Error Bounded Sensing for Packet-Based Networked Control Systems

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***Abstract*—An error bounded sensing strategy is proposed within the packet-based control framework for networked control systems (NCSs). This strategy reduces the data transmissions in both the sensor-to-controller and the controller-to-actuator channels by allowing the transmissions of only the sensing and control data packets that satisfy some predetermined transmission rules. By fitting it into the packet-based control framework for NCSs, this strategy can achieve the goal of reducing the use of the communication resources while at the same time maintaining the system performance at an acceptable level. Stabilized controllers are designed within this framework, and the effects on the system stability brought by this approach are also investigated. Numerical and experimental examples illustrate the effectiveness of the proposed approach.**

***Index Terms*—Error bounded sensing (EBS), Internet-based test rig, networked control systems (NCSs), packet-based control.**

I. Introduction

NETWORKED control systems (NCSs) have been widely studied in recent years due to their extensive applications, existing ones of which include smart home, remote surgery, and smart transportation, just to name a few, and a lot of potentials are also expected in the near future [1]. These promising applications, generally speaking, benefited from two essential advantages brought by NCSs, i.e., the capability of both remote and distributed control. Apparently, these capabilities are due to the introduction of the communication network to NCSs, thus making the communication network essential in NCSs. An increasing trend is also noticed that more and more network-based applications are now configured over the Internet, mainly due to the low cost, easy maintenance, remote-control capability, etc., brought by the Internet. However, unlike those conventional control networks such as ControlNet, DeviceNet, etc., that have been particularly optimized for control applications [2], the Internet is essentially a data network, rather than a real-time network, meaning that the Internet has difficulty in meeting the critical real-time requirement of control systems. This fact implies that worse communication conditions in the Internet, such as larger delay, more data-packet dropout, and disorder, etc., require even more careful treatment before Internet-based control systems can be reliably applied in practice.

To date, many efforts have been made to deal with these so-called communication constraints in NCSs, ranging from the mathematical modeling and analysis from conventional control-theory perspective [3]–[5] to controller design and performance evaluation, by taking advantage of the characteristics of the communication network in NCSs [6]–[8], and further, to control-oriented communication protocol design from the communication-technology perspective [9], [10], and so forth. Whatever specific methods are used in NCSs, a consensus is always held that the communication constraints are critical in NCSs, and a promising approach is required to reduce the negative effects brought by the communication constraints as much as possible. Most of such approaches can be divided into the following two categories. One is to dynamically schedule the communication resources among different control tasks in order to make full use of the communication resources efficiently, as done in [11]–[13]. The other way is to reduce the necessary data transmissions while maintaining the system performance at an acceptable level, i.e., to find the tradeoff between the use of the communication resource and the system performance [14], [15]. These two means are not fungible but rather, have different focuses. The former is applied to the scenario where the communication network is occupied by multiple NCSs so that the efficient allocation of the communication resources is vital, while the latter more focuses on the reduction of the dependence on the communication network for a single NCS.

In this paper, a special case of the second category is considered by reducing the data exchanges in NCSs. This is obtained by means of a so-called “error bounded sensing” (EBS) strategy within the packet-based control framework for NCSs. Using this strategy, all the sensing data are not sent to the controller but only those that have changed dramatically compared with the sensing signal at the previous step. Consequently, all the control signals are not sent to the actuator but only those based on up-to-date sensing data. This approach artificially introduces bounded-sensing error, or equivalently, extra delay to the system, which can possibly degrade the system performance. However, it can still be of great significance due to the following reasons. First, this approach considerably reduces the use of the communication resources and thus, is beneficial for other control applications that share the same communication network which is often seen in practice. Second, this approach can even give rise to better system performance than conventional ones under poor communication conditions since

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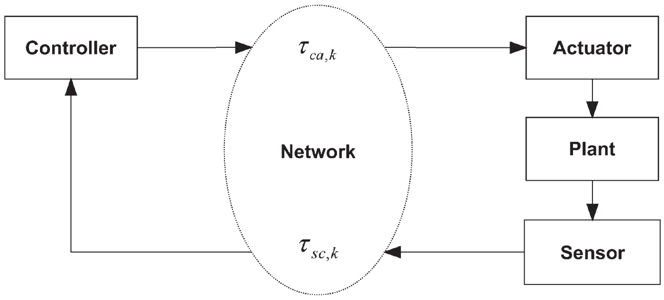

Fig. 1. Block diagram of an NCS.

it reduces the risk of causing congestion in the communication network. Furthermore, by setting an appropriate threshold of transmitting the sensing signals, the sensing error can be bounded at a predetermined level and thus, will not affect the system performance severely.

The proposed strategy is designed within the packet-based control framework for NCSs. This referred framework takes advantage of the packet-based data transmission in NCSs to compensate for the negative effects of the communication constraints which is not, however, intended to reduce the use of the communication resources [6]. It is noticed that with the EBS strategy, the data exchanges in both the sensor-to-controller and the controller-to-actuator channels can be reduced considerably while at the same time, the system performance can still be maintained at an acceptable level. Therefore, the EBS strategy, in some sense, completes the packet-based control for NCSs and thus enables the latter to be a complete solution to NCSs.

The remainder of this paper is organized as follows. In Section II, the design details of the EBS strategy within the packet-based control framework are presented. The corresponding closed-loop system is then modeled and analyzed, and the effects brought by this approach are also investigated in Section III. The effectiveness of the proposed approach is illustrated by both numerical and experimental examples in Section IV, and Section V concludes this paper.

II. EBS FOR PB-NCSs

The block diagram of the NCS considered in this paper is shown in Fig. 1. Although not explicitly shown in the figure, it is usually the case that the communication network is shared with other applications and not private to the considered control system. The applications are also not limited solely to the control purpose. This system setting justifies the claim made earlier, i.e., the dependence on the data exchanges in Internet-based NCSs ought to be reduced as much as possible, particularly in the presence of heavy communication burdens since the consuming of the communication resources can 1) affect the access to the communication resources of other applications and 2) increase the risk of causing congestion in the communication network, which can then degrade the overall system performance.

The EBS strategy proposed in this paper is exactly intended for the very purpose of reducing the use of the communication resources. With the help of the packet-based control approach to NCSs, this strategy can achieve the goal of reducing the use of the communication resources while maintaining the system performance at an acceptable level at the same time. In what follows, the EBS strategy is discussed first, which is then fitted into the packet-based control framework to form a complete solution to NCSs.

Before proceeding with the EBS strategy for packet-based NCSs (PB-NCSs), however, it is necessary to make the following assumption on the characteristics of the communication constraints in NCSs, which guarantees that the sensing data at the controller side and the control signals at the actuator side are updated within finite-time intervals. This assumption is reasonable in practice as well as important in theory.

Assumption 1: The network-induced delay in the sensor-to-controller and the controller-to-actuator channels are upper bounded by $\bar{\tau}_{sc}$ and $\bar{\tau}_{ca}$, respectively.

A. EBS in the Sensor-to-Controller Channel

As mentioned earlier, the implementation of the EBS strategy is based on the tradeoff between the system performance and the use of the communication resources. Regardless of the specific implemental procedures, the goal of the strategy is clear, i.e., it is aimed at reducing the sensing-data transmissions as much as possible while at the same time guaranteeing the sensing error at the controller side being bounded by a predetermined bound, for example, $\delta_s > 0$. Therefore, it is fairly clear that the key procedure of the EBS strategy is to determine whether the sensing signal at a specific time is sent to the controller or not. We refer to this key procedure as the "sensor transmission rule" (STR) which is discussed in detail as follows.

In order to present the STR in a precise manner, first, define δ_k and $\sigma(\cdot)$: $\mathbb{N} \rightarrow \{0, 1\}$ as follows:

$$\delta_k \triangleq \|x(k) - x(k-1)\| \tag{1a}$$

$$\sigma(k) \triangleq \begin{cases} 1, & \text{if } x(k) \text{ is sent to the controller} \\ 0, & \text{otherwise} \end{cases} \tag{1b}$$

where $x(k)$ is the system state at time k and $\|\cdot\|$ indicates the Euclidean norm. For simplicity, the system states are assumed to be fully accessible in this paper. However, even if this is not the case, the system states can still be obtained (probably with error) by using an appropriate state observer and thus, will not affect the discussions that follow. It is readily seen from the definitions in (1) that $\sigma(\cdot)$, as an indicator function, indicates whether a sensing signal at a specific time is sent to the controller or not. Therefore, the function $\sigma(\cdot)$ actually defines the STR in a mathematical manner, whose specific definition will be given as follows.

Suppose that, for some integers $k_0 > 1$ and $0 \leq j \leq N_s$, the sensing signal at time $k_0 - 1$ is sent to the controller, while those from time k_0 to $k_0 + j - 1$ are not. The STR can then be defined at time $k_0 + j$, as follows,

$$\sigma(k_0 + j) = \begin{cases} 1, & \text{if } \delta_{k_0+j} > \alpha_j \|x(k_0 + j)\| \\ & \text{or } j = N_s \\ 0, & \text{otherwise} \end{cases} \tag{2a}$$

where $\alpha_j \triangleq \frac{\delta_s}{N_s+(N_s-j)\delta_s}$. Notice here that N_s, referred to as the "maximum transmission interval," is an integer being chosen to guarantee that the sensing signals at the controller side are updated within a finite time interval. In fact, by the STR defined in (2a), at least one sensing signal will be sent to the controller within N_s time steps, and therefore, the sensing data at the controller side will be updated by no more than $\bar{\tau}_{sc}^* \triangleq \bar{\tau}_{sc} + N_s$ time steps. It is also noticed that the definition of the STR in (2a) is complete in the sense that it has been defined for all the time instants $k \geq 1$. To interpret this, for any $k \geq 1$, define $k_\sigma = \max\{j|1 \leq j \leq k, \sigma(j) = 1\}$, and the STR in (2a) can then be reformed as

$$\sigma(k) = \begin{cases} 1, & \text{if } \delta_k > \alpha_{k-k_\sigma} \|x(k)\| \\ & \text{or } k - k_\sigma = N_s \\ 0, & \text{otherwise} \end{cases} \tag{2b}$$

which clearly is a complete definition for all $k \geq 1$.

The rationality of the STR defined in (2) may not seem straightforward at the first sight, for one can readily propose a much simpler transmission rule by simply letting the sensing signal being sent at time k if δ_k is larger than a predetermined constant threshold. However, the transmission rule defined in (2a) is different from this simple rule in two aspects; the presence of the maximum transmission interval N_s and the use of variable thresholds α_j, for good reasons. First, as mentioned earlier, with the definition of N_s, it is guaranteed that the sensing data at the controller side is updated no more than $\bar{\tau}_{sc}^*$ time steps, while without it, a particular case could occur in principle, where, for a sufficient long time, no sensing data is updated at the controller side which can destabilize the system readily. Second, with the carefully chosen variable thresholds α_j, it is shown later that the sensing error at the controller side is always upper bounded by δ_s, which is essential for the sake of maintaining the system performance.

B. Packet-Based Control in the Controller-to-Actuator Channel

As mentioned earlier, using the Internet as the communication media may cause worse communication conditions. The optimistic aspect lies, however, in the fact that the Internet uses data packets with a much larger size than that in conventional control networks. For example, the minimum effective load in the Ethernet [which is part of the Internet, serving as a local area network (LAN)] is 46 B, with a fixed 26-B overhand (checksum as well), while in the DeviceNet, the maximum effective load is only 8 B. On the other hand, a 2-B (i.e., 16-b) data can encode $2^{16} = 65\,536$ different levels of sensing signals, which is believed to be ample for a large number of control applications. Therefore, one data packet in the Ethernet can then contain at least 23 such sensing signals. The expression "at least" makes sense since the typical size of the data packet used in Ethernet is around several hundred bytes, and the maximum is 1500 B. In view of the fact that the time delay in the Internet is caused mainly by the distance between the source and destination nodes, the routing selected, and, more importantly, possible congestion in transmission rather than the data-packet size [2], [16], we are confident to conclude that the conventional way of sending the sensing data, i.e., one sensing signal in one data packet is, to a certain extent, a severe waste of the limited communication resources.

This observation, therefore, has motivated the work of the packet-based control for NCSs [6], [17]. The basic idea of this approach is to send a sequence of forward-control signals in one data packet, so-called the "forward control sequence" (FCS), simultaneously, instead of sending only one step control signal at each step. On receiving this FCS, the actuator is then able to compensate for the communication constraints by selecting the appropriate control signal according to the current network condition. With the use of the EBS strategy, the FCS at time k can be constructed as follows:

$$\hat{U}(k) \triangleq [\hat{u}(k) \; \ldots \; \hat{u}(k+N-1)] \tag{3}$$

where $\hat{u}(k+1)$, $i = 1, 2, \ldots, \bar{\tau}_{ca}$ are the forward-control signals based on the sensing data $\hat{x}(k)$ at time k, and N is the number of the control signals that one data packet can contain (for example, $N \geq 23$ in the Ethernet example given earlier). Note here that the symbol $^\wedge$ is used to indicate the fact that the control signals are calculated based on the sensing data with error $\hat{x}(k)$ due to the use of the EBS strategy. For more details of conventional packet-based control approach to NCSs, the reader is referred to [6] and [15].

In conventional packet-based control approach to NCSs, the FCSs are sent to the actuator at every step. However, in view of the fact that the sensing data at the controller side is not updated at every step, it is therefore not necessary to send the FCS in the case of no sensing data being updated. This strategy, referred to as the "controller transmission rule" (CTR), which is analogous to the STR discussed in the previous section, can considerably reduce the data transmissions in the controller-to-actuator channel. In fact, the total number of the FCS that is actually sent would be the same as that of the sensing data packets received by the controller. Therefore, analogously, the upper bound of the delay in the controller-to-actuator channel after applying the CTR can be obtained as $\bar{\tau}_{ca}^* = \bar{\tau}_{ca} + N_s$.

C. EBS Strategy for PB-NCSs

Notice that with the EBS strategy, the sensing data at the controller side $\hat{x}(k)$ at time k is actually the real sensing signal at a previous time $k - \tau_{sc,k}^*$, i.e.,

$$\hat{x}(k) = x\left(k - \tau_{sc,k}^*\right) \tag{4}$$

where $\tau_{sc,k}^* \leq \bar{\tau}_{sc}^*$ and $k - \tau_{sc,k}^*$ indicates the time when the sensing signal $\hat{x}(k)$ was sampled at the sensor side. This facts enables us to modify the conventional packet-based control for NCSs by reconstructing the FCS defined in (3)

$$U\left(k|k-\tau_{sc,k}^*\right) = \left[u\left(k|k-\tau_{sc,k}^*\right) \quad \ldots \quad u\left(k+N-1|k-\tau_{sc,k}^*\right)\right] \tag{5}$$

where the sampling time of the sensing database on which the FCS is calculated is explicitly indicated. Note here that both the FCS and the forward-control signals in (5) use a dual-time indicator $(k_1|k_2)$ in which k_1 stands for the time instant of the

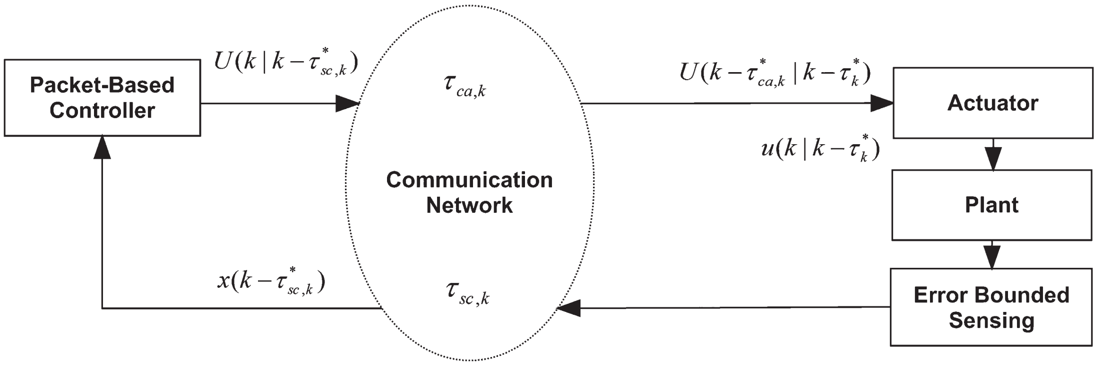

Fig. 2. EBS for PB-NCSs.

control action, while k_2 stands for the time instant of the sensing data that is used to produce the control signal. In light of (4), this FCS can be equivalent to the one in (3) provided the same controller-design methods are used. Their difference only lies on the different perspectives from which we look at the EBS strategy. That is, the effects brought by the EBS for PB-NCSs can be interpreted by two different but equivalent ways, which is either sensing error without delay in the sensor-to-controller channel (3) or pure extra delay without sensing error (5).

Based on (5), the control signal that is actually applied to the plant at time k at the actuator side can be determined as follows. Denote the delay of the FCS from which the control signal is selected at time k by $\tau^*_{ca,k}$. This FCS was thus calculated based on the sensing data at time $\tau^*_k \triangleq \tau^*_{sc,k} + \tau^*_{ca,k}$, and therefore, it should be $U(k - \tau^*_{ca,k}|k - \tau^*_k)$ based on the time at the actuator side. The control signal actually applied to the plant at time k can then be chosen as

$$u(k) = u\left(k|k - \tau^*_k\right) \tag{6a}$$

which can compensate for the current network-induced delay in a precise way. Let $\bar{\tau}^* \triangleq \bar{\tau}^*_{sc} + \bar{\tau}^*_{ca}$ be the modified upper bound of the delay in the round trip after the application of the EBS strategy and define $\Omega^* = \{2, 3, \ldots, \bar{\tau}^*\}$ as the set of all possible round trip delays; it is held that

$$\tau^*_k \in \Omega^* \; \forall k \tag{6b}$$

which, with (6a), defines the complete control law for the proposed approach in this paper.

The algorithm of the EBS strategy for PB-NCSs can now be organized as follows, the block diagram of which is shown in Fig. 2:

Algorithm 1 (The EBS strategy for PB-NCSs):

S1. Initialization. Set $k = 1$, $k_\sigma = 1$. Sample the system state $x(1)$ and send it to the controller.

S2. Let $k = k + 1$. If $\delta_k > \alpha_{k-k\sigma}\|x(k)\|$ or $k - k_\sigma = N_s$, sample the system state $x(k)$, send it to the controller, and let $k_\sigma = k$.

S3. Check if the system state is updated at the controller side. If so, then calculate the FCS by (5) and send it to the actuator.

S4. The control signal in (6) is applied to the plant. Return to S2.

Remark 1: One may wonder why we do not construct a model of the plant at the controller side and update the system states using this model if the real sensing data is unavailable, as done in [18] and [19], in which, the developed model seemingly can be used to reduced the sensing error. The reasons of not doing so are twofold. First, the data transmission in both the sensor-to-controller and the controller-to-actuator channels can be effectively reduced using the EBS strategy within the packet-based control framework, which has not been considered in this model-based approach. Second, with the use of the packet-based control approach, which is capable of producing forward-control signals based on delayed sensing data, the reconstruction of the system states is, thus, not necessary, which is however the main concern of using the model-based approach.

III. Stabilization and Further Discussion

In this section, the stability and stabilization issues of the proposed approach are considered first, and the effects on the system stability brought by the EBS strategy are then investigated by comparing it with conventional packet-based control approach. This analysis is based on two different models for the proposed approach, i.e., in the former analysis, the delay effect brought by the approach is explicitly formulated with the FCS in (3), while for the latter, the focus is mainly on the sensing error introduced by the approach with the FCS in (5).

For simplicity, the following linear plant in discrete time is considered in Fig. 1; however, it is worth pointing out that the proposed approach is applicable to any system and not limited to this particular type

$$x(k+1) = Ax(k) + Bu(k) \tag{7}$$

where $x \in \mathbb{R}^n$, $u \in \mathbb{R}^m$, $A \in \mathbb{R}^{n\times n}$, and $B \in \mathbb{R}^{n\times m}$. The controller is assumed to be of the form of state feedback. In light of (6), the controller can be obtained as follows:

$$u(k) = u\left(k|k - \tau^*_k\right) = K_{\tau^*_k} x\left(k - \tau^*_k\right). \tag{8a}$$

Note here that the controller gains $K_{\tau^*_k}$ are delay dependent, which is one of the most important characteristics of the packet-based control approach. This characteristic distinguishes this approach from conventional control approaches to NCSs, where, normally, a constant controller gain is used for all network conditions [6], [13].

It is noticed that by (4), the control law in (8a) can also be written in the following way:

$$u(k) = u\left(k|k-\tau_k^*\right) = K_{\tau_{ca,k}^*}\hat{x}\left(k-\tau_{ca,k}^*\right). \tag{8b}$$

Notice that the controller in (8b) is now based on sensing data $\tau_{ca,k}^*$ instead of τ_k^*, as in (8a), meaning that the delay in the sensor-to-controller channel is eliminated in this model. However, this is obtained at the cost of introducing a sensing error to the system, which is defined as

$$e_s(k) \triangleq \|x(k) - \hat{x}(k)\|, \qquad k \geq 1. \tag{9}$$

Although it is possible to define the same control gains in both (8a) and (8b), it is preferred, however, to define the controller gains based on the current delays, as done previously. It is thus clear that the two controllers are not exactly equivalent, as will be shown later in Fig. 4 in Example 1.

A. Stabilization

It is noticed that the closed-loop system in (7) and (8a) is in its standard form within the packet-based control framework. As far as the model is concerned, the EBS strategy only increases the upper bound of the delay but does not affect the formulation of the system, meaning that the standard analysis techniques for PB-NCSs can still be applied here. Therefore, for completeness, the stability and stabilization results for the closed-loop system in (7) with the control law defined in (8a) are presented as follows, without proving, since the proofs can be obtained following similar procedures, as done in [15].

Theorem 1 (Stability): Given $\lambda \geq 1$ and the feedback gains K_i, $i \in \Omega^*$. The system in (7) with the control law in (8a) is stable if there exist $P_i = P_i^{\mathrm{T}} > 0$, $Q_i = Q_i^{\mathrm{T}} > 0$, $R_i = R_i^{\mathrm{T}} > 0$, and $S_i = \begin{pmatrix} S_i^{11} & S_i^{12} \\ (S_i^{12})^{\mathrm{T}} & S_i^{22} \end{pmatrix} \geq 0$, T_i^1, T_i^2, with appropriate dimensions such that we have the following.

1) $\forall i \in \Omega^*$,

$$\Phi_i = \begin{pmatrix} \Phi_i^{11} & \Phi_i^{12} & (A-I)^{\mathrm{T}}H_i \\ * & \Phi_i^{22} & (BK_i)^{\mathrm{T}}H_i \\ * & * & -H_i \end{pmatrix} < 0$$

$$\Psi_i = \begin{pmatrix} \lambda S_i^{11} & \lambda S_i^{12} & \lambda T_i^1 \\ * & \lambda S_i^{22} & \lambda T_i^2 \\ * & * & R_i \end{pmatrix} \geq 0$$

2) $\forall i, j \in \Omega^*$

$$P_i \leq \lambda P_j, \quad Q_i \leq \lambda Q_j, \quad R_i \leq \lambda R_j$$

where

$$\begin{aligned} \Phi_i^{11} &= (\lambda-1)P_i + Q_i + 2\lambda P_i(A-I) \\ &\quad + T_i^1 + \left(T_i^1\right)^{\mathrm{T}} + iS_i^{11} \\ \Phi_i^{12} &= \lambda P_i BK_i - T_i^1 + (T_i^2)^{\mathrm{T}} + iS_i^{12} \\ \Phi_i^{22} &= -T_i^2 - \left(T_i^2\right)^{\mathrm{T}} + iS_i^{22} \\ H_i &= \lambda P_i + \bar{\tau}^* R_i. \end{aligned}$$

Based on Theorem 1, the following stabilization result can then be obtained, which is computationally feasible due to the cone complementarity linearization technique [20].

Theorem 2 (Stabilization): Given $\lambda \geq 1$. Define the following nonlinear minimization problem $\mathcal{P}_i$ involving linear matrix inequality (LMI) conditions for $i,j \in \Omega^*$

$$\mathcal{P}_i: \begin{cases} \text{Minimize Tr}(Z_iR_i + L_iP_i + M_iQ_i) \\ \text{Subject to :} \\ L_i = L_i^{\mathrm{T}} > 0, W_i = W_i^{\mathrm{T}} > 0, M_i = M_i^{\mathrm{T}} > 0 \\ L_i \leq \lambda L_j, M_i \leq \lambda M_j, W_i \leq \lambda M_j \\ X_i = \begin{pmatrix} X_i^{11} & X_i^{12} \\ (X_i^{12})^{\mathrm{T}} & X_i^{22} \end{pmatrix} \geq 0 \\ \Phi_i' < 0, \Psi_i' \geq 0, \Theta_i^1 \geq 0, \Theta_i^2 \geq 0, \Theta_i^3 \geq 0, \Theta_i^4 \geq 0 \end{cases}$$

where

$$\Phi_i' = \begin{pmatrix} \Phi_i^{11'} & \Phi_i^{12'} & \lambda L(A-I)^{\mathrm{T}} & \bar{\tau}L(A-I)^{\mathrm{T}} \\ * & \Phi_i^{22'} & \lambda(BV_i)^{\mathrm{T}} & \bar{\tau}(BV_i)^{\mathrm{T}} \\ * & * & -\lambda L_i & 0 \\ * & * & * & -\bar{\tau}M_i \end{pmatrix}$$

$$\Psi_i' = \begin{pmatrix} \lambda X_i^{11} & \lambda X_i^{12} & \lambda Y_i^1 \\ * & \lambda X_i^{22} & \lambda Y_i^2 \\ * & * & Z_i \end{pmatrix}$$

$$\Theta_i^1 = \begin{pmatrix} R_i & P_i \\ * & Q_i \end{pmatrix}, \quad \Theta_i^2 = \begin{pmatrix} Z_i & I \\ * & R_i \end{pmatrix}$$

$$\Theta_i^3 = \begin{pmatrix} L_i & I \\ * & P_i \end{pmatrix}, \quad \Theta_i^4 = \begin{pmatrix} M_i & I \\ * & Q_i \end{pmatrix}.$$

If the solution of $\mathcal{P}_i = 3n \forall i \in \Omega$, the system in (7) is then stabilizable with the control gains in (8a) being $K_i = V_iL_i^{-1}$.

Remark 2: The aforementioned LMI-based stabilization approach is only one of the possible ways to design the controller within the proposed framework. Indeed, the designed EBS strategy for PB-NCSs is intended to reduce the data transmissions, and it does not affect directly the design of the controllers. This means that all the previously designed controllers within the packet-based control framework can still be used for this modified framework. However, further improvement is still necessary, as it is straightforward that a design approach with the EBS strategy taken into consideration, rather than one without it, can potentially improve the system performance further.

B. Effects of the EBS Strategy

In order to investigate the effects of the EBS strategy for PB-NCSs, the upper bound of the sensing error defined in (9) is first discussed in the following proposition.

Proposition 1: The sensing error $e_s(k)$ brought by the EBS strategy is upper bounded by δ_s, $\forall k$, i.e.,

$$e_s(k) \leq \delta_s \|x(k)\| \forall k. \tag{10}$$

Proof: For simplicity of notation, let $j \triangleq \tau_{sc,k}^*$ in (4). Noticing that $\sigma(k-i) = 0$ for $0 \leq i \leq j-1 < N_s$, the following inequality for $0 \leq i \leq j-1$ is thus held in light of (2)

$$\|x(k-i) - x(k-i-1)\| \leq \alpha_{j-i}\|x(k-i)\|$$

From the earlier discussion, it is concluded that for $1 \leq i \leq j$

$$\|x(k-i)\| \leq (1+\alpha_{j-i+1}) \|x(k-i+1)\| .$$

Repeatedly using the aforementioned yields

$$\alpha_{j-i} \|x(k-i)\| \leq \alpha_{j-i} \prod_{l=0}^{i-1} (1+\alpha_{j-i+1+l}) \|x(k)\| .$$

Notice that, by the definition of α_i, we have $\alpha_1(1+\alpha_{i+1}) = \alpha_{i+1}$, $0 \leq i \leq N_2 - 1$. Therefore

$$\alpha_{j-i} \prod_{l=0}^{i-1} (1+\alpha_{j-i+1+l}) \leq \alpha_{j-i} \prod_{l=0}^{i-1+N_s-j} (1+\alpha_{j-i+1+l}) = \alpha_{N_s}$$

Thus

$$\begin{aligned} e_s(k) &\leq \sum_{i=0}^{j-1} \|x(k-i) - x(k-i-1)\| \\ &\leq \sum_{i=0}^{j-1} \alpha_{j-i} \|x(k-i)\| \\ &\leq j\alpha_{N_s} \|x(k)\| \\ &\leq N_s \alpha_{N_s} \|x(k)\| \\ &= \delta_s \|x(k)\| \end{aligned}$$

which completes the proof. ■

With (10), the control law in (8b) can then be reformed as

$$u(k) = K_{\tau^*_{ca,k}} (I+\Delta_k) x\left(k - \tau^*_{ca,k}\right)$$

with

$$(I+\Delta_k) x\left(k - \tau^*_{ca,k}\right) \triangleq \hat{x}\left(k - \tau^*_{ca,k}\right)$$

where, by (10), we have

$$\|\Delta_k\| \leq \delta_s \forall k.$$

The closed-loop system can then be obtained as

$$x(k+1) = Ax(k) + BK_{\tau^*_{ca,k}} (I+\Delta_k) x\left(k - \tau^*_{ca,k}\right) \quad (11)$$

Correspondingly, without the EBS strategy, the closed-loop system should be of the following form:

$$x(k+1) = Ax(k) + BK_{\tau_k} x(k-\tau_k), \qquad \tau_k \in \Omega \quad (12)$$

where $\Omega = \{2, 3, \ldots, \bar{\tau}\}$.

Remark 3: From (11) and (12), it is seen that the EBS strategy modifies the system in two ways: the introduction of the bounded-sensing error (represented by Δ_k) and the modification of the delay to the system. The former invariably introduces negative effects to the system, which is the cost that we have to pay in order to reduce the use of the communication resources. However, noticing that $\bar{\tau}^*_{ca} = \bar{\tau}_{ca} + N_s$ and $\bar{\tau} = \bar{\tau}_{sc} + \bar{\tau}_{ca}$, the latter can, at least, in principle, reduce the delay bound to the system (when $N_s < \bar{\tau}_{sc}$), which can potentially be beneficial to the system performance.

To quantitatively interpret these effects, a special case of the closed-loop system in (11) is considered by letting $N_s = \bar{\tau}_{sc}$, thus making $\bar{\tau}^*_{ca,k} = \tau_k$ and (11) being reformed to

$$x(k+1) = Ax(k) + BK_{\tau_k}(I+\Delta_k) x(k-\tau_k) \quad (13)$$

where $\tau_k \in \Omega$.

For the closed-loop systems in (12) and (13), their stability conditions are compared in the following theorem. It is seen that the stability conditions for both systems are closely related, and the system in (13) requires relatively stronger conditions for stability due to the sensing error introduced, which makes sense in practice.

Theorem 3: Given that $\lambda \geq 1$ and the feedback gains K_i, $i \in \Omega$. The closed-loop system in (12) is stable if there exist $P_i = P_i^{\mathrm{T}} > 0$, $Q_i = Q_i^{\mathrm{T}} > 0$, $R_i = R_i^{\mathrm{T}} > 0$, and $S_i = \begin{pmatrix} S_i^{11} & S_i^{12} \\ \left(S_i^{12}\right)^{\mathrm{T}} & S_i^{22} \end{pmatrix} \geq 0$, T_i^1, T_i^2 with appropriate dimensions and a scalar $\gamma > 0$ such that we have the following.

1) $\forall i \in \Omega$,

$$\Phi''_i < 0 \quad (14)$$

$$\Psi''_i \geq 0 \quad (15)$$

2) $\forall ij \in \Omega$,

$$P_i \leq \lambda P_j, \quad Q_i \leq \lambda Q_j, \quad R_i \leq \lambda R_j \quad (16)$$

where Φ''_i and Ψ''_i are similarly defined as in Theorem 1 by replacing Ω^* by Ω. Furthermore, The closed-loop system in (13) is stable if (15) and (16) hold, and (14) is replaced by

$$\begin{pmatrix} \Phi''_i & \Upsilon_i^{\mathrm{T}} \\ * & -\gamma I \end{pmatrix} < 0 \quad (17)$$

where $\Upsilon_i = [\lambda\delta P_i B \quad 0 \quad \delta H_i B]$, $\delta = \delta_s \bar{K}$, and $\bar{K} = \max\{\|K_i\| | i \in \Omega\}$.

Proof: The stability conditions for the system in (12) can be obtained directly from Theorem 1. From the definition of δ, it is noticed that

$$BK_{\tau_k}(I+\Delta_k) = BK_{\tau_k} + \delta B \times K_{\tau_k}\Delta_k/\delta$$

with $\|K_{\tau_k}\Delta_k/\delta\| \leq 1$. The closed-loop system in (13) can then be well treated as a time-delay system with time-varying uncertainty, and (17) can be obtained by replacing BK_{τ_k} in (14) by $BK_{\tau_k} + \delta B \times K_{\tau_k}\Delta_k/\delta$ and then follow a standard robust stability analysis, as done in [21]. The technical details are therefore omitted in this paper. ■

IV. Numerical and Experimental Examples

In this section, both numerical and experimental examples are considered to illustrate the effectiveness of the EBS strategy for PB-NCSs.

Example 1: In this example, the system in (7) is considered with the following system matrices borrowed from [6]:

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

This system is readily seen to be open loop unstable. In the simulation, the initial state for the previous system is set as $x_0 = [-1 \quad 1]^{\mathrm{T}}$, the upper bound of the delay in both channels are $\bar{\tau}_{sc} = \bar{\tau}_{ca} = 3$, respectively, $N_s = 2$, and $\delta_s = 0.35$. Other parameters can then be obtained as follows: $\bar{\tau} = \bar{\tau}_{sc} + \bar{\tau}_{ca} = 6$, $\bar{\tau}^*_{sc} = \bar{\tau}_{sc} + N_s = 5$, $\bar{\tau}^*_{ca} = \bar{\tau}_{sc} + N_s = 5$, $\bar{\tau}^* = \bar{\tau}^*_{sc} + \bar{\tau}^*_{ca} = 10$, and α_j, $0 \le j \le N_s$ can also be obtained accordingly, which are not listed here for simplicity of notations.

The main purpose of this example is to illustrate the effectiveness of the proposed EBS strategy within the packet-based control framework, by comparing it with conventional packet-based control approach proposed in [6]. In order to eliminate possible effects on the system performance brought by different controller design methods, the controllers for both approaches are therefore designed using the same receding-horizon approach as proposed in [6], which yields the following feedback gain K for the packet-based control approach in [6] with $\bar{\tau} = 6$

$$K = \begin{pmatrix} K_2 \\ K_3 \\ K_4 \\ K_5 \\ K_6 \end{pmatrix} = \begin{pmatrix} -0.4280 & -0.9753 \\ -0.3412 & -0.8704 \\ -0.2660 & -0.7739 \\ -0.2012 & -0.6853 \\ -0.1458 & -0.6040 \end{pmatrix}$$

and the following feedback gain K^* for the EBS strategy for PB-NCSs with $\bar{\tau}^* = 10$:

$$K^* = \begin{pmatrix} K^*_2 \\ K^*_3 \\ K^*_4 \\ K^*_5 \\ K^*_6 \\ K^*_7 \\ K^*_8 \\ K^*_9 \\ K^*_{10} \end{pmatrix} = \begin{pmatrix} -0.4280 & -0.9753 \\ -0.3412 & -0.8704 \\ -0.2660 & -0.7739 \\ -0.2012 & -0.6853 \\ -0.1458 & -0.6040 \\ -0.0990 & -0.5296 \\ -0.0600 & -0.4616 \\ -0.0280 & -0.3996 \\ -0.0023 & -0.3432 \end{pmatrix}.$$

Four different cases are considered in the simulation: 1) the conventional packet-based control approach in [6] with all the sensing and control data packets being sent; 2) the EBS strategy for PB-NCSs with the control law in (8a), where the delay effect is explicitly considered; 3) the EBS strategy for PB-NCSs with the control law in (8b), where the extra delay is explicitly considered; and 4) the conventional packet-based control approach in [6] with only partial sensing and control data packets being sent (with the same transmission ratio as using the EBS strategy). The last case is considered mainly to illustrate the effectiveness of the proposed EBS strategy by comparison with the presence of poor communication conditions and is simulated by applying zero control when no sensing data is available.

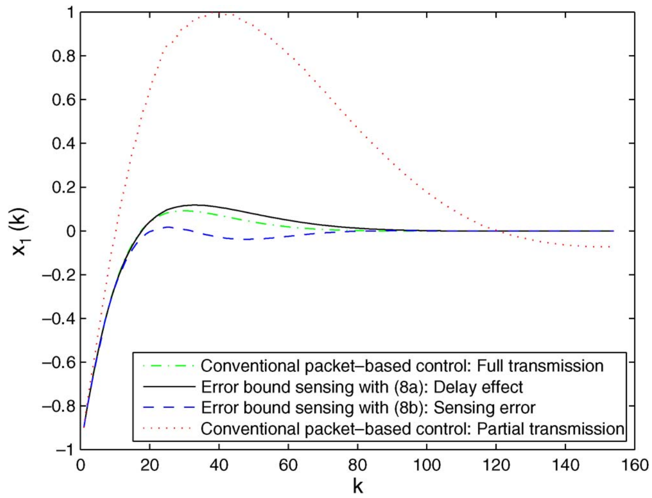

Fig. 3. Illustrating the effectiveness of the EBS strategy for packet-based control for NCSs.

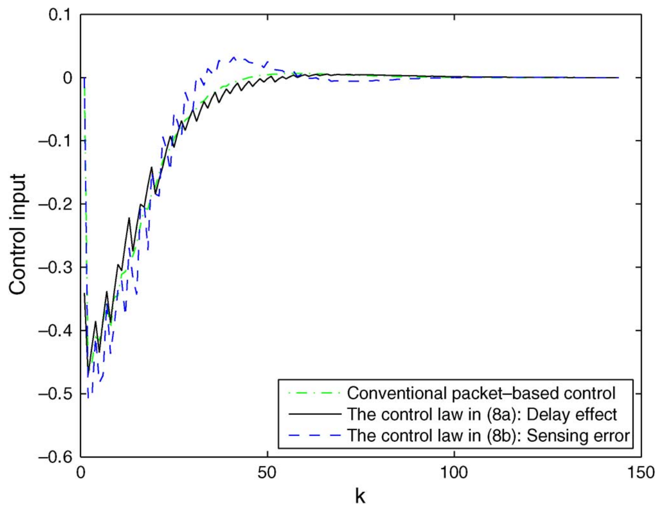

Fig. 4. Comparing the control signals with and without the EBS strategy.

The state responses for the previous four cases are shown in Fig. 3. It is seen that the system performance of case 1) is the best which is reasonable since this case has used the most communication resources. Although slightly worse than case 1), the system performances with the EBS strategy [the solid line for case 2) and the dashed line for case 3)] are still maintained at a satisfactory level, which illustrates the effectiveness of the proposed approach. This result can be verified by looking into the comparison of the control inputs for these three cases shown in Fig. 4. All these control inputs are seen to be very close. It is worth mentioning that the acceptable system performances using the EBS strategy are achieved with a 65% reduction of the communication resources, meaning that only around 35% of the sensing data packets and the FCSs are actually sent.

The effectiveness of the EBS strategy can further be proven by comparing with case 4) (the dotted line in Fig. 3) where the same amount of the sensing data packets and FCSs are sent but conventional packet-based control approach in [6]

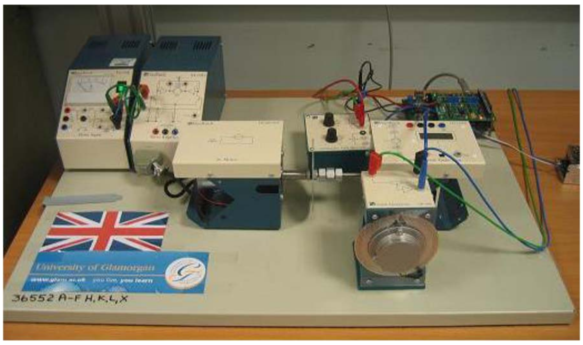

Fig. 5. DC servo plant in the University of Glamorgan.

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

gives rise to much worse system performance. This also proves the effectiveness of the EBS strategy in the presence of poor communication conditions.

As for the two control laws, (8a) and (8b), for the EBS strategy for PB-NCSs, it is noticed that the control law in (8a) results in a little better system performance than that in (8b). This makes sense in this particular example since the used controller design method in this example only takes delay effect into account but not the sensing error [6].

Example 2: In order to verify the effectiveness of the proposed approach in practice, an experiment based on an Internet-based test rig for NCSs is conducted. This test rig is an Internet-based servo system, with the dc servo motor (Fig. 5) being located in the University of Glamorgan, Pontypridd, U.K., and the remote controller being located in the Institute of Automation, Chinese Academy of Sciences, Beijing, China (Fig. 6). Simply speaking, using this test rig, one can control the dc servo motor in the U.K. remotely by the controller in China, with the sensing and control data packets being transmitted over the Internet. Both the control algorithm and the parameters can be configured and updated online at http://www.ncslab.net/. For further information of this test rig, the reader is referred to [22] and its Website.

In the experiment, the following state-space model for the dc servo system is used, which was identified in [22] with the sampling period being 0.04 s:

$$\begin{cases} x(k+1) = Ax(k) + Bu(k) \\ y(k) = Cx(k) \end{cases}$$

with

$$A = \begin{pmatrix} 1.12 & 0.213 & -0.333 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{pmatrix} \quad B = \begin{pmatrix} 1 \\ 0 \\ 0 \end{pmatrix}$$

$$C = (0.0541 \quad 0.0050 \quad 0.0001).$$

The system states are obtained using the following state observer with $L = [6\,6\,6]^{\mathrm{T}}$:

$$x(k+1|k) = Ax(k|k-1) + Bu(k) + L\,(y(k) - Cx(k|k-1))$$

where $x(k+1|k)$ is the observed state at time k.

It is observed that the round trip delay between U.K. and China is typically upper bounded by 0.32 s, which is eight sampling periods for this particular system, i.e., $\bar{\tau} = 8$. Although we have not particularly measured the delay bound for individual channels, it is reasonable to assume that they are equivalent since the same Internet is used for both channels, implying that $\bar{\tau}_{sc} = \bar{\tau}_{ca} =$ four sampling periods. In the experiment, we set $N_s = 4$, $\delta_s = 0.4$, and thus, $\bar{\tau}^*_{sc} = \bar{\tau}^*_{ca} = 8$ sampling periods and $\bar{\tau}^* = 16$ sampling periods. The controller is designed using Theorem 2, as follows:

$$K = \begin{pmatrix} K_2 \\ K_3 \\ K_4 \\ K_5 \\ K_6 \\ K_7 \\ K_8 \\ K_9 \\ K_{10} \\ K_{11} \\ K_{12} \\ K_{13} \\ K_{14} \\ K_{15} \\ K_{16} \end{pmatrix} = \begin{pmatrix} -0.0735 & 0.0065 & 0.0294 \\ -0.0671 & 0.0057 & 0.0260 \\ -0.0626 & 0.0051 & 0.0236 \\ -0.0601 & 0.0052 & 0.0225 \\ -0.0579 & 0.0051 & 0.0215 \\ -0.0564 & 0.0048 & 0.0209 \\ -0.0536 & 0.0045 & 0.0198 \\ -0.0530 & 0.0045 & 0.0194 \\ -0.0524 & 0.0044 & 0.0191 \\ -0.0517 & 0.0043 & 0.0188 \\ -0.0506 & 0.0042 & 0.0181 \\ -0.0496 & 0.0041 & 0.0177 \\ -0.0491 & 0.0039 & 0.0175 \\ -0.0483 & 0.0040 & 0.0170 \\ -0.0481 & 0.0041 & 0.0169 \end{pmatrix}.$$

The system response is shown in Fig. 7, where it is seen that the system performance is fairly satisfactory. Meanwhile, it is noticed that with the EBS strategy and the aforementioned parameters, in both channels only, around 26% of the data packets are actually sent, meaning that the system performance in Fig. 7 is achieved with a reduction of 74% of the use of the communication resources in both channels. This reduction is beneficial for other applications that share the Internet and also beneficial for the considered system in the sense that it can still perform well in the case of poor communication conditions with the use of the EBS strategy for PB-NCSs. This thus proves the effectiveness of both the EBS strategy as well as the stabilization controller designed in this paper.

V. Conclusion

Reducing the use of the communication resources is one of the important design principles in NCSs, which is beneficial for other applications that share the same communication network

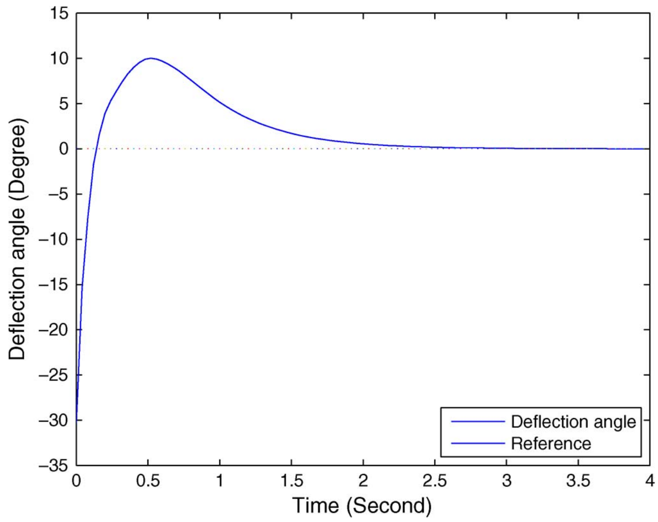

Fig. 7. Experimental response using the EBS strategy for PB-NCSs.

and also of potential significant importance to the system itself in the presence of poor communication conditions. An EBS strategy has been proposed within the packet-based control framework for NCSs by sending only the sensing and control data packets that are absolutely necessary for the purpose of maintaining the system performance. The efficient reduction of the use of the communication resources by the proposed approach has been obtained at the cost of introducing bounded-sensing error, or equivalently, extra delay to the system. Theoretical analysis reveals that these negative effects can be well treated within the packet-based control framework and do not affect the system performance severely. Numerical and experimental examples have verified the theoretical results and have also illustrated its effectiveness in the presence of poor communication conditions. Therefore, in some sense, this strategy completes the packet-based control approach and enables the latter to be an efficient and a complete solution to NCSs.

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1. Error bounded sensing for packet-based networked control systems

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