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# Design, Analysis and Real-time Implementation of Networked Predictive Control Systems

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**Abstract** This paper is concerned with the design, analysis and real-time implementation of networked control systems using the predictive control strategy. The analysis of the characteristics of networked control systems is detailed, which shows that a networked control system is much different from conventional control systems. To achieve the desired performance of closed-loop networked control systems, the networked predictive control scheme is introduced. The design, stability analysis and real-time implementation of networked predictive control systems are studied. It is illustrated by simulations and practical experiments that the networked predictive control scheme can compensate for random network communication delay and data dropout, achieve desired control performance and have good closed-loop stability.

**Key words** Networked control systems, networked predictive control, real-time implementation, stability analysis, network delay

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Networked control systems (NCSs) are such control systems where the control loop is closed via communication networks, as illustrated in Fig. 1. In NCSs, perfect data exchanges among the control components are not available which however is a fundamental basis of conventional control systems (CCSs). These communication constraints in NCSs greatly degrade the performance of the control system or even destabilize the system at certain conditions and therefore are the main concerns of the research on NCSs[1−5].

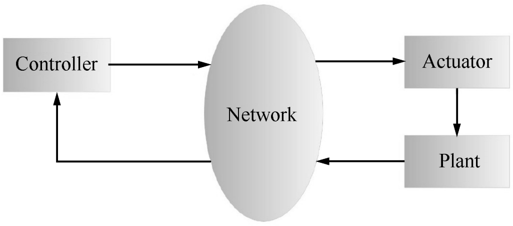

Fig. 1 The networked control system

The research on NCSs has been done mainly within the control theory community. Researchers are concerned with the theoretical analysis on the performance of NCSs where the communication network in NCSs is modelled by predetermined parameters to the control system. In this kind of research, the communication constraints, mostly the network-induced delay, may be carefully described and formulated, and incorporated into the description of the system to form a special class of CCSs, and then a CCS instead of an NCS is considered. This kind of research simplifies the modelling and analysis of NCSs and, more importantly, all the previous results in CCSs can now be readily applied to NCSs, thus enabling it to be the mainstream for a significant period[3−4]. Conventional control approaches applied in this way include, for example, time delay system theory[6−8], stochastic control theory[9−11], optimal control theory[12−14], switched system theory[15−17], and so on.

In parallel with the theoretical analysis of NCSs, the synthesis issue is also a main concern within the control theory community. However, despite considerable work to date, the limitations are obvious: most work concentrates on the extension of existing control approaches to NCSs without a full use of the characteristics of NCSs. Bearing in mind that it is the communication network which replaces the direct connections among the control components in CCSs that makes NCSs distinct from CCSs, it is therefore natural and necessary to highlight the effects of the communication network when investigating NCSs. This approach, referred to as the co-design approach to NCSs, has been an emerging trend in recent years. In this kind of research, the communication constraints are no longer assumed to be predetermined parameters but act as designable factors, and by their efficient use a better system performance can be expected[18−27].

Within the co-design framework, a networked predictive control approach is introduced in this paper. By making effective use of the packet-based transmission, the communication constraints can be actively compensated for with this approach. Both theoretical design and analysis, and practical implementation are presented to show the effectiveness of the networked predictive control approach.

## 1 Characteristics of networked control systems

The distinct characteristics of NCSs are briefly discussed from the control theory perspective, focusing on the effects brought by the communication network to the control system. These effects are caused, roughly speaking, by three distinct features of the communication network, namely, the network topology, the packet-based transmission and the limited network resources.

1) Network topology

a) Time-synchronization: Time-synchronization, or clock synchronization, is a fundamental basis of implementing distributed communication networks[28]. Time-synchronization among the control components in NCSs may not be a necessary condition if the network-induced delay in the backward channel (“backward channel delay”)

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is not required for the calculation of the control signals and/or the network-induced delay in the forward channel ("forward channel delay") is not required for the implementation of the control actions, which is typically the case in CCSs. However, as discussed in [29 − 30], time-synchronization together with the use of time stamps in NCSs can offer an advantage over CCSs in that the backward channel delay is known by the controller and the forward channel delay (round trip delay as well) is known by the actuator. This advantage can then be used to derive a better control structure for NCSs as discussed in this paper.

b) Drive mechanism: Two drive mechanisms for the control components in NCSs are usually used, that is, time-driven and event-driven. The difference between the two drive mechanisms lies in the trigger method that initiates the control components. For the time-driven mechanism, the control components are trigged to work at regular time intervals, while for event-driven mechanism the control components are only trigged by a predefined "event". Generally speaking, the sensor is always time-driven, while the controller and the actuator can either be time-driven or event-driven. For more information on the drive mechanism for the control components, the reader is referred to [31] and the references therein. It is worth mentioning though, with different drive mechanisms different system models for NCSs are obtained and event-driven control components generally lead to a better system performance.

2) Packet-based transmission

Packet-based transmission is one of the most important characteristics of NCSs that are distinct from CCSs[3, 32].

This characteristic can mean that the perfect data transmission as assumed in CCSs is absent in NCSs, thus producing the greatest challenge in NCSs. The communication constraints caused by the packet-based transmission in NCSs include the network-induced delay, data packet dropout, data packet disorder, etc., which are detailed as follows.

a) Network-induced delay: Due to the network inserted into the control loop in NCSs, network-induced delays are introduced in both the forward and backward channels, which are well known to degrade the performance of the control systems. The delays in the two channels may have different characteristics[33, 34]. In most cases, however, these delays are not treated separately and only the round trip delay is of interest[35].

According to the types of the communication networks being used in NCSs, the characteristics of the network-induced delay vary as follows[1, 36]:

i) Cyclic service networks (e.g., Toking-Ring, Toking-Bus): Bounded delays which can be regarded as constant for some occasions;

ii) Random access networks (e.g., Ethernet, CAN): Random and unbounded delays;

iii) Priority order networks (e.g., DeviceNet): Bounded delays for the data packets with higher priority and unbounded delays for those with lower priority.

Network-induced delay has widely been addressed in the literature to date, see, e.g., in [5, 10, 19, 37].

b) Data packet dropout: Data packet dropout can occur either in the backward or forward channel, and it makes either the sensing data or the control signals unavailable to NCSs, thus significantly degrading the performance of NCSs.

In communication networks, two different strategies are applied when a data packet is lost, that is, either to send the packet again or simply discard it. Using the terms from communication networks, these two strategies are referred to as transmission control protocol (TCP) and user datagram protocol (UDP) respectively[28]. It is readily seen that with TCP, all the data packets will be received successfully, although it may take a considerably long time for some data packets; while with UDP, some data packets may be lost forever. As far as NCSs is concerned, UDP is used in most applications due to the real-time requirement and the robustness of control systems. As a result, the effect of data packet dropout in NCSs has to be explicitly considered, as done in, e.g., [10, 12, 38−41].

c) Data packet disorder: In most communication networks, different data packets suffer different delays. It therefore produces a situation where a data packet sent earlier may arrive at the destination later or vice versa, that is, data packet disorder. This characteristic in NCSs can mean that a newly arrived control signal in NCSs may not be the latest, which never occurs in CCSs. Therefore, the effect of data packet disorder has to be specially dealt with[42].

3) Limited network resources

The limitation of the network resources in NCSs is primarily caused by the limited bandwidth of the communication network, which results in the following three situations in NCSs that are distinct from CCSs.

a) Sampling period, network loads and system performance: NCSs are a special class of sampled data systems due to the digital transmission of the data in communication networks. However, in NCSs, the limited bandwidth of the network produces a situation, where a smaller sampling period may not result in a better system performance which, however, is normally true for sampled data systems.

This situation happens because, with too small a sampling period, too much sensing data will be produced; thus overloading the network and causing congestion, which will result in more data packet dropouts and longer delays, and thus degrade the system performance. The relationship between the sampling period, network loads and system performance in NCSs is illustrated in Fig. 2. For example, when the sampling period decreases from the value corresponding to point "a" to "b", the system performance is getting better as in conventional sampled data systems since the network congestion does not appear until point "b"; However, the system performance is likely to deteriorate due to the network congestion when the sampling period is getting even smaller from the value corresponding to point "b" to "c". Therefore, the relationship shown in Fig. 2 implies that there is a trade-off between the period of sampling the plant data and the system performance in NCSs, that is, in NCSs an optimal sampling period exists which offers the best system performance (point "b" in Fig. 2).

b) Quantization: Due to the use of data networks with limited bandwidth, signal quantization is inevitable in NCSs, which has a significant impact on the system performance.

Quantization in the meantime is also a potential method to reduce the bandwidth usage which enables it to be an effective tool to avoid the network congestion in NCSs and thus improve the system performance of NCSs. For more information on the quantization effects in NCSs, the reader is referred to [44] and the references therein.

c) Network access constraint and scheduling: It is often the case that the communication network is shared by several control applications in NCSs, either used to transmit the sensing data, the control signals or both. In such a case, the limited bandwidth of the network produces a situation where all the subsystems cannot access the network resource at the same time. A scheduling algorithm is therefore needed to schedule the timeline of when and how long a specific subsystem can occupy the network resource[30]. The system performance can be severely affected by this scheduling algorithm, for leaving the control system open-loop for a long time can readily destabilize the system at certain conditions.

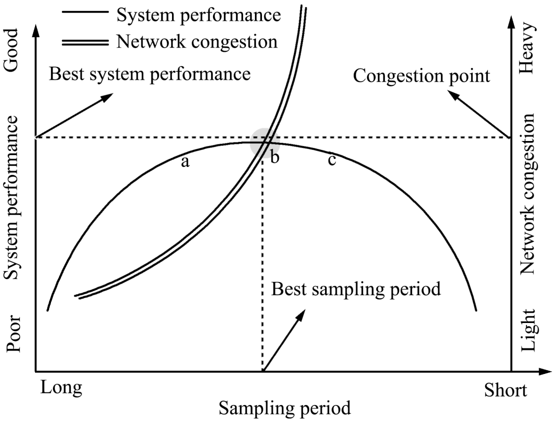

Fig. 2 The relationship between the sampling period, network loads and system performance in NCSs (reproduced from [43])

## 2 Design of networked predictive control systems

The design of networked control systems to be studied in this paper is to compensate for random network communication delay and data dropout, achieve desired control performance and have a good closed-loop stability. Recently, a networked control strategy, named as networked predictive control, has been proposed by Liu et al.[45]. The networked predictive control strategy, as shown in Fig. 3, actively compensates for the random network delay and data dropouts so that the closed-loop networked control performance is almost the same as the one without the network, which can hardly be achieved by other existing methods. It mainly consists of two parts: the control prediction generator and network delay compensator. The control prediction generator generates a set of control predictions which achieve the required control performance. The network delay compensator compensates for the unknown random communication delay and data dropout. A novel design of networked predictive control systems is discussed in details in this section.

For the sake of simplicity, the following assumptions are made.

**Assumption 1.** The network delay from the controller to the actuator in the forward channel $\tau_{ca}$ is bounded by $n_0 \le \tau_{ca} \le n_f$.

**Assumption 2.** The network delay from the sensor to the controller in the feedback channel $\tau_{sc}$ is bounded by $n_1 \le \tau_{sc} \le n_b$.

**Assumption 3.** The number of consecutive data package drops in both the feedback and forward channels is bounded by $n_d$.

**Assumption 4.** The data transmitted through a network are with a time stamp.

In a practical NCS, there exists data loss. For instance, if the data packet does not arrive at a destination in a certain transmission time (i.e., the upper bound of the network delay), it means this data packet is lost, based on commonly used network protocols. From the physical point of view, it is natural to assume that only a finite number of consecutive data dropouts can be tolerated in order to avoid the NCS becoming open-loop. The time stamp of the data transmitted through a network is very important for networked control systems. This is because a control sequence of a control system is based on time. In addition, the synchronisation is also an issue in networked control systems. There exist various ways to synchronise the time clocks in digital components (or computers). In this paper, it is assumed that the components in the system have been synchronised.

Consider a linear discrete-time plant to be controlled:

$$\begin{aligned} x_{t+1} &= Ax_t + Bu_t \\ y_t &= Cx_t \end{aligned} \tag{1}$$

where $x_t \in \mathbf{R}^n$, $y_t \in \mathbf{R}^l$ and $u_t \in \mathbf{R}^m$ are the state, output and control input vectors of the system, respectively, and $A \in \mathbf{R}^{n\times n}$, $B \in \mathbf{R}^{n\times m}$ and $C \in \mathbf{R}^{l\times n}$ are the system matrices.

Let $j$ and $k$ denote the time-varying delays of real-time data in the forward channel and feedback channel, respectively. Also, let $d_1 = n_f + n_d$, $d_2 = n_b + n_d$ , $n_m = n_0 + n_1$ and $d = d_1 + d_2$. From Assumptions 1~3, it is clear that $j \in \{n_0,\ n_0+1,\ \cdots,\ d_1\}$ and $k \in \{n_1,\ n_1+1,\ \cdots,\ d_2\}$.

It is assumed that the states of the plant are not measurable but the system output is available. To obtain the state vector of the plant on the controller side, an observer is designed as

$$\begin{aligned} x_{t-k+1|t-k} &= Ax_{t-k|t-k-1} + Bu_{t-k|t-k-1} + \\ &\quad L(y_{t-k} - y_{t-k|t-k-1}) \\ y_{t-k|t-k-1} &= Cx_{t-k|t-k-1} \end{aligned} \tag{2}$$

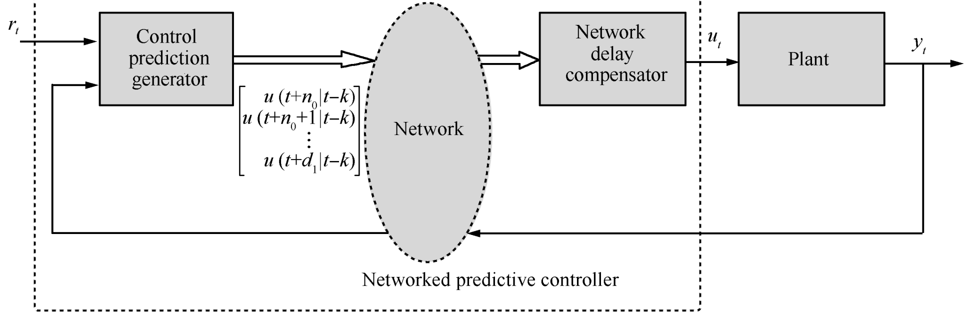

Fig. 3 The networked predictive control system

where $x_{t-i|t-k} \in \mathbf{R}^n$ $(i < k)$ denotes the state prediction for time $t-i$ on the basis of the information to time $t-k$ and $y_{t-k|t-k-1} \in \mathbf{R}^l$ is the output vector of the observer, and the gain matrix $L \in \mathbf{R}^{n\times l}$, which can be designed using standard observer design approaches.

Since there exists a network delay, the output signal $y$ at time $t$ is delayed for $k$ steps when it arrives on the controller side. Although the observer provides a one-step ahead prediction of the plant states using the output at time $t-k$, the state predictions from time $t-k+2$ to $t+d_1$ are still not known. Based on the information available on the controller side at time $t-k$, the other state predictions up to time $t+d_1$ can be constructed by

$$x_{t-k+i|t-k} = Ax_{t-k+i-1|t-k} + Bu_{t-k+i-1|t-k} \tag{3}$$

for $i = 2, 3, \cdots, k+d_1$. When the states of the plant are estimated, there are many control methods available for the system. To illustrate the networked predictive control strategy, the observer based state-feedback control method is employed. So, the control predictions to be generated on the controller side are

$$u_{t+i-k|t-k} = Kx_{t+i-k|t-k} \tag{4}$$

for $i = 1, 2, \cdots, k+d_1$, where $K \in \mathbf{R}^{m\times n}$ is the controller gain matrix. So, the control prediction generator on the controller side is to produce a set of control predictions calculated by (4).

To deal with the control input data dropout in networked control systems, there are three main methods. Method 1 is that if the control input data are dropped, the control input is set to zero. Method 2 is that if the control input data are dropped, the control input keeps the previous control input until the new control input data arrive. Method 3 is that if the control input data are dropped, the control input uses the control prediction. These methods have advantages and disadvantages. Method 1 is simple but the control input causes an unsmooth switching, which may not be allowed in some control systems. Method 2 has a smooth switching control input but it is hard to achieve the desired control performance. Method 3 provides the desired control performance but it costs a little communication efficiency.

At time $t$, the future network delay and data dropout are unknown. According to the networked predictive control strategy and Assumptions 1 and 3, the control predictions $\begin{bmatrix} u_{t|t-k} & u_{t+1|t-k} & \cdots & u_{t+d_1|t-k} \end{bmatrix}$ at time $t$, which are calculated by (4), are packed together and are sent from the controller side to the actuator side. If the minimum network delay in the forward channel is known, the control predictions to be sent from the controller side at time $t$ will be $\begin{bmatrix} u_{t+n_0|t-k} & u_{t+n_0+1|t-k} & \cdots & u_{t+d_1|t-k} \end{bmatrix}$. From Assumption 3, the output data set $\begin{bmatrix} y_t & y_{t-1} & \cdots & y_{t-n_d} \end{bmatrix}$ at time $t$ is transmitted from the sensor side to the controller side to avoid the output data loss in the feedback channel. In this way, the needed control prediction data on the actuator side and the needed output data on the controller side are always available at time $t$.

To avoid the data packet disorder, two data buffers are needed to reorder the received data and keep the latest data. One is for the control input data on the actuator side and the other for the output data on the controller side. So, under Assumption 4, the latest output data on the controller side and the latest control input data on the actuator side are available for use.

On the actuator side, the control input will be taken as

$$u_t = u_{t|t-k-j} = Kx_{t|t-k-j} \tag{5}$$

which implies that the network delay compensator selects $u_{t|t-k-j}$ from the latest control predictions in the data buffer on the actuator side. It has already been shown that the control performance of the closed-loop networked predictive control system is similar to the one without the network in [45]. Thus, the gain $K$ can be designed like normal state-feedback control systems without the network so that the desired control performance of the closed-loop system is satisfied. Therefore, the network delay can actively be compensated and desired control performance can be achieved by the above control strategy.

## 3 Stability analysis of networked predictive control systems

Stability analysis is a very important part of the control system design. Normally, the analysis of networked control systems is much harder than that of conventional control systems (i.e., without network). The stability analysis of closed-loop networked predictive control systems is simplified in this section.

Let $\tau = k+j$, which represents the round trip delay of the real-time data in the system. Combining (2) and (4) leads to

$$\begin{aligned} x_{t-\tau+1|t-\tau} = \ & Ax_{t-\tau|t-\tau-1} + BKx_{t-\tau|t-\tau-1} + \\ & L(Cx_{t-\tau} - Cx_{t-\tau|t-\tau-1}) = \\ & (A+BK-LC)x_{t-\tau|t-\tau-1} + LCx_{t-\tau} \end{aligned}$$

which is equivalent to

$$x_{t+1|t} = (A+BK-LC)x_{t|t-1} + LCx_t \tag{6}$$

Using (4), the state predictions at time $t-\tau$ in (3) can be calculated by

$$\begin{aligned} & x_{t-\tau+i|t-\tau} = \\ & \quad Ax_{t-\tau+i-1|t-\tau} + BKx_{t-\tau+i-1|t-\tau} = \\ & \quad (A+BK)x_{t-\tau+i-1|t-\tau} = \\ & \quad (A+BK)^{i-1}(A+BK-LC)x_{t-\tau|t-\tau-1} + \\ & \quad (A+BK)^{i-1}LCx_{t-\tau} \end{aligned}$$

for $i \in 2, 3, \cdots, d$. So, letting $i = \tau$ yields

$$\begin{aligned} x_{t|t-\tau} = \ & (A+BK)^{\tau-1}(A+BK-LC)x_{t-\tau|t-\tau-1} + \\ & (A+BK)^{\tau-1}LCx_{t-\tau} \end{aligned}$$

So, with controller (5), the state of plant (1) can be given by

$$\begin{aligned} & x_{t+1} = Ax_t + BKx_{t|t-\tau} = \\ & \quad Ax_t + BK(A+BK)^{\tau-1}LCx_{t-\tau} + \\ & \quad BK(A+BK)^{\tau-1}(A+BK-LC)x_{t-\tau|t-\tau-1} \end{aligned} \tag{7}$$

It is clear from (6) and (7) that the closed-loop networked predictive control system can be described as:

$$Z_{t+1} = A_1 Z_t + B_\tau Z_{t-\tau} \tag{8}$$

where

$$Z_t = \begin{bmatrix} x_t \\ x_{t|t-1} \end{bmatrix}, \quad A_1 = \begin{bmatrix} A & 0 \\ LC & A+BK-LC \end{bmatrix}$$

$$B_\tau = \begin{bmatrix} BK(A+BK)^{\tau-1}LC & BK(A+BK)^{\tau-1}(A+BK-LC) \\ 0 & 0 \end{bmatrix}$$

Actually, system (8) can be seen as a following switched system with a mode-dependent delay $\tau \in \{n_m,\ n_m+1,\ \cdots,\ d\}$. In recent years, switched systems with mode-dependent delay have been well investigated and many results of analysing their stability have been obtained[15−17]. Those results can be employed to analyse the stability of the closed-loop networked predictive control system.

## 4 Implementation of networked predictive control systems

To implement networked predictive control systems, the NetCon (networked control) platform has been developed, as shown in Fig. 4. The platform is based on the visual configuration technology for implementation of real-time control systems through Intranet/Internet. It provides an ideal integrated solution for control system development and implementation, which can be used for research, development, experiment and assessment of control theory and control technology. This platform offers a tool chain for development, implement and evaluation of new control algorithms and can also be used for rapid control prototyping. For the systems based on network (Ethernet/Internet/wireless network), the user can construct networked control test rigs, carry out remote control, monitoring and supervision, and study networked control systems.

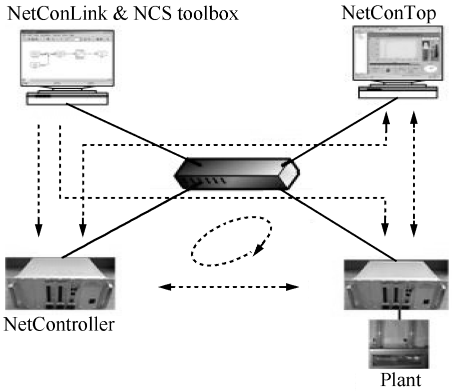

Fig. 4 NetCon platform for networked predictive control systems

The NetCon platform mainly consists of four parts: NetController, NetConLink, NetConTop and NCS toolbox. NetController, which has a microprocessor for fast real-time computation of user′s control algorithms, and can construct both a networked control system and local control system with the plant. Using the NetConLink, the user can carry out block-diagram based simulation designed using the NCS toolbox, then generate executable codes automatically and upload them to the remote NetController through networks. Remote monitoring and on-line parameters tuning can also be implemented using the NetConTop. The NetController, control configuration workstation (running the NetConLink) with the NCS toolbox and supervisory configuration workstation (running the NetConTop) can be employed to construct various structures of closed-loop control systems, such as networked control system over Ethernet, networked control system over wireless local area network, networked control system over Internet.

The NetController is the hardware part of the NetCon platform. Various real-time control algorithms can run on the NetController. It is an ideal solution for Ethernet-based systems and industrial modular design. The NetController is based on a cost-effective high-performance 32-bit RISC microprocessor, equipped with an embedded real-time Linux operating system and multi-channel standard I/O interface, including A/D, D/A, PWM, etc.

The NetConLink is the visual control configuration software of the NetCon platform and provides the user with a convenient way to implement control strategies of real-time control systems in a visual graphic form through the Internet. It is seamlessly integrated with Matlab/Simulink/Real-time workshop and various hardware drivers, and can automatically and rapidly generate executable codes from block diagrams in Simulink.

The NetConTop is the visual supervisory configuration software of the NetCon system. It provides the user various tools to configure a visual diagram to monitor the operation conditions of real-time control systems running on the NetController through a network. It has real-time data acquisition and management functions, is equipped with various visual configurable virtual graphs and virtual instruments, supports the client/server structure, and implements real-time remote monitoring, tuning and supervision

The NCS toolbox (networked control system toolbox) is developed in the Matlab/Simulink-based environment. With the sole NCS toolbox, the user can build his/her simulations and real-time experiments of networked control systems. This toolbox is composed of four parts: network simulation, network interface, plant interface and control schemes. The network simulation part has the "Random delay" and "Markov delay" blocks to simulate communication networks as a random transmission delay unit and a Markov-chain transmission delay unit, respectively. The network interface part provides two categories of data sending/receiving blocks for simulation and real-time experiments, respectively, where the UDP network protocol is adopted for real-time data transmission. The plant interface part offers various input-output data acquisition blocks, for example, A/D, D/A, DI, DO, PWM and PIO blocks, to exchange the information between the plant and the NetController. The control scheme part gives many different control algorithm blocks, for example, NPC scheme (networked predictive control), GPC scheme (generalised predictive control), MPC (model predictive control), and RLS estimator (recursive least squares algorithm).

Therefore, simulation and experiments of networked predictive control systems can easily be implemented in the NetCon platform.

## 5 Simulations of networked predictive control systems

To illustrate the performance of networked predictive control systems, a DC servo control system is considered[11]. The discrete-time model of the servo system is given by

$$A = \begin{bmatrix} 1.2998 & -0.4341 & 0.1343 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix},\quad B = \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix}$$

$$C = \begin{bmatrix} 3.5629 & 2.7739 & 1.0121 \end{bmatrix}$$

The sampling period is 0.04 s. Let the desired poles of the closed-loop state feedback control system be [−0.1, 0.6+0.3i, 0.6−0.3i] and the desired poles of the observer be [0, 0, 0]. Using the pole assignment method, the control gain and observer gain are designed to be

$$K = \begin{bmatrix} -0.1998 & 0.1041 & -0.1793 \end{bmatrix}$$
$$L = \begin{bmatrix} 0.1739 & 0.1918 & 0.1463 \end{bmatrix}^{\mathrm{T}}$$

In order to show the effectiveness of the proposed method, some simulations have been carried out using Matlab/Simulink. Two types of network delay are considered in the simulations. One is the constant network delay, and the other is the random network delay.

1) Constant network delay

The network delay, either the constant or random delay, is often one of the causes of the poor performance and even makes the system unstable. The step responses of the system with 3-and 8-step constant round-trip network delay are given in Figs. 5 and 6. From these two figures, it can be seen that the control performance deteriorates with the increase of the network delay. Especially, when the network delay is 8-step, the closed-loop system is unstable. For this case, using the networked predictive control method proposed in this paper, the control performance is illustrated in Fig. 7. It can be seen from Fig. 7 that the effect of the network delay is actively compensated and the performance is the same as the case of no network delay if the model of the plant is perfectly accurate.

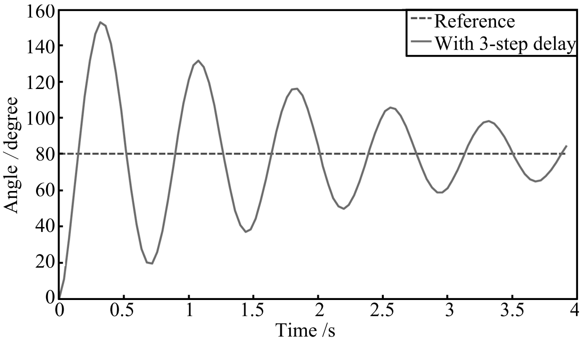

Fig. 5 Step responses with 3-step network delay

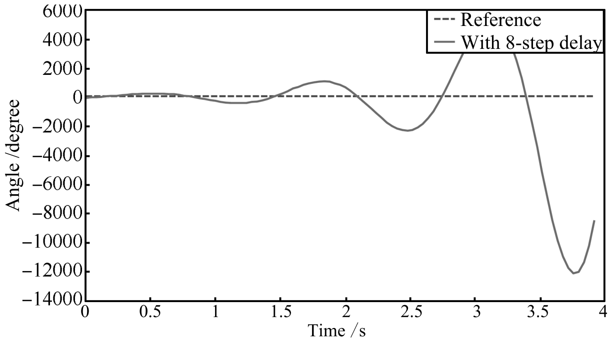

Fig. 6 Step responses with 8-step network delay

2) Random network delay

It is assumed that the round-trip network delay belongs to an interval [3, 8] as shown in Fig. 8. The step responses of the system without delay compensation or with delay compensation are given in Fig. 9. It can be seen that the networked predictive control method can greatly improve the performance of the networked control system in the case of the random delay. It indicates that the proposed method is capable of compensating for the network delay and data packet dropout for the Internet based control system.

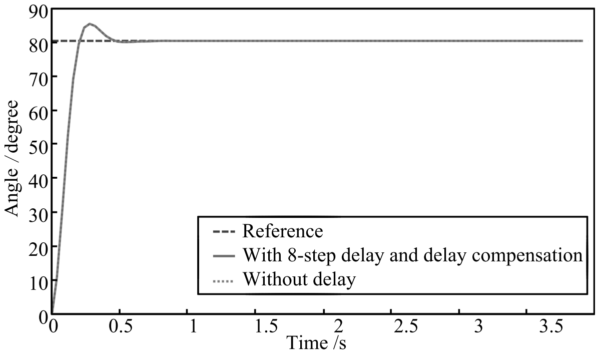

Fig 7 Step responses with 8-step network delay and delay compensation

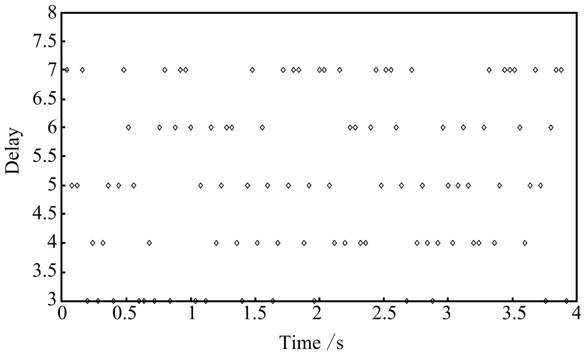

Fig. 8 Random network delay

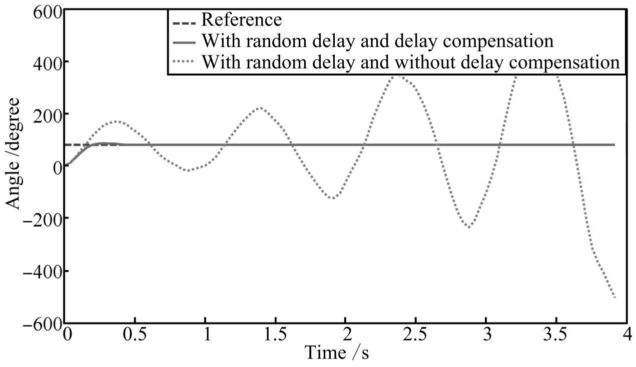

Fig. 9 Step responses with random network delay and with or without delay compensation

## 6 Experiments of networked predictive control systems

To test the networked predictive control method, a test rig has been established. This test rig consists of two NetControllers and one DC servo system (Fig. 10). One NetController was placed at the controller side and implemented the proposed networked predictive control algorithm and generated the future control input signals. The other NetController was placed at the plant side and acted as the network delay compensator. These two NetControllers were connected via Internet and UDP was adopted as the communication protocol between them. The controlled plant is a servo system. This system consists of DC motor, magnetic plate load and angle sensor. The control system is designed to achieve a pre-set angle against the magnetic plate load. The motor is driven by a servo amplifier and the position angle of the servo system is measured by a position sensor. This servo system and its model were used for the simulation and practical experiment of the networked predictive control method through Internet.

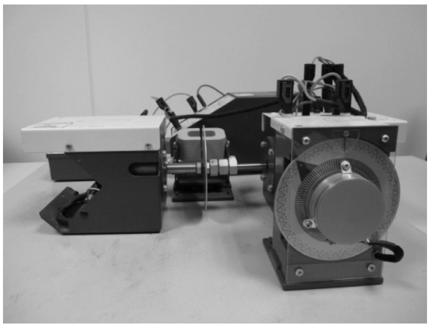

Fig 10 The DC servo system

In order to illustrate the operation of the networked predictive control method, experimental results presented in this part. The implementation diagram is shown in Fig. 11. In the experiment, two NetControllers are placed at University of South Wales in the UK and Tsinghua University in China, respectively. The IP addresses of these two NetController are 193.63.131.219 and 159.226.20.109, respectively.

The round-trip network delay in the system varies from 0.12 s to 0.32 s according to the experimental results. The sampling period is chosen as 0.04 s, so the round-trip network delay varies from 3 to 8 steps. The same controller and observer as those used in the simulations are adopted in the practical experiment. If this controller and observer are applied to control the servo system over Internet without any delay compensations, the closed-loop system will be unstable, which is shown in Fig. 12. Using the proposed networked predictive control method, the step response of the closed-loop system is shown in Fig. 13 where the local control response is also given for the sake of comparison. From Fig. 13, it can be seen that the proposed method has compensated for the effect of the network delay effectively and yields a similar control performance as the local control.

## 7 Conclusions

The design, analysis and real-time implementation of networked predictive control systems have been investigated in this paper. The control approaches and theories that have been applied to NCSs have been summarized. An analysis on the characteristics of networked control systems (NCSs), which are much different from the conventional control systems, has been detailed. In order to overcome the effect of network delay and data dropout, the networked predictive control method has been introduced. The stability of the networked predictive control system can be

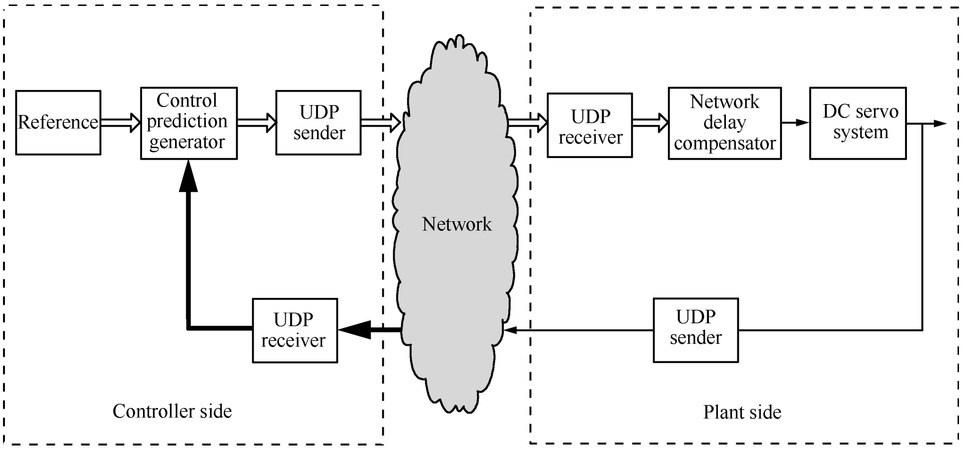

Fig 11 Implementation diagram of the networked predictive control system

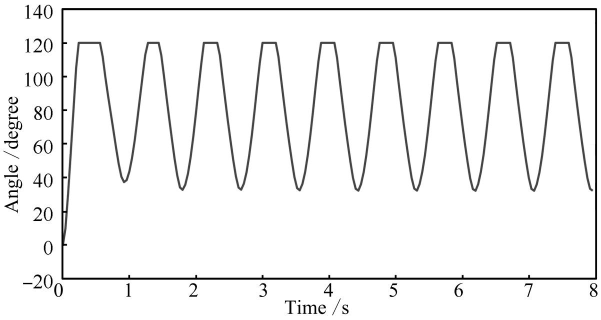

Fig. 12 Step response without compensation

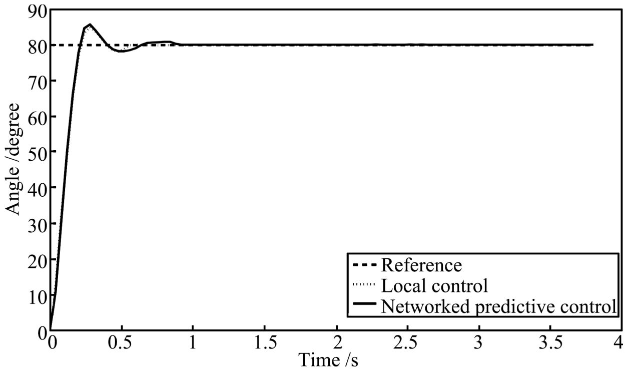

Fig. 13 Step responses of local control and networked predictive control

studied using switched system approaches or switched delay system approaches. Simulations and practical experiments have illustrated that the proposed networked predictive control scheme has compensated for random network communication delay and data dropout, and achieved desired control performance which is similar to the local control.

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