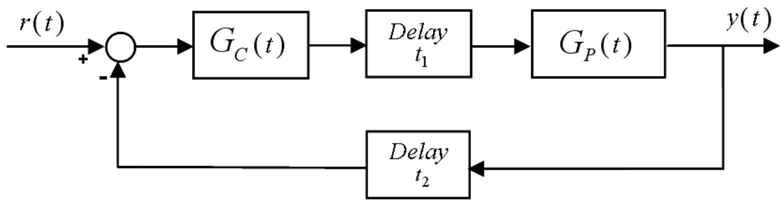


Fig. 2.5 The simplified block diagram of NCS

In Fig. 2.5, t_1 is the command delay time, t_2 is the feedback delay time, and $G_c(s)$ is the controller. $G_p(s)$ denotes the transfer function of the real plant model without the delay time. The transfer function from input r to output y is obtained as follows:

$$\frac{Y(s)}{R(s)} = \frac{G_C(s)G_P(s)e^{-t_1 s}}{1+G_C(s)G_P(s)e^{-(t_1+t_2)s}} = \frac{G_C(s)G_P(s)e^{-t_1 s}}{1+G_C(s)G_P(s)e^{-t_p s}} \tag{2-1}$$

where $t_p = t_1 + t_2$.

The known delayed process can be effectively handled by applying the Smith predictor if the information regarding its delay is known and constant (Vrecko et al., 2001; Peng et al., 2004). Since the time delay in the Internet can be measured between sending and receiving a packet, the delay in a closed-loop NCS can be well-compensated by applying the Smith predictor, as shown in Fig. 2.6.

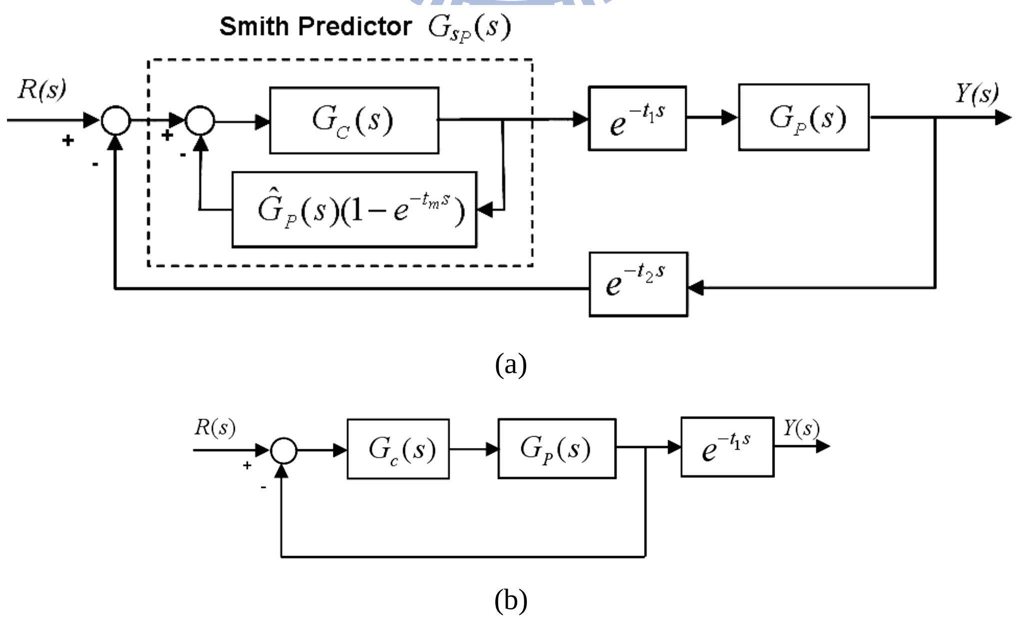


Fig. 2.6 The system with the Smith predictor (a) the original system and (b) the equivalent system

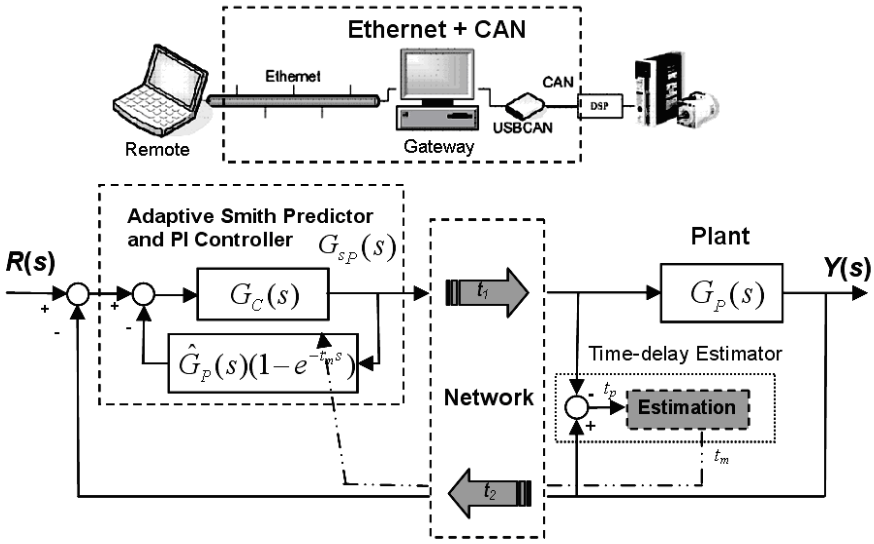


Fig. 2.7 The block diagram of the adaptive Smith predictor with a PI controller

The nominal delay time and system model adopted for the Smith predictor is t_m and $\hat{G}_p(s)$, respectively. In ideal conditions, $\hat{G}_p(s) = G_p(s)$ and $t_m = t_p$, the block diagram in Fig. 2.6(a) can be simplified into Fig. 2.6(b) with an additional pure time delay term applied for the Smith predictor. In this study, the delay time is estimated from the real-time measured RTT for the Smith predictor. To cope with significant variation in the delay time due to network transmission, an adaptive method is proposed for the present remote control systems with the integration of the Smith predictor, the PI controller, and the real-time delay estimation, as shown in Fig. 2.7.

2.3.1 On-line estimation of the delay time

A method for estimating the delay time within the Internet for the NCS architecture with a combination of the time-driven and event-driven processes is proposed in this section. The designed control algorithm is realized on the present network by integrating both the Ethernet and the CAN bus with a serial data communications bus in-between. Technically, the standard CAN bus transmits only 8 bytes per frame. However, the minimum data length to realize the proposed RTT measurement is 9 bytes. A programming method wherein messages will be divided into two parts and each part will be sent at each half sampling period through the CAN network is proposed here, as shown in Fig. 2.8.

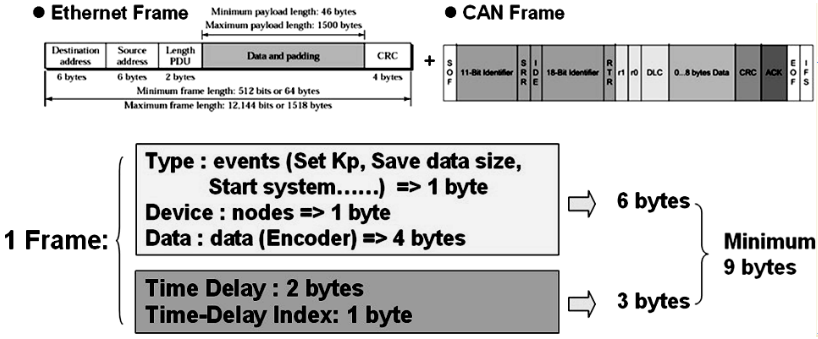


Fig. 2.8 The CAN data frame in the proposed NCS for measuring RTT

To illustrate the estimation of the induced network time delay from the measurement of RTT, the NCS transmission is shown in Fig. 2.9. At the beginning of the sampling period, the clock-driven sensor node transmits the sampling data to the controller node. By assuming the sensor-to-controller delay as t_2 for this setup, the event-driven controller node uses the sensor data to compute the control signal and then transmits it to the actuator node. By assuming the controller-to-actuator delay as t_1, the time-driven transmission is applied. The measurement of RTT is adopted due to its easy implementation and the fact that no clock synchronization is required because all computations are operated in the same device. The RTT measurement is crucial in providing accurate delay measurements periodically. A higher resolution performance counter of the DSP timer is used to measure the network delay between the remote and client nodes, as shown in Fig. 2.5. A real-time method for estimating the delay time in the Internet is proposed with all measurements for counters, indices, and delays denoted as

- S_c : sending counter
- R_c : receiving counter
- N : number of packets
- i : index of a sequence number, $i = 1, 2, \ldots, N$.
- $t_p[i]$: round-trip delay measurement of the *i-th* packet, using counter and $i = 1, 2, \ldots, N$.

$$t_p[i] = S_c[i] - R_c[i]$$

An example of message transmission based on a 20 *ms* sampling time is shown in Fig. 2.9(b). If the time delay is less than one sampling time, its effect on control performance is one-sample delay. Moreover, the first frame is in normal transmission. The second frame is sent 20 *ms* later and a packet is received at 68 *ms*. The corresponding RTT is 48 *ms*. There is no data frame received at the sampling times of

40 and 60 *ms*. This phenomenon is called vacant sampling (Halevi and Ray, 1998). Two data messages (2 and 3) arrive in the same sampling period. However, only the most recent data message is used while the other data are discarded. This is referred as message rejection (Halevi and Ray, 1998; Chow and Tipsuwan, 2001). For messages 4–8, all data arrive sequentially at each sampling point, although the exact receiving time varies slightly. This occurrence is similar to delayed transmission. In summary, the delay time of NCS can be modeled using four phenomena: normal transmission, vacant sampling, message rejection, and delayed transmission. The time delay t_m adopted for the adaptive Smith predictor is estimated from the measured RTT (t_p) with the following rules:

(1) Normal transmission:

When the time delay is less than one sampling period, its delay effect is negligible and the measured RTT is directly adopted as t_m.

(2) Vacant sampling:

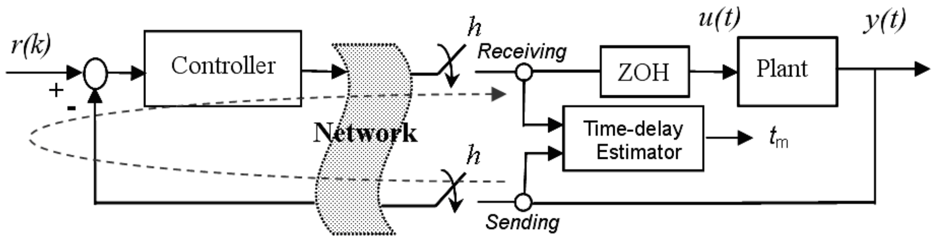
When the data message is not received before occurrence of the next sampling period, the previous measured RTT added with one sampling period is recognized as the current estimation of the delay time t_m.

(3) Message rejection:

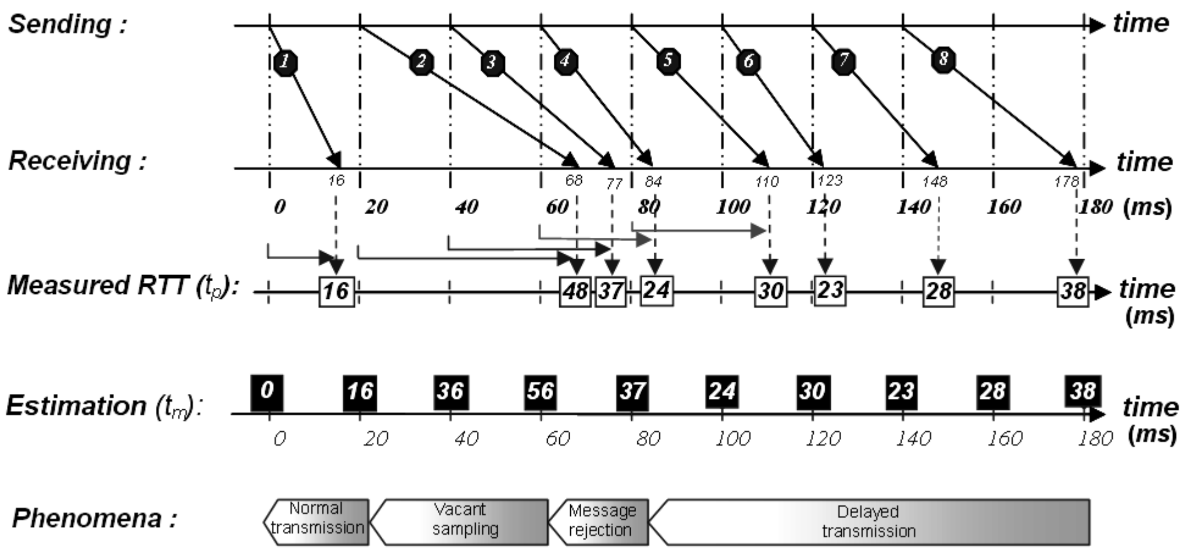
When more than two data messages arrive at the same sampling period, only the most recently measured RTT is adopted as t_m and all the previous measured data are discarded.

(4) Delayed transmission:

The continuously measured RTT is the estimated time delay and is directly adopted for the time delay compensation.



(a)



(b)

Fig. 2.9 The illustrative example for the time-delay estimation: (a) the architecture of the proposed RTT measurement, and (b) the four transmitted models for the RTT and the time delay estimation

2.3.2 Adaptive Smith predictor design

Fig. 2.10 shows the block diagram of the network control system with a time delay estimator. The total time of the command delay time and the feedback delay time is t_p. The Smith predictor is proposed as a control structure to compensate for the delay time in NCS (Vrecko et al., 2001; Peng et al., 2004). As shown in Fig. 2.10, $\hat{G}_p(s)$ is the nominal model of the system without the delay time. The transfer function for the system with the adaptive Smith predictor is expressed as follows:

$$\frac{Y(s)}{R(s)} = \frac{G_c(s)G_P(s)e^{-t_1 s}}{1+\hat{G}_P(s)(1-e^{-t_m s})G_c(s)+G_c(s)G_P(s)e^{-(t_1+t_2)s}} = \frac{G_c(s)G_P(s)e^{-t_1 s}}{1+G_c(s)\hat{G}_P(s)-G_c(s)\hat{G}_P(s)e^{-t_m s}+G_c(s)G_P(s)e^{-t_p s}} \tag{2-3}$$

In Fig. 10, the part of $G_{sp}(s)$ with the dotted line is the Smith predictor. Its transfer function is simplified as follows:

$$\mathrm{G}_{sp}(\mathrm{s}) = \frac{G_c(s)}{1+(1-e^{-t_m s})\hat{G}_P(s)G_c(s)} \tag{2-4}$$

When $\hat{G}_p(s) = G_p(s)$ and $t_m = t_p$, then the Eq. (2.3) simply becomes

$$\frac{Y(s)}{R(s)} = \frac{G_c(s)G_p(s)}{1 + G_c(s)G_p(s)} e^{-t_1 s} \tag{2-5}$$

Equation (2-5) shows that the transfer function when combined with the delay time and the system model transforms to two simple parts as the adaptive Smith predictor is adopted. The first part is the transfer function of the system without time delay, while the other is pure time delay. The equivalent block diagram of Eq. (2-5) is also shown in Fig. 2.6(b). Here, the system presents the same closed-loop system but only with the pure command (forward) delay time as t_1. In this case, the adaptive Smith predictor is applied because the network delay is significant and the nominal value of the delay time is adopted directly from the estimated value t_m from the measured RTT.

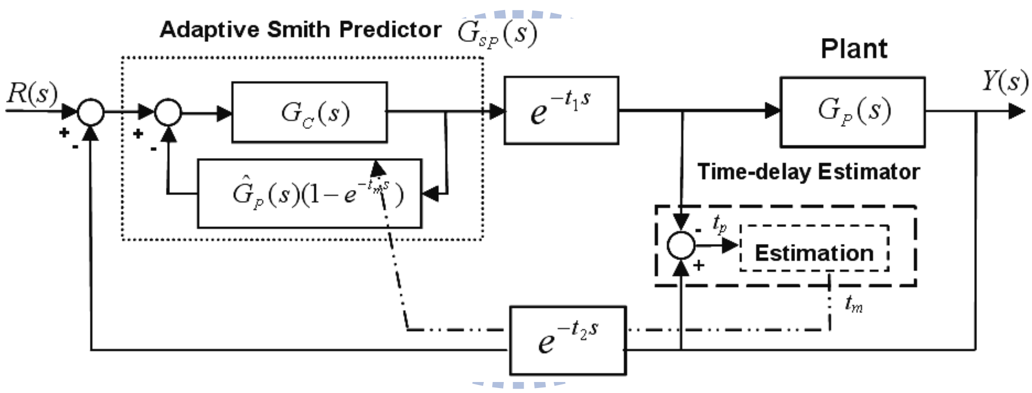


Fig. 2.10 The control structure with the adaptive Smith predictor

2.4 Experimental results

The experimental setup was implemented to verify the effect of time delay induced by the network. To apply a remote control system on an AC 400*W* servo motor, both the proposed adaptive Smith predictor control method and the on-line time delay estimation algorithm were implemented efficiently on the DSP micro-controller. The position control loop is located on the remote/client site. Due to the high encoder gain of 10000 P/R, coefficients of the PI controller are tuned as $K_p = 0.0001$ and $K_i = 0.00000001$.

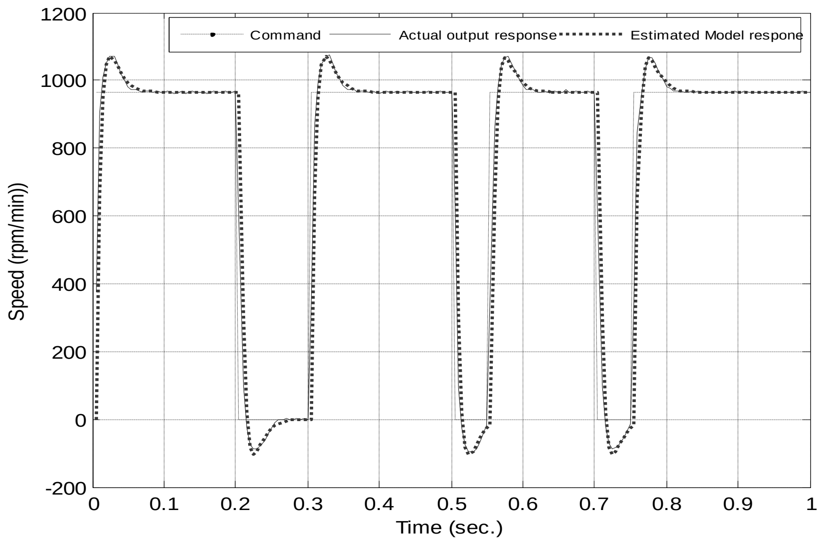
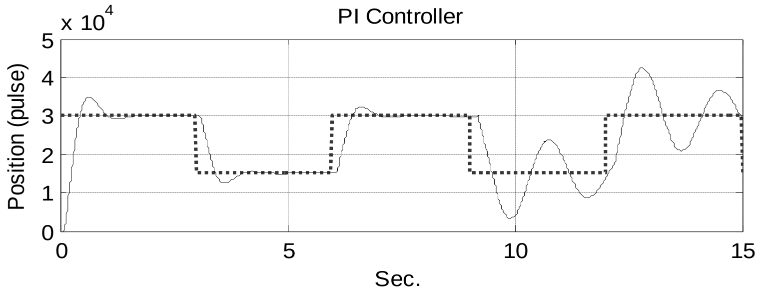


Fig. 2.11 Experimental results for system identification

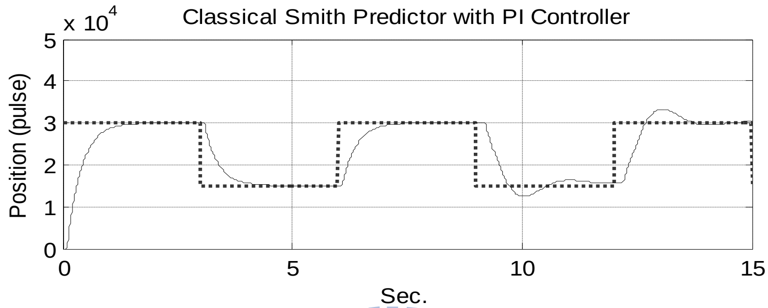
The system identification result of the speed-control loop from the pseudo-random binary signal (PRBS) response for the present AC permanent magnet synchronous motor is shown in Fig. 2.11. The open positional loop is identified as

$$G_P(s) = \frac{10^4(0.058s + 3.221)}{s(0.0001s^2 + 0.019s + 1)}$$

Different controllers were tested as follows: (1) the PI controller only, (2) the Smith predictor with the PI controller designed with a fixed delay time, and (3) the adaptive Smith predictor with the PI controller. For the client, the sampling time of the experiments was 20 *ms* with a square-wave command. The upper/lower commands of 30,000/15,000 pulses were provided. As the delay time increases (Fig. 2.12(d)), simulation results indicate that the control performance of the proposed adaptive Smith predictor presents the best performance compared with the PI controller and the Smith predictor. Experiments were also set up with different sites to test the proposed design. The delay time within the NCTU Laboratory is much smaller than the sampling time. Hence, the effect of time delay is negligible as shown in Fig. 2.13(d). Experimental results indicate that the control performance for different controllers is similar if the delay is small (Fig. 2.13).



(a)



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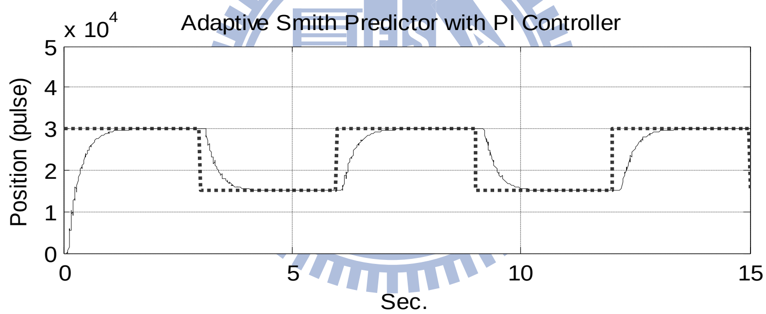

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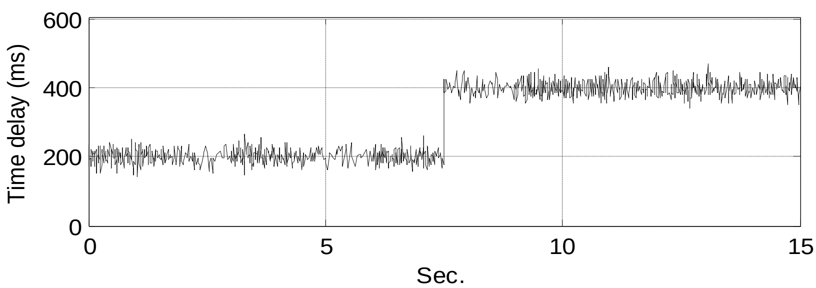
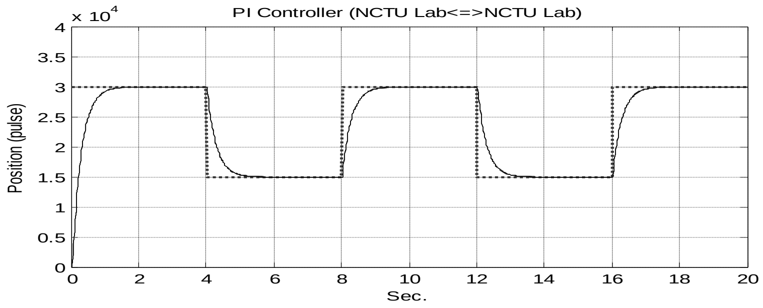
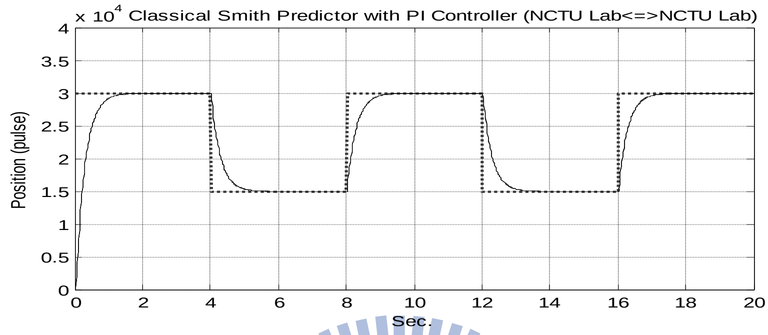


(d)

Fig. 2.12 Simulation results for (a) the PI controller, (b) the Smith predictor (t_m =200 *ms*) with PI controller, and (c) the adaptive Smith predictor with PI controller.



(a)



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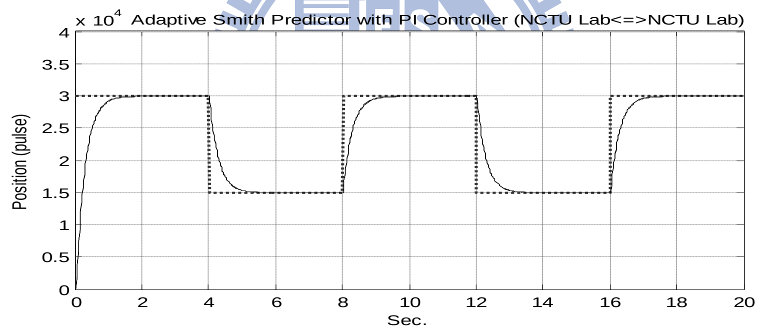

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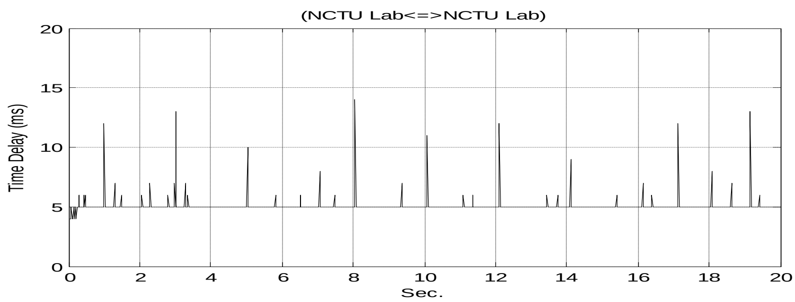
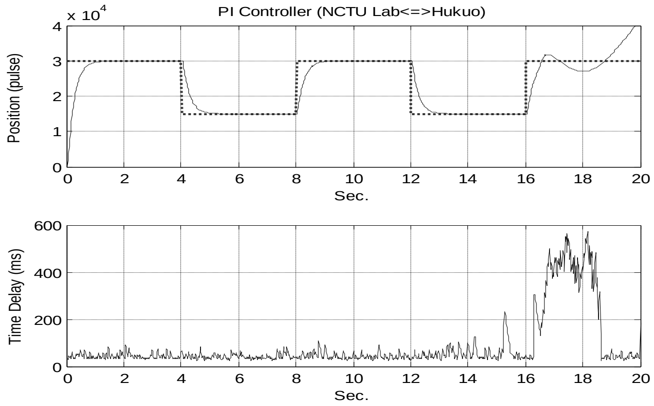
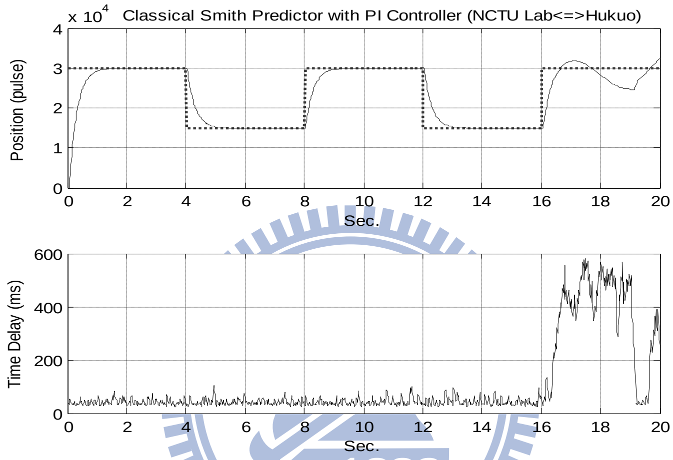


(d)

Fig. 2.13 Experimental results on Intranet (NCTU Lab⇔NCTU Lab) (a) PI controller, (b) Smith predictor (t_m =5 *ms*), and (c) adaptive Smith predictor



(a)



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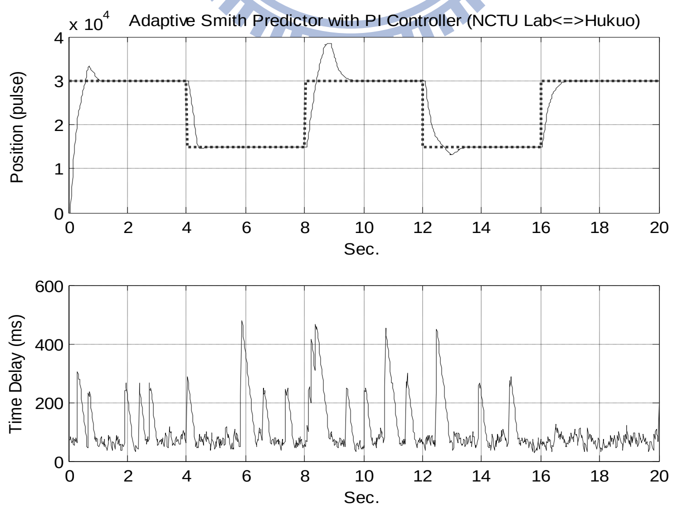


(c)

Fig. 2.14 Experimental results on Internet (NCTU Lab⇔Hukuo, 15 *Km*) (a) PI controller, (b) Smith predictor (t_m = 46 *ms*), and (c) adaptive Smith predictor

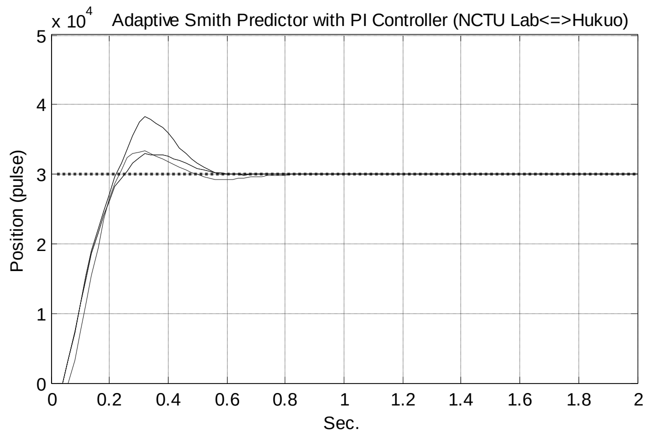


Fig. 2.15 Experimental results for the adaptive Smith predictor (without the initial delay)

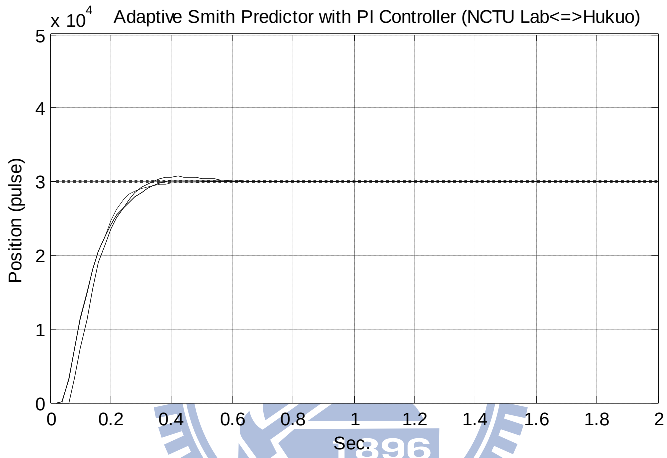


Fig. 2.16 Experimental results for the adaptive Smith predictor (with the initial time delay)

For the experiments tested between the NCTU Laboratory and Hukou, which had 15 *Km* distance and massive download data at 16 seconds from multiple users sharing the limited network bandwidth, the results indicate that the time delay increases accordingly to a certain level. Moreover, the PI controller with a fixed-delay Smith predictor becomes unsuitable, as shown in Figs. 2.14(a) and (b). However, even with the dramatically varied network-induced time delay, the proposed adaptive Smith predictor still renders improved performance as shown in Fig. 2.14(c). Compared with the three continuous responses of the proposed adaptive Smith predictor without considering the initial value as shown in Fig. 2.15, the proposed design with proper initial delay time renders much improved performance as shown in Fig. 2.16.

2.5 Summary

In this chapter, the remote control system was realized on the integrated Ethernet and CAN bus. By applying the adaptive Smith predictor with an on-line estimator for the time delay, the significantly induced time delay effect on the NCS was successfully reduced. Experimental results are summarized as follows:

(1) Since the present network integrates both the Ethernet and the CAN bus, the transmitted message is restricted by the CAN frame because its data length is limited to 8 bytes per frame only. For real-time applications, the present measurement of RTT requires 9 bytes for the data length. Therefore, in this study, an algorithm is proposed by sending the measurement of each frame at the half sampling period to achieve on-line estimation of the delay time for the proposed NCS.

(2) The adaptive Smith predictor is adopted with the on-line estimated time delay to achieve improved performance of NCS. The significant time-varying delay effect mainly on the Ethernet is thus reduced. Experimental results on an AC servo motor over 15 *Km* away also indicate that the proposed approach leads to significantly improved stability and control performance.

(3) The present remote controller applying the adaptive Smith predictor may present a larger overshoot because the initial estimation error exists. By measuring the time delay in advance as the initial value in the adaptive Smith predictor, better performance can thus be obtained.

Although the remote control system with a general NCS is stable for most of the time because the varied delay is bounded, system stability is not guaranteed especially when a serious time delay occurs. To prove the feasibility of the proposed approach, the adaptive Smith predictor was successfully applied to NCS under significantly time-varying delay time to control an AC servo motor.

Chapter 3

Robust NCS Design

Most NCS control designs are based on the nominal system model. However, modeling error and disturbance exist in real environments. The robust NCS design is proposed to cope with both the time varied delay and the external loading in this chapter. Compared with commercial networks, industrial networks in the NCS usually present minor variation in the time delay; on the other hand, the commercial Internet usually presents significant time delay. A template expressed as the phase and gain for the quantitative feedback theory (QFT) design has been constructed by considering the bounded variations with the time delay and the external loading. In addition, as the significant time delay of the NCS occurs over the wired Ethernet, the adaptive Smith predictor with QFT controller can be suitably adopted by employing the proposed online estimated RTT. Both simulation and experimental results on AC servo motor with the integrated CAN bus and the Ethernet have proven feasibility and improved performance of the proposed robust NCS.

3.1 The varied time delay effect

Most robust methods assume that the varying delay is relatively smaller than the system sampling time without considering the critical vacant sampling or message rejection (Halevi and Ray, 1998); however, these phenomena happen frequently in real applications. The reported robust design approaches face difficulties in NCS realization especially in the remote control system combining the industrial CAN bus and the commercial Ethernet. As shown in Fig. 2.2, the present NCS is mainly comprised of the remote node and the client node. They communicate with each other from a distance through the Ethernet network. The client at a location includes two parts. The first part is the gateway to computer communication with the USBCAN, which is designed to communicate between the Ethernet network and the CAN bus (Cheng et al., 2007). The gateway is linked with TI TMS320F2812 DSP through the CAN network, and the remote site is linked via the Ethernet network. The second part is the servo motor controller implemented on TI TMS320F2812 DSP with a speed-control mode. Finally, the data communication protocol adopts the TCP to achieve the desirable position loop control for the guaranteed eventual delivery of packets. This research considers the delay time to be the RTT, which is the required period for a packet to travel from the client node to the remote node and back to the original client node. The delay measurement relies on the RTT due to its easy implementation, and no clock synchronization is required as all computations are running in the same device (Vatanski et al., 2009). In Fig. 3.1, the comparison of the results between the CAN bus and Ethernet network obviously shows that the time delay in the Ethernet network remains the bottleneck during the transmission for the NCS.

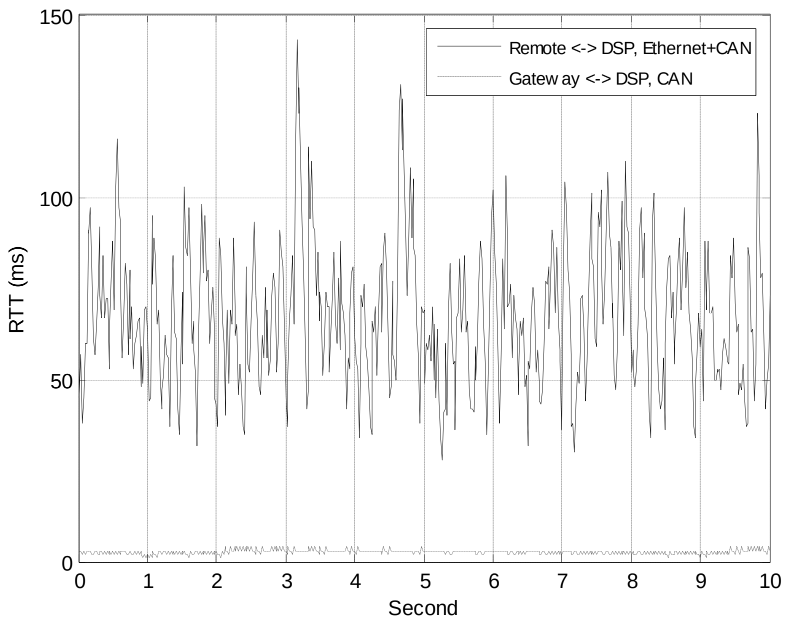
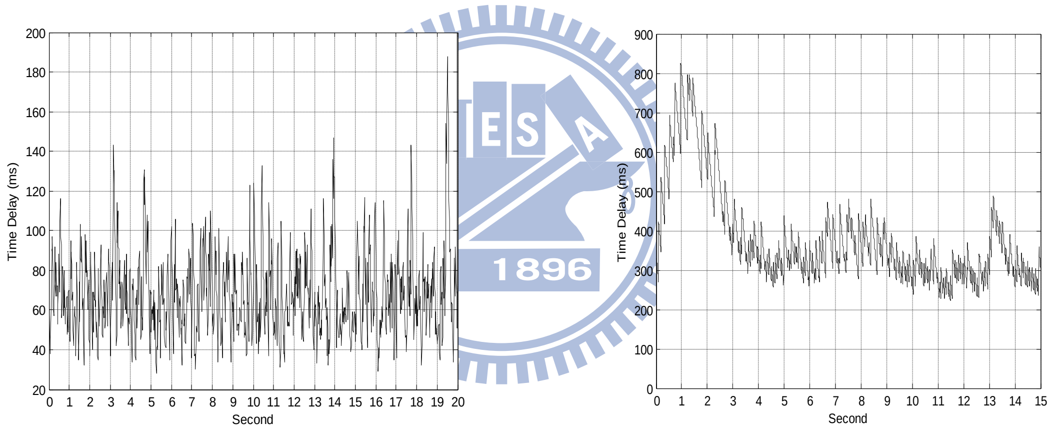


Fig. 3.1 Measured time delay

The time delay occurs between the application layer of the plant and the application layer of the gateway, and it is measured mainly from the plant to the client, which implements different network services (ADSL, Cable modem, and Intranet). Packets with different lengths whose payloads consist of a sequence number were sent out at periodic intervals. Experimental results as shown in Fig. 3.1 indicate that the time delay in the CAN bus is relatively small and stable compared with that of the Ethernet network, which is greatly affected by its environments, as shown in Table 3.1. Moreover, as the transmission rate decreases and the sampling period increases, the delay time of the network increases dramatically. Furthermore, as shown in Fig. 3.2, the measured drifting time delay presents both bounded and random natures.

Table 3.1 The averaged delay time for the Ethernet and CAN networks (1000 Samples, Unit: *ms*)

Sampling Time (*ms*)	Network delay time (*ms*)		
	Intranet (10 *Mbps*)	Cable Modem (6 *Mbps*)	ADSL (2 *Mbps*)
5	35.741	198.843	380.424
10	31.819	153.257	372.496
15	27.235	135.932	298.991
20	25.740	130.926	276.215



(a) (b)

Fig. 3.2 The time delay effect measured RTT at (a) 9:00 am, and (b) 12:00 pm

3.2 QFT design

The previous experiments indicate that network time delay has two characteristics: (1) bounded and (2) drifting. For the bounded delay, a robust QFT design with a suitable plant template is proposed in this study. The frequency-response template for a class of transfer functions with the time-varying delay in the phase and with the payload variation in the gain is likewise proposed. For the drifting delay, an adaptive Smith predictor control scheme integrated with the QFT controller is proposed. The scheme utilizes the on-line estimator for the time delay to improve control performance of the present NCS with the integration of the Ethernet network and the CAN bus.

The QFT is a frequency-domain technique utilizing the Nichols chart in order to achieve the desired robustness over a specified region of plant uncertainty (Horowitz, 1963; Horowitz and Sidi, 1972). The desired time-domain responses are transformed into frequency domain tolerance, which leads to the bounds on the loop transformation function. A two-degree-of-freedom (2-DOF) feedback system is typically adopted for the QFT technique (Wang and Horowitz,1988; Chien and Wang, 1990; Hwang and Yang, 2002) to design the controller with the prefilter to achieve the following objectives: (1) reduce the sensitivity of the overall system with respect to the plant uncertainty to attenuate the disturbance effect and (2) reshape the overall system response to meet the design specifications. The system transfer function is derived through

$$P(s)=\frac{b_m s^m + b_{m-1}s^{m-1}+\cdots b_1 s + b_0}{a_n s^n + a_{n-1}s^{n-1}+\cdots a_1 s + a_0},\quad (m<n) \tag{3-1}$$

where $\forall \mathrm{a}_\mathrm{i} \in \left[a_{i,\min}, a_{i,\max}\right]$, $\forall \mathrm{b}_\mathrm{i} \in \left[b_{i,\min}, b_{i,\max}\right]$.

According to Equation (2-1), the loop transfer function is defined as

$$L(s)=G_c(s)G_p(s)e^{-t_p s} \tag{3-2}$$

where $t_p = t_1 + t_2$. We allow the plant to include a mixture of both parametric and non-parametric uncertainties. The inclusion of the parameter variations of time-varying delay and the payload variation in the above models suggests the following plant family ρ with mixed uncertainty in parameter variations. It can be represented by

$$\rho=\left\{P(s)=G_p(s)\times D\times e^{-t_p s}:\ D=[D_{\min}, D_{\max}],\ t_p=[t_{p,\min}, t_{p,\max}]\right\} \tag{3-3}$$

The Padé approximation is then applied as follows:

$$e^{-t_p s}\approx P_d(s)=\frac{N_d(s)}{D_d(s)}=\frac{\sum_{k=0}^{n}(-1)^k c_k {t_p}^k s^k}{\sum_{k=0}^{n} c_k {t_p}^k s^k} \tag{3-4}$$

where $c_k = \dfrac{(2n-k)!n!}{2n!k!(n-k)!}$, $k = 0,1, \ldots, n$. The result with the first-order Padé approximation is derived by

$$P_d(s) = \left(\frac{1-t_p s/2}{1+t_p s/2}\right) \tag{3-5}$$

To consider the required position response under the variations of inertia load and time delay, the set for containing all possible transfer functions of the uncertain plant ρ is as follows:

$$\rho = \left\{ P(s) = G_p(s) \times D \times \left(\frac{1-t_p s/2}{1+t_p s/2}\right) : \ D = [0.5,\ 2],\ t_p = [0.05, 0.3] \right\} \tag{3-6}$$

The system identification result from the pseudo-random binary signal (PRBS) response for the present AC permanent magnet synchronous motor is obtained as follows:

$$G_P(s) = \frac{10^4(0.058s + 3.221)}{s(0.0001s^2 + 0.019s + 1)}$$

The frequency response of the system must lie within the upper bound $T_U(jw)$ and the lower bound $T_L(jw)$ as

$$T_L(jw) \le \left|T\ (jw)\right|_{db} \le T_U(jw)\,, \tag{3-7}$$

where $T(jw) = \left| F(jw) \dfrac{L(jw)}{1+L(jw)} \right|$

The transformation of the time-domain specifications into transfer functions of the upper and lower bound is respectively derived by

$$T_U(s) = \frac{1.3574s + 407.227}{s^2 + 18.4000s + 407.227} \text{ , and}$$

$$T_L(s) = \frac{69.9504}{0.005s^3 + 1.092s^2 + 18.7498s + 69.9504} \tag{3-8}$$

The templates of the control plant at $\omega = 0.5,\ 2,\ 10,\ 30,\ 70,\ 150$ Hz are plotted as shown in Fig. 3.3. A controller designed by the loop shaping method in the QFT

MATLAB Toolbox is directly obtained as follows:

$$G_c(s) = \frac{0.0002s^3 + 0.0042s^2 + 0.0299s + 0.0945}{s^3 + 30.5088s^2 + 310.1803s + 1050.9267} \tag{3-9}$$

The prefilter is then obtained to satisfy the tracking requirements as follows:

$$F(s) = \frac{47.2893s + 139.4771}{s^2 + 16.6994s + 139.4771} \tag{3-10}$$

The frequency response with parameter variations is shown in Fig. 3.4. The results indicate that the QFT design meets the desired frequency-domain specifications.

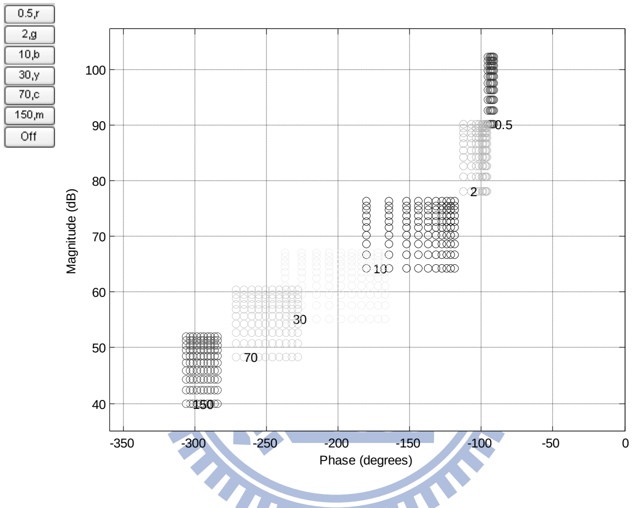


Fig. 3.3 Plant templates at certain frequencies

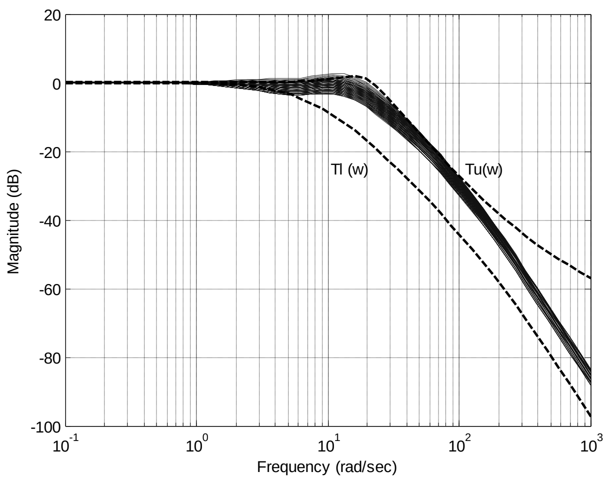


Fig. 3.4 Frequency responses with parameter variation

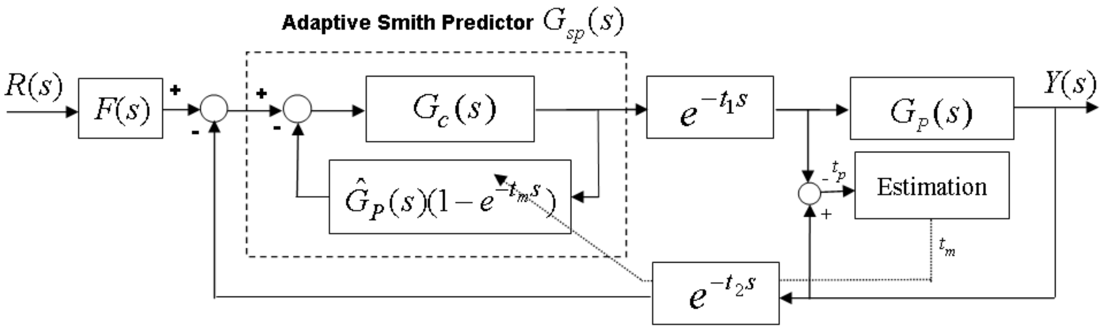


Fig. 3.5 The control structure with the adaptive Smith predictor

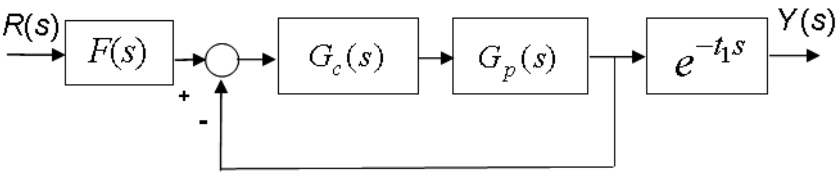


Fig. 3.6 The equivalent system by applying the Smith predictor

3.3 Adaptive Smith predictor with Robust NCS

Considering the system dynamics of the NCS, the Smith predictor is generally adopted if the delay time is constant (Baigorria et al., 2003; Majumder et al., 2005). The forward transfer function of the system is shown in Fig. 3.5 as

$$G_{sp}(s) = \frac{G_c(s)}{1+(1-e^{-t_m s})\hat{G}_p(s)G_c(s)} \tag{3-11}$$

where $G_{sp}(s)$ is the Smith predictor; $G_c(s)$ is the controller; $G_p(s)$ denotes the transfer function of the plant without the delay time, $\hat{G}_p(s)$ is its nominal model; t_p is the total delay time; t_1 is the command delay time of the network; and t_2 is the feedback delay time of the network. The overall closed-loop transfer function then becomes

$$\frac{Y(s)}{R(s)} = \frac{F(s)G_c(s)G_p(s)e^{-t_1 s}}{1+\hat{G}_p(s)G_c(s)-\hat{G}_p(s)G_c(s)e^{-t_m s}+G_c(s)G_p(s)e^{-(t_1+t_2)s}} \tag{3-12}$$

Without considering the modeling error, $\hat{G}_p(s)=G_p(s)$ and $t_m = t_1 + t_2$, Eq. (3-12) simply becomes

$$\frac{Y(s)}{R(s)} = \frac{F(s)G_c(s)G_p(s)e^{-t_1 s}}{1+G_c(s)G_p(s)} \tag{3-13}$$

As shown in Eq. (3-13), the transfer function is simplified as a system with the pure time delay as illustrated in Fig. 3.6. An adaptive mechanism is applied to maintain the robust stability and performance of the system by considering the various delay time over real networks. An on-line delay estimation algorithm is implemented for the adaptive Smith predictor in the robust NCS design. Thus, as the delay time increases progressively in the remote control, the present design still effectively handles the delay well. Consequently, stability and performance of NCS are maintained to some extents. Thus, the above QFT control design, which considers both the bounded delay and payload variation, is proposed to be integrated with the adaptive Smith predictor to construct the robust NCS to cope with the significant time delay and variation of the external load in remote control systems.

3.4 Results

In order to show the effectiveness of the robust NCS proposed in the chapter, both simulations and experiments are carried out. In this study, the adaptive Smith predictor with QFT controller based on the on-line delay estimation is developed to overcome the large time-varying delay effect.

3.4.1 Simulation results

To verify the effectiveness of the proposed robust NCS design in real applications with significant time-varying delay, simulation results provided with the same sinusoidal command are analyzed for three different controllers: (1) PI controller, (2) PI with Smith predictor, and (3) PI with the adaptive Smith predictor. Due to the high gain of the encoder with 10000 *P/R*, coefficients of the PI controller are tuned as $K_p = 0.0002$ and $K_i = 0.00001$ to obtain satisfactory performance. Figure 3.7 shows that the PI-controlled system response becomes unstable as the delay time increases. Furthermore, the delay compensation of Smith predictor with a fixed delay time as shown in Fig. 3.7 (b) is not suitable as the delay time shown in Fig. 3.7 (d) increases. Moreover, the control performance of the adaptive Smith predictor as the delay time increases is much better than that of other methods as shown in Fig. 3.7 (c).

Moreover, the QFT controller obtained in Eqs. (3-9)-(3-10) is compared with the PI controller. Both were implemented with the same adaptive Smith predictor, as shown in Fig. 3.8. Simulation results indicate that the NCS performance is not seriously affected by the small time-delay variations. However, results show that the QFT controller obtains better performance as significant variation of the time delay occurs under the external disturbance.

3.4.2 Experimental results

The proposed QFT integrated with the adaptive Smith predictor and with the on-line RTT estimator was further tested on the Panasonic AC 400*W* servo motor and on the TI DSP 2812 microcontroller. The position controlled motor is located in the client node. When the vacant sampling occurs, the previous data are held to continue the operation. When two data messages arrive at the same sampling period, only the most recent data message is adopted, and all the previous data are discarded. Fig. 3.9 shows experimental results under different network loads. The measured network delay time around 10 *ms*, 100 *ms*, and 200 *ms* are categorized as low, medium, and heavy traffic jam, respectively. Tracking errors of different controllers are shown in Fig. 3.10. It is clear that the proposed QFT controller renders a lower root mean square (*RMS*) compared with the PI controller under a heavy network load.

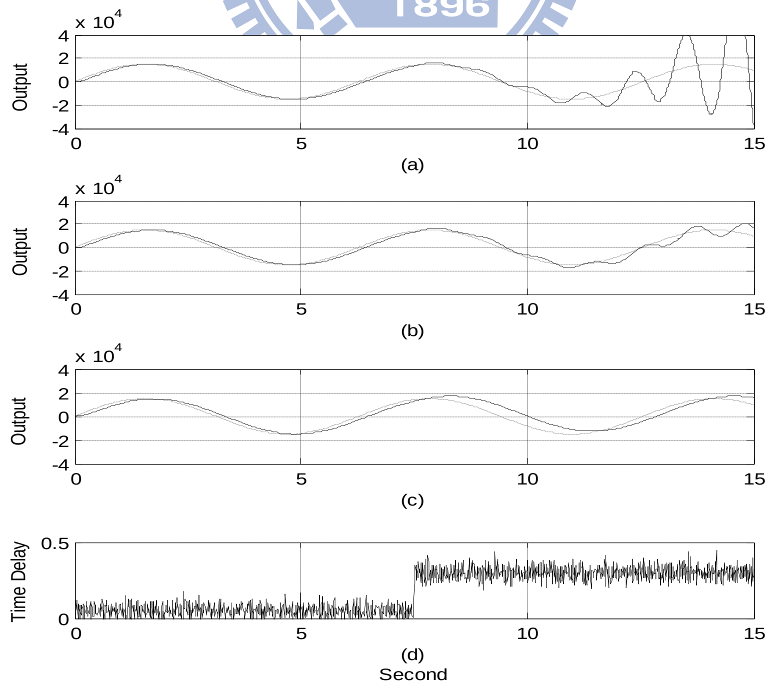


Fig. 3.7 Simulation sinusoidal responses of NCS for (a) PI controller, (b) PI + Smith predictor, and (c) PI + adaptive Smith predictor

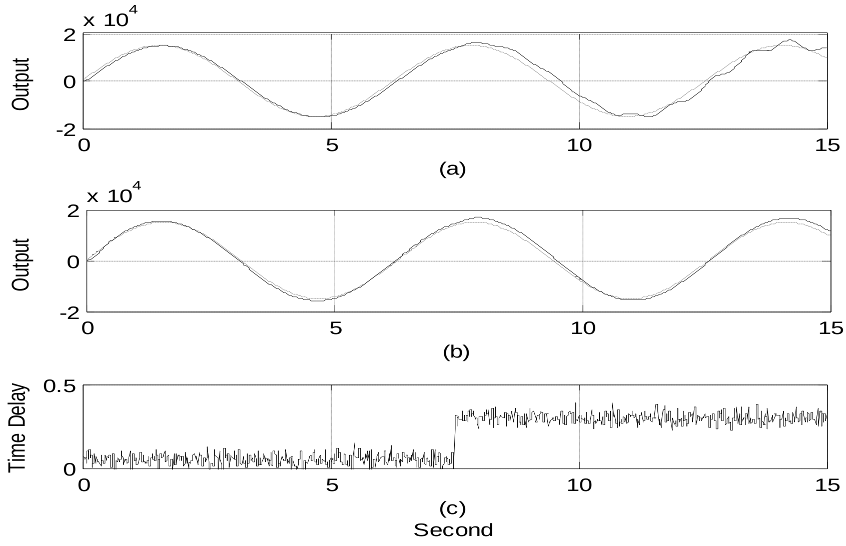


Fig. 3.8 Responses of (a) PI and (b) QFT, both applying the adaptive Smith predictor (with 1*J* payload variation)

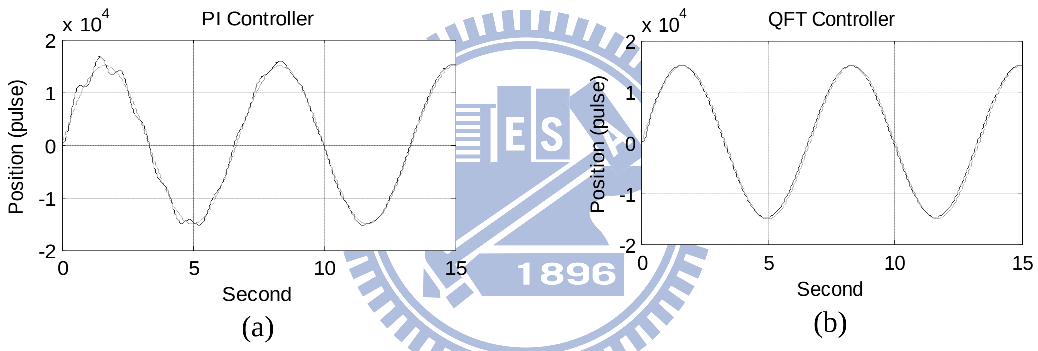


Fig. 3.9 Experimental results of the different controllers in heavy traffic load for (a) PI and (b) QFT

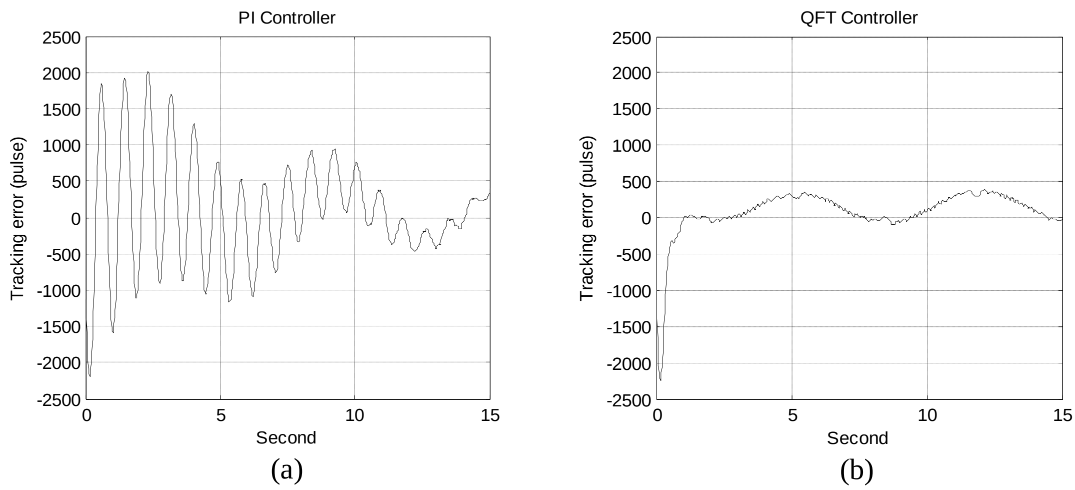
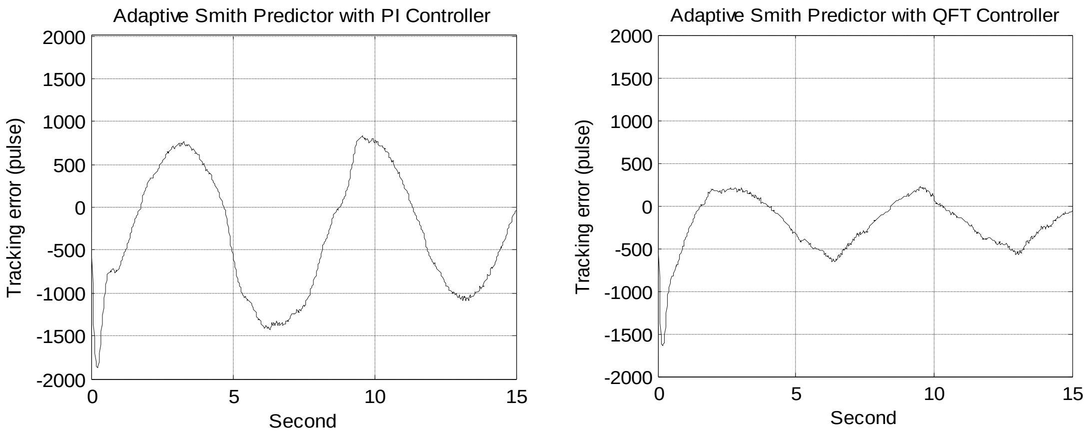


Fig. 3.10 Tracking errors of the different controllers in a high traffic load for (a) PI and (b) QFT



(a) (b)

Fig. 3.11 Tracking errors with the adaptive Smith predictor under the external disturbance (1*J*) in high traffic load with (a) PI and (b) QFT

The experiments with an extra ring (0.34 $kg \cdot cm^2$) attached to the motor (inertia of 0.36 $kg \cdot cm^2$) as the external disturbance were tested as illustrated in Fig. 3.11, while the tracking errors are illustrated in Fig. 3.11(a) and Fig. 3.11(b). Experimental results indicate that the proposed QFT controller with the adaptive Smith predictor renders better control responses against the variations of inertia.

Table 3.2 Comparison of tracking performance (without external disturbance)

	Network traffic load					
	Low		Median		High	
Controller	Tracking error (*RMS*)	Average delay (*ms*)	Tracking error (*RMS*)	Average delay (*ms*)	Tracking error (*RMS*)	Average delay (*ms*)
PI	7.6667	5.6546	11.5333	88.9199	18.6333	195.3013
QFT	8.2667	5.3885	6.3099	85.8398	3.8493	185.7958
PI +ASP	2.7000	5.8378	3.1333	93.9719	3.7333	185.8188
QFT+ASP	4.3667	6.03503	4.6333	93.8648	3.7233	190.1291

ASP : Adaptive Smith Predictor

As summarized in Table 3.2, control performance of all the different controllers is similar under a light traffic load with a relatively small network delay. As network delay increases, control performance of PI controller is degraded drastically. In contrast, the QFT controller maintains its performance well. Under a high traffic load, experimental results demonstrate the robustness of the proposed QFT controller with the adaptive Smith predictor, as shown in Table 3.3.

Table 3.3 Comparison of tracking performance (with external disturbance)

	Network traffic load					
	Low		Median		High	
Controller	Tracking error (*RMS*)	Average delay (*ms*)	Tracking error (*RMS*)	Average delay (*ms*)	Tracking error (*RMS*)	Average delay (*ms*)
PI +ASP	1.4667	12.5585	6.6000	94.6756	18.0667	188.004
QFT+ASP	5.6333	6.9912	4.0227	94.9469	6.1294	195.2883

3.5 Summary

(1) The proposed plant templates applying the QFT design are constructed by considering the network-delay variation in the phase and the external disturbance in the gain to achieve the robust NCS design.

(2) The QFT controller is more capable than the PI controller to deal with the bounded variation in the delay time with a stochastic nature, as shown in both simulation and experimental results.

(3) As the delay time becomes significant and unbounded, the designed robust NCS of QFT becomes unsuitable. Thus, an on-line delay estimator is proposed by including the adaptive Smith predictor to cope the unpredictable time delay on the network for remote control systems.

Chapter 4
Multi-rate Design for Wireless NCS

Industrial area networks generally provide short-distance applications in automation and manufacturing systems. To extend network-based applications to remote control systems, this study integrates the IEEE 802.11g ad-hoc wireless network and the control area network (CAN) as the hybrid networked control system (HNCS) by implementing a communication gateway between the two protocols. As network congestion of HNCS mainly occurs in the wireless system and its irregularly induced time delay seriously degrades its stability and performance, information of the wireless network time delay is crucial to the quality and stability of remote control systems. In this study, an on-line delay estimation algorithm with a short-window median filter is adopted for the adaptive Smith predictor in the HNCS design. Moreover, the sampling rate is automatically switched according to the estimated delay time as network congestion occurs to render the reliable control performance of HNCS. Analytical and experimental results have proven the feasibility of the present HNCS design to achieve a satisfactory remote control system under the serious time delay for the wireless network.

4.1 Design of the gateway for HNCS

Recently, the development of wireless NCS (WNCS) which reduces connection problems has attracted increasing attentions in the development of remote control systems and all sensors, actuators, and controllers are interconnected (Gast, 2002; Lian et al., 2001; Li, 2008). Moreover, the technology that integrates both commercial networks and industrial networks has resulted in easy maintenance and expendability for remote control systems (Sanchez et al., 2004; Yang et al., 2008). On the other hand, it has also led to time delays, data dropout, and package collision. Network time delays may be constant, bounded, stochastic, and even random or unpredictable depending on the network protocols and hardware. Basically, HNCS performance is inherently limited by its system sampling rate owing to the limited network bandwidth; moreover, it may easily become unstable because of unpredictable network delays in wireless communication, even with a robust control design. Therefore, the control design of HNCS in real applications should concern both time-invariant characteristics such as the plant dynamic model and the average time delay, and the time-varied characteristics such as the instantaneous time delay variation. To integrate different network protocols for an HNCS, the design of a gateway is required. A typical closed-loop NCS where the sensor and the actuator encounter different time delays induced in general network structures as shown in Fig. 4.1 and its real application in the present study is shown in Fig. 4.2. The transmission between the controller and its actuator input over a communication network introduces a command time delay t_1 into HNCS, and t_2 is the feedback delay time. The network time delay in fact includes the total transmission time of a message and the transformation time of the package. As shown in Fig. 4.1, the total time delay (round-trip time, RTT) can be explicitly expressed by the following:

$$t_{RTT} = t_1 + t_2 \tag{4-1}$$

where $t_1 = t_{command1} + t_{tf1} + t_{command2}$, $t_2 = t_{feedback1} + t_{tf2} + t_{feedback2}$

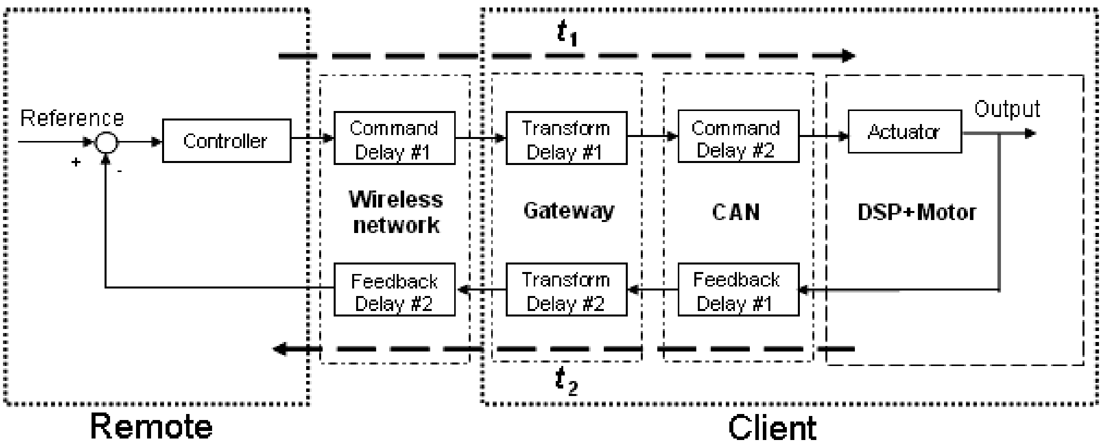
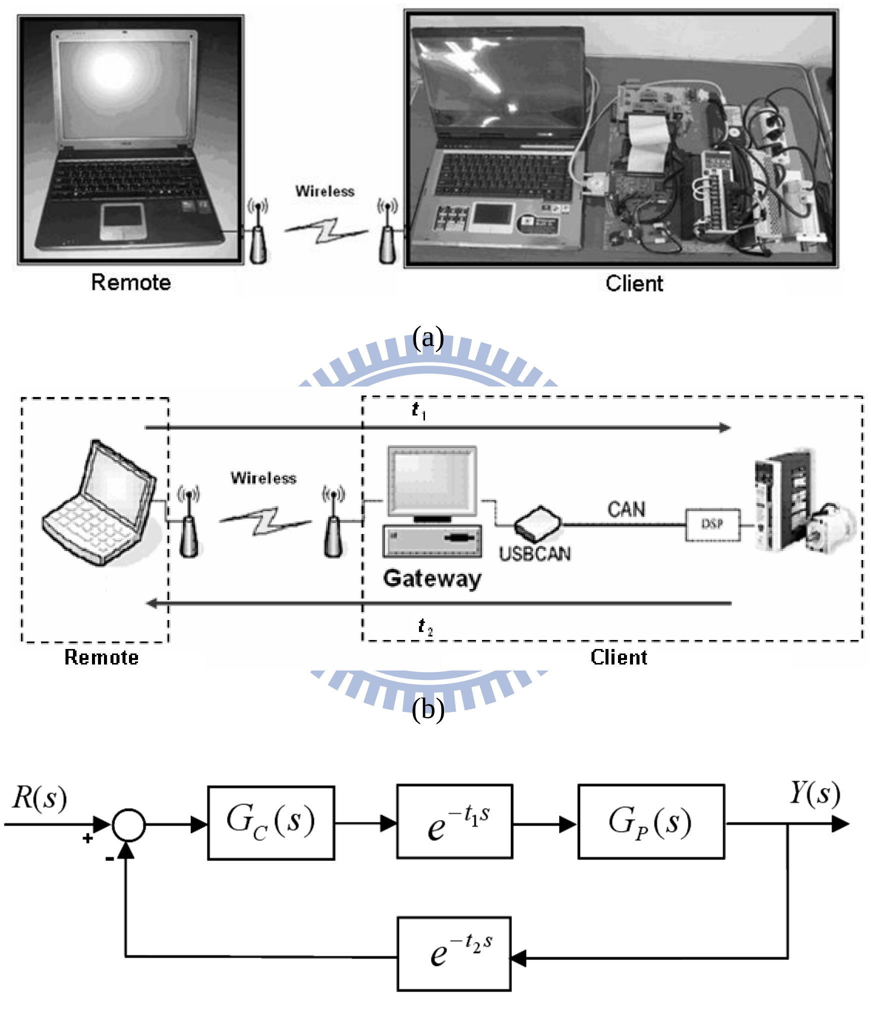


Fig. 4.1 The block diagram of HNCS

As shown in Figs. 4.2 (a) and (b), the present HNCS mainly comprises the remote node and the client node, and both nodes communicate with each other from a distance through the wireless network. The client node includes two parts; the first part is the gateway on a computer communication with the USBCAN, which is designed to communicate between the wireless network and the CAN bus (Nolte et al., 2005). The gateway is linked with TI TMS320F2812 DSP through the CAN network and the remote site is linked via the wireless network. The second part is the servo motor and its controller is implemented on TI TMS320F2812 DSP with a speed-control mode. Finally, the data communication protocol adopts the transmission control protocol (TCP) to achieve the desirable position loop control for the guaranteed eventual delivery of packets (Cheng et al., 2007).



(c)

Fig. 4.2 Experimental setup (a) experimental platform, (b) diagram of HNCS , and (c) the HNCS block diagram

The communication network can be modeled as the time delay on the forward-command direction for actuators and on the feedback direction for sensors. As shown in Fig. 4.2 (c), t_1 is the command delay time, t_2 is the feedback delay time, and

$G_c(s)$ is the controller. $G_p(s)$ denotes the transfer function of the plant without the delay time. The transfer function from input R to output Y is obtained as follows:

$$\frac{Y(s)}{R(s)} = \frac{G_c(s)G_p(s)e^{-t_1 s}}{1+G_c(s)G_p(s)e^{-(t_1+t_2)s}} \tag{4-2}$$

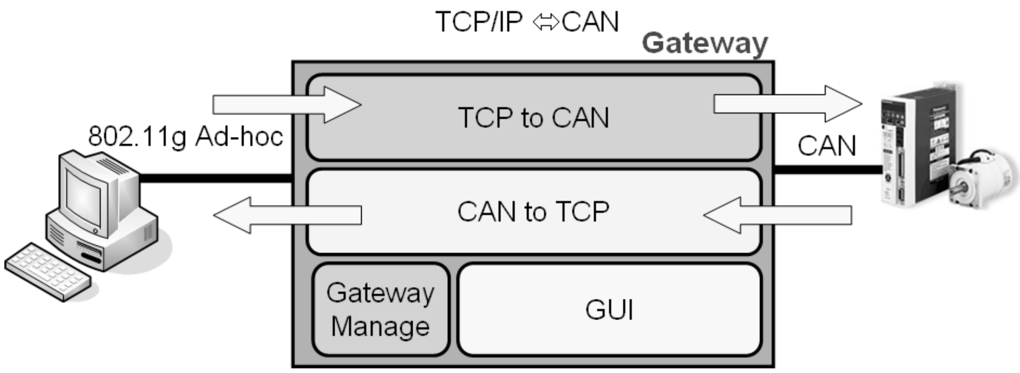


Fig. 4.3 The diagram block of the gateway between wireless 802.11g and CAN

4.1.1 The structure of the gateway

The CAN communication protocol is embedded in TI TMS320F2812 DSP and the data are transmitted to the remote node through the CAN bus and the wireless network with the TCP communication protocol. These two protocols, TCP and CAN, cannot communicate with each other directly, and thus message packages have to be processed through a gateway, as shown in Fig. 4.3. The block diagram of the proposed gateway is divided into four parts. The upper part accepts the CAN package from the CAN network, then this package is transferred through the wireless network; all packages are then sent to the remote site. The second part receives the TCP package from the wireless network and transfers the CAN package to the client with a DSP controller via the CAN network. The third part is the gateway management program which allows just one client to be connected through the communication channel at one time by sending the warning message to another node to avoid interference from other nodes. The fourth part is the operation interface for users, as shown in Fig. 4.3.

4.1.2 The procedure of the package transformation

In remote control systems, when data have to be transmitted to the client node with the CAN protocol, the type and transmission data in the data frame should be set up in advance. They are included in the CAN package transmitted to the gateway through the CAN network, as shown in Step 1 in Fig. 4.4. After the gateway receives the package from the CAN network, the data of the CAN package will be included in the TCP package, and the wireless network can thus be transmitted directly to the remote node as shown in Step 2. When the remote site has received the package from the wireless network, the message in the CAN package will be extracted from the TCP package, and the data defined by users can thus be obtained at the end of Step 3. The package transformation will analyze the data frame and follow the procedure (1) ➔(2) ➔(3) to transmit the message to a remote node. When data have to be transmitted from the remote node, the inverse procedure is followed: (4) ➔(5) ➔(6), as shown in the left part of Fig. 4.4.

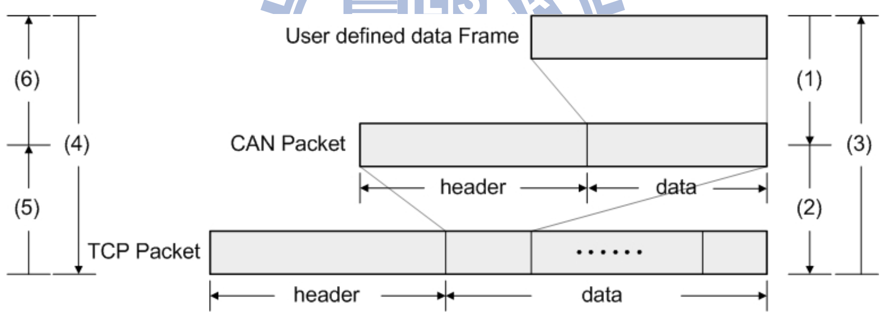


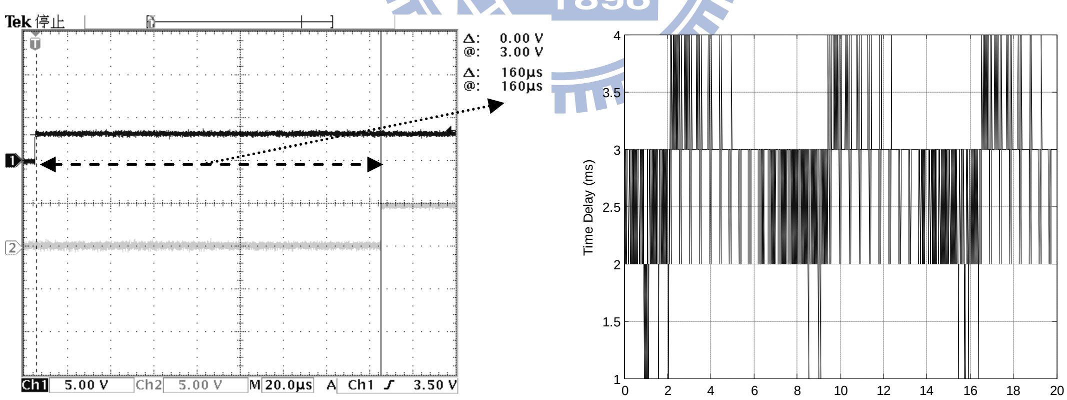
Fig. 4.4 The package transmission diagram

4.2 Analysis of time delay in HNCS

In general, the induced network time delay presents different characteristics depending on both the network hardware and protocols; moreover, it varies owing to network loading, scheduling policies, and the number of nodes. Research on HNCS is much more difficult than those on general delayed systems where the time delay is usually assumed to be constant or bounded. In this study, the total time delay in HNCS is categorized into three types as they occur at (1) the gateway node, (2) the network channel, and (3) the remote site. The summed time delay at each node actually includes all the network node preprocessing time, the controller computation time, the encoding time, the waiting time, the total queuing time, and the blocking time (Lian et al., 2002). The total time delay, also called the round-trip delay, is the required period for a packet to travel from the client node to the remote node and back to the original client node. The proposed networked control architecture combines both the time-driven and the event-driven processes and the typical NCS structure is the same as shown in Fig. 2.9(a).

4.2.1 Delay time analysis

The RTT is measured from the client node to the control center station through the gateway, and back to the original client node. In this experimental setup, a notebook computer with Intel® Pentium CPU 1.60 *GHz* was tested with 496 *MB* of RAM, Intel(R) PRO/Wireless 2200BG Network Connection Card, and with Windows XP Professional Version 2002 OS with Service Pack 2. For the CAN bus, the experimental results indicate that the time delay in the CAN bus is relatively small as compared to that of the wireless network, as shown in Fig. 4.5.



(a) (b)

Fig. 4.5 Measurement of the delay time on CAN network (a) the transmit time for a node-to-node and (b) the RTT between the gateway and the client

The time delays on both IEEE 802.11g ad-hoc wireless network and the CAN network (transmitted with different sampling rates and various environments) were measured as shown in Fig. 4.6, and the results are summarized in Tables 4.1- 4.2.

(a) (b)

Fig. 4.6 Measurements of time delay in (a) a simple environment and (b) a complex environment

Table 4.1 The averaged delay time of the hybrid networks in a simple environment (unit: *ms*)

Sampling Time	No. 1	No. 2	No. 3	No. 4
5 *ms*	2.807961	11659.09	2.474295	5574.375
10 *ms*	4453.212	5489.112	2910.771	3.897898
20 *ms*	20.2813	470.5569	23.0162	5590.872

Table 4.2 The averaged delay time of the hybrid networks in a complex environment. (unit: *ms*)

Sampling Time	No. 1	No. 2	No. 3	No. 4
5 *ms*	22797.18	15326.39	4855.466	22797.18
10 *ms*	7818.727	16693.98	8716.06	12349.45
20 *ms*	21.59492	21.16303	10726.56	535.6239
50 *ms*	37.0036	45.71434	44.39008	49.5021

The results indicate that different environments and sampling rates greatly affect the delay time of HNCS. Results also indicate that an increasing network load and longer messages lengths also cause a significant increase in the delay time. Furthermore, the delay time increases dramatically in a more complex environment with a faster sampling time. Too many wireless devices use a 2.4 *GHz* unlicensed band in our daily living environment. Owing to the limited bandwidth in wireless networks, most ad-hoc networks use a contention-based protocol for controlling channel access resource. Performance of wireless ad-hoc networks is thus poor because of network congestion with abundant medium contest. The previously mentioned definition of a transmission is then implemented using TCP. Due to network congestion, traffic load balancing, or other unpredictable network behavior, TCP detects these problems, requests the retransmission of lost packets, and rearranges out-of-order packets to reduce the occurrence of other problems. TCP sometimes incurs relatively long delays while waiting for out-of-order messages or retransmissions of lost messages. Therefore, the probability that the time delay in a complex environment is dramatically changed increases when it is under the same sampling time. Comparing the results of the CAN bus and wireless systems, it is obvious that no matter the environment is simple or complex, the time delay in wireless systems remains to be the bottleneck during the transmission for HNCS.

4.2.2 Stability of HNCS

Experiments were conducted for the present HNCS and the position controller was located on the control center station. The coefficients of PI controller were tuned as K_p=0.0001 and K_i=0.00000001. The system identification result from the pseudo random binary signal (PRBS) response for the present AC permanent magnet synchronous motor is obtained as

$$G_p(s) = \frac{10^5(0.029s + 1.6105)}{s(0.0001s^2 + 0.019s + 1)}$$

For the wireless 802.11g with a 54 *Mbps* transmission rate, the measured time delay is shown in Fig. 4.7. The results indicate that although the time delay effect in the wireless network is in a stochastic nature, it is basically bounded. For the client of the servo motor, the sampling time is 20 *ms* with a square wave command input and the upper/lower commands are 30000/15000 pulse of the encoder readout. As shown in Fig. 4.8, the communication congestion occurs around 4.5 seconds and note that the PI control cannot maintain a stable HNCS with a fixed sampling time under such circumstances. Analytical results of the Nyquist plot of the $L(s) = G_c G_p e^{-(t_1+t_2)s}$ by applying the first-order Padé approximation to the time delay are shown in Fig. 4.9. When t_m is greater than 100 *ms*, the Nyquist plot encloses -1, and the system becomes unstable.

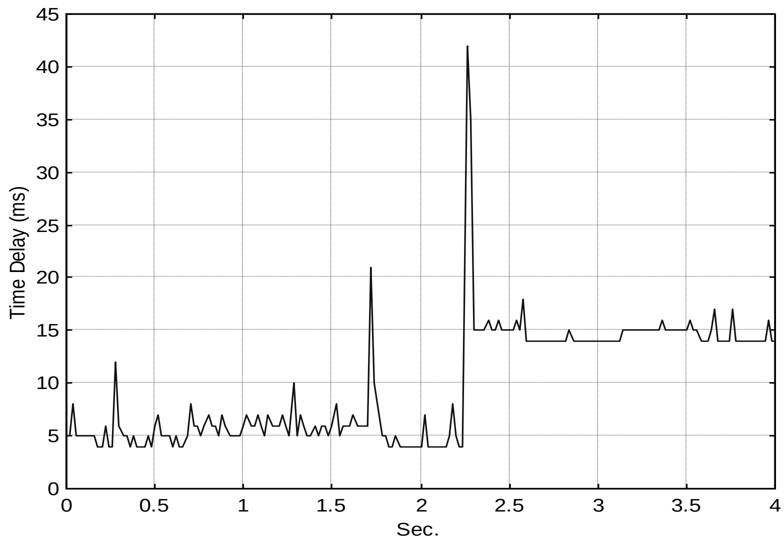


Fig. 4.7 The bounded time delay effect measured in HNCS

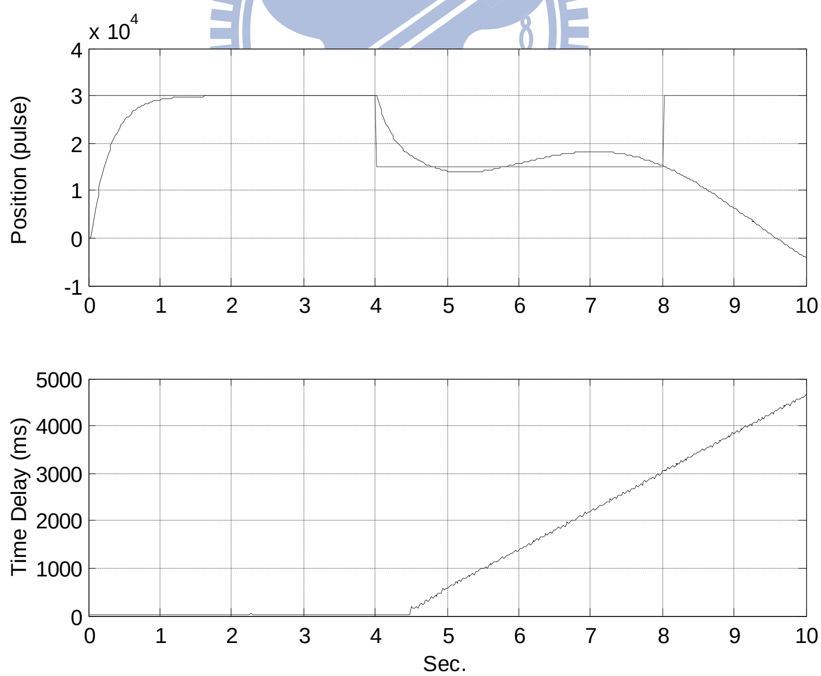


Fig. 4.8 The HNCS performance with the bounded time-delay effect (1 *s* ~ 4.5 *s*) and the unbounded time-delay effect (after 4.5 *s*)

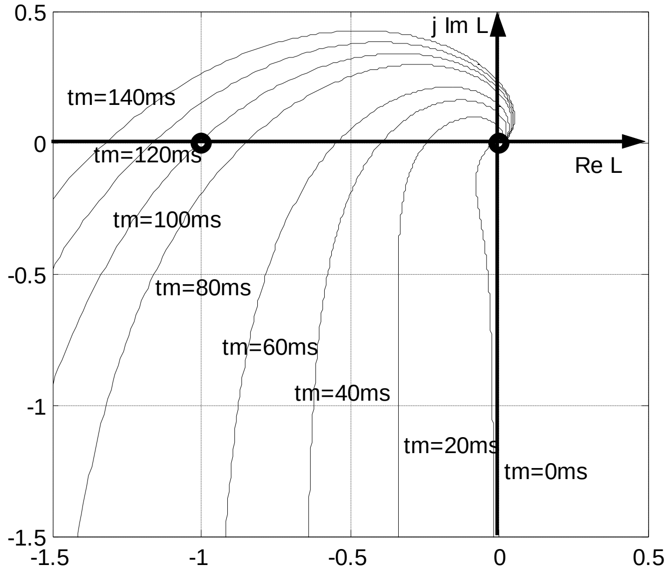


Fig. 4.9 Nyquist plots with different time delay

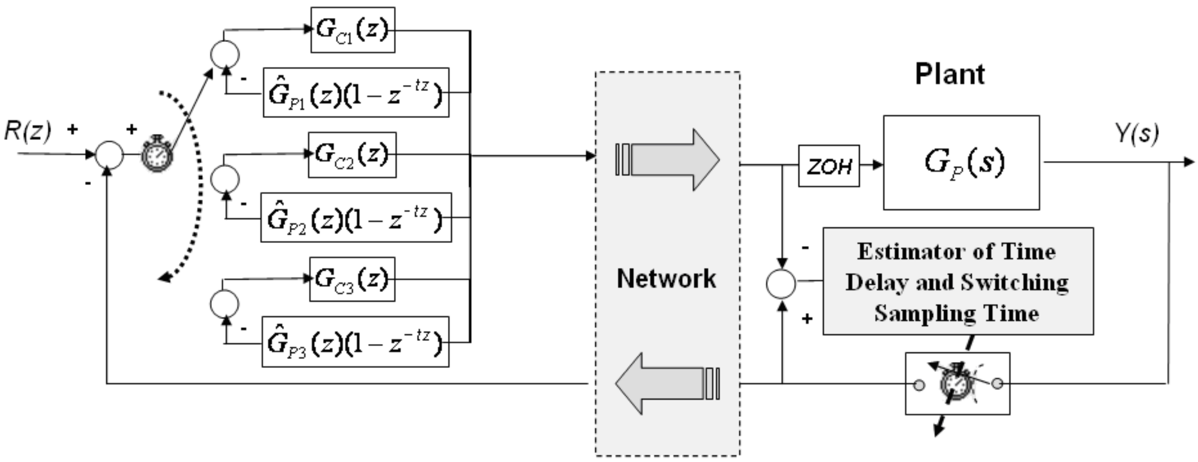


Fig. 4.10 Structure of the multi-rate design method

4.3 Multi-rate HNCS

As the time delay induced during transmission over the communication network is unavoidable and unpredictable, the control design of HNCS will mainly cope with the time delay that occurs irregularly. Traditionally, the Smith predictor has been applied successfully to industrial processes usually with a constant delay time model. However, because the time delay of the present HNCS is significantly varied, the delay must be estimated in real time for the proper implementation of the Smith predictor.

Furthermore, a multi-rate design method by applying both the adaptive Smith predictor and the switching sampling time based on the RTT is proposed here, as shown in Fig. 4.10.

4.3.1 The on-line estimation of the delay time

The procedure for estimating the delay time on the present HNCS is proposed here by applying the measurement of RTT. The delay measurement relies on RTT due to its easy implementation. It does not require clock synchronization between the sender and the receiver since corresponding computations are operated on the same device. The data length of CAN is limited to only 8 bytes for a single frame with the serial data communications bus, but the minimum data length to measure RTT is 10 bytes in the present experiment. Therefore, the measured data are sent at each half sampling period to overcome the limitation of the CAN network, as shown in Fig. 4.11. It is clear that the smaller the sampling period is, the more data packets are transmitted. This makes the network traffic load heavier and it thus increases the possibility of obtaining a greater constant time, and data loss increases in a bandwidth-limited network and time delays become longer (Lian et al., 2002). Basically, when a network is busy, the sampling time can be adjusted to a larger period so that the data can be transmitted on time. Therefore, the variable sampling period based on the online measured RTT to switch the sampling time is proposed in this chapter to avoid the network traffic jam and maintain satisfactory performance of NCS.

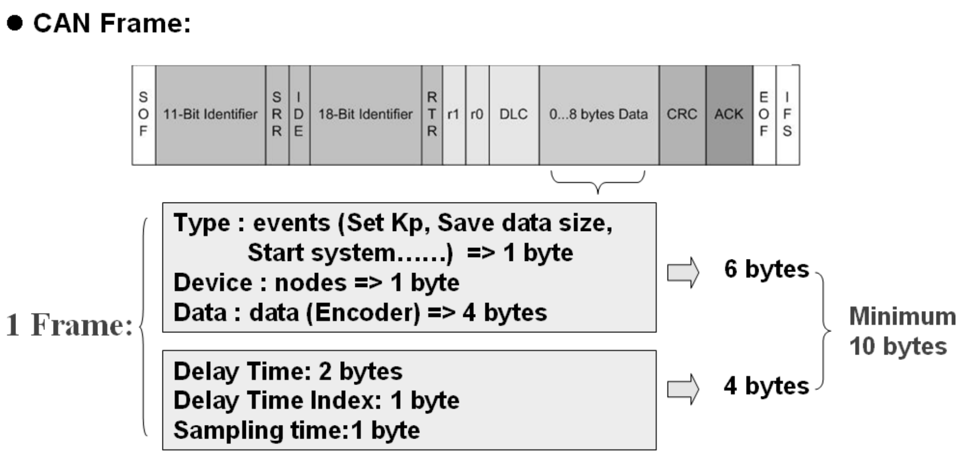
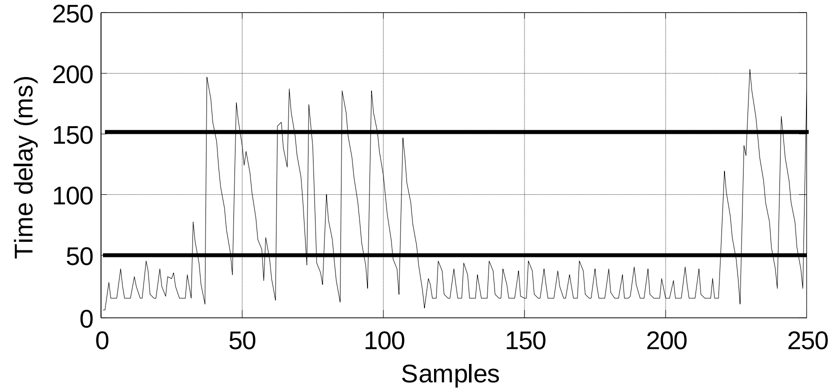
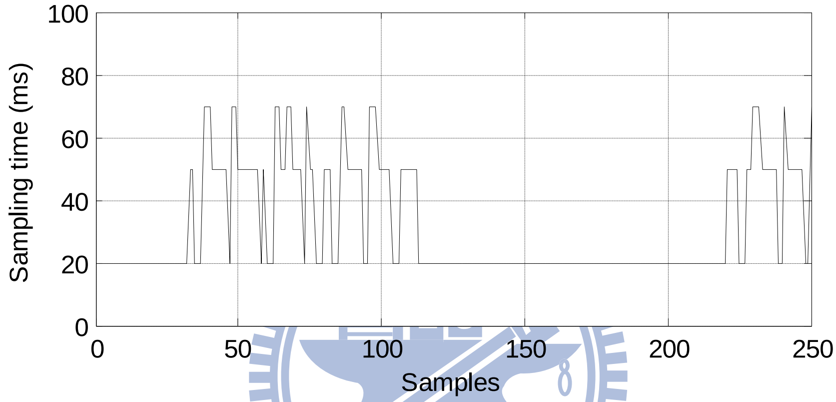


Fig. 4.11 The frame of the CAN network in the proposed HNCS.



(a)



(b)

Fig. 4.12 Experimental results (a) the measured time delay and (b) the switching the sampling time

4.3.2 Switching the sampling time

In wireless network systems, the delay time increases dramatically in a complex environment or faster sampling time is processed. The proposed switching sampling time strategy is designed mainly based on the estimated RTT to cope with serious network congestion. RTT is measured from the transmitting node to the receiving node and back to the transmitting node. The switching is based on the following algorithm:

$$\text{Sampling time } ST(k) = \begin{cases} 20\ ms, & \text{RTT}(k) < 50\ ms \\ 50\ ms, & 50\ ms \le \text{RTT}(k) \le 150\ ms \\ 70\ ms, & \text{RTT}(k) > 150\ ms \end{cases}$$

As shown in Fig. 4.12 and Table 4.3, experimental results indicate that the delay time is convergent and bounded by the proposed policy with the switching sampling time policy. The delay time under such arrangement is bounded within 200 *ms* four experiments.

Table 4.3 The averaged delay time by switching the sampling time

Switching sampling time based on RTT (unit: *ms*)				
Environment	No. 1	No. 2	No. 3	No. 4
Simple	132.3329	26.08322	179.6125	165.5099
Complex	168.0632	127.0632	193.15	174.3076

4.3.3 The short-window median filter

Since the online measured RTT is not reliable, a median filter which is a nonlinear digital filtering technique often used to remove noise from signals and reserve the interrupt change (Astola and Neuvo, 2002) is adopted. Thus, the present multi-rate HNCS will avoid frequent switching which may lead to improper compensation of the delay time adopted in the Smith predictor. The short-window median filter applied to the measured RTT removes the short-term variation of the measured delay time and maintains a relatively constant delay time. To obtain the output of a median filter, the sample values are sorted and the median value is used as the filter output shown as follows (Burian and Kuosmanen, 2002):

$$y[k] = Median\ [x(k-(N-1)), ..., x(k-3), x(k-2), x(k-1), x(k)] \tag{4-3}$$

where $x(k)$ and $y(k)$ are the *K-th* samples of the input and output sequences with a window length N, respectively. As shown in Fig. 4.13, as the numbers of sorted data N becomes larger, the switching times are reduced. The length N = 5 was suitably chosen with an elbow rule and the filtering results are shown in Fig. 4.14. Results indicate that the processed time delay can be more suitably adopted as the switching index for the sampling time.

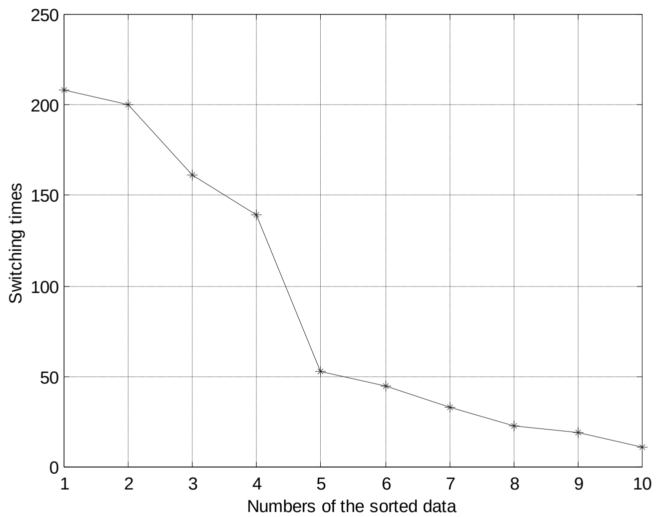


Fig. 4.13 The total switching times versus the window length

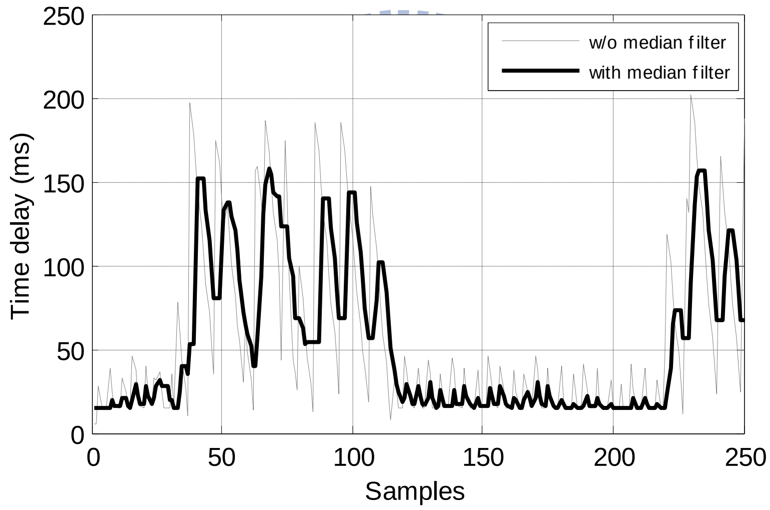


Fig. 4.14 The responses of estimation results applying the median filter (N=5)

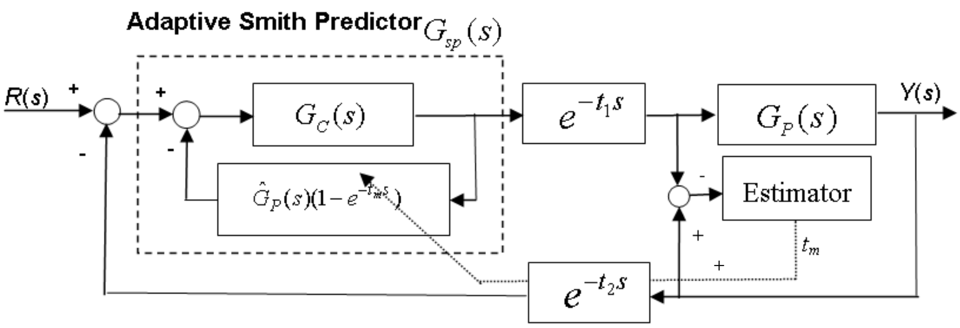


Fig. 4.15 The control structure of NCS with the adaptive Smith predictor

4.3.4 The adaptive Smith Predictor

Considering the system dynamics of HNCS, the Smith predictor can be properly adopted if the delay time is constant, as shown in Fig. 4.15. $G_{sp}(s)$ is the Smith predictor, $G_c(s)$ is the controller, $G_p(s)$ denotes the transfer function of the plant without the delay time, and $\hat{G}_p(s)$ is its nominal model (Peng et al., 2002; Sourdille and O'wyer, 2003). The forward transfer function of the system as shown in Fig. 4.19 is

$$G_{sp}(s) = \frac{G_c(s)}{1+(1-e^{-t_m s})\hat{G}_p(s)G_c(s)} \tag{4-4}$$

where t_m is estimation of the total delay time (RTT), t_1 is the command delay time of the network, and t_2 is the feedback delay time of the network. The closed-loop transfer function then becomes

$$\begin{aligned}\frac{Y(s)}{R(s)} &= \frac{G_c(s)e^{-t_1 s}G_p(s)}{1+\hat{G}_p(s)(1-e^{-t_m s})G_c(s)+G_c(s)e^{-t_1 s}G_p(s)e^{-t_2 s}} \\ &= \frac{G_c(s)G_p(s)e^{-t_1 s}}{1+\hat{G}_p(s)G_c(s)-\hat{G}_p(s)G_c(s)e^{-t_m s}+G_c(s)G_p(s)e^{-(t_1+t_2)s}}\end{aligned} \tag{4-5}$$

When $\hat{G}_p(s)=G_p(s)$ and $t_m = t_1 + t_2$, Equation (4-5) simply becomes

$$\frac{Y(s)}{R(s)} = \frac{G_c(s)G_p(s)e^{-t_1 s}}{1+G_c(s)G_p(s)} \tag{4-6}$$

Therefore, the dynamic filtered delay, $t_m = Median\,[RTT]$, can be adopted in the present control as the adaptive Smith predictor. Even as the delay time significantly increases, the present design can still handle the delay well in order to improve the stability and performance of the proposed HNCS.

4.4 Experimental results

The presently developed remote control system was applied to the Panasonic AC 400*W* servo motor. Both algorithms of the proposed adaptive Smith Predictor control and the switching sampling time with the on-line time-delay estimator were implemented on the TI DSP 2812 microcontroller (Lai et al., 2008). The position control loop is located on the remote/client site and the coefficients of PI controller were determined as $K_{p1} = K_{p2} = K_{p3} = 0.0001$, $K_{i1} = 0.00000001$, $K_{i2} = 0.000000025$, and $K_{i3} = 0.000000035$ When the vacant sampling occurs, the previous data are held; when two data messages arrive at the same sampling period, only the most recent data message is adopted and all the previous data are discarded. Different controllers were implemented and tested for the following three cases:

Case 1: the switching-time PI controller only,

Case 2: the classical Smith predictor with the switching-time PI, and

Case 3: the adaptive Smith predictor with the switching-time PI.

Experimental results with commands of a square wave 30000/15000 pulse indicate that the closed-loop HNCS without the Smith predictor is still stable as the delay time varied significantly by switching the sampling period, as shown in Fig. 4.16. By applying the Smith predictor with a fixed time delay, the results indicate that the delay effect is well compensated, but its performance still becomes worse as the delay increases, as shown in Fig. 4.17. The present adaptive Smith predictor with the switching sampling period obtains the best system stability and control performance, as shown in Fig. 4.18.

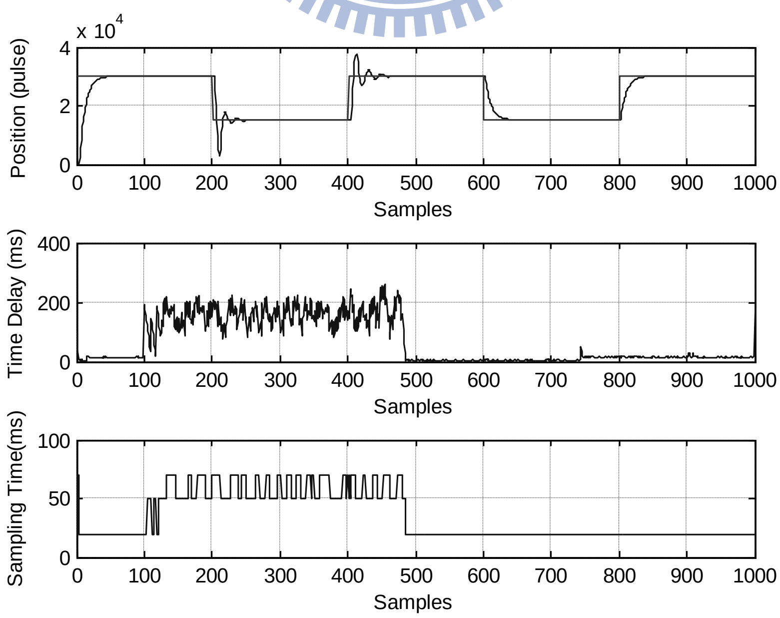


Fig. 4.16 Experimental results with the switching sampling time.

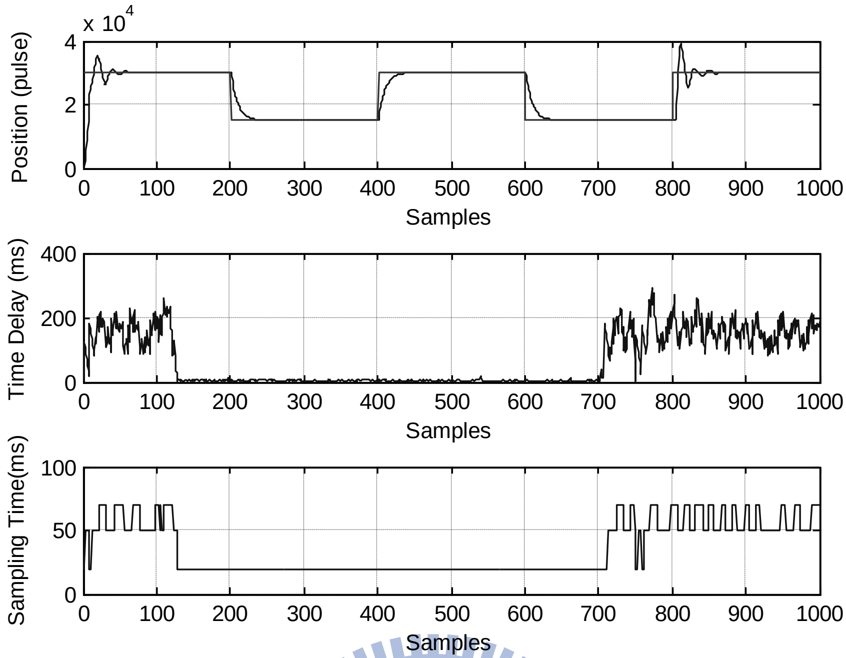


Fig. 4.17 Experimental results with a Smith predictor and the switching sampling time.

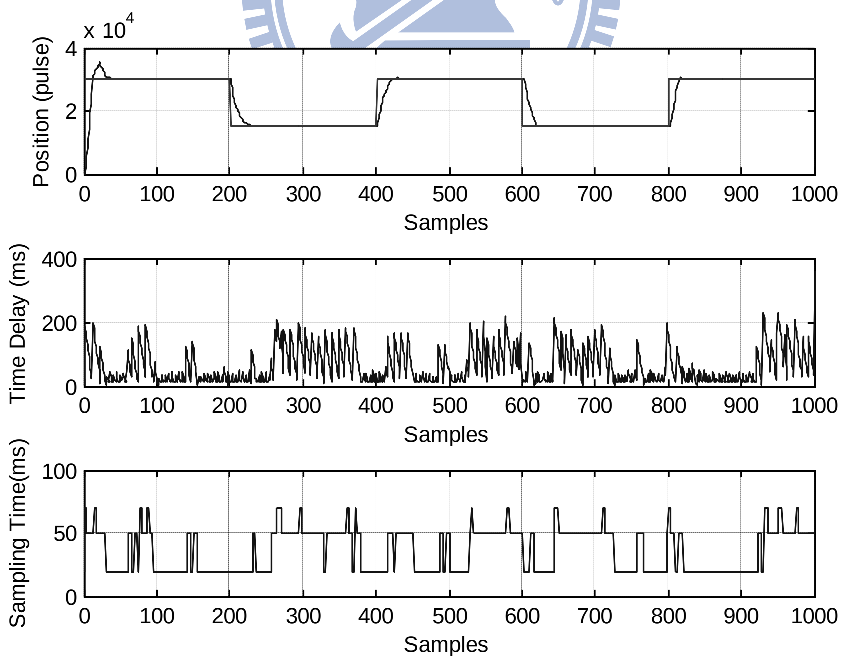


Fig. 4.18 Experimental results with an adaptive Smith predictor and the switching sampling time

4.5 Summary

The goal is to achieve improved stability and performance for remote control systems considering the network congestion effect in an ad-hoc wireless network. In this chapter, based on the online time delay estimated by applying the short-window medium filter, a multi-rate HNCS combining the adaptive Smith predictor is proposed for HNCS in this chapter. Experimental results are summarized as follows:

(1) The on-line estimation of time delay has been applied successfully to HNCS. By applying the short-window median filter, the smooth response of the estimation results was obtained and the unnecessary frequent change was thus avoided. Also, the immediate change of the different levels of delay was encountered in the present design.

(2) By applying the proposed switching sampling time, both congestion effect and stability of HNCS are improved in real applications.

Chapter 5
Model-free Perfect Delay Compensation Scheme

Most available networked control system (NCS) designs are developed with known system models and the delay time. However, such design approaches become impractical in real concerns due to the nature of significantly varied network- induced time delay, which in turn leads to a serious phase lag and jeopardizes the stability of NCS. To deal with the network- induced time delay, this study presents a novel NCS structure with the proposed perfect delay compensation (PDC) scheme. The PDC is a model-free approach and consists of only modified butterfly elements. Both analytical and simulation results in this chapter prove that the proposed model-free PDC scheme effectively compensates for the unknown and variable delay effects successfully even without information on the system model and the delay time. Furthermore, the proposed PDC is carried out using Ethernet tested from a 15 *Km* distance, and a well-tuned PI controller, obtained simply as a digital control for the AC servo motor, was directly networked to the NCS. Experimental results indicate that the significantly changed delay, measured as the round-time trip (RTT) in the range of 50 *ms* to 700 *ms*, is effectively handled to maintain a stable remote control system. Moreover, a notch filter precisely designed for vibration suppression, which is sensitive to its model of a flexible arm, was also directly applied at its remote node. Successful results indicate that as the time delay is significantly varied in real NCS applications, the proposed PDC renders satisfactory and desirable design results by considering all design procedures, implementation, and control performances.

5.1 Introduction

The challenges of NCS have attracted the attention of researchers in recent studies on time delay and packet loss. Lian et al. (2002) have identified several key components of the time delay to determine suitable sampling periods for the NCS. Nilsson (1998) has conducted an extensive work for the network-delay model with both forward and feedback delays formulated as a Markov chain process (Shi and Yu, 2009). The robust Smith predictor with the TCP model has also been implemented with the online measured RTT delay (Chen et al., 2007). Considering system modeling, robust methods and state feedback design are achieved generally assuming that the varied delay is relatively smaller than its system sampling time (Gao and Chen, 2008; Tang et al., 2008). Thus, those robust design results are merely suitable for NCS with a very small time delay, such as in the Intranet only within a limited range. The switched system to study asymptotical stability for a large but known time-delay model was also investigated (Xie et al, 2008; Li et al., 2009). A packet-based control framework has also been proposed with a sequence of control signals to be sent to compensate for the time delay with a known communication constraints (Yang et al., 2007; Zhao et al, 2009). In real remote control systems implemented in the Internet, the time delay, which usually varies depending on the number of user nodes and communication data loads, is relatively larger compared with the sampling time. Tipsuwan and Chow (2004) have proposed the use of a gain scheduler middleware (GSM) to adjust the controller gains externally at the controller output in order to maintain control performance and stabilize the system with respect to the current network traffic conditions with the measured RTT in real time. An adaptive Smith predictor was proposed to handle the problem on varying-time delays in accordance with an online estimated delay and an accurate system model (Lai and Hsu, 2010). A time-delayed control system with an unknown and fixed delay time based on network disturbance as the communication disturbance observer (CDOB) has also been proposed (Natori and Ohnishi, 2008).

Recently, the scattering transformation with known system model and controller has also been proposed to effectively compensate for unknown constant delays (Matiakis et al., 2009). Under the NCS structure with the scattering transformation, its closed-loop transfer function is equivalent to its original control design with a pure time delay item without considering the time delay. However, the design of that operator is not straightforward and the varied time-delay will not be compensated properly within the control loop in NCS.

In this chapter, the perfect delay compensation (PDC) with the butterfly elements is proposed to deal with unknown and varied time delay without considering the system model. Both simulation and experiments, performed on a remote control system with a servo motor from a 15 *Km* distance through the Ethernet, render satisfactory control performance to further indicate that the proposed PDC is feasible and reliable With the proposed PDC element in NCS, the remote control system can be realized directly from the digital control design. An example for suppressing vibration of a motor-driven flexible arm through the Internet has been successfully provided to prove that the precisely-designed control block can be directly applied to its NCS realization.

5.2 Background

As shown in Fig. 5.1, the transfer function of the closed-loop system without network-induced delay (t_1 and t_2) is obtained as follows:

$$G_o(s) = \frac{G_c(s)G_p(s)}{1+G_c(s)G_p(s)} \tag{5-1}$$

Moreover, the NCS communication network can be modeled as the time delays t_1 and t_2 on the forward direction for the controller and on the feedback direction for the sensor, respectively, and $G_p(s)$ denotes the transfer function of the plant without the delay time, and $G_c(s)$ is the controller, as shown in Fig. 5.1.

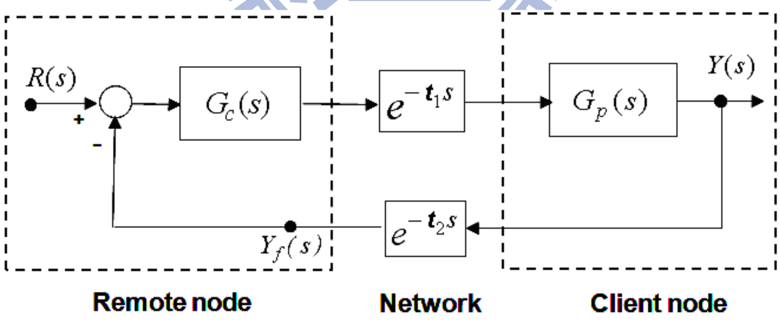


Fig. 5.1 The block diagram of the general NCS

The network-induced delays are different depending on the hardware and software used in the network. Most control designs for the time-delay NCS have been proposed with a known system model and a constant network-induced time delay. Traditionally, the known- delayed process can be effectively handled by applying the Smith predictor and eliminating the time-delay effect from its closed control loop. Furthermore, some methods have been proposed in real applications mainly in the adaptive Smith predictor

(Lai and Hsu, 2010), the communication disturbance observer (CDOB) (Natori and Ohnishi, 2008), and scattering transformation (Matiakis et al., 2009). Basically, all these methods require a system model or an online estimated time delay.

5.2.1 Adaptive Smith predictor

Compared with the Smith predictor with a fixed time delay, the adaptive Smith predictor is proposed with the online estimated time delay (t_m) to achieve an improved performance of NCS in real applications (Lai and Hsu, 2010). As shown in Fig. 5.2, its equivalent transfer function of the general NCS with an adaptive Smith predictor can be expressed by

$$G_{NCS}(s)=\frac{Y(s)}{R(s)}=\frac{G_c(s)G_p(s)e^{-t_1 s}}{1+\hat{G}_p(s)G_c(s)-\hat{G}_p(s)G_c(s)e^{-t_m s}+G_c(s)G_p(s)e^{-(t_1+t_2)s}} \tag{5-2}$$

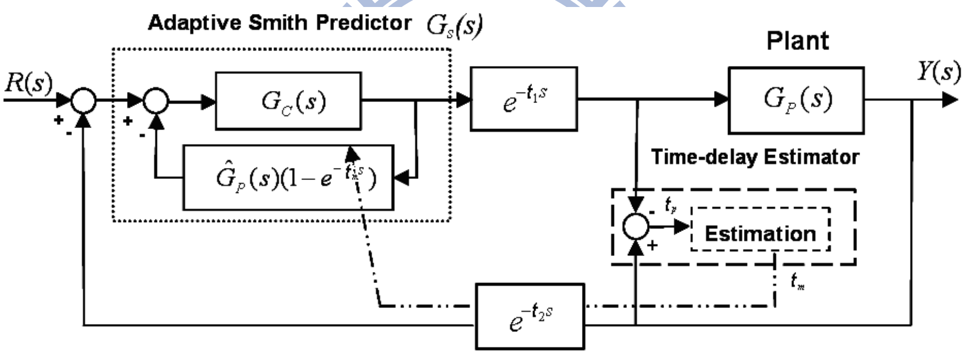


Fig. 5.2 The NCS with the adaptive Smith predictor (Lai and Hsu, 2010)

When the model $\hat{G}_p(s)$ is equal to the real system $G_p(s)$ and $t_m = t_1 + t_2$, the closed-loop NCS system $G_{NCS}(s)$ simply becomes the desirable closed-loop system $G_o(s)$ with a pure forward delay time t_1 as

$$G_{NCS}(s)=G_o(s)e^{-t_1 s} \tag{5-3}$$

Note that the Smith predictor design for NCS requires an accurate system model $\hat{G}_p(s)$ and a known time delay t_m. In real NCS, network-induced delays t_m vary significantly and it requires on-line measurement for the adaptive Smith predictor. In addition, because parameter uncertainties exist in both the system model and the time delay, a robust control design was preferred for the NCS with the adaptive Smith predictor to further improve performance (Natori and Ohnishi, 2008). However, given that the on-line measurement for the time delay consumes the bandwidth of network transmission and the system model is also varied in practice, Equation (5-3) may not be held and its performance is thus degraded compared with the original design without considering the network implementation.

5.2.2 Communication disturbance observer (CDOB)

A time-delay compensation method based on the communication disturbance observer (CDOB) has been proposed by Natori et al. (2008) to estimate and compensate for the delay effect. CDOB obtains desirable closed-loop system performance with a pure delay term as shown in Fig. 3. Based on the known the system model, the time delay $t_p = t_1 + t_2$ is thus formulated as disturbance and expressed by

$$D_{net}(s) = U(s) - U(s)e^{-t_p s} \quad \text{and} \tag{5-4}$$

$$d_{net}(t) = d(t) - d(t - t_p) \tag{5-5}$$

The state space equations for the NCS are then obtained as follows

$$\begin{aligned} \dot{x}(t) &= Ax(t) + Bu(t) - Bd_{net}(t) \\ y(t) &= Cx(t) \end{aligned} \tag{5-6}$$

If the disturbance item is accurately estimated, the effect of the delay in NCS can be properly eliminated as shown in Fig. 5.3. Thus, with a general DOB algorithm (Natori and Ohnishi, 2008), the equivalent transfer function of NCS with the CDOB is obtained as

$$G_{NCS}(s) = \frac{Y(s)}{R(s)} = C(sI - A)^{-1}Be^{-t_p s} = G_o(s)e^{-t_p s} = G_o(s)e^{-(t_1+t_2)s} \tag{5-7}$$

In practice, oscillation and noise exist in the output $y(t)$ of CDOB as in Fig. 5.3 because it is actually measured at the output $y_f(t)$, however, it is contaminated by the feedback time-varying delay t_2 as shown in Fig. 5.1.

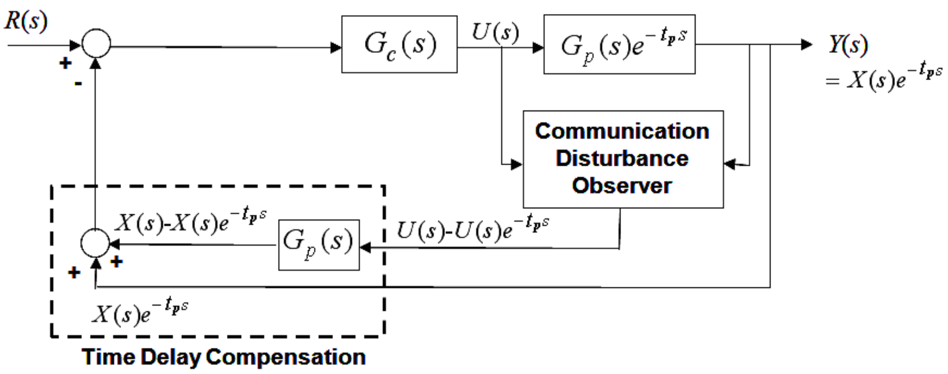


Fig. 5.3 The block diagram of CDOB (Natori and Ohnishi, 2008)

5.2.3 Scattering transformation

The scattering transformation is recently proposed to deal with an unknown constant time delay (Matiakis et al., 2009), as shown in Fig. 5.4. The transfer function of the closed loop system is obtained as follows

$$\frac{Y(s)}{R(s)} = \frac{G_c(s)G_p(s)}{1+G_c(s)G_p(s)} \times \frac{2e^{-t_1 s}}{K(s)(1-e^{-(t_1+t_2)s})+(1+e^{-(t_1+t_2)s})} \tag{5-8}$$

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

If $K(s) = 1$ holds with a suitable b, the closed loop transfer function of NCS is reduced to

$$G_{NCS}(s) = \frac{G_c(s)G_p(s)}{1+G_c(s)G_p(s)}e^{-t_1 s} = G_o(s)e^{-t_1 s} \tag{5-9}$$

With a constant time delay t_1, the scattering transformation results in equivalent behaviors as those shown in (5-3) and (5-7). Moreover, compared with the adaptive Smith predictor and CDOB, the scattering transformation does not need the time-delay model. However, it is difficult to make $K(s)$ equal to one for all s. If $K(s)\neq 1$, performance of the scattering transformation is thus degraded.

All the aforementioned methods require an accurate system model; some of them require that the time delay is known and constant. These requirements are impractical since in real NCS, the system model is uncertain and the time delay is unknown and significantly varied. Thus it is desirable to design a network time-delay compensation scheme based on neither the time delay model nor the system model.

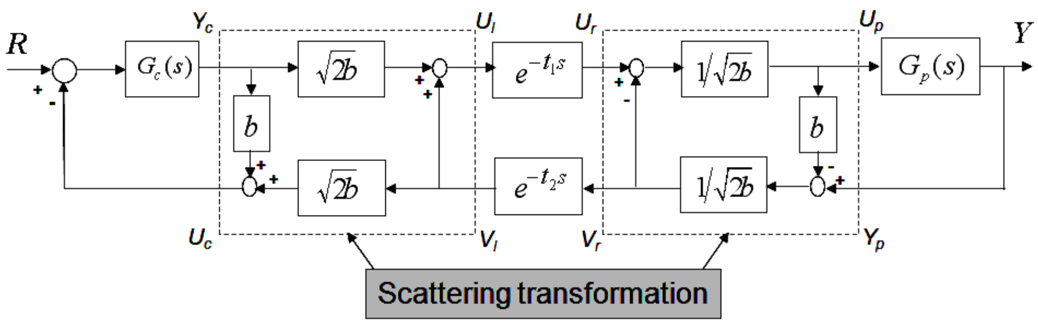


Fig. 5.4 NCS with scattering transformation (Matiakis et al., 2009)

5.3 Perfect delay compensation

Our survey of previous methods has shown that network time-delay compensation should be designed without including the time-delay model, since network time delay significantly varies due to all the varied network loads, scheduling, number of nodes, and protocols. As the time delay induced during the transmission over the communication network, it becomes more unpredictable. Also, the data dropout becomes more irregular and the NCS control design based on a nominal model with a known delay time also becomes invalid. In this study, the PDC with the modified butterfly elements is proposed to effectively deal with network-induced delays requiring neither the delay time model nor the plant model.

5.3.1 The delay compensation operator

The architecture of the scattering transformation uses the passivity formalism and concepts from network theory to construct a passive block with the interconnection element as shown in Fig. 5.4.

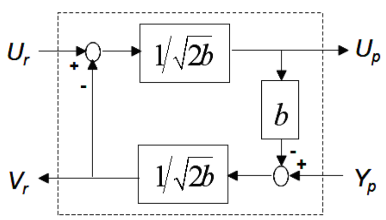


Fig. 5.5 The scattering transformation (Matiakis et al., 2009)

Based on the condition of the delay compensation operator guaranteed passivity of the network block, which is independent of networks, the scattering transformation shown in Fig. 5.5 are given as

$$U_r = \frac{bU_p + Y_p}{\sqrt{2b}}; \; V_r = \frac{Y_p - bU_p}{\sqrt{2b}} \tag{5-10}$$

The transfer function from input U_r to output V_r is obtained as

$$G_r(s) = \frac{V_r(s)}{U_r(s)} = \frac{\left(Y_p - bU_p\right)\Big/\sqrt{2b}}{\left(bU_p + Y_p\right)\Big/\sqrt{2b}} = \frac{G_p(s) - b}{G_p(s) + b} \tag{5-11}$$

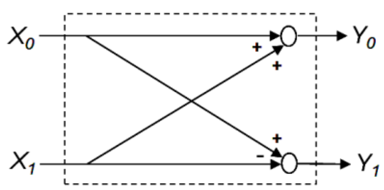
where $G_p(s) = \dfrac{Y_p(s)}{U_p(s)}$

Positive realness is an equivalent notion to passivity for linear time-invariant (LTI) systems in the frequency domain. In the case of $b > 0$, a transfer function $G_r(s)$ is positive real if and only if the H_∞ norm of the scattering operator is less than or equal to one (Matiakis et al., 2009). Given that the passivity condition is satisfied, the input/output behavior is considered as a passive system. With a suitably designed b and $K(s) = 1$, the NCS becomes a desirable closed-loop control system with a pure delay term. Note that b is not easily obtained, and the system model for the plant is required in this structure. As the delay time varies in a real application, the $K(s) = 1$ does not hold and Eq. (5-9) of the scattering transformation could not be valid in practice.

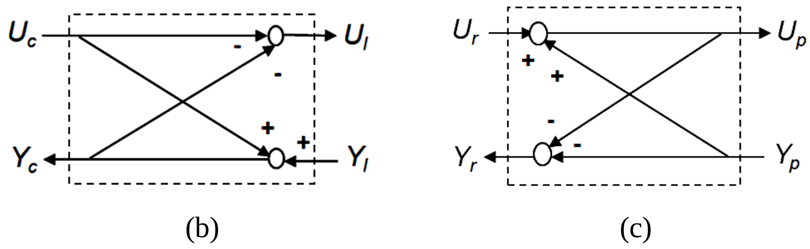
5.3.2 Modified butterfly element

According to the basic concept of scattering transformation, the modified butterfly element is proposed in the present PDC design for delay compensation. The butterfly elements are the basic blocks in the FFT/IFFT processor, as shown in Fig. 5.6(a), which are used to save computations with inputs (X_0, X_1) and outputs (Y_0, Y_1) as follows:

$$Y_0 = X_0 + X_1 \; ; \; Y_1 = X_0 - X_1 \tag{5-12}$$



(a)



(b) (c)

Fig. 5.6 (a) Butterfly element, (b) modified anti-butterfly element, and (c) modified butterfly element

A novel design for PDC is proposed here to modify the butterfly element by reversing two interconnections, as shown in Figs. 5.6 (b) and (c). The modified butterfly element is applied to the passive communication network as follows:

$$U_p(s) = U_r(s) + Y_p(s)\,;\;\; Y_r(s) = -U_p(s) - Y_p(s) \tag{5-13}$$

Thus, the transfer function from input U_r to output Y_r becomes

$$\frac{Y_r(s)}{U_r(s)} = \frac{-U_p(s) - Y_p(s)}{U_p(s) - Y_p(s)} = \frac{G_p(s) - 1}{G_p(s) + 1}\,,\;\text{where}\;\; G_p(s) = \frac{-Y_p(s)}{U_p(s)} \tag{5-14}$$

The formulation of the modified butterfly element is similar to the scattering transformation as shown in Eq. (5-11). However, the modified butterfly element can be directly obtained with much easier design and realization.

To simplify the derivation of PDC, the control structure, as shown in the right of Fig. 5.7, is first located in the client node. The modified butterfly and anti-butterfly elements are implemented in both sides of the network. Note that both butterfly elements are implemented without knowing any delay information of the network communication.

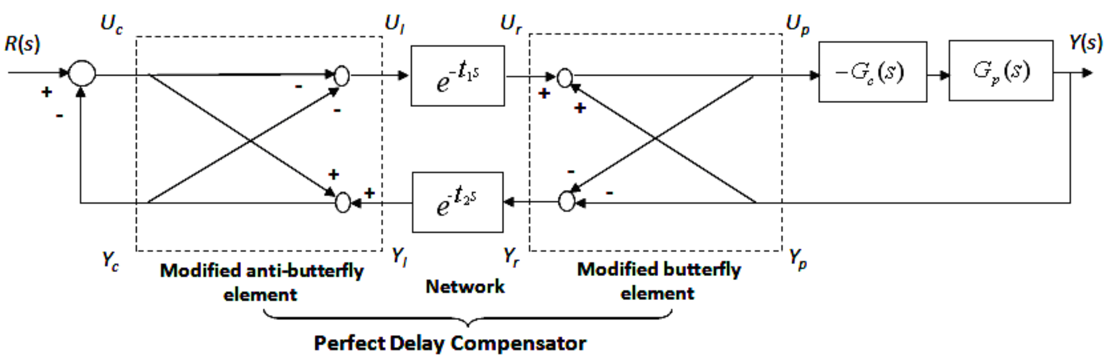


Fig. 5.7 The control structure with PDC in the proposed NCS

Similarly, the output transformation equations of modified butterfly element can be obtained as follows:

$$U_p(s)=U_r(s)+Y_p(s)\,;\quad Y_r(s)=-U_p(s)-Y_p(s) \tag{5-15}$$

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

$$\frac{Y_r(s)}{U_r(s)}=\frac{-U_p(s)-Y_p(s)}{U_p(s)-Y_p(s)}=\frac{G_c(s)G_p(s)-1}{G_c(s)G_p(s)+1} \tag{5-16}$$

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

To analyze the effects of the proposed structure, the signal flow is characterized by considering the relationship between the modified butterfly element and the anti-butterfly element. Figure 5.7 shows the open-loop transfer function between the input U_c and the output Y_c, which are on the left of the element and can be expressed as follows:

$$\frac{Y_c(s)}{U_c(s)}=\frac{(1+G_c(s)G_p(s))-(G_c(s)G_p(s)-1)e^{-(t_1+t_2)s}}{(1+G_c(s)G_p(s))+(G_c(s)G_p(s)-1)e^{-(t_1+t_2)s}} \tag{5-17}$$

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

$$\frac{Y_c(s)}{R(s)}=\frac{(1+G_c(s)G_p(s))-(G_c(s)G_p(s)-1)e^{-(t_1+t_2)s}}{2(1+G_c(s)G_p(s))} \tag{5-18}$$

Combining Eq. (5-17) with Eq. (5-18) yields:

$$U_c(s)=R(s)-Y_c(s)\quad\text{and} \tag{5-19}$$

$$(-U_p(s)-Y_p(s))e^{-t_2s}+U_c(s)=Y_c(s) \tag{5-20}$$

By integrating Eqs. (5-18) and (5-19) into Eq. (5-20), the transfer function of the close-loop system of the present NCS with the PDC structure can be directly obtained as follows:

$$G_{NCS}(s)=\frac{Y(s)}{R(s)}=\frac{G_c(s)G_p(s)e^{-t_1s}}{1+G_c(s)G_p(s)}=G_o(s)e^{-t_1s} \tag{5-21}$$

Equation (5-21) shows that the complicated NCS with delay time now becomes two simple parts: (a) the desirable transfer function of the system $G_o(s)$ without the delay time and (b) the pure time delay t_1, as in Eq. (5-21). There is no time-delay effect in the closed loop of the NCS, and the stability obtained without considering the network in $G_o(s)$ can be thus properly maintained in the implementation with NCS for remote control systems.

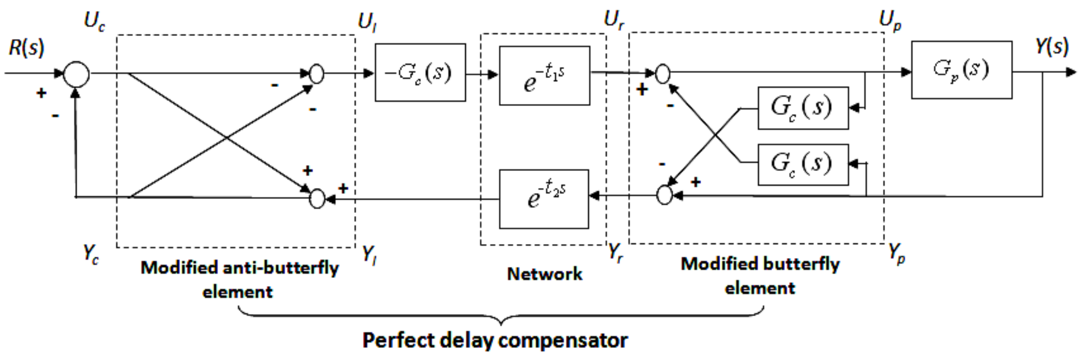


Fig. 5.8 The control structure with PDC in the general NCS

5.3.3 The general element of PDC in NCS

Without losing generality, the controller $G_c(s)$ in the client node with PDC is extended to a general NCS by implementing the controller in the remote node, as shown in Fig. 5.8. The output equations of the modified butterfly element can also be expressed as

$$U_p(s)=U_r(s)-G_c(s)Y_p(s)\,;\;\; Y_r(s)=-G_c(s)U_p(s)+Y_p(s) \tag{5-22}$$

The transfer function from input U_r to output Y_r becomes

$$\frac{Y_r(s)}{U_r(s)}=\frac{-G_c(s)U_p(s)+Y_p(s)}{U_p(s)+G_c(s)Y_p(s)}=\frac{G_p(s)-G_c(s)}{1+G_c(s)G_p(s)} \tag{5-23}$$

where $\frac{Y_p(s)}{U_p(s)}=G_p(s)$. As shown in Fig. 5.8, the transfer function of input U_c to output Y_c on the left of element can be expressed as

$$\frac{Y_c(s)}{U_c(s)}=\frac{(1+G_c(s)G_p(s))+G_c(s)(G_p(s)-G_c(s))e^{-(t_1+t_2)s}}{(1+G_c(s)G_p(s))-G_c(s)(G_p(s)-G_c(s))e^{-(t_1+t_2)s}} \tag{5-24}$$

Also, the transfer function of the open-loop system can be expressed by

$$\frac{Y_c(s)}{R(s)}=\frac{(1+G_c(s)G_p(s))-G_c(s)(G_p(s)-G_c(s))e^{-(t_1+t_2)s}}{2(1+G_c(s)G_p(s))} \tag{5-25}$$

Thus, the transfer function of the close-loop NCS can be obtained by:

$$G_{NCS}(s)=\frac{Y(s)}{R(s)}=\frac{G_c(s)G_p(s)e^{-t_1s}}{1+G_c(s)G_p(s)}=G_o(s)e^{-t_1s} \tag{5-26}$$

Equation (5-26) also shows that the equivalent system presents the same desirable closed-loop transfer function $G_o(s)$ with the pure forward delay time t_1. Note that the controller $G_c(s)$ is originally designed for the system without the network implementation. The feedback time delay t_2 will not affect the output response of the present NCS with the PDC structure. For example, considering the worst case if the feedback loop is disconnected and t_2 is infinite and the forward path is still in normal operation with the delay t_1, the transfer function of the close-loop system of the proposed NCS with PDC becomes

$$G_{NCS}(s)=\frac{Y(s)}{R(s)}=\frac{G_c(s)G_p(s)e^{-t_1s}}{1+G_c(s)G_p(s)}=G_o(s)e^{-t_1s} \tag{5-27}$$

It is reasonably indicate that the proposed structure still maintains its original closed-loop control performance with a pure delay t_1, and the forward path in the network only possess the function of sending the forward command message.

5.4 Simulation

In this section, an example is considered to illustrate the effectiveness of the proposed PDC. By applying equal forward and feedback time delays $t_1 = t_2 = (RTT/2)$, both conditions of constant and varied time delays were tested with the plant $G_p(s)=73/(s^2+10.15\,s)$ as provided by (Matiakis et al., 2009), and the lead-lag controller is obtained as $G_c(s)=1.3981(s+9.9114)/(s+9.1558)$ with b = 0.6203. In the constant time $t_1 = t_2 = 200$ *ms* as shown in Fig. 5.9 (a), simulation results indicate that NCS performance had a slower response and less overshoot by applying the scattering transformation shown in Fig. 5.9 (b). The original design leads to 147 *ms* rise time and zero steady-state error. As summarized in Table 5.1, due to the fact that $K(s)$ is not equal to unit through the whole frequency range. Its 254.8 *ms* rise time becomes slower with a 0.013 steady-state error. On the other hand, the NCS with the PDC presents the same system performance (rise time = 147 *ms*, overshoot = 19.2 %, and steady-state error = 0) without the network delay effect and only with a pure delay 200 *ms*. In the time-varying case as shown Fig. 5.10 (a), an online measured time delay RTT in real network was used. The results also showed that the system response became unstable using scattering transformation as shown Fig. 5.10 (b). In addition, the PDC obtained better performance as shown Fig. 5.10 (c). Note that the PDC with varied time delay maintained its original performance with a pure delay.

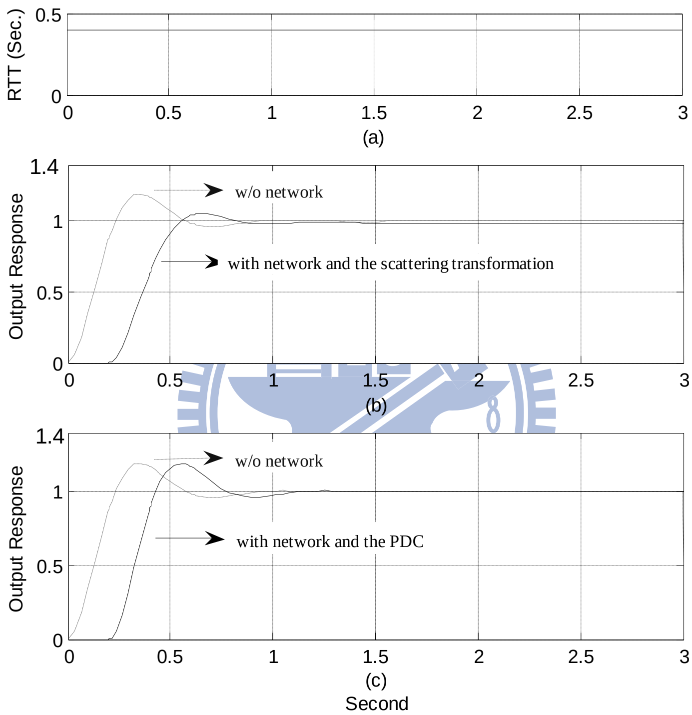


Fig. 5.9 Simulation results of the NCS for (a) constant time delay (RTT = 400 *ms*) with (b) scattering transformation and (c) PDC

Table 5.1 Comparison of control performance under different methods

Methods	Rise time (*ms*)	Overshoot (%)	Steady-state error
Original design w/o network	145.54	19.3	0
Scattering transformation	254.8	5.4	0.013
PDC	147.0	19.2	0

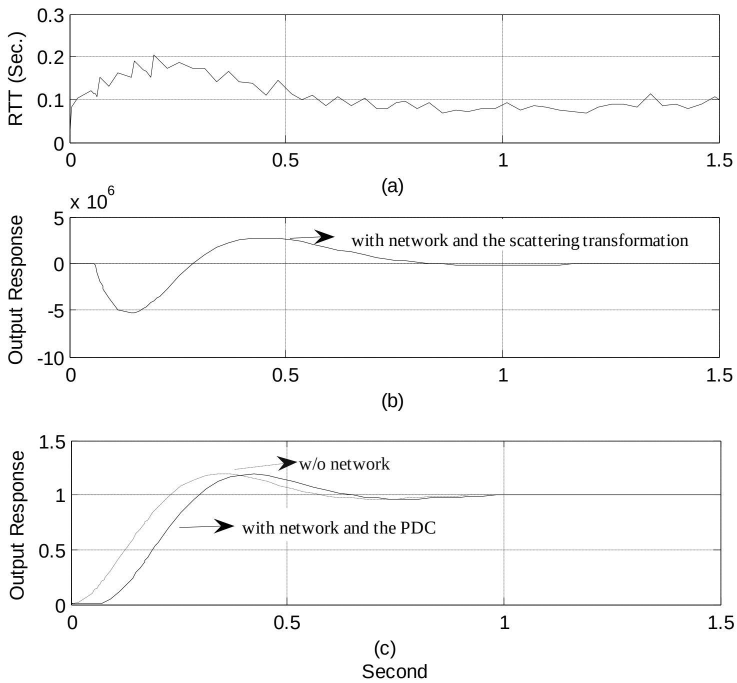


Fig. 5.10 (a) Time-varying delay, (b) NCS with scattering transformation, and (c) NCS with PDC

Accordingly, the following summaries are obtained as.

(1) To deal with significantly varied RTT in NCS, the adaptive Smith predictor required both an accurate system model and the online measured time delay, thereby increasing the cost of implementation.

(2) The CDOB method was proposed without providing time-delay information; however, it still required the system model in the design. When the delay time was varied, the CDOB showed a degraded output performance.

(3) The scattering transformation renders satisfying results with a steady-state error when the delay time is constant, as shown in Fig. 5.9(b). Moreover, scattering transformation is not applicable to real conditions of NCS with varied time delay.

(4) The proposed PDC successfully deals with network-induced delay without information from either the time delay or the system model. Moreover, the proposed method is easily implemented in NCS, as shown in Figs. 5.7 and 5.8.

(5) As shown in Table 5.2, comparison of the four NCS design approaches clearly indicates the superiority of the proposed method with PDC.

Table 5.2 Comparison of the four NCS approaches

	Design Requirement	**Implementation Cost**	**Varied Time Delay**	**Robust** (variation of the G_p or T_m)	**Control Performance**	**Direct Networking**
Adaptive Smith Predictor	X (known G_p and T_m)	X (online measurement T_m)	√	X	√	X
CDOB	X (known G_p)	X (computation)	X (oscillation)	X	√	X
Scattering Transformation	X (known G_p and G_c ; $K(s) = 1$)	√	X ($K(s) = 1$)	X ($K(s) \neq 1$)	X	X
PDC	√	√	√	√	√	√

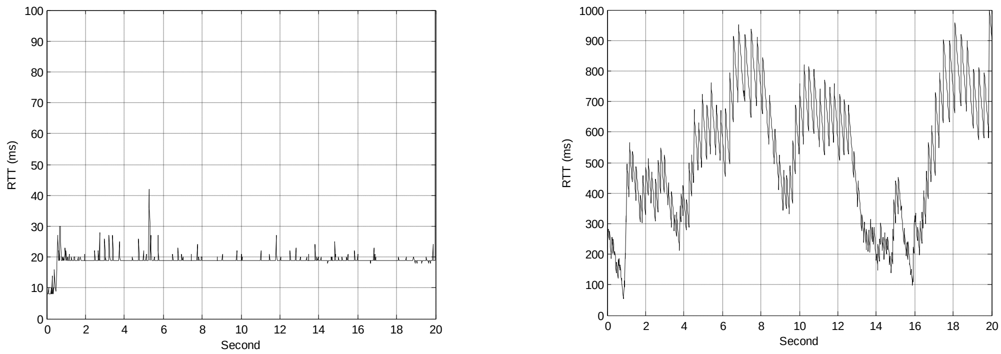
Note: √ is advantage or good; X is disadvantage or bad.

5.5 PDC in remote control systems

To implement the proposed NCS, the NCS architecture is shown in Fig 2.2. The remote node and the client node communicated with each other from a distance through the Ethernet (Lai and Hsu, 2010). The computer networking is used by transport layer protocols of the Internet protocol suite, such as the transmission control protocol (TCP) and the user datagram protocol (UDP). The UDP is suitable for real-time NCS but the lost of data needs to be coped with by applying the message estimator; on the other hand, the TCP is adopted with the unavoidable time delay but without loss of data. In this study, the data communication protocol adopts the TCP to achieve the desirable position loop control for the guaranteed eventual delivery of packets, but the unavoidable time delay will seriously degrade system stability and reliability and thus, the proposed PDC is critical to NCS design and implementation in real concerns.

In the experimental setup, the remote node was provided with the reference command, and the client node was implemented with the controller and the AC servo motor. The proposed PDC was tested through both (a) the Intranet in a local area, and (b) the Internet with a 15 *km* distance. The PI controller was tuned as $K_p = 0.0002$ and $K_i = 0.0000001$ with a 20 *ms* sampling time implemented on the TI TMS320F2812 DSP microcontroller with CAN bus. The client node included the gateway with TCP protocol with the transmission control protocol (TCP) with the unavoidable time delay but without loss of data as the interface to communicate between the Ethernet network and the CAN bus. To record the network-induced delay, the proposed NCS with PDC was based on a combination of both time-driven in the client and event-driven in the remote node. At the beginning of each sampling period, the clock-driven sensor node transmitted the sampling data to the remote node. A real-time measurement of the delay time was adopted in this study with all counters, indexes, and delays. Moreover, the resolution performance of the counter was 1 *ms*.

Experimental results indicate that the time delay measurement is approximated to a constant delay in the Intranet, as shown in Fig. 5.11 (a). Comparing the results of the Intranet and Internet shown in Figs. 5.11 (a) and (b), respectively, the delay was greatly affected by its variable operating conditions in Internet, such as congestion and channel quality. The measured drifting time delay is either bounded or random. When the delay time RTT was small for an Intranet at 10 - 20 *ms*, the time-delay effect in NCS becomes negligible as shown in Fig. 5.12. Fig. 5.13 shows that as the delay time is increased to 235 *ms* as communication becomes busy due to the massive data transmission, the NCS system response without including the proposed PDC becomes unstable. However, with the proposed PDC, desirable control performance is thus obtained as shown in Fig. 5.14. Furthermore, the PDC implemented on the Internet and its delay time is significantly varied between 50 *ms* to 700 *ms*, as shown in Fig. 5.15, the proposed PDC still renders satisfactory performance to prove the feasibility and superiority of the proposed PDC.



(a) (b)

Fig. 5.11 The time-delay measurement in (a) Intranet and (b) Internet

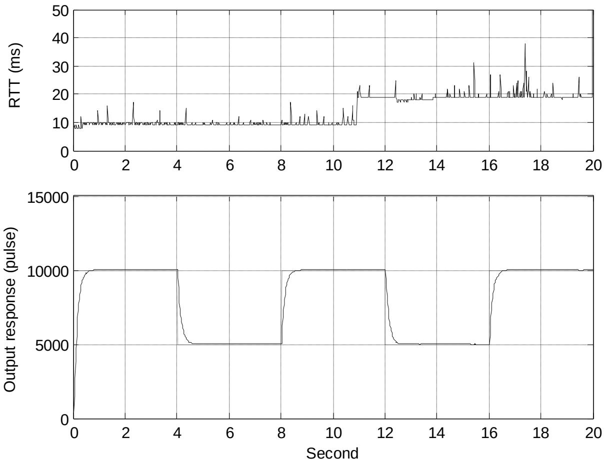


Fig. 5.12 Output response of the proposed NCS without PDC for a small time delay in Intranet

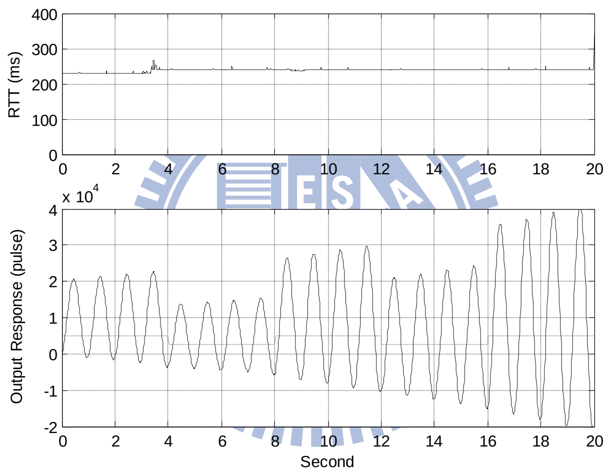


Fig. 5.13 NCS without PDC for a large but constant time delay

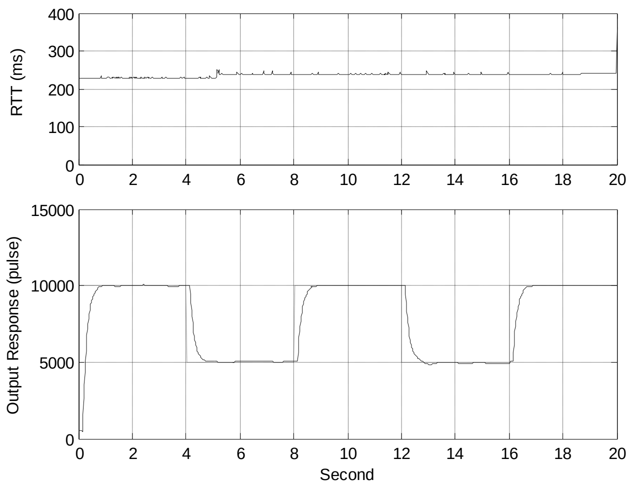


Fig. 5.14 NCS with PDC for a large but constant time delay

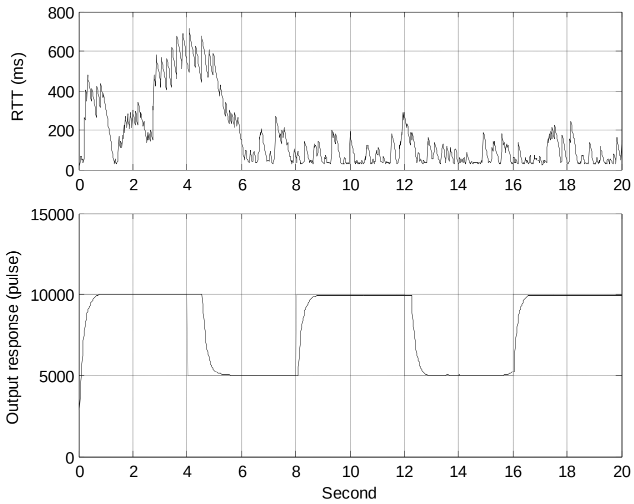


Fig. 5.15 NCS with PDC in a varied time delay

5.6 Direct NCS implementation with PDC

Due to the rapid development in Internet technology, the real-time networked applications such as critical control design teleoperation, remote mobile robots, and factory automation become more important (Suzuki et al., 1996; Hespanha et al., 2007). Thus, there is a need to implement networking systems with desirable performance directly obtained from traditional system control design without considering networking. The proposed PDC, which handles unknown and variable time delays without knowing the model and its variation, is an ideal solution that can be adopted in direct networking.

5.6.1 Vibration suppression for the flexible arm

A notch filter precisely designed for vibration suppression on an 18 *cm* flexible beam driven by an AC 400*W* motor is shown in Fig. 5.16. The flexible beam easily causes vibration as shown in Fig. 5.17(a). The DSP-embedded frequency-domain identification method based on a frequency compound excitation sequence and fast Fourier transform was proposed in (Hsu et al., 2010), and its Bode plot of the identified system can be reconstructed as shown in Fig. 5.17(b) without considering the networking effect. The vibration that occurred in the position loops for flexible beam exhibited a dominant low frequency vibrational mode at 20.6 *rad/sec*. The nature frequency ω_r was set at 20.6 *rad/sec* in this case, and the damping ratio ζ_z was determined by setting the width of its relative -3 *dB* frequency at both hand sides of the nature frequency ω_r, because its ω_{UdB} is 23.44 *rad/sec* and ω_{LdB} is 15.84 *rad/sec*, respectively. Thus, the damping ratio was estimated using the following formula as:

$$\xi_z = \frac{\omega_{Udb-}\omega_{Ldb}}{2\omega_r} = 0.184$$

The notch filter (NF) was designed to suppress flexible beam vibration in the position loop so that control performance can be improved (Wells et al., 1990). Its notch filter was obtained directly from pole/zero cancellation to improve its damping ratio as in the following (Franklin et al., 2002; Kang et al., 2005):

$$F(s) = \frac{s^2 + 7.581s + 424.36}{s^2 + 41.2s + 424.36}$$

Furthermore, the notch filter was designed to be implemented with the bilinear transformation in order to convert an s-domain transfer function to a discrete system in implementation.

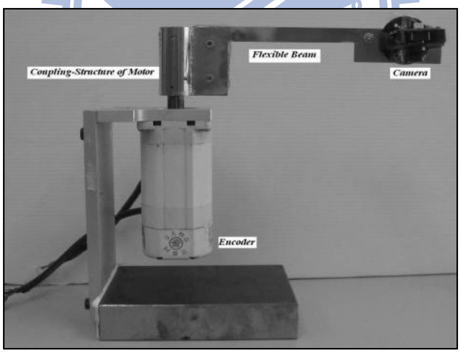
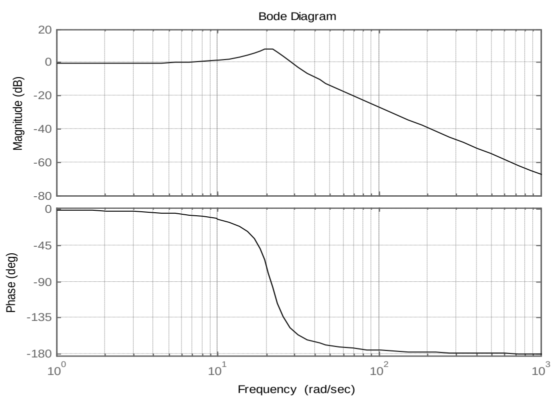
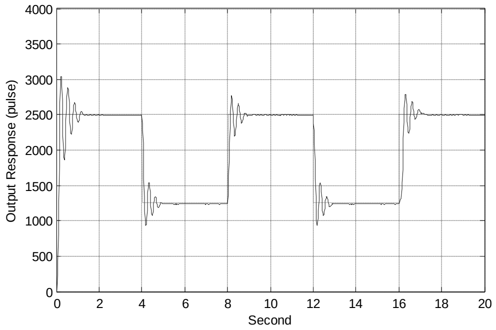


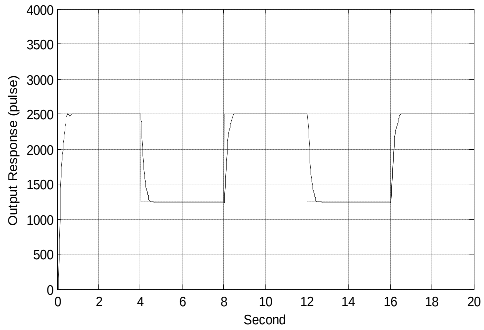
Fig. 5.16 Experimental platform with an 18 *cm* flexible beam driven



(a)



(b)



(c)

Fig. 5.17 (a) The Bode diagram of the flexible system, (b) the time response without vibration suppression, and (c) the time response with the notch filter

5.6.2 The direct networking technology with PDC

To implement direct networking of control design with PDC, this test rig consisted of a designed notch filter, which was located in the Hukuo, and the servo motor with flexible arm which was located in the National Chiao Tung University, Taiwan, with a 15 *Km* distance. Both nodes were connected via the Internet with IP addresses 123.110.223.109 and 140.113.150.24, respectively.

All experimental results are summarized in Table 5.3.

Case 1 : Original control system.

Case 2 : The position loop with a notch filter

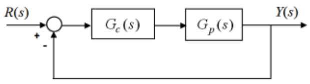
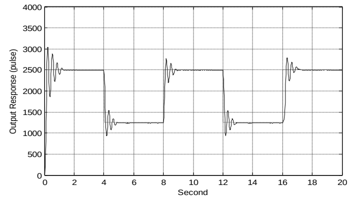
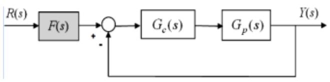
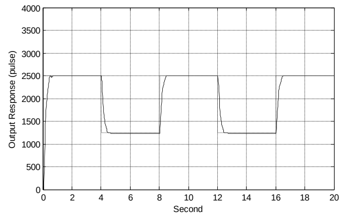
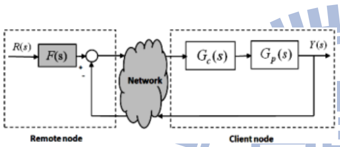
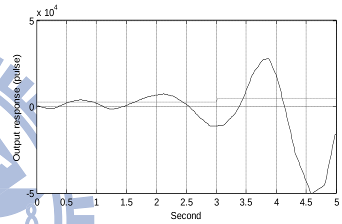
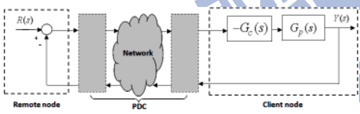
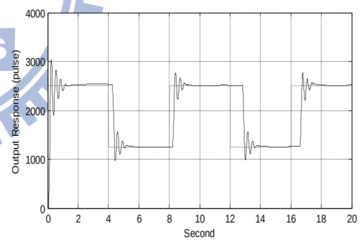
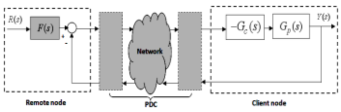
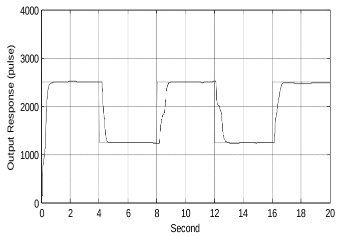
Case 3 : NCS without the PDC

Case 4 : NCS for direct networking with PDC from Case 1 without the notch filter.

Case 5 : NCS for direct networking with PDC from Case 2, with a notch filter.

Through the above a series testing, experimental results showed that the proposed PDC can handle network-induced delay effectively to demonstrate its effectiveness and feasibility.

Table 5.3 Direct networking of control systems

	Block diagram of control system	Output response
Case 1: Original system w/o NF		
Case 2: With NF		
Case 3: Networking w/o PDC		
Case 4: Networking + PDC w/o NF		
Case 5: Networking + PDC with NF		

5.7 Summary

The PDC in NCS has been proposed to efficiently deal with the unknown network-induced delay even without the system model. The PDC comprised the modified butterfly and anti-butterfly elements on the client and the remote sides of the network, respectively. Both simulation and experimental results have rendered satisfactory performance to verify feasibility and effectiveness of the proposed PDC. Several critical summaries are presented as follows.

(1) The PDC has been derived to demonstrate that the transfer function of the NCS is simplified as the desirable closed-loop system with a pure time delay. In other words, the network-induced delay does not affect the NCS feedback loop based on the control system design without the networking effect.

(2) Simulation results with a simple structure has proven that NCS with PDC is the most effective structure that can deal with time delays, even with an unknown delay time model and the plant model.

(3) Experimental results indicate that the proposed PDC has been successfully implemented on a remote control system from a 15 *Km* distance through the Internet. The proposed PDC has also been directly implemented for suppressing vibration with a notch filter carefully designed for a flexible arm with successful and satisfactory results.

Both simulation and experimental results indicate that the proposed NCS showed satisfactory performance even when the measured network delay is significantly varied with the proposed PDC elements. Provided experimental results have further proven that well-designed control systems, even with high sensitivity, can be directly implemented in networking systems by including the proposed PDC to maintain its desirable feedback-loop characteristics in real applications.

Chapter 6

PDC for MMO Control Systems

With the rapid development of network technology and the popularity of information networks, networking technologies save wiring cost and make them easier to reconfigure into a large multi-input multi-output (MIMO) systems. However, implementation of control systems over a network is challenging mainly due to the network-induced time delay. Since the delay is usually significantly varied in real network communication like the Ethernet in remote control systems, modeling and control design for NCS by considering the time delay becomes much more difficult, particularly for multi-input multi-output (MIMO) plants. Unless, a radical change in the NCS scheme is developed. This study presents a novel NCS scheme to effectively compensate for the unknown delays induced in the communication networks. Then, the MIMO NCS is simply equivalent to a closed-loop system without the delay effect in the feedback loop, and an additional pure time delay outside the loop is added. Furthermore, well-designed controllers, which are obtained without considering the network, can be thus directly implemented on NCS by adopting the proposed scheme to maintain its closed-loop characteristics. Both simulation and experimental results have been provided to verify the proposed scheme with satisfactory performance and stability.

6.1 MIMO NCS with the time delay modeling

In MIMO NCS research, some progress was made toward the extension of these ideas from SISO systems to MIMO systems. Nilsson (1998) and Lian et al. (2003) have developed stochastic optimal controllers based on discrete-time models if the total delay is less than a sampling period. The robust feedback controller design has been further discussed for NCS with uncertainty in the system model (Yue et al., 2004; 2005). The drawbacks of these methods, which were defined with a limited delay usually small than one sampling period, is that as the time delay increases the order of the discrete-time system model also drastically increase. Some studies have been proposed to obtain the maximum allowable delay bound (MADB) based on both the plant model and well-design controllers, also called maximum allowable transfer interval (MATI), which can guarantee the stability of the NCS (Walsh et al., 2002; Yan et al., 2008; Cao et al., 2008; Tang et al., 2008). Several methodologies have been proposed to estimate robust stability bounds against variations of the maximum allowable delay that the closed-loop system can tolerate (Pana et al., 2006; Dritsas et al., 2009). Network-induced delay is usually unpredictable, especially in the shared Internet with a huge number of user nodes. Most of the above-mentioned research results are limited to delays in a constant, less time-varying, and bounded format; however, they are not realistic in real network environments. The NCS design results obtained generally based on assumed limitations also become invalid for real NCS applications.

Due to the rapid development of Internet technologies, there is an emergent need to realize NCS with desirable performance as obtained in the system control design without considering network effects. The NCS design is a challenging task for general SISO control systems, without mentioned that MIMO NCS design is much more difficult. Consider a plant with r inputs and n outputs, the process $\mathbf{G_p}(s)$ is expressed as

$$\mathbf{G}_p(s) = \begin{bmatrix} G_{p_{11}}(s) & G_{p_{12}}(s) & \cdots & G_{p_{1r}}(s) \\ G_{p_{21}}(s) & G_{p_{22}}(s) & \cdots & \vdots \\ \vdots & \vdots & \ddots & \vdots \\ G_{p_{n1}}(s) & \cdots & \cdots & G_{p_{nr}}(s) \end{bmatrix} \tag{6-1}$$

$\mathbf{G_c}(s)$ is the transfer function matrix of the corresponding MIMO controller as follows:

$$\mathbf{G}_c(s) = \begin{bmatrix} G_{c_{11}}(s) & G_{c_{12}}(s) & \cdots & G_{c_{1n}}(s) \\ G_{c_{21}}(s) & G_{c_{22}}(s) & \cdots & \vdots \\ \vdots & \vdots & \ddots & \vdots \\ G_{c_{r1}}(s) & \cdots & \cdots & G_{c_{rn}}(s) \end{bmatrix} \tag{6-2}$$

The general closed-loop MIMO system, without the networking effect, is an input-output map relating the vector of multiple outputs $\mathbf{Y}(s)$ to the vector of multiple inputs $\mathbf{R}(s)$ as

$$\begin{aligned} \mathbf{Y}(s) &= (I_n + \mathbf{G}_P(s)\mathbf{G}_c(s))^{-1}\mathbf{G}_P(s)\mathbf{G}_c(s)\mathbf{R}(s) \\ &= \mathbf{G}_P(s)(I_n + \mathbf{G}_P(s)\mathbf{G}_c(s))^{-1}\mathbf{G}_c(s)\mathbf{R}(s) = \mathbf{M}(s)\mathbf{R}(s) \end{aligned} \tag{6-3}$$

where **M**(s) is the desirable controller with satisfactory stability and control performance without considering the network. **R**(s) is a diag$\{r_1, r_2, \ldots, r_n\}$ matrix for the reference commands (Chen, 1999). As the MIMO control system is implemented through a network where data exchange among sensors, controllers, and actuators as shown in Fig. 6.1, the MIMO NCS can be modeled as the multiple time delays T_{1i} on the forward direction and the multiple time delay T_{2j} on the feedback direction, separately, as

$$\mathbf{G_{T1}}(s)=\begin{bmatrix} e^{-T_{11}s} & 0 & \cdots & 0 \\ 0 & e^{-T_{12}s} & \cdots & \vdots \\ \vdots & \vdots & \ddots & \vdots \\ 0 & \cdots & \cdots & e^{-T_{1r}s} \end{bmatrix};\ \mathbf{G_{T2}}(s)=\begin{bmatrix} e^{-T_{21}s} & 0 & \cdots & 0 \\ 0 & e^{-T_{22}s} & \cdots & \vdots \\ \vdots & \vdots & \ddots & \vdots \\ 0 & \cdots & \cdots & e^{-T_{2n}s} \end{bmatrix} \quad (6\text{-}4)$$

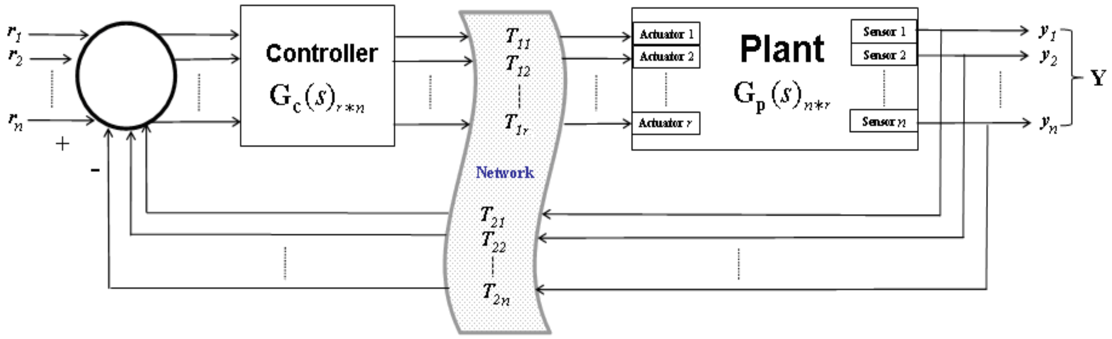


Fig. 6.1 Block diagram of the general MIMO NCS

For the MIMO networked control system, the transfer function matrix of output signal is given by

$$\mathbf{Y}(s)=(I+\mathbf{G_P}(s)\mathbf{G_{T1}}(s)\mathbf{G_c}(s)\mathbf{G_{T2}}(s))^{-1}(\mathbf{G_P}(s)\mathbf{G_{T1}}(s)\mathbf{G_c}(s))\mathbf{R}(s) \quad (6\text{-}5)$$

Equation (6-5) indicate that the network-induced time delay mixed with the plant and controller so that it makes the design of NCS more difficult to meet specifications as **M**(s) without the network.

Most of available modeling and stability analysis of MIMO NCS are based on multi-packet transmission and each sensor or actuator encounters different network-induced time delays. For some commercial network like Ethernet, it was originally designed to transmit massive data in a single packet. Hence, it is more efficient to lump all sensors or actuators signals into one packet and transmits it together in one packet. Therefore, the block diagram of the networked MIMO system can be simplified as shown in Fig. 6.2. Moreover, the NCS communication network can be formulated as the time delays T_1 and T_2 on the forward direction from controllers to actuators, and on the feedback direction for sensors to controllers, respectively. If n sensors and n actuators are adopted, the transfer function matrices of time delays are simplified as below.

$$\mathbf{G}_{\mathbf{T1}}(s)=e^{-T_1 s}\times I \quad ; \quad \mathbf{G}_{\mathbf{T2}}(s)=e^{-T_2 s}\times I \tag{6-6}$$

The transfer function matrix of output signal for MIMO NCS is given by

$$\mathbf{Y}(s)=(I_n+\mathbf{G}_P(s)(e^{-T_1 s}I_n)\mathbf{G}_c(s)(e^{-T_2 s}I_n))^{-1}(\mathbf{G}_P(s)(e^{-T_1 s}I_n)\mathbf{G}_c(s))\mathbf{R}(s) \tag{6-7}$$

where $\mathbf{Y}(s)$ is an $n\times n$ matrix for the output and $\mathbf{R}(s)$ is an $n\times n$ matrix for the reference commands.

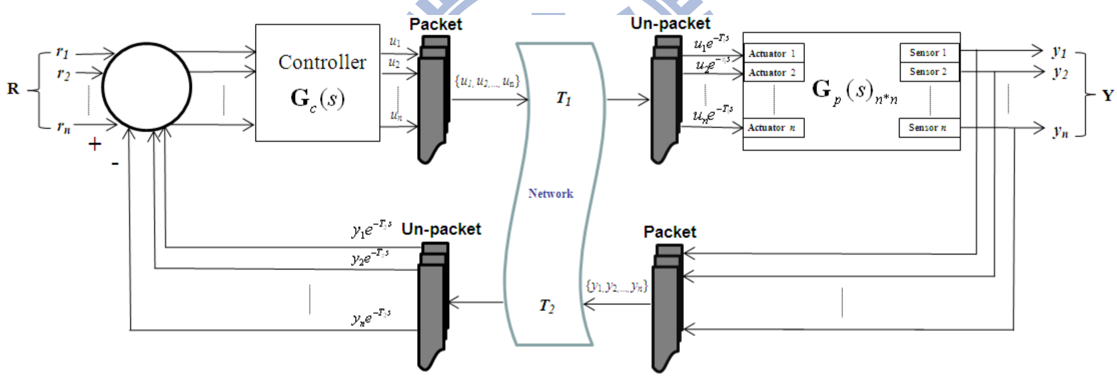
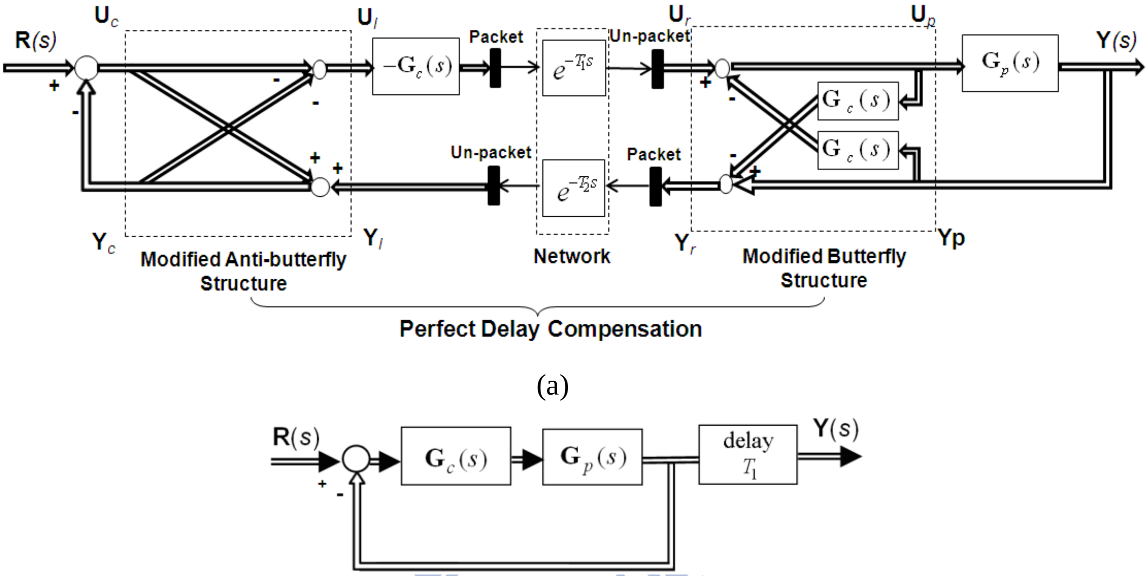


Fig. 6.2 The block diagram of the packet-based MIMO NCS

Equation (6-7) which simplifies the NCS time-delay modeling still makes the design more difficult based on the given model including the plant and the time delay. Moreover, NCS in remote control applications are implemented with the discrete-time realization. As the delay time varied, problems of discrete-time NCS modeling indicate that both (a) vacant sampling and (b) message rejection will occur (Halevi and Ray, 1988); thus, all those modeling with the time delay will become invalid (Nilsson, 1998; Lian et al., 2003; Yue et al., 2004; Cao et al., 2008; Tang et al., 2008). In other words, there is no suitable linear model-based control design will be suitable for the real NCS even with higher-order models. In the present paper, a continuous-time scheme is proposed to cope with the unknown and varied network-induced time delay, and its implementation on discrete-time NCS has proven that the proposed scheme is valid and feasible in real remote control applications.

6.2 The Perfect delay compensation scheme

As discussed in Sessions 5.3, the control structure of the networked MIMO system with PDC is shown in Fig. 6.3(a).



(a)

(b)

Fig. 6.3 (a) The control structure with PDC in the MIMO NCS and (b) Equivalent of the block diagram for MIMO NCS

From Fig. 6.3(a), the output equations of the modified butterfly element can be expressed as

$$\mathbf{U_p}(s)=\mathbf{U_r}(s)-\mathbf{G_c}(s)\mathbf{Y_p}(s)\;;\;\; \mathbf{Y_r}(s)=-\mathbf{G_c}(s)\mathbf{U_p}(s)+\mathbf{Y_p}(s) \tag{6-8}$$

The transfer function matrix of $\mathbf{Y_r}(s)$ is derived as

$$\mathbf{Y}_r(\mathbf{s})=(\mathbf{G}_p(s)-\mathbf{G}_c(s))(I_n+\mathbf{G}_p(s)\mathbf{G}_c(s))^{-1}\mathbf{U}_r(\mathbf{s}) \tag{6-9}$$

Moreover, the transfer function matrix from input $\mathbf{U_c}(s)$ to output $\mathbf{Y_c}(s)$ on the modified anti-butterfly element can be expressed as

$$\mathbf{Y}_c(s)=(I_n+(e^{-T_2 s}I_n)(\mathbf{G}_p(s)-\mathbf{G}_c(s))(I_n+\mathbf{G}_p(s)\mathbf{G}_c(s))^{-1}(e^{-T_1 s}I_n)\mathbf{G}_c(s))\cdot$$
$$(I_n-(e^{-T_2 s}I_n)(\mathbf{G}_p(s)-\mathbf{G}_c(s))(I_n+\mathbf{G}_p(s)\mathbf{G}_c(s))^{-1}(e^{-T_1 s}I_n)\mathbf{G}_c(s))^{-1}\mathbf{U}_c(\mathbf{s}) \tag{6-10}$$

The transfer function matrix of the open-loop MIMO NCS from input $\mathbf{R}(s)$ to output $\mathbf{Y_c}(s)$ can also be obtained as

$$\mathbf{Y}_c(\mathbf{s})=(I_n+(I_n-(e^{-T_2 s}I_n)(\mathbf{G}_p(s)-\mathbf{G}_c(s))(I_n+\mathbf{G}_c(s)\mathbf{G}_p(s))^{-1}(e^{-T_1 s}I_n)\mathbf{G}_c(s))\cdot$$
$$(I_n+(e^{-T_2 s}I_n)(\mathbf{G}_p(s)-\mathbf{G}_c(s))(I_n+\mathbf{G}_c(s)\mathbf{G}_p(s))^{-1}(e^{-T_1 s}I_n)\mathbf{G}_c(s))^{-1})^{-1}\mathbf{R}(\mathbf{s}) \quad (6\text{-}11)$$

By combining Eq. (19) with Eq. (20),

$$\mathbf{U}_c(\mathbf{s})=\mathbf{R}(\mathbf{s})-\mathbf{Y}_c(\mathbf{s}) \quad \text{and} \quad (6\text{-}12)$$

$$\mathbf{Y}_c(s)=\mathbf{Y}_l(s)+\mathbf{U}_c(s)=(e^{-T_2 s}I_n)(\mathbf{Y}_p(s)-\mathbf{G}_c(s)\mathbf{G}_p^{-1}(s)\mathbf{Y}_p(s))\ +\mathbf{U}_c(s) \quad (6\text{-}13)$$

By substituting Eqs. (6-10) and (6-11) into Eq. (6-13), the equivalent transfer function matrix of the closed-loop networked MIMO system between inputs and outputs is expressed as follows:

$$\begin{aligned}\mathbf{Y}(s)=\mathbf{Y}_P(s)&=\mathbf{G}_p(s)(I_n+\mathbf{G}_c(s)\mathbf{G}_p(s))^{-1}\mathbf{G}_c(s)(e^{-T_1 s}I_n)\mathbf{R}(s)\\ &=\mathbf{M}(s)(e^{-T_1 s}I_n)\mathbf{R}(s)\end{aligned} \quad (6\text{-}14)$$

Equation (6-14) shows that the equivalent system simply presents the same desirable closed-loop system $\mathbf{M}(s)$ as in Eq. (6-3), but with an additional pure forward delay time T_1, as shown in Fig. 6.3 (b). Note that the controller $\mathbf{G}_c(s)$ is originally designed for the system without the network implementation. In other words, the proposed scheme successfully eliminates the delay effect from the NCS design with much more direct design and easier realization. In summary, the proposed scheme for NCS still maintains its original closed-loop control performance with an additional pure delay T_1 as it is realized on NCS.

6.3 Results with the delay compensator

To verify the present PDC for MIMO applications, an unstable batch reactor (Rosenbrock, 1974; Green and Limebeer, 1995) modeled as a two-input-two-output system is linearized as

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

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

and it leads to the transfer function as

$$\mathbf{G_p}(s) = \frac{\begin{bmatrix} 29.2s + 263.3 & -(3.146s^3 + 32.67s^2 + 89.93s + 31.81) \\ 5.679s^3 + 42.67s^2 - 68.84s - 106.8 & 9.43s + 15.15 \end{bmatrix}}{s^4 + 11.67s^3 + 15.75s^2 - 88.31s - 5.514}$$

The reactor is unstable because the system has two positive eigenvalues. To achieve zero steady-state tracking error, the $\bar{\sigma}(S(0)) = 0$ is required with the sensitivity function S. By choosing the gain part and adding integral action in the two loops to eliminate steady-state error, the controller can be obtained as follows (Green and Limebeer, 1995; Walsh et al., 2002):

$$\mathbf{G_c}(s) = \begin{bmatrix} 0 & \dfrac{2s+2}{s} \\ \dfrac{-5s-8}{s} & 0 \end{bmatrix}$$

With this designed controller, the present design meets the performance requirements as $\bar{\sigma}(S(j\omega)) \le 1/\sqrt{2}$, $\omega \in [1.8\ ,\ 27.3]$ and $\bar{\sigma}(\Delta \mathbf{G_M}(s)) \le 0.75$. The step responses are shown in Fig. 6.4. Note that this design is suitable for the system without the networking implementation.

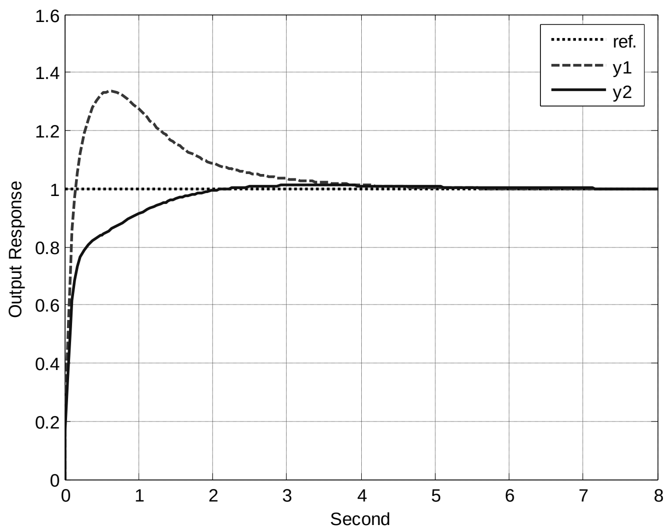


Fig. 6.4 Step response without the network

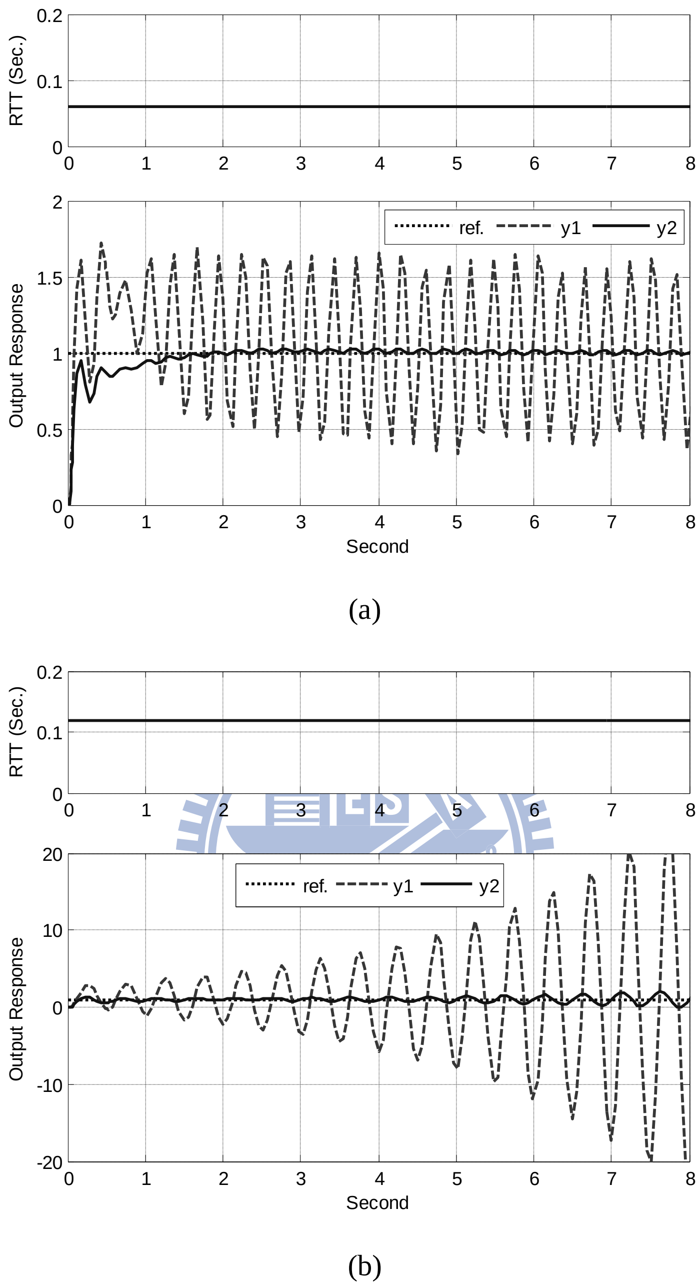


Fig. 6.5 Simulation results without PDC (a) RTT = 80 *ms* and (b) RTT = 120 *ms*

6.3.1 Simulation over a constant delay

To verify the effectiveness of the proposed PDC scheme, simulation results were obtained with the same condition to directly implement the designed results as in Eq. (6-14) on the MIMO NCS control system. By assuming the forward and feedback time delays $T_1 = T_2 = (RTT/2)$, two cases RTT = 80 *ms* and RTT = 120 *ms* were applied to the above networked MIMO system. Simulation results show that the system response is degraded as the delay time increases, as shown in Fig 6.5 (a) compared with Fig. 6.4. Walsh et al. (2002) found the value of the maximum allowable transfer interval (MATI), which the desired performance (e.g., stability) of an NCS is guaranteed to preserve. The Monte Carlo simulation was used because of the random nature of the network traffic load in their simulation for the same example. Results show that the step response becomes an unstable trajectory for MATI > 120 *ms*. The MIMO NCS system response which did not include the proposed PDC becomes unstable as the delay increases to RTT = 120 *ms*, as shown in Fig 6.5 (b). However, the PDC obtained better performance with a constant time delay under the condition of RTT = 120 *ms*, as shown in Fig. 6.6. Compared with Fig. 6.4, results have proven that applying PDC maintains its original performance as in the NCS with varied time delay.

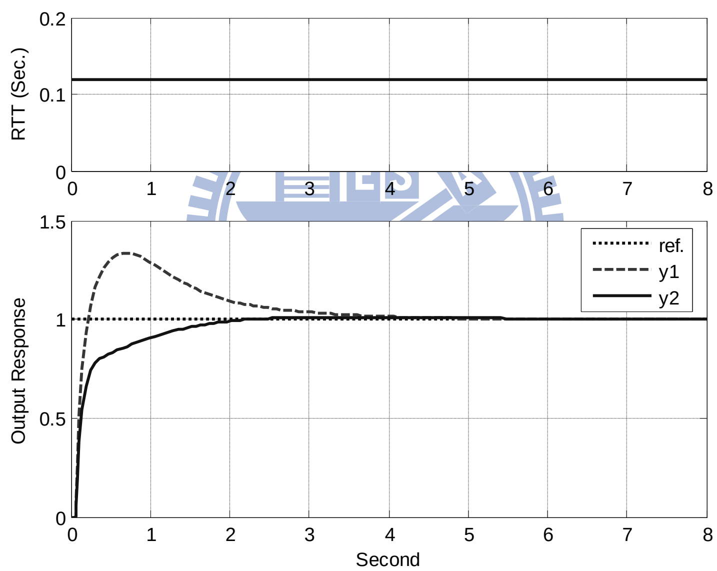


Fig. 6.6 Simulation result with PDC for the constant RTT = 120 *ms*

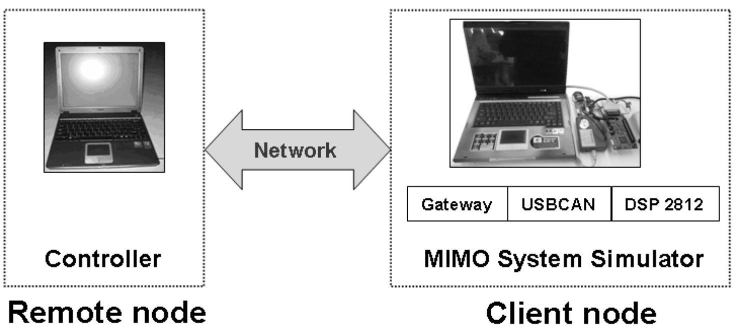


Fig. 6.7 Experimental setup

6.3.2 Experiments

The experimental setup integrated over two networks (802.11g ad-hoc wireless network and Ethernet wired network) is shown in Fig. 6.7. Two laptops working as the controller and the gateway, separately, were connected through the Internet. Communication signals between the remote node and the client node with 15 *Km* distance is transmitted by the TCP sockets, which provide guaranteed transmitted data packets. In other words, TCP results in packet delay rather than the packet loss is concerned in this experiment. The gateway of the USBCAN was designed to facilitate communication between different networks and the CAN bus. The TI DSP TMS320F2812 microcontroller core with CAN bus was used to build the MIMO system simulator for the example adopted in the above simulation. The C++ program received the control signal from the CAN bus and sent the output according to the linearized plant model to the gateway. At the remote node working as the controller, the Visual C# program obtained the plant output from the network and generated control signals to the gateway. The measured RTT due to the network-induced delay was also obtained from the DSP, the sender and the receiver were synchronized on the same DSP. The Windows Forms Timer component in the operating system is single-threaded and a higher resolution performance counter of the DSP timer is used to measure RTT.

When the NCS adopting the controller designed as in Eq. (6-3) without PDC was implemented over IEEE 802.11g ad-hoc wireless network, results of the MIMO NCS with a minor time delay indicate that the step responses become worse, as shown in Fig. 6.8. The MIMO NCS with the proposed PDC obtained the greatly improved system stability and control performance, as shown in Fig. 6.9. Moreover, the NCS with the major time delay (varied from 141 to 412 *ms*, average 219.17 *ms*) was also implemented over Ethernet wired network with ADSL network services. Figure 6.10 shows that the MIMO NCS system response without the proposed PDC thus became unstable. Moreover, desirable control performance was still obtained as shown in Fig. 6.11 with the proposed PDC even with severe time delay. Experimental results for the remote control systems for the proposed NCS scheme even on MIMO NCS have demonstrated satisfactory performance of the proposed PDC.

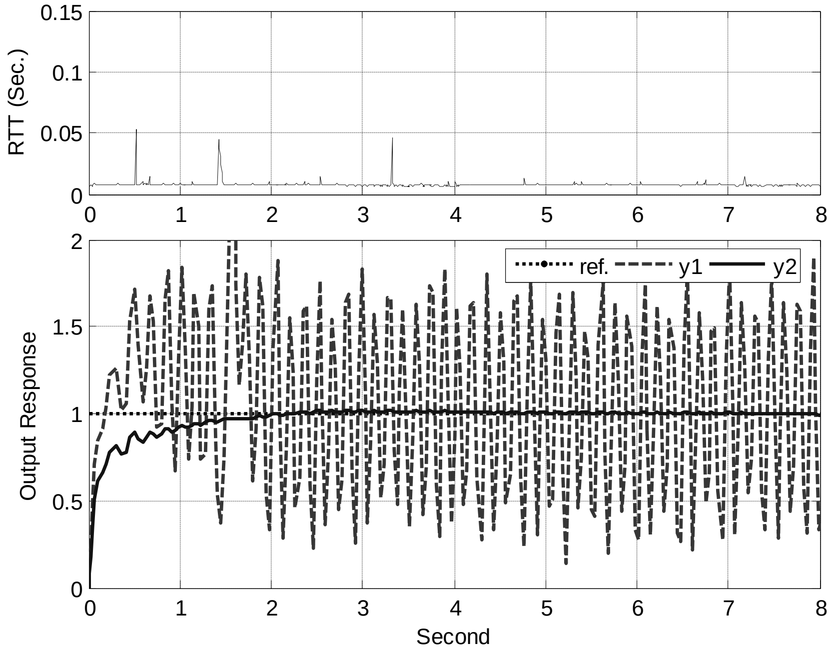


Fig. 6.8 Experimental results without PDC under a minor delay (varied from 6 to 52 *ms*, average 15.91 *ms*)

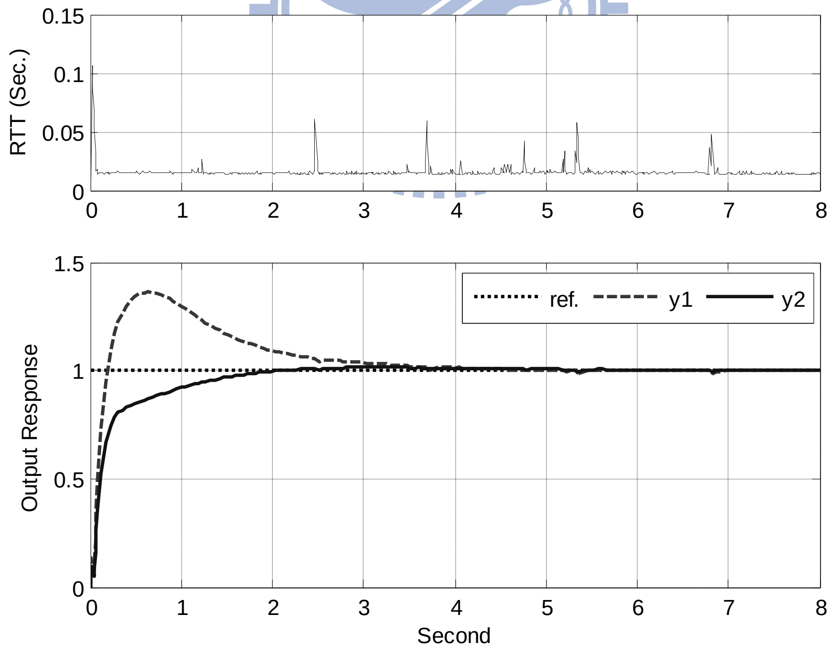


Fig. 6.9 Experimental results with PDC under a minor delay (varied from 14 to 107 *ms*, average 19.51 *ms*)

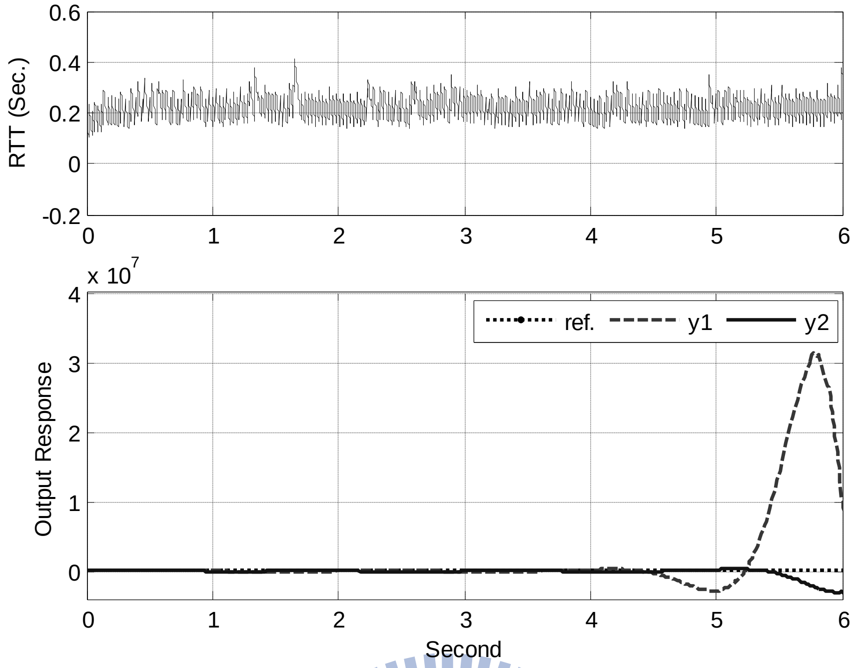


Fig. 6.10 Experimental results without PDC under a major delay (varied from 141 to 412 *ms*, average 219.17 *ms*)

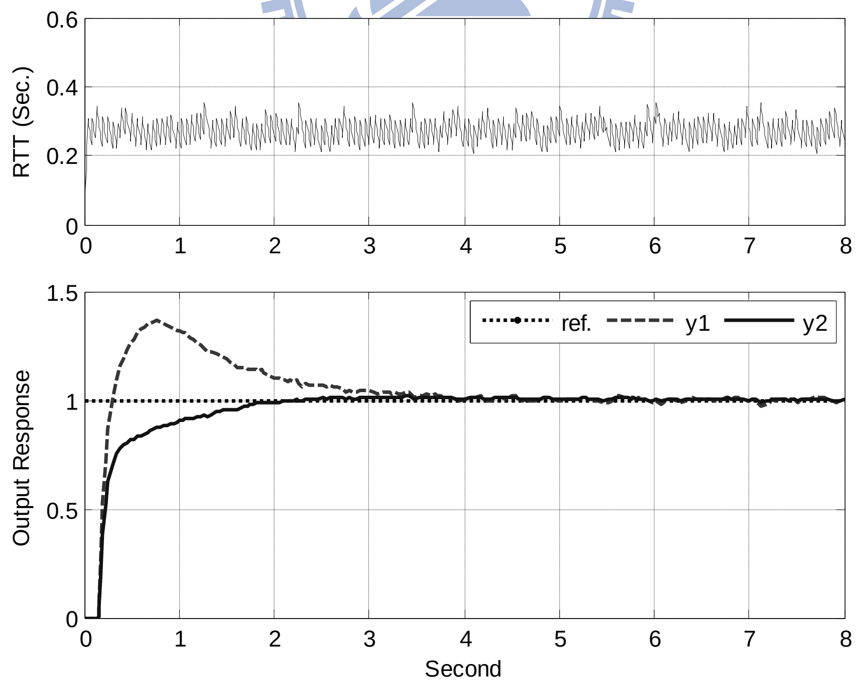


Fig. 6.11 Experimental results with PDC under a major delay (varied from 210 to 356 *ms*, average 278.34 *ms*)

6.4 Summary

In this chapter, the novel scheme for delay compensation in NCS is proposed to deal with the network-induced delays even without considering the system model and the delay information. Thus, direct networking of MIMO control systems can be directly realized since there is no model required either for the plant nor for the network delay to achieve desirable both stability and performance for MIMO NCS. The summaries are as follows:

1) By applying the proposed scheme on NCS, network-induced delay will not affect the NCS feedback-loop characteristics. The delay will become an additional term outside the feedback loop as a pure time delay between the input command and the output response.

2) Simulation results with a simple structure over a constant delay have proven that MIMO NCS with the proposed scheme is the most effective structure for NCS design, even without the delay time model and the plant model.

3) Experimental results for the MIMO system implemented over the IEEE 802.11g ad-hoc wireless network and the Ethernet wired network have verified the feasibility of the proposed PDC scheme for MIMO NCS.

Chapter 7

Conclusions and Future Work

7.1 Conclusions

This dissertation presents two major approaches to deal with significantly varied time delay in an actual communication network. The first proposed approach applying the RTT measurement is further applied to the adaptive Smith predictor, the robust NCS design, and the multi-rate design, as in Chapter 2, 3, and 4, respectively. The PDC is applied to direct networking implementation of the control systems as in Chapter 5 and 6 for SISO NCS and MIMO NCS, respectively. Conclusions of this dissertation are as follows:

(1) The adaptive Smith predictor control scheme is developed by directly applying the estimated time delay from RTT to achieve improved performance of NCS as the significantly time-varying delay effect occurs.

(2) The robust design with a suitable plant template that applies the QFT with the adaptive Smith predictor achieves the robust NCS design.

(3) The variable sampling periods based on the online measured RTT is proposed to avoid the network traffic jam in wireless NCS. Furthermore, a multi-rate design method by applying both the switching sampling time and the adaptive Smith predictor is proposed to achieve improved stability and performance of the NCS in wireless network.

(4) The PDC with the modified butterfly elements is proposed to effectively deal with unknown network-induced delays. The inclusion of PDC in the NCS is simplified as the desirable closed-loop system with a pure time delay only.

(5) Provided experimental results have further proven that MIMO systems can be directly implemented in networking systems by including the proposed PDC to maintain its feedback-loop characteristics in real network environments.

7.2 Future work

Recently, cloud computing is considered as one of the most potential trends of information technology. The main idea is to make applications available on flexible execution environments primarily located in the Internet. As information systems become larger and more complicated, the NCS design also becomes more difficult accordingly. The NCS applications in the future may exist multiple sensors in image, position, and velocity, etc. More advanced design method considering effects of large-scale spatial data in the shared communication network should be investigated. The security and reliability of NCS such as the message error and channel disconnection should also be concerned. In the mean while, designing a fault-diagnosis/fault-tolerance control system for a large-scale complex NCS will be further developed due to the large number of sensors and actuators spatially distributed on a network communication.

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PUBLICATION LIST

A. Journal papers

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