Design of a Packet-Based Control Framework for Networked Control Systems

Yun-Bo Zhao, Guo-Ping Liu, and David Rees

***Abstract*—A packet-based control framework is proposed for networked control systems (NCSs). This framework takes advantage of the characteristic of the packet-based transmission in a networked control environment, which enables a sequence of control signals to be sent over the network simultaneously, thus making it possible to actively compensate for the communication constraints in NCSs. Under this control framework and a deriving delay-dependent feedback gain scheme, a novel model for NCSs is proposed which can deal with network-induced delay, data packet dropout and data packet disorder in NCSs simultaneously and a receding horizon controller is also designed to implement the packet-based control approach. This approach is then verified by a numerical example and furthermore an Internet-based test rig which illustrates the effectiveness of the proposed approach.**

***Index Terms*—Communication constraints, delay-dependent feedback gain, internet-based test rig, networked control systems (NCSs), packet-based control, receding horizon control.**

I. INTRODUCTION

DISTINCT from conventional control systems (CCSs) where the data exchange between sensors, controllers, actuators, etc., is assumed to be costless, networked control systems (NCSs) can contain a large number of control devices interconnected through some form of network and data is exchanged through communication networks which inevitably introduces communication constraints to the control systems, e.g., network-induced delay, data packet dropout, data packet disorder, data rate constraint, etc. Though NCSs provides great advantages of remote and distribute control; examples of application areas include building automation, office automation, intelligent vehicle, etc., the communication constraints in NCSs however present great challenges for conventional control theory [1]–[11].

Though the theoretical foundation of NCSs has been improved considerably during the last decade, it is still in its infancy. Most work in this area is inclined to model NCSs into CCSs with some communication constraints, see, e.g., [12] and [13]. While this enables standard design and analysis tools in CCSs to be applied to NCSs, it has not taken full advantage of the characteristics of the network, especially those which may be positive to the system performance. As a result, the design and analysis of NCSs using these kind of approaches can be considerably conservative.

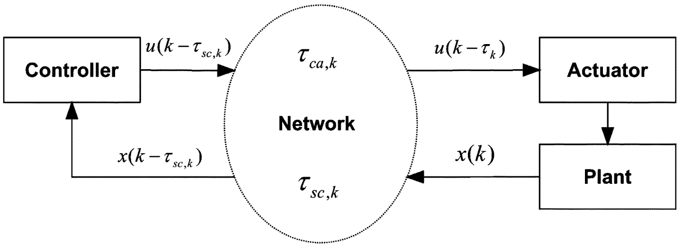

Fig. 1. Block diagram of a networked control system.

In this brief, we exploit the fact that in most communication networks, data is transmitted in "packet" and within its effective load sending a single bit or several hundred bits consumes the same amount of network resources [6]. This makes it possible in NCSs to actively compensate for the communication constraints by sending a sequence of control predictions in one data packet and then selecting the appropriate one corresponding to current network condition. This is the motivation for the design of the so called "packet-based control" approach for NCSs which is considered in this brief. Due to the active compensation process in the packet-based control approach, a better performance can be expected than those from previous implementations where no characteristics of the network are specifically considered in the design. Under this packet-based framework, a receding horizon controller is designed as an example with the consideration of the communication constraints, which is then verified by using a numerical example and an Internet-based test rig.

The remainder of this brief is organized as follows. The problem that is studied is first defined in Section II, following which the design details and the stability criterion of the packet-based control approach is presented in Section III and a receding horizon controller is also designed in Section IV for implementation considerations; In Section V examples to illustrate the effectiveness of the proposed approach are presented and Section VI concludes this brief.

II. PROBLEM STATEMENT

It is worth mentioning that any type of plant can be dealt with under the packet-based control framework. In this brief, however, the following linear plant in discrete-time is considered for simplicity

$$x(k+1) = Ax(k) + Bu(k) \tag{1}$$

where $x(k) \in \mathbb{R}^n, u(k) \in \mathbb{R}^m, y(k) \in \mathbb{R}^r, A \in \mathbb{R}^{n\times n}, B \in \mathbb{R}^{n\times m}$. In this brief, the plant is assumed to be controlled over the network and the full state information is available for measurements, see Fig. 1.

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Y.-B. Zhao and D. Rees are with the Faculty of Advanced Technology, University of Glamorgan, Pontypridd, CF37 1DL, U.K. (e-mail: yunbozhao@gmail.com.).

G.-P. Liu is with the Faculty of Advanced Technology, University of Glamorgan, Pontypridd, CF37 1DL, U.K., and also with CTGT Centre, Harbin Institute of Technology, CSIS Lab in the Chinese Academy of Sciences, China.

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For a control system without the communication constraints in NCSs, the conventional state feedback law is obtained as follows

$$u(k) = Kx(k) \tag{2}$$

where the feedback gain K is time-invariant.

However, in the presence of the communication constraints considered in this brief, i.e., network-induced delay, data packet dropout, data packet disorder, etc., the state feedback law can not be simply defined as in (2). The influence of these communication constraints to the feedback control law design is analyzed as follows.

1) Network-Induced Delay: The state feedback control law will be based on delayed sensing data when network-induced delay is considered. Let $\tau_k = \tau_{\mathrm{sc},k} + \tau_{\mathrm{ca},k}$ be the round trip delay at time k, where $\tau_{\mathrm{sc},k}$ and $\tau_{\mathrm{ca},k}$ are the network-induced delays in the backward and forward channel respectively. The control law using conventional time-delay system (TDS) theory can then be designed as

$$u(k) = Kx(k - \tau_k). \tag{3}$$

Notice here that the feedback gain K is still time-invariant, that is, the same feedback gain applies to different delays, which will be shown in Section V to be considerably conservative. However, with the proposed packet-based control approach in this brief, a delay-dependent feedback gains (DFG) scheme which is less conservative, is shown to be suitable for implementation in a networked control environment.

2) Data Packet Dropout: From Fig. 1, we can see no matter whether in the backward or forward channel data packet dropout occurs, a certain control input will be unavailable to the actuator. In previously reported results, there are mainly two ways to deal with this problem, that is either to use the previous control input [14]

$$u(k) = \begin{cases} \bar{u}(k), & \text{if transmitted successfully} \\ u(k-1), & \text{otherwise.} \end{cases} \tag{4}$$

or zero control [15]

$$u(k) = \begin{cases} \bar{u}(k), & \text{if transmitted successfully} \\ 0, & \text{otherwise} \end{cases} \tag{5}$$

where $\bar{u}(k)$ is the newly arrived control signal at time k.

Though these strategies are simple to implement, it is conservative in that it overlooks the possibility of providing an active prediction for the unavailable control input using available information of the system dynamics and previous system trajectory as in [16]. It is important to point this out that this drawback in CCSs can be easily dealt with by the proposed packet-based control approach (see Section III-B).

3) Data Packet Disorder: In NCSs, different data packets may experience different delays which produces a situation that a packet sent earlier may arrive at the destination later (so called "data packet disorder"). This situation occurs when a data packet experiences at least one step delay less than its subsequent data packet, i.e., $\tau_k > \tau_{k-1} + 1$. Due to the real-time requirement in NCSs, the disordered data packet will be simply discarded and this produces additional dropout. For this reason, hereafter the data packet disorder will not be treated separately but regarded as part of data packet dropout.

These negative effects of the communication constraints make the conventional state feedback law in (2) not appropriate in a networked control environment and thus require a novel design approach for NCSs. Fortunately, the packet-based transmission in a networked control environment enables us to actively compensate for these negative effects. A packet-based control approach for NCSs is therefore designed in the following section, yielding the following state feedback law with DFG:

$$u(k) = K_{\tau_{\mathrm{sc},k},\tau_{\mathrm{ca},k}} x(k - \tau_k) \tag{6}$$

where for different network conditions, different feedback gains apply. As will be presented later, this control law can actively deal with the network-induced delay, data packet dropout and data packet disorder simultaneously, and therefore can be regarded as a unified model for NCSs.

III. PACKET-BASED CONTROL FOR NCSS

The packet-based transmission in NCSs is one of its key characteristics different from CCSs, yet it has not been fully considered in the literature before. This characteristic can mean that in NCSs transmitting one step control signal or several control signals consumes the same amount of network resource. Based on this observation, we design as follows the packet-based control framework for NCSs which can actively compensate for the communication constrains without any additional requirements for the network.

The following assumptions are first made for the implementation of the packet-based control approach.

Assumption 1: All the components considered in the system including the sensor, the controller and the actuator are time-synchronized.

Assumption 2: All the data packets sent from both the sensor and the controller are time-stamped to notify when they are sent.

Assumption 3: The sum of the maximum network-induced delay in the forward channel (backward channel) and the maximum number of continuous data packet dropout (disorder as well) is upper bounded by $\bar{\tau}_{\mathrm{ca}}(\bar{\tau}_{\mathrm{sc}}$ accordingly) and

$$\bar{\tau}_{\mathrm{ca}} \le \frac{B_{\mathrm{packet}}}{B_{\mathrm{control}}} - 1 \tag{7}$$

where B_{packet} is the size of the effective load of the data packet and B_{control} is the bits required to encode a single step control signal.

Remark 1: From Assumption 1, 2, the network-induced delay that each data packet experiences can be known by the control device (the controller and the actuator) as soon as it arrives.

Remark 2: The constraint in (7) is introduced in order to implement successfully the packet-based control approach, see Section III-A1). This constraint is easy to be satisfied, e.g., $B_{\mathrm{packet}} = 368$ bit for Ethernet IEEE 802.3 frame which is commonly used [17], while an 8-bit data (i.e., $B_{\mathrm{control}} = 8$ bit) can encode $2^8 = 256$ different control signals which is ample for most control implementations; In this case, 45 steps of network-induced delay is allowed by (7) which can actually meet the requirements of most practical control systems.

Based on the aforementioned assumptions, the following schemes to compensate for the network-induced delay and data packet dropout (disorder) are proposed, respectively.

A. Compensate for the Network-Induced Delay

In order to actively compensate for the network-induced delay in both channels by taking advantage of the packet-based transmission in NCSs, we design the following packet-based controller at the controller side and control action selector at the actuator side, respectively.

1) Packet-Based Controller: As stated previously, the sensing state data received by the controller at time k is denoted by $x(k-\tau_{\mathrm{sc},k})$, where $\tau_{\mathrm{sc},k}$ denotes the network-induced delay of the data packet in the backward channel (see Fig. 1). Based on this state data, the following control predictions are obtained as in (6)

$$u(k+i|k-\tau_{\mathrm{sc},k}) = K_{\tau_{\mathrm{sc},k},i}x(k-\tau_{\mathrm{sc},k}),\quad i=0,1,2,\ldots,\bar{\tau}_{\mathrm{ca}} \tag{8}$$

which can be written in the form of a forward control sequence $U(k|k-\tau_{\mathrm{sc},k}) = [u(k|k-\tau_{\mathrm{sc},k})\, u(k+1|k-\tau_{\mathrm{sc},k}),\ldots,\, u(k+\bar{\tau}_{\mathrm{ca}}|k-\tau_{\mathrm{sc},k})]^T$. This is different from CCSs where only one control signal is processed at any single time and that is why the controller designed in this brief is called a "packet-based controller".

From Assumption 3, this forward control sequence $U(k|k-\tau_{\mathrm{sc},k})$ can be packed into one data packet and sent to the actuator. Notice here that sending a sequence of control predictions instead of only one step control signal does not consume more network resources provided Assumption 3 holds, yet this simple technique enables us to actively compensate for the communication constraints as shown in the following.

2) Control Action Selector: In order to compensate for the network-induced delay, a control action selector is designed at the actuator side. This is designed to be capable of storing only one forward control sequence (one data packet) at any one time. At every execution time instant, the actuator picks out the appropriate control prediction which can compensate for the current network-induced delay in the forward channel from the control action selector and applies it to the plant. In this way, the network-induced delays in both channels can be exactly compensated for.

Notice that the network-induced delays in the forward and backward channel are $\tau_{\mathrm{ca},k}$ and $\tau_{\mathrm{sc},k}$, respectively, the forward control sequence used by the actuator at time k can then be represented by $U(k-\tau_{\mathrm{ca},k}|k-\tau_k) = [u(k-\tau_{\mathrm{ca},k}|k-\tau_k)u(k-\tau_{\mathrm{ca},k}+1|k-\tau_k)\cdots u(k|k-\tau_k)\cdots u(k+\bar{\tau}_{\mathrm{ca}}|k-\tau_k)]^T$, and $u(k|k-\tau_k)$ is the one actually applied to the plant.

It is necessary to point out that this appropriate control signal is always available provided Assumption 3 holds.

B. Compensate for the Data Packet Dropout (Disorder)

A comparison process in the control action selector is introduced to deal with the data packet dropout (disorder). When a data packet arrives at the control action selector, it does not simply replace the one already in the control action selector since the one arrives later does not necessarily contain the latest data because of the presence of data packet dropout (disorder). Denote the forward control sequence already in the control action selector and the one just arrived by $U(k_1-\tau_{\mathrm{ca},k_1}|k_1-\tau_{k_1})$ and $U(k_2-\tau_{\mathrm{ca},k_2}|k_2-\tau_{k_2})$, respectively, then the comparison process can be determined by the following rule:

$$\begin{aligned} &U(k-\tau^*_{\mathrm{ca},k}|k-\tau^*_k) \\ &= \begin{cases} U(k_2-\tau_{\mathrm{ca},k_2}|k_2-\tau_{k_2}), & \text{if } k_1-\tau_{k_1} < k_2-\tau_{k_2} \\ U(k_1-\tau_{\mathrm{ca},k_1}|k_1-\tau_{k_1}), & \text{otherwise.} \end{cases} \end{aligned} \tag{9}$$

where the superscript $*$ is used to denote corresponding network-induced delays of the latest forward control sequence in the control action selector after the comparison process. As a result of the comparison process, the forward control sequence stored in the control action selector is always the latest one available at any specific time.

The algorithm of the packet-based control approach for NCSs can now be summarized as follows.

Algorithm 1 (Packet-based control approach): S1. At time k, if the packet-based controller does not receive the delayed state data $x(k-\tau_{\mathrm{sc},k})$, let $k=k+1$; otherwise do S1a-S1c:

S1a. Read the current network-induced delay in the backward channel $\tau_{\mathrm{sc},k}$;

S1b. Calculate the forward control sequence $U(k|k-\tau_{\mathrm{sc},k})$ using the forward control controller designed in Section III-A1;

S1c. Pack $U(k|k-\tau_{\mathrm{sc},k})$ into one data packet and send it to the actuator with time stamps k and $\tau_{\mathrm{sc},k}$.

S2. Update the control action selector using (9) once a data packet arrives;

S3. Apply $u(k|k-\tau^*_k)$ to the plant.

The schematic structure of the packet-based control framework is illustrated in Fig. 2.

C. Stability of the Closed-Loop System

Let $Z(k) = [x(k)\ x(k-1)\ \cdots\ x(k-\bar{\tau})]$, where $\bar{\tau} = \bar{\tau}_{\mathrm{sc}} + \bar{\tau}_{\mathrm{ca}}$ is the upper bound of the round trip delay and continuous dropout (disorder). The closed-loop formula for system (1) using the packet-based controller in (6) can then be represented by

$$Z(k+1) = \Lambda_{\tau_{\mathrm{sc},k},\tau_{\mathrm{ca},k}}Z(k) \tag{10}$$

where

$$\Lambda_{\tau_{\mathrm{sc},k},\tau_{\mathrm{ca},k}} = \begin{pmatrix} A & \cdots & K_{\tau_{\mathrm{sc},k},\tau_{\mathrm{ca},k}} & \cdots & \cdots \\ I_n & & & & 0 \\ & I_n & & & 0 \\ & & \ddots & & \vdots \\ & & & I_n & 0 \end{pmatrix}$$

with I_n being the identity matrix with rank n.

Theorem 1 (Closed-Loop Stability): The closed-loop system (10) is stable if there exists a positive definite solution $P = P^T > 0$ for the following $(\bar{\tau}_{\mathrm{sc}}+1)\times(\bar{\tau}_{\mathrm{ca}}+1)$ LMIs

$$\Lambda^T_{\tau_{\mathrm{sc},k},\tau_{\mathrm{ca},k}} P \Lambda_{\tau_{\mathrm{sc},k},\tau_{\mathrm{ca},k}} - P < 0. \tag{11}$$

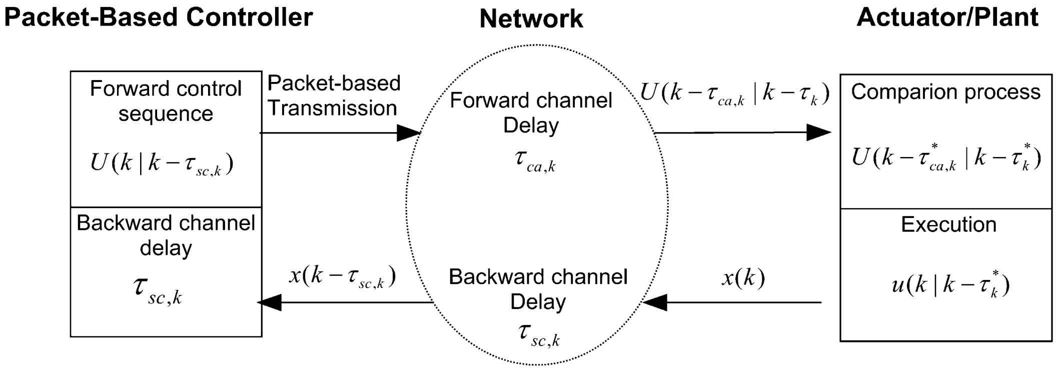

Fig. 2. The packet-based control approach for NCSs.

Proof: Let $V(k) = Z(k)PZ(k)$ be a Lyapunov candidate, then its increment along system (10) can be obtained

$$\begin{aligned}\Delta V(k) &= V(k+1) - V(k)\\ &= Z^T(k)(\Lambda^T_{\tau_{\mathrm{sc},k},\tau_{\mathrm{ca},k}} P \Lambda_{\tau_{\mathrm{sc},k},\tau_{\mathrm{ca},k}} - P)Z(k) < 0\end{aligned} \tag{12}$$

which completes the proof. ■

Up to now we have provided the packet-based control structure for NCSs whilst the controller design remains to be open. It is necessary to point out that under the framework of the packet-based control approach, any conventional design approach is eligible to be applied to obtain the delay-dependent feedback gains in (6) provided it can result in a good system performance. In the following section, a receding horizon controller is designed as an example.

IV. RECEDING HORIZON CONTROLLER

In receding horizon control, an optimization process is repeated at every control instant to determine a sequence of forward control signals that optimize future open-loop plant behavior based on current system information. Different from conventional receding horizon implementations where only the first control prediction is actually applied to the plant, in this brief the first $\bar{\tau}_{\mathrm{ca}} + 1$ forward control predictions are all used to implement the packet-based control approach proposed in the previous section.

Taking account of the communication constraints in NCSs which delay the sensing data, the objective function for open-loop optimization in the receding horizon controller design is therefore defined as follows:

$$\begin{aligned}J_{k,\tau_{\mathrm{sc},k}} = X^T&(k|k-\tau_{\mathrm{sc},k})QX(k|k-\tau_{\mathrm{sc},k})\\ &+U'^T(k|k-\tau_{\mathrm{sc},k})RU'(k|k-\tau_{\mathrm{sc},k})\end{aligned} \tag{13}$$

where $J_{k,\tau_{\mathrm{sc},k}}$ is the objective function at time $k, U'(k|k-\tau_{\mathrm{sc},k}) = [u(k-\tau_{\mathrm{sc},k}|k-\tau_{\mathrm{sc},k}) \cdots u(k+N_u-1|k-\tau_{\mathrm{sc},k})]^T$ is the forward control sequence, $X(k|k-\tau_{\mathrm{sc},k}) = [x(k+1|k-\tau_{\mathrm{sc},k}) \cdots x(k+N_p|k-\tau_{\mathrm{sc},k})]^T$ is the predictive state trajectory, Q and R are constant weighting matrixes and N_p and N_u are the prediction horizon and the control horizon, respectively.

The predictive states at time k based on the state at time $k - \tau_{\mathrm{sc},k}$ and the control sequences from $k - \tau_{\mathrm{sc},k}$ can be obtained by iteration for $j = 1, 2, \ldots, N_p$ as

$$\begin{aligned}x(k+j|k-\tau_{\mathrm{sc},k}) &= A^{j+\tau_{\mathrm{sc},k}}x(k-\tau_{\mathrm{sc},k})\\ &+ \sum_{l=-\tau_{\mathrm{sc},k}}^{j-1} A^{j-l-1}Bu(k+l|k-\tau_{\mathrm{sc},k}).\end{aligned} \tag{14}$$

Thus

$$X(k|k-\tau_{\mathrm{sc},k}) = E_{\tau_{\mathrm{sc},k}}x(k-\tau_{\mathrm{sc},k}) + F_{\tau_{\mathrm{sc},k}}U'(k|k-\tau_{\mathrm{sc},k}) \tag{15}$$

where $E_{\tau_{\mathrm{sc},k}} = [(A^{\tau_{\mathrm{sc},k}+1})^T \cdots (A^{\tau_{\mathrm{sc},k}+N_p})^T]^T$ and $F_{\tau_{\mathrm{sc},k}}$ is a block lower triangular matrix with its non-null elements defined by $(F_{\tau_{\mathrm{sc},k}})_{ij} = A^{\tau_{\mathrm{sc},k}+i-j}B, j-i \leq \tau_{\mathrm{sc},k}$.

The optimal control inputs can then be calculated by substituting (15) to (13) and optimizing $J_{k,\tau_{\mathrm{sc},k}}$, which turns out to be state feedback control

$$\begin{aligned}u(k+j|k-\tau_{\mathrm{sc},k}) &= K_{\tau_{\mathrm{sc},k},j}x(k-\tau_{\mathrm{sc},k}),\\ j &= 0, 1, 2, \ldots, \bar{\tau}_{\mathrm{ca}}.\end{aligned} \tag{16}$$

Let $K_{\tau_{\mathrm{sc},k}} = [K^T_{\tau_{\mathrm{sc},k},0} \cdots K^T_{\tau_{\mathrm{sc},k},\bar{\tau}_{\mathrm{ca}}}]^T$, where $K_{\tau_{\mathrm{sc},k}}$ can be calculated by $K_{\tau_{\mathrm{sc},k}} = -M_{\tau_{\mathrm{sc},k}} (F^T_{\tau_{\mathrm{sc},k}}QF_{\tau_{\mathrm{sc},k}} + R)^{-1} F^T_{\tau_{\mathrm{sc},k}} QE_{\tau_{\mathrm{sc},k}}$, and $M_{\tau_{\mathrm{sc},k}} = [0_{m(\bar{\tau}_{\mathrm{ca}}+1)\times m\tau_{\mathrm{sc},k}} \; I_{m(\bar{\tau}_{\mathrm{ca}}+1)\times m(\bar{\tau}_{\mathrm{ca}}+1)} \; 0_{m(\bar{\tau}_{\mathrm{ca}}+1)\times m(N_u-\bar{\tau}_{\mathrm{ca}}}]$, then the forward control sequence to be sent to the actuator can be constructed by

$$U(k|k-\tau_{\mathrm{sc},k}) = K_{\tau_{\mathrm{sc},k}}x(k-\tau_{\mathrm{sc},k}). \tag{17}$$

Remark 3 (State Observer): If the state vector x is not available, an observer must be included

$$\begin{aligned}\hat{x}(k+1|k) = A\hat{x}&(k|k-1) + Bu(k)\\ &+ L(y_m(k) - C\hat{x}(k|k-1))\end{aligned} \tag{18}$$

where $\hat{x}(k)$ is the observed state at time k, and $y_m(k)$ is the measured output. If the plant is subject to white noise disturbances affecting the process and the output with known covariance matrices, the observer becomes a Kalman filter and the gain L is calculated solving a Riccati equation.

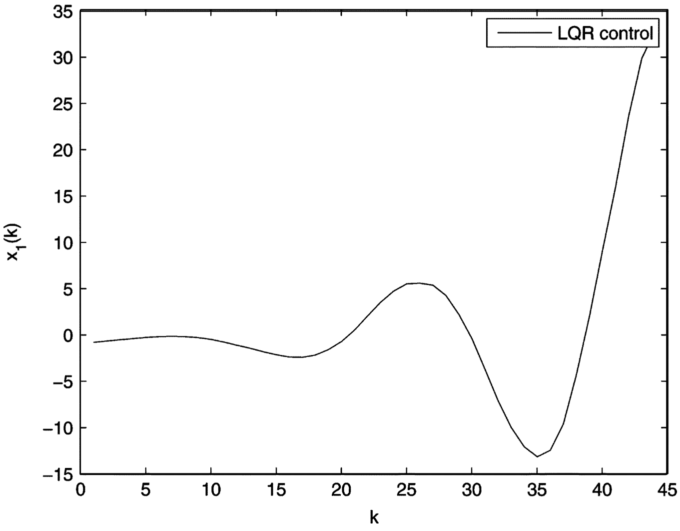

Fig. 3. System is unstable using conventional design approach.

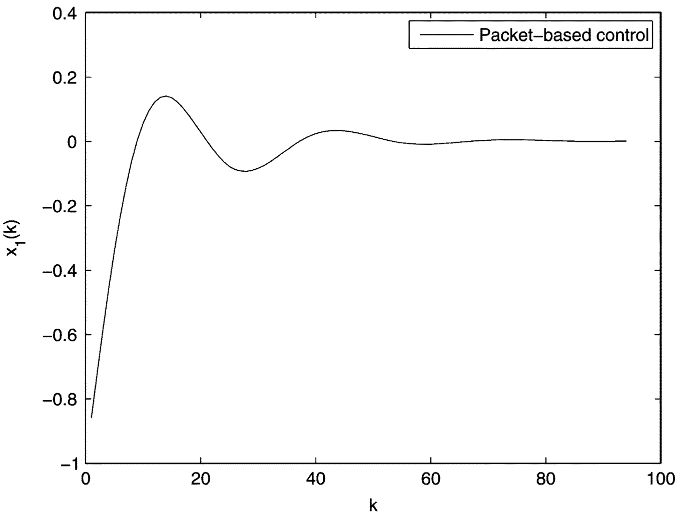

Fig. 4. System is stable using the packet-based control approach.

Remark 4 (Computation Delay): As an online optimization approach, the receding horizon controller designed in this section also experiences computation delay. It is noticed, however, under the packet-based control framework, this delay can be considered as part of the network-induced delay in the forward channel and thus can be compensated within this framework without additional considerations.

V. NUMERICAL AND EXPERIMENTAL EXAMPLES

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

Example 1: A second order model of the system in (1) is adopted, which is open-loop unstable with the following system matrices:

$$A = \begin{pmatrix} 0.98 & 0.1 \\ 0 & 1 \end{pmatrix}, \quad B = \begin{pmatrix} 0.04 \\ 0.1 \end{pmatrix}.$$

In order to illustrate the effectiveness of the proposed packet-based controller approach compared with conventional design approach, the linear quadratic optimal (LQR) control method is used to design a state feedback law for this system without consideration of the communication constraints, which yields the time-invariant feedback gain $K_{\mathrm{LQR}} = [0.7044\ 1.3611]$. In the simulation, the initial state $x_0 = [-1 -1]^T$, the upper bounds of the delays and continuous dropout (disorder) are $\bar{\tau} = 3, \bar{\tau}_{\mathrm{ca}} = 2, \bar{\tau}_{\mathrm{sc}} = 1$, and the control and prediction horizon in the receding horizon controller are set as $N_u = 8, N_p = 10$, respectively. The delays in both channels are set to vary randomly within their upper bounds.

The simulation results show that it is unstable using this LQR control (see Fig. 3) while it is stable using the proposed approach in this brief (see Fig. 4) in the presence of the communication constraints.

Example 2: In this example, an Internet-based test rig is used to verify the effectiveness of the packet-based control approach. This test rig consists of a plant (DC servo system, see Fig. 5) which is located in the University of Glamorgan, Pontypridd, UK, and a remote controller which is located in the Institute of Automation, Chinese Academy of Sciences, Beijing, China (see Fig. 6). The plant and the controller are connected via the Internet, whose IP addresses are 193.63.131.219 and 159.226.20.109, respectively. A web-based laboratory is also available at http://www.ncslab.net to implement experiments online. For further information of this test rig, the reader is referred to [18] and [19].

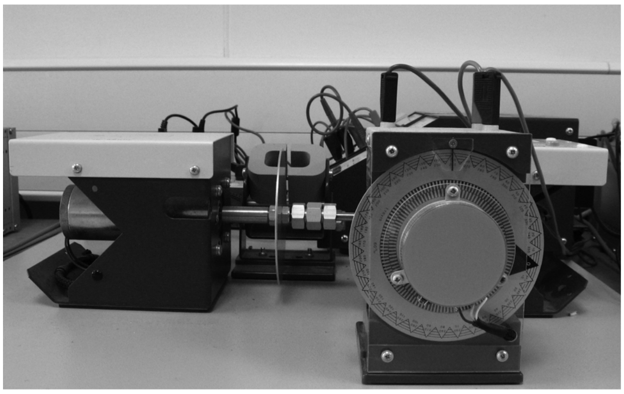

Fig. 5. DC servo plant in the University of Glamorgan.

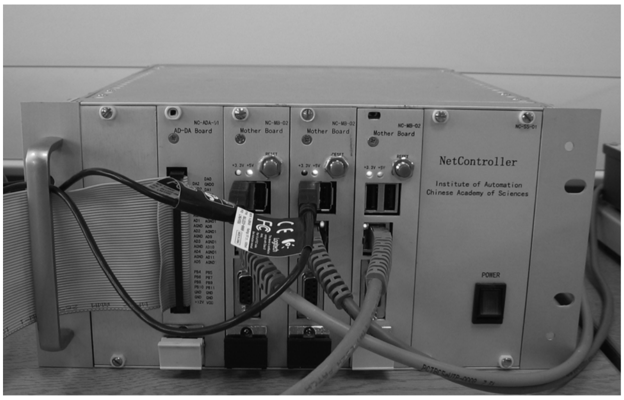

Fig. 6. Network controller in the Chinese Academy of Sciences.

The DC servo system is identified to be a third-order system and in state-space description has the following system matrices [18]:

$$A = \begin{pmatrix} 1.12 & 0.213 & -0.333 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{pmatrix}$$
$$B = \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix}$$
$$C = \begin{pmatrix} 0.0541 & 0.0050 & 0.0001 \end{pmatrix}.$$

To enable the use of state feedback in the packet-based control approach, a state observer as in Remark 3 is designed with $L = [6\ 6\ 6]^T$. The packet-based controller is then calculated by using the approach proposed in Section IV. To this end, the upper bounds of the network-induced delays (data packet dropout as well) in both forward and backward channels are assumed to be 4 steps of the sampling period (The sampling period is set as 0.04 s and thus the delay bounds are 0.16 s for both backward and forward channel delays.), since typically the round trip delay in the experiment is not larger than 0.32 s. The packet-based controller can then be obtained as

$$K = \left[K_0^T K_1^T K_2^T K_3^T K_4^T\right]^T$$
$$K_0 = \begin{pmatrix} -1.3217 & 0.1276 & 0.4296 \\ -0.1356 & 0.0306 & 0.0445 \\ 0.2688 & -0.0220 & -0.0816 \\ 0.1255 & -0.0096 & -0.0396 \\ 0.0610 & -0.0061 & -0.0190 \end{pmatrix}$$
$$K_1 = \begin{pmatrix} -0.2193 & 0.0219 & 0.0844 \\ 0.2177 & -0.0032 & -0.0662 \\ 0.1298 & -0.0087 & -0.0381 \\ 0.0621 & -0.0035 & -0.0198 \\ 0.0114 & -0.0014 & -0.0035 \end{pmatrix}$$
$$K_2 = \begin{pmatrix} 0.1120 & 0.0005 & -0.0201 \\ 0.1183 & 0.0032 & -0.0348 \\ 0.0726 & -0.0050 & -0.0201 \\ 0.0192 & -0.0007 & -0.0062 \\ 0.0035 & -0.0009 & -0.0010 \end{pmatrix}$$
$$K_3 = \begin{pmatrix} 0.0894 & 0.0021 & -0.0130 \\ 0.0832 & 0.0056 & -0.0239 \\ 0.0398 & -0.0028 & -0.0099 \\ 0.0106 & -0.0001 & -0.0035 \\ 0.0007 & -0.0007 & -0.0002 \end{pmatrix}$$
$$K_4 = \begin{pmatrix} 0.0721 & 0.0030 & -0.0076 \\ 0.0515 & 0.0073 & -0.0140 \\ 0.0267 & -0.0021 & -0.0058 \\ 0.0059 & 0.0001 & -0.0021 \\ 0.0005 & -0.0007 & -0.0001 \end{pmatrix}$$

where the subscripts of K_0, K_1, K_2, K_3, and K_4 are with respect to different backward channel delays.

The comparison between the simulation and experimental results is illustrated in Fig. 7, which shows that the packet-based control approach is valid in practice.

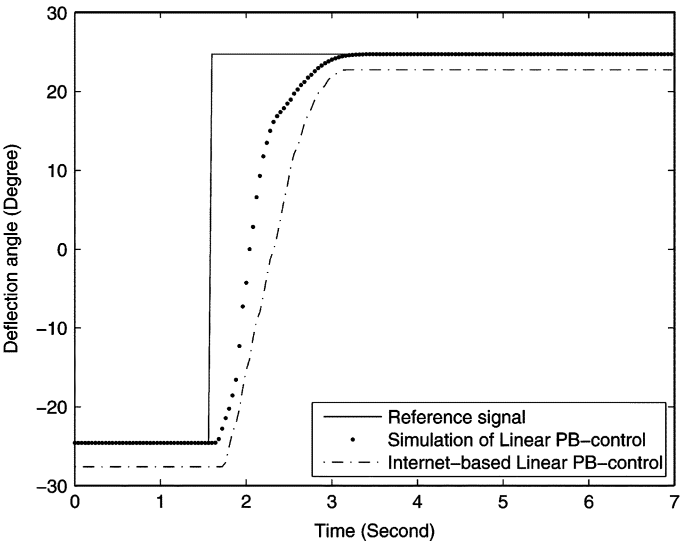

Fig. 7. Comparison between simulation and experimental results of linear packet-based control system.

It is seen however that there is some difference between simulation and experimental results. Several possible reasons may contribute to this difference: 1) the identified model for the DC servo system may not be accurate enough; 2) the dead zone of the DC servo plant has not been considered; 3) the measurement of the network-induced delays is not accurate in practice; and 4) accurate time-synchronization between all the control components is hard to obtain in the experiment.

VI. CONCLUSION

Since NCSs is actually the integration of CCSs and the communication networks, a natural way to deal with the communication constraints is to put the problem under the codesign framework—design with integration of control and communication theories. Based on the observation of the packet-based transmission in the networked control environment, a packet-based control framework was proposed for NCSs, which can effectively deal with the network-induced delay, data packet dropout and data packet disorder simultaneously. Numerical and experimental examples illustrated the effectiveness of the proposed approach with a receding horizon controller.

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