Packet-Based Deadband Control for Internet-Based Networked Control Systems

Yun-Bo Zhao, Guo-Ping Liu, *Senior Member, IEEE*, and David Rees

***Abstract*—A packet-based deadband control approach is proposed for networked control systems (NCSs). Compared with previously reported packet-based control approaches to NCSs, the approach proposed in this paper takes full advantage of the packet-based data transmission in NCSs, and thus considerably reduces the use of the communication resources in NCSs whilst maintaining the system performance at a satisfactory level. A stabilized controller design method is obtained using time delay switched system theory, which has not been achieved in previously reported packet-based control approaches. The proposed deadband control strategy and the stabilized controller design method are verified using a numerical example as well as practical experiments based on an Internet-based test rig for NCSs.**

***Index Terms*—Deadband control, Internet-based test rig, networked control systems, packet-based control, stability.**

I. Introduction

MOST CONTROL systems are designed under the assumption of perfect data transmission in both the sensor-to-controller and the controller-to-actuator channels. This assumption holds for most point-to-point control structures but unfortunately, is invalid for a class of control systems widely used nowadays, where the control loop is closed via some form of communication networks, that is, networked control systems (NCSs) [1]. It is noticed that, though the inserted communication network in NCSs enables its application to a vast range of remote and distributed control areas, such as remote surgery, automated highway systems, etc. [2], the introduction of the communication channels can also mean imperfect data transmission in NCSs, which brings to the control system such communication constraints as network-induced delay, data packet dropout, data packet disorder, etc., and thus significantly degrades the system performance or even destabilizes the system at certain conditions. These communication constraints present a great challenge for conventional control and communication theory and the properties specially brought by NCSs have therefore attracted a lot of researchers from multiple disciplines including, for example, control engineers, communication specialists, mathematicians, etc. [3]–[9].

The early work on NCSs has been done mainly from the perspective of control theory. To name a few, in [10]–[13], NCSs with variable delays was modeled within the time delay system framework and various results with respect to stability and stabilization were obtained. In [14]–[17], the communication constraints were further modeled stochastically and analyzed using stochastic control theory. Similar problems have also been investigated using switched system theory in [18] and [19], with a different perspective of modeling the dynamics in NCSs. In these aforementioned studies, the communication constraints brought by the network in NCSs have typically been modeled as some uncontrollable parameters within the control system and then a conventional control system rather than an NCS is actually considered. However, the reality is that the system performance of NCSs are affected by the properties of both the control system and the communication network. Therefore the absence of fully investigating the properties of the communication network invariably introduces considerable conservativeness to both the analysis and synthesis of NCSs. This is why researchers have sought to investigate NCSs with the integration of both control and communication theories, that is, the "co-design" approach to NCSs. In this kind of studies, the imperfect packet-based data transmission has been extensively explored and as a result, a better system performance is expected than those using conventional control approaches [20]–[24].

Within the codesign framework, recently a packet-based control approach is proposed for NCSs where the packet-based data transmission structure in NCSs is more efficiently used to send a sequence of forward control signals [i.e., forward control sequence (FCS)] together instead of one at a time, which as a result can simultaneously deal with network-induced delay, data packet dropout and data packet disorder in NCSs in an effective way [25]–[27]. Using this approach, a better system performance is achieved without requiring any additional communication resource. Though effective, there are two limitations on the previously reported packet-based control approach. First, the length of FCS in [25]–[27] is determined by the upper bound of the communication constraints rather than the capacity of the network. This can mean that the packet structure of the network has not been fully taken advantage of and can thus result in considerable conservativeness. Secondly, in previously

Manuscript received April 07, 2009; revised July 30, 2009; accepted September 02, 2009. Manuscript received in final form September 18, 2009. First published October 16, 2009; current version published August 25, 2010. Recommended by Associate Editor Z. Wang. The work of Y.-B.Zhao and G.-P.Liu was supported in part by the National Natural Science Foundation of China under Grant 60934006.

Y.-B. Zhao was with the Faculty of Advanced Technology, University of Glamorgan, Pontypridd CF37 1DL, U.K. He is now with the Department of Aerospace Engineering, University of Glasgow, Glasgow, G12 8QQ, U.K. (e-mail: yzhao@eng.gla.ac.uk).

D. Rees is with Faculty of Advanced Technology, University of Glamorgan, Pontypridd CF37 1DL, U.K. (e-mail: drees@glam.ac.uk).

G.-P. Liu is with Faculty of Advanced Technology, University of Glamorgan, Pontypridd CF37 1DL, U.K. and also with CTGT Centre, Harbin Institute of Technology, Harbin 150001, China (e-mail: gpliu@glam.ac.uk).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TCST.2009.2033118

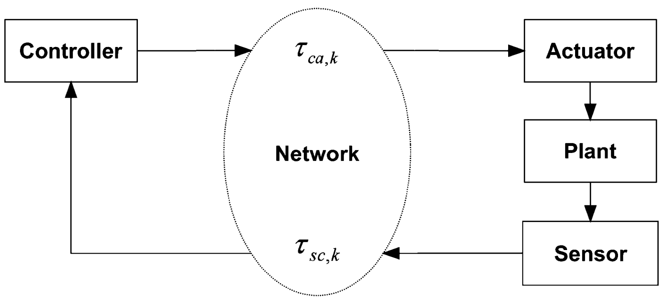

Fig. 1. Block diagram of a networked control system.

reported results, generalized predictive control (GPC) approach is used to design the packet-based controller. Though GPC is quite suitable for the packet-based control framework and has been proven to be effective, unfortunately no stabilization results have been obtained due to the essential deficiency of GPC. This limitation greatly constraints the applications of the packet-based control approach in practice.

Based on the above observations, this paper proposes a packet-based deadband control approach by using more efficiently the packet structure in NCSs. This is done by extending the length of FCS to the maximum of what the network can contain, and then setting a deadband on FCS which allows transmission only in the presence of a sufficiently large change between the current FCS and the one last sent [28], [29]. As a result, this approach can significantly reduce the data transmissions in NCSs and in the meanwhile maintain the system performance at a satisfactory level. The closed-loop system model is obtained and, without using the GPC approach, a stabilized controller design method is proposed based on LMIs. The stability properties of the closed-loop system with and without the deadband control strategy are also compared within the packet-based control framework, which proves the effectiveness of the deadband control strategy. The performance of the proposed packet-based deadband control approach and the corresponding stabilized controller design method are then illustrated by both numerical and experimental examples, showing that the proposed approaches are effective in practice.

The remainder of this paper is organized as follows. Within the packet-based control framework, Section II presents the packet-based deadband control approach to NCSs. The corresponding closed-loop system is then obtained, with stability analysis and a stabilized controller design method obtained based on LMIs in Section III. In Section IV both numerical and experimental examples are considered to illustrate the effectiveness of the theoretical results and Section V concludes this paper.

II. Packet-Based Deadband Control for NCSs

The following linear plant in discrete time is considered in this paper, which is controlled over the network by a remote controller, as shown in Fig. 1

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

where $x \in \mathbb{R}^n$, $u \in \mathbb{R}^m$, $A \in \mathbb{R}^{n\times n}$, $B \in \mathbb{R}^{n\times m}$.

For the implementation of the packet-based deadband control approach to NCSs, we assume that the dynamics of the control system and the characteristics of the communication network in Fig. 1 satisfy the following assumptions [25]–[27]. The rationality and implication of the assumptions are further discussed in Remark 1.

Assumption 1 (Delay Bound): The sum of the network-induced delay and consecutive data packet dropout in both the sensor-to-controller and the controller-to-actuator channels (denoted by $\bar{\tau}_{sc}$ and $\bar{\tau}_{ca}$, respectively) are upper bounded, i.e.,

$$\bar{\tau}_{sc} \triangleq \max_{k\geq 1}\{\tau_{sc,k} + \bar{\chi}_{sc}\} < \infty \tag{2a}$$

$$\bar{\tau}_{ca} \triangleq \max_{k\geq 1}\{\tau_{ca,k} + \bar{\chi}_{ca}\} < \infty \tag{2b}$$

where $\tau_{sc,k}$, $\bar{\chi}_{sc}$ and $\tau_{ca,k}$, $\bar{\chi}_{ca}$ represent the network-induced delay and the upper bound of consecutive data packet dropout in the sensor-to-controller and the controller-to-actuator channels, respectively.

Assumption 2 (Time Stamp): The control components in NCSs including the sensor, the controller and the actuator are time synchronized and data packets are sent with time stamps to notify when they were sent.

Remark 1: Assumption 1 actually states that, the controller (the actuator) is always able to receive the sampled data (the control signal) within a finite time period, which is reasonable in practice as well as necessary in theory. Assumption 2 implies that the delays in the sensor-to-controller channel and in the round trip are known to the controller and the actuator, respectively.

In order to present the packet-based deadband control approach to the system in (1) clearly and for completeness, the basic ideas of packet-based control for NCSs will first be presented in the following subsection. We then point out its deficiency and propose the packet-based deadband control approach to NCSs, by more efficiently using the packet structure in NCSs.

A. Exploring the Packet Structure-Packet-Based Control for NCSs

Denote the effective load of the data packet being used in the NCS illustrated in Fig. 1 by B_p and the data size required for encoding a single step of the control signal by B_c. The number of control signals that one data packet can contain can then be obtained as

$$N = \left\lfloor \frac{B_p}{B_c} \right\rfloor \tag{3}$$

where $\lfloor B_p/B_c \rfloor = \max\{\varsigma | \varsigma \in \mathbb{N}, \varsigma \leq B_p/B_c\}$.

The key point of the previously reported packet-based control approach is to realize that N in (3) is usually larger than $\bar{\tau}_{ca}$. This observation thus enables us to send a sequence of forward control signals simultaneously over the network instead of one at a time as typically done in conventional control systems, with the length of the sequence being $\bar{\tau}_{ca} + 1$. That is, at time k, instead of calculating and sending only current control signal $u(k)$, the following FCS $U^p(k|k - \tau_{sc,k})$ is packed into one data packet and sent to the actuator, which is calculated based on sampled data at time $k - \tau_{sc,k}$

$$U^p(k|k-\tau_{sc,k}) = [u(k|k-\tau_{sc,k}) \ \dots \ u(k+\bar{\tau}_{ca}|k-\tau_{sc,k})]. \quad (4)$$

On receiving $U^p(k|k-\tau_{sc,k})$, the actuator is then able to select from it the appropriate control signal to actively compensate for current communication constraints in NCSs. For example, if the delay in the control-to-actuator channel for $U^p(k|k-\tau_{sc,k})$ is $\tau_{ca,k}$, the actuator may thus choose $u(k+\tau_{ca,k}|k-\tau_{sc,k})$ at time $k+\tau_{ca,k}$ to apply it to the plant to compensate for the communication constraints (Notice here that all the time instants mentioned are based on the controller side). This packet-based control approach, as shown in [25]–[27], generally leads to a better performance of NCSs than that using conventional control approaches, since more of the properties of the control system and the communication network in NCSs have been considered. The reader is referred to [25]–[27] for further details of this approach.

B. Making Full Use of the Packet Structure-Packet-Based Deadband Control for Internet-Based NCSs

Conventional control networks, such as ControlNet, DeviceNet, etc., which have been specially optimized for control applications and thus can meet the real time requirement of control systems to a certain extent, have been widely used in industrial processes for several decades [30]. However, it is seen that more and more network-based control applications are now using the Internet rather than conventional control networks, due to the low cost, easy maintenance, remote control capability, etc. brought by the Internet. Unlike conventional control networks, the Internet is a data network instead of a real time network, which means, it is optimized for data transmission and thus difficult to meet the critical real time requirement of control systems. Therefore, for Internet-based NCSs, we have to deal with worse communication conditions such as larger delay, more data packet dropout and disorder, etc.

In the meanwhile, it is noticed that as a data network, the Internet uses data packets with a much larger size than that in conventional control networks. Take Ethernet as an example, which is widely used as the Local Area Network (LAN) in the Internet. The minimum size of the data field (effective load) in Ethernet is 46 bytes with a fixed 26 bytes overhand (checksum as well), while in DeviceNet, the maximum size of the data field is only 8 bytes. In addition, using IPv4, the length of the overhead of an IP data packet is typically from 20 to 60 bytes, which in some sense implies a small data field is a waste of the communication resource. This is true since, generally speaking, the Internet time delay 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 [30], [31].

On the other hand, a 16-bit data which can encode $2^{16} = 65\,536$ different control signals is often used and ample for most control applications. In the Ethernet case, one data packet can then contain at least 23 such control signals (it can contain much more since the typical size of the data packet used in Ethernet is around several hundreds bytes and the maximum is 1500 bytes) while in a typical Internet-based control application, where for example the plant and the controller are located respectively in the University of Glamorgan, Pontypridd, U.K. and the Chinese Academy of Sciences, Beijing, China, the network-induced delay (data packet dropout as well) in the controller-to-actuator channel is upper bounded by 4 sampling periods with the sampling period being 0.04 s [27]. From this analysis, it is readily seen that N in (3) is normally much larger than $\bar{\tau}_{ca}$ in practice. This observation thus motivates us to design the following modified FCS where the length of FCS is extended to the maximum of what a data packet can contain but not determined by the upper bound of the communication constrain in the controller-to-actuator channel as in [25]–[27]

$$U(k|k-\tau_{sc,k}) = [u(k|k-\tau_{sc,k}) \ \dots \ u(k+N-1|k-\tau_{sc,k})]. \quad (5)$$

It is seen that using such a modified FCS, we have hardly increase the delay of transmitting it and what is more, by using the following deadband control strategy, we can significantly reduce the use of the communication resources while maintain the system performance at a satisfactory level.

The motivation of proposing the deadband control strategy is due to the fact that the communication constraints play a dominant role in the system performance of NCSs and for a better system performance, we have to decrease possible congestion in the network by reducing the use of the communication resources. On the other hand, much more redundant forward control signals are packed into one data packet using FCS in (5). This enables us to set a deadband for FCSs and send only those that have a sufficiently large change compared with the last sent FCS. In this way, the use of the communication resources can be significantly reduced and the system performance can still be maintained at a satisfactory level if the deadband is carefully chosen.

The block diagram of the packet-based deadband control approach to NCSs is illustrated in Fig. 2, where it is seen that this structure is different from conventional control approaches mainly in two aspects: the packet-based deadband controller and the so-called control action selector (CAS) at the actuator side. For the latter, which consists of a register to store only the latest data packet and a logic comparator to determine which data packet contains the latest information and thus can be used to deal with data packet disorder and to actively compensate for network-induced delay, the reader is referred to [25]–[27] for details.

The packet-based deadband controller is used to produce FCS in (5) and, different from previously reported packet-based control approach, also to determine whether a newly produced FCS should be sent or not. For this purpose, a register is present at the controller side to store the last sent FCS which is denoted by $U(k-\varrho_k|k-\varrho_k-\tau_{sc,k-\varrho_k})$ at time k at the controller side, where $k-\varrho_k$ is the time when the last FCS was sent. The newly produced FCS $U(k|k-\tau_{sc,k})$ at time k will be sent to the actuator if it has changed dramatically compared with the one last sent, i.e.,

$$\delta_k \triangleq \max_{0 \le i \le N-\varrho_k-1} \frac{\|\Delta u_{ki}\|}{\|u(k+i|k-\tau_{sc,k})\|} > \delta \quad (6)$$

where δ is the deadband set for FCSs, $\|\cdot\|$ denotes the Euclidean norm and $\Delta u_{ki} = u(k+i|k-\tau_{sc,k})-u(k+i|k-\varrho_k-\tau_{sc,k-\varrho_k})$. On the other hand, in order that there is always a control signal available at the actuator side, FCS has to be sent at least once within $N-\bar{\tau}_{ca}$ time steps, which also implies that $\varrho_k \leq N - \bar{\tau}_{ca} - 1, \forall k$.

The algorithm of packet-based deadband control for NCSs can be organized as follows.

Algorithm 1 (Packet-Based Deadband Control)

S1. Initiation. Set $k=0$, $\varrho_k = 0$.

S2. The sensor samples the plant and sends the sampled data packet to the controller.

S3. At time k at the controller side, if either 1) (6) is satisfied; or 2) $\varrho_k = N - \bar{\tau}_{ca} - 1$, then send the current FCS to the actuator, update the register of the controller to be this FCS, and let $\varrho_{k+1} = 1$, $k = k+1$; otherwise let $\varrho_{k+1} = \varrho_k + 1$, $k = k+1$ and wait for the next time instant.

S4. On receiving a new FCS, CAS compares its time stamp with the one already in its register and only the latest is stored. The register is updated accordingly.

S5. The appropriate control signal is selected from FCS by (7b) and applied to the plant. Go to S2.

It is readily seen that this packet-based deadband control approach is different from previous packet-based control approach since not all the FCSs are sent to the actuator, but only those that have changed dramatically compared with the one last sent. This strategy reduces the demand on the communication resource in NCSs and, furthermore, can improve the system performance in the presence of heavy transmission load on the network being used in NCSs, as illustrated in Section IV.

III. Stability and Stabilization of Packet-Based Deadband Control

In this section, the control law using the packet-based deadband control approach is explicitly presented, with a comparative analysis with the previous packet-based control approach. The stability of the derived closed-loop systems is then investigated from a time delay switched system theory perspective [32]–[35], with also a comparison of the stability conditions for both approaches. Finally, an LMI-based stabilization result is obtained, which can be solved using the well-known cone complementarity technique [36], [37].

A. Control Laws

It is noticed that one major difference between the previous packet-based control approach and the packet-based deadband control approach in this paper lies in the use of different FCSs, as presented in (4) and (5), respectively. Using FCS in (4), that is, with the use of the packet-based control approach, the control action taken at time k at the actuator side is determined by

$$u^p(k) = u\left(k|k-\tau_k^{*p}\right), \quad \tau_k^{*p} \in \Omega^p \tag{7a}$$

where τ_k^{*p} denotes the round trip delay of the FCS being used at time k, $\bar{\tau}^p = \bar{\tau}_{sc} + \bar{\tau}_{ca}$ is the upper bound of the delay and consecutive data packet dropout for the round trip and $\Omega^p = \{2, 3, \ldots, \bar{\tau}^p\}$. It is worth mentioning that $\tau_k^{*p} \geq 2$ is due to the fact that the data packets in both the sensor-to-controller and the controller-to-actuator channels experience at least one step delay respectively in practice. For the determination of the control law in (7a), the reader is referred to Fig. 2 and references [25]–[27].

With the use of FCS in (5) and the corresponding deadband control strategy in (6), the control signal used may be based on older sampled data information with the control action taken at time k being

$$u(k) = u\left(k|k-\tau_k^*\right), \quad \tau_k^* \in \Omega \tag{7b}$$

where τ_k^* denotes the round trip delay of the FCS being used in the packet-based deadband control case, $\bar{\tau} = \bar{\tau}_{sc} + N - 1$, $\Omega = \{2, 3, \ldots, \bar{\tau}\}$ and it is seen that $\tau_k^* \geq \tau_k^{*p}, \forall k$.

Though the control signal in (7b) may be based on older sampled data information, with the deadband control strategy in (6), the difference between $u(k)$ and $u^p(k)$ is however restrained within a small range, which helps to maintain the system performance using the packet-based deadband control approach at a satisfactory level

$$\|u(k) - u^p(k)\| \leq \delta \|u^p(k)\|, \quad \forall k. \tag{8}$$

For simplicity, in this paper state feedback is used and thus the control law in (7a) and (7b) can be explicitly represented by

$$u^p(k) = K^p_{\tau_k^{*p}} x\left(k-\tau_k^{*p}\right), \quad \tau_k^{*p} \in \Omega^p \tag{9a}$$

and

$$u(k) = K_{\tau_k^*} x\left(k-\tau_k^*\right), \quad \tau_k^* \in \Omega \tag{9b}$$

respectively, where the feedback gains $K^p_{\tau_k^{*p}}$, $K_{\tau_k^*}$ with respect to the corresponding round trip delays τ_k^{*p} and τ_k^*, are to be designed.

With the control laws defined in (9a) and (9b), the closed-loop system model with the packet-based control approach can be obtained as

$$x(k+1) = Ax(k) + BK^p_{\tau_k^{*p}} x\left(k-\tau_k^{*p}\right), \quad \tau_k^{*p} \in \Omega^p \tag{10a}$$

and for the packet-based deadband control approach, it is obtained

$$x(k+1) = Ax(k) + BK_{\tau_k^*} x\left(k-\tau_k^*\right), \quad \tau_k^* \in \Omega. \tag{10b}$$

In light of the relationship between both control laws in (8), the closed-loop system model for the packet-based deadband control approach in (10b) can also be represented by the following system model with time-varying uncertainty

$$x(k+1) = Ax(k) + (B + \Delta B_k) K^p_{\tau_k^{*p}} x\left(k-\tau_k^{*p}\right), \quad \tau_k^{*p} \in \Omega^p \tag{10c}$$

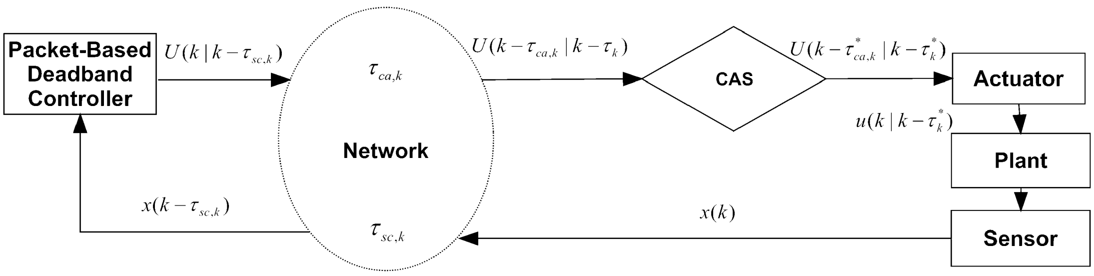

Fig. 2. Block diagram of packet-based deadband control for networked control systems where CAS represents the control action selector.

where ΔB_k satisfies

$$(B+\Delta B_k)K^p_{\tau_k^{*p}}x\left(k-\tau_k^{*p}\right)=BK_{\tau_k^*}x\left(k-\tau_k^*\right)$$

and $\|\Delta B_k\|\leq\delta_B\triangleq\delta\|B\|$ in light of (8).

B. Stability and Stabilization

In this subsection, we first investigate the stability of the closed-loop system in (10b) for the packet-based deadband control approach to NCSs, and then compare the stability conditions for both approaches, with and without the deadband control strategy.

Theorem 1: Given $\lambda\geq 1$ and the feedback gains in (10b) for the packet-based deadband control approach $K_i, i\in\Omega$. The closed-loop system in (10b) is stable if there exist $P_i=P_i^T>0$, $Q_i=Q_i^T>0$, $R_i=R_i^T>0$, $S_i=\begin{pmatrix}S_i^{11} & S_i^{12}\\ (S_i^{12})^T & S_i^{22}\end{pmatrix}\geq 0$, T_i^1, T_i^2 with appropriate dimensions such that:

1) $\forall i\in\Omega$

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

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

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

$$P_i\leq\lambda P_j, Q_i\leq\lambda Q_j, R_i\leq\lambda R_j \tag{13}$$

where

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

Proof: Suppose at time k, $\tau_k^*=i\in\Omega$. Let

$$z(l)=x(l+1)-x(l). \tag{14}$$

We then obtain

$$x(k)-x\left(k-\tau_k^*\right)-\sum_{l=k-\tau_k^*}^{k-1}z(l)=0. \tag{15}$$

Define the following Lyaponuv functional and notice that the choices of the matrices $P_{\tau_k^*}, Q_{\tau_k^*}, R_{\tau_k^*}$ at time k are dependent on the corresponding round trip delay $\tau_k^*\in\Omega$

$$V_i(k)=V_i^1(k)+V_i^2(k)+V_i^3(k) \tag{16a}$$

with

$$V_i^1(k)=x^T(k)P_ix(k) \tag{16b}$$

$$V_i^2(k)=\sum_{m=-\bar{\tau}+1}^{0}\sum_{l=k+m-1}^{k-1}z^T(l)R_{\tau_l^*}z(l) \tag{16c}$$

$$V_i^3(k)=\sum_{l=k-\tau_k^*}^{k-1}x^T(l)Q_{\tau_l^*}x(l). \tag{16d}$$

Define $\Delta V_i(k)=V_{\tau_{k+1}^*}(k+1)-V_i(k)$. Then along the trajectory of the system in (10b), we have

$$\begin{aligned}\Delta V_i^1(k)&=x^T(k+1)P_{\tau_{k+1}^*}x(k+1)-x^T(k)P_ix(k)\\ &\leq\lambda x^T(k+1)P_ix(k+1)-x^T(k)P_ix(k)\\ &=(\lambda-1)x^T(k)P_ix(k)+2\lambda x^T(k)P_iz(k)\\ &\quad+\lambda z^T(k)P_iz(k)\\ \Delta V_i^2(k)&=\sum_{m=-\bar{\tau}+1}^{0}\left(\sum_{l=k+m}^{k}-\sum_{l=k+m-1}^{k-1}\right)z^T(l)R_{\tau_l^*}z(l)\\ &=\bar{\tau}z^T(k)R_iz(k)-\sum_{l=k-\bar{\tau}}^{k-1}z^T(l)R_{\tau_l^*}z(l)\\ &\leq\bar{\tau}z^T(k)R_iz(k)-\sum_{l=k-\tau_k^*}^{k-1}z^T(l)R_{\tau_l^*}z(l)\\ \Delta V_i^3(k)&=\left(\sum_{l=k-\tau_{k+1}^*+1}^{k}-\sum_{l=k-\tau_k^*}^{k-1}\right)x^T(l)Q_{\tau_l^*}x(l)\\ &=\left(\sum_{l=k-\tau_{k+1}^*+1}^{k-1}-\sum_{l=k-\tau_k^*}^{k-1}\right)x^T(l)Q_{\tau_l^*}x(l)\\ &\quad+x^T(k)Q_ix(k).\end{aligned}$$

In light of the fact that using the packet-based deadband control approach, data packet disorder has been effectively eliminated by CAS, that is, the actuator will never use an older control signal as long as the latest is available. Therefore, we have the following relationship:

$$k+1-\tau_{k+1}^*\geq k-\tau_k^*,\quad\forall k\geq 1 \tag{17}$$

and thus

$$\Delta V_i^3(k) \leq x^T(k)Q_i x(k).$$

Notice that

$$z(k) = (A-I)x(k) + BK_i x(k-\tau_k^*)$$

and

$$R_i \geq \frac{1}{\lambda}R_j, Q_i \geq \frac{1}{\lambda}Q_j, \forall i,j.$$

We then obtain

$$\begin{aligned}\Delta V_i(k) \leq & x^T(k)\left((\lambda-1)P_i + Q_i + 2\lambda P_i(A-I) + (A-I)^T H_i(A-I)\right)x(k) \\ &+ 2x^T(k)\left(\lambda P_i BK_i + (A-I)^T H_i BK_i\right)x(k-\tau_k^*) \\ &+ x^T(k-\tau_k^*)(BK_i)^T H_i BK_i x(k-\tau_k^*) \\ &- \frac{1}{\lambda}\sum_{l=k-\tau_k^*}^{k-1} z^T(l)R_i z(l) \end{aligned} \tag{18}$$

where $H_i = \lambda P_i + \bar{\tau} R_i$.

In addition, we have for any T_i^1, T_i^2 with appropriate dimensions

$$2\left[x^T(k)T_i^1 + x^T(k-\tau_k^*)T_i^2\right] \times \left[x(k) - x(k-\tau_k^*) - \sum_{l=k-\tau_k^*}^{k-1} z(l)\right] = 0 \tag{19}$$

and for any S_i with appropriate dimensions

$$i\zeta_1^T(k)S_i\zeta_1(k) - \sum_{l=k-\tau_k^*}^{k-1} \zeta_1^T(k)S_i\zeta_1(k) = 0 \tag{20}$$

where $\zeta_1(k) = [x^T(k)\ x^T(k-\tau_k^*)]^T$.

From (18)–(20), we obtain

$$\Delta V_i(k) \leq \zeta_1^T(k)\Xi_i\zeta_1(k) - \frac{1}{\lambda}\sum_{l=k-\tau_k^*}^{k-1}\zeta_2^T(k,l)\Psi_i\zeta_2(k,l) \tag{21}$$

where

$$\begin{aligned}\Xi_i &= \begin{pmatrix}\Phi_i^{11}+\Pi_i^{11} & \Phi_i^{12}+\Pi_i^{12} \\ * & \Phi_i^{22}+\Pi_i^{22}\end{pmatrix} \\ \Pi_i^{11} &= (A-I)^T H_i(A-I) \\ \Pi_i^{12} &= (A-I)^T H_i BK_i \\ \Pi_i^{22} &= (BK_i)^T H_i BK_i \end{aligned} \tag{22}$$

and $\zeta_2(k,l) = [\zeta_1^T(k), z^T(l)]^T$. If $\Xi_i < 0$ and $\Psi_i \geq 0$, then we can guarantee that the system is stable. Furthermore, notice that by Schur complement, $\Xi_i < 0$ is equivalent to $\Phi_i < 0$. Thus, we complete the proof. ■

The stability result for packet-based deadband control in Theorem 1 can be readily extended to the packet-based control approach since both of them have similar closed-loop models, as presented in (10a) and (10b), respectively.

Corollary 1: Given $\lambda \geq 1$ and the feedback gains for the packet-based control approach K_i^p, $i \in \Omega^p$. The closed-loop system in (10a) is stable if there exist $P_i = P_i^T > 0$, $Q_i = Q_i^T > 0$, $R_i = R_i^T > 0$, $S_i = \begin{pmatrix} S_i^{11} & S_i^{12} \\ (S_i^{12})^T & S_i^{22}\end{pmatrix} \geq 0$, T_i^1, T_i^2 with appropriate dimensions such that:

1) $\forall i \in \Omega^p$

$$\Phi_i^p = \begin{pmatrix}\Phi_i^{11} & \Phi_i^{12^p} & (A-I)^T H_i \\ * & \Phi_i^{22} & (BK_i^p)^T H_i \\ * & * & -H_i\end{pmatrix} < 0 \tag{23}$$

$$\Psi_i^p = \Psi_i \geq 0 \tag{24}$$

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

$$P_i \leq \lambda P_j, Q_i \leq \lambda Q_j, R_i \leq \lambda R_j \tag{25}$$

where Φ_i^{11}, Φ_i^{22}, H_i, and Ψ_i are defined in Theorem 1 and

$$\Phi_i^{12^p} = \lambda P_i BK_i^p - T_i^1 + \left(T_i^2\right)^T + iS_i^{12}.$$

From Theorem 1 and Corollary 1 it is readily to obtain the following relationship of the closed-loop stability conditions between packet-based control and packet-based deadband control for NCSs.

Corollary 2: If $K_i^p = K_i$, $i \in \Omega^p$ and the stability conditions in Theorem 1 for the closed-loop system in (10b) using the packet-based deadband control approach are satisfied, then the closed-loop system in (10a) using the packet-based control approach is stable.

Consider the closed-loop system description in (10c) from the robust control perspective and let $\Delta B_k K_{\tau_k^*} = \delta_B \bar{K}^p \cdot (\Delta B_k K_{\tau_k^*}/\delta_B \bar{K}^p)$, where $\bar{K}^p = \max\{\|K_i^p\| | i \in \Omega^p\}$. It is readily seen that $\|\Delta B_k K_{\tau_k^*}/\delta_B \bar{K}^p\| \leq 1$. The comparison of the stability conditions between packet-based control and packet-based deadband control for NCSs can then be revealed from the following theorem.

Theorem 2: Given $\lambda \geq 1$ and the feedback gains for the packet-based control approach K_i^p, $i \in \Omega^p$. The closed-loop system with the packet-based deadband control approach in (10c) is stable if there exist $P_i = P_i^T > 0$, $Q_i = Q_i^T > 0$, $R_i = R_i^T > 0$, $S_i = \begin{pmatrix} S_i^{11} & S_i^{12} \\ (S_i^{12})^T & S_i^{22}\end{pmatrix} \geq 0$, T_i^1, T_i^2 with appropriate dimensions and a scalar $\gamma > 0$ such that:

1) $\forall i \in \Omega^p$

$$\begin{pmatrix}\Phi_i^p & \Upsilon_i^T \\ * & -\gamma I\end{pmatrix} < 0 \tag{26}$$

$$\Psi_i^p \geq 0 \tag{27}$$

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

$$P_i \leq \lambda P_j, Q_i \leq \lambda Q_j, R_i \leq \lambda R_j \tag{28}$$

where Φ_i^p and Ψ_i^p are defined in Corollary 1 and $\Upsilon_i = [\lambda\delta_B\bar{K}^p\ 0\ \delta_B\bar{K}^p H_i]$.

Proof: The theorem can be obtained following a standard robust stability analysis for systems with time-varying uncertainty, as done in [32], and thus we omit the technical details. ■

Remark 2: Suppose $K_i^p = K_i$, $i \in \Omega^p$. With the use of the deadband control strategy in (6) we have $\delta \neq 0$. In this case, it is readily seen that (26) in Theorem 2 is harder to be satisfied than (11) in Corollary 1, that is, the system with the deadband control strategy is more likely to be unstable than the system without it, which is true in reality. On the other hand, if $\delta = 0$, that is, no deadband control strategy is used, we have $\Delta B_k \equiv 0$ and thus the closed-loop system model in (10c) is equivalent to (10a). In this case, it is seen that $\Upsilon_i = 0$ in Theorem 2 and then (26) is equivalent to (11), thus enabling Theorem 2 and Corollary 1 to be equivalent. From this point of view, Theorem 2 effectively presents the effects of the deadband control strategy on the closed-loop stability of the system considered.

Based on Theorem 1, we obtain the following stabilized controller design method.

Theorem 3: Given $\lambda \geq 1$. The system in (10b) is stabilizable if there exist $L_i = L_i^T > 0$, $W_i = W_i^T > 0$, $M_i = M_i^T > 0$, $X_i = \begin{pmatrix} X_i^{11} & X_i^{12} \\ (X_i^{12})^T & X_i^{22} \end{pmatrix} \geq 0$, Y_i^1, Y_i^2, V_i with appropriate dimensions such that:

1) $\forall i \in \Omega$

$$\Phi_i' = \begin{pmatrix} \Phi_i^{11'} & \Phi_i^{12'} & \lambda L(A-I)^T & \bar{\tau}L(A-I)^T \\ * & \Phi_i^{22'} & \lambda(BV_i)^T & \bar{\tau}(BV_i)^T \\ * & * & -\lambda L_i & 0 \\ * & * & * & -\bar{\tau}M_i \end{pmatrix} < 0 \quad (29)$$

$$\Psi_i' = \begin{pmatrix} \lambda X_i^{11} & \lambda X_i^{12} & \lambda Y_i^1 \\ * & \lambda X_i^{22} & \lambda Y_i^2 \\ * & * & L_i M_i^{-1} L_i \end{pmatrix} \geq 0 \quad (30)$$

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

$$L_i \leq \lambda L_j, M_i \leq \lambda M_j, W_i \leq \lambda W_j \quad (31)$$

where

$$\Phi_i^{11'} = (\lambda-1)L_i + W_i + 2\lambda(A-I)L_i + Y_i^1 + \left(Y_i^1\right)^T + iX_i^{11}$$
$$\Phi_i^{12'} = \lambda BV_i - Y_i^1 + \left(Y_i^2\right)^T + iX_i^{12}$$
$$\Phi_i^{22'} = -Y_i^2 - \left(Y_i^2\right)^T + iX_i^{22}.$$

Furthermore, the control law is defined in (9b) with $K_i = V_i L_i^{-1}$.

Proof: Stability condition (11) in Theorem 1 can be reformed as

$$\begin{pmatrix} \Phi_i^{11} & \Phi_i^{12} & \lambda(A-I)^T P_i & \bar{\tau}(A-I)^T R_i \\ * & \Phi_i^{22} & \lambda(BK_i)^T P_i & \bar{\tau}(BK_i)^T R_i \\ * & * & -\lambda P_i & 0 \\ * & * & * & -\bar{\tau}R_i \end{pmatrix} < 0. \quad (32)$$

Pre- and post multiply (32) and (12) by $diag(P_i^{-1}, P_i^{-1}, P_i^{-1}, R_i^{-1})$ and $diag(P_i^{-1}, P_i^{-1}, P_i^{-1})$, respectively, and let $L_i = P_i^{-1}$, $M_i = R_i^{-1}$, $W_i = P_i^{-1}Q_iP_i^{-1}$, $X_i = diag(P_i^{-1}, P_i^{-1}) \cdot S_i \cdot diag(P_i^{-1}, P_i^{-1})$, $Y_i^j = P_i^{-1}T_i^jP_i^{-1}$, $j = 1, 2$, $V_i = K_iP_i^{-1}$. We then complete the proof. ■

It is noticed that (30) in Theorem 3 is no longer LMI conditions due to the term $L_iM_i^{-1}L_i$. There are several techniques available to deal with this difficulty, among which the cone complementarity linearization technique is one of the most commonly used [36], [37]. In the following corollary, this technique is used to derive a suboptimal solution for (30) by transforming it to a nonlinear minimization problem involving LMI conditions.

Corollary 3: Given $\lambda \geq 1$. Define the following nonlinear minimization problem involving LMI conditions for $i \in \Omega$

$$\mathcal{P}_i : \begin{cases} \text{Minimize Tr}(Z_iR_i + L_iP_i + M_iQ_i) \\ \text{Subject to (29), (31), } L_i = L_i^T > 0, W_i = W_i^T > 0, \\ M_i = M_i^T > 0,\ X_i = \begin{pmatrix} X_i^{11} & X_i^{12} \\ (X_i^{12})^T & X_i^{22} \end{pmatrix} \geq 0, \\ \Psi_i'' \geq 0, \Theta_i^1 \geq 0, \Theta_i^2 \geq 0, \Theta_i^3 \geq 0, \Theta_i^4 \geq 0 \end{cases}$$

where

$$\Psi_i'' = \begin{pmatrix} \lambda X_i^{11} & \lambda X_i^{12} & \lambda Y_i^1 \\ * & \lambda X_i^{22} & \lambda Y_i^2 \\ * & * & Z_i \end{pmatrix}$$
$$\Theta_i^1 = \begin{pmatrix} R_i & P_i \\ * & Q_i \end{pmatrix},\ \Theta_i^2 = \begin{pmatrix} Z_i & I \\ * & R_i \end{pmatrix}$$
$$\Theta_i^3 = \begin{pmatrix} L_i & I \\ * & P_i \end{pmatrix},\ \Theta_i^4 = \begin{pmatrix} M_i & I \\ * & Q_i \end{pmatrix}.$$

If the solution of $\mathcal{P}_i = 3n, \forall i \in \Omega$, the system in (10b) is then stabilizable with the control law being defined in Theorem 3.

Remark 3: In this paper, LMI-based stability and stabilization results are obtained which are feasible in practice (Corollary 3) and will be proven to be effective by both numerical and experimental examples in the next section. However, it is worth mentioning that as a control framework, the performance of the packet-based deadband control approach to NCSs can certainly be investigated by any appropriate control theories and the controller can be designed according to the closed-loop system models in (10b) and (10c), independently from the deployment of the packet-based deadband control strategy. In this sense further theoretical analysis and improvement are still needed, in order to reduce the conservativeness of the LMI-based results presented in this paper.

IV. Numerical and Experimental Examples

In this section, both numerical and experimental examples are considered to illustrate the effectiveness of the proposed packet-based deadband control approach to NCSs and the stabilized controller design method within this framework.

Example 1: Consider the system in (1) with the following system matrices borrowed from [27], which is seen to be open-loop unstable

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

In the simulation, the initial state for the system in (1) is set as $x_0 = [-1\ 1]^T$, the upper bound of the delay and consecutive dropout for the round trip is $\bar{\tau} = 4$ and the deadband for the packet-based deadband approach is chosen as $\delta = 0.1$.

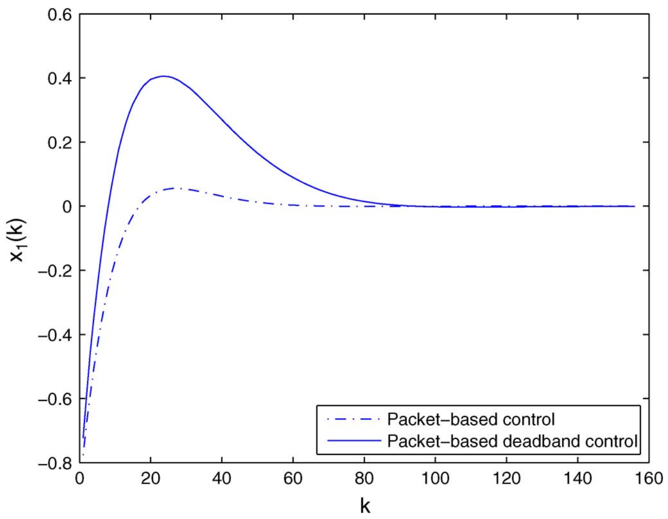

Fig. 3. Comparison of the state responses between with and without the deadband control strategy.

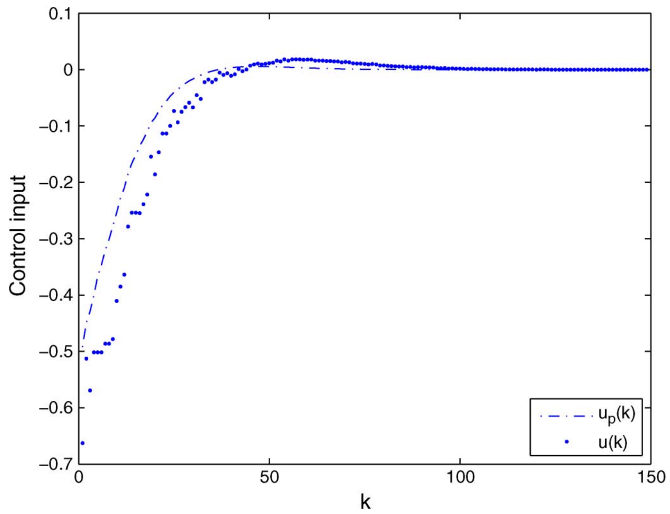

Fig. 4. Comparison of the control inputs between with and without the deadband control strategy.

In this example, our main purpose is to illustrate the effectiveness of the proposed deadband control strategy within the packet-based control framework, by comparing it with the previous packet-based control approach in [27]. In order to eliminate possible effects on the system performance brought by different controller design methods, in this example the controllers for both cases are designed using the same receding horizon approach as proposed in [27], which yields the following feedback gain for the packet-based control approach:

$$K^p = \begin{pmatrix} K_2^p \\ K_3^p \\ K_4^p \end{pmatrix} = \begin{pmatrix} -0.6438 & -1.4748 \\ -0.5242 & -1.3079 \\ -0.4198 & -1.1549 \end{pmatrix}$$

and the feedback gain for the packet-based deadband control approach with $N = 9$

$$K = \begin{pmatrix} K_2 \\ K_3 \\ K_4 \\ K_5 \\ K_6 \\ K_7 \\ K_8 \\ K_9 \\ K_{10} \end{pmatrix} = \begin{pmatrix} -0.4371 & -1.0510 \\ -0.3428 & -0.9334 \\ -0.2615 & -0.8251 \\ -0.1921 & -0.7257 \\ -0.1334 & -0.6346 \\ -0.0843 & -0.5515 \\ -0.0439 & -0.4759 \\ -0.0114 & -0.4074 \\ 0.0142 & -0.3454 \end{pmatrix}$$

where both of the feedback gains K_i^p and K_i are designed from $i = 2$ due to the fact that the round trip delays in both cases are not less than two sampling periods, as stated in (7a).

It is seen from the comparison of the state responses in Fig. 3 that the system performance with the deadband control strategy is still maintained at a satisfactory level. This can also be verified by looking into the comparison of the control inputs for both cases shown in Fig. 4 where it is seen that the control inputs to both systems are very close. It is worth mentioning, however, only around 60% of FCSs are sent to the actuator using the deadband control strategy. The effectiveness of the packet-based deadband control approach can also been seen from Fig. 5, where the packet-based deadband control approach yields a far better system performance than the packet-based control approach, when the latter also transmit only around 60% of its FCSs.

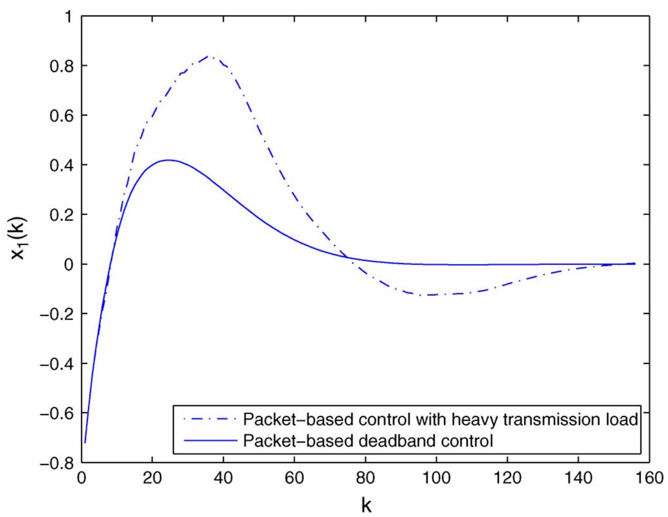

Fig. 5. Comparison of the state responses with heavy transmission load.

Example 2: An Internet-based test rig for NCSs is used in this example to illustrate the effectiveness of the proposed packet-based deadband control approach and the stabilized controller design method. This test rig consists of a DC servo system (see Fig. 6) located in the University of Glamorgan, Pontypridd, U.K., and a remote controller located in the Institute of Automation, Chinese Academy of Sciences, Beijing, China (see Fig. 7). The plant and the controller are connected via the Internet, and can be configured using the web-based laboratory available at http://www.ncslab.net/. For further information of this test rig, the reader is referred to [38].

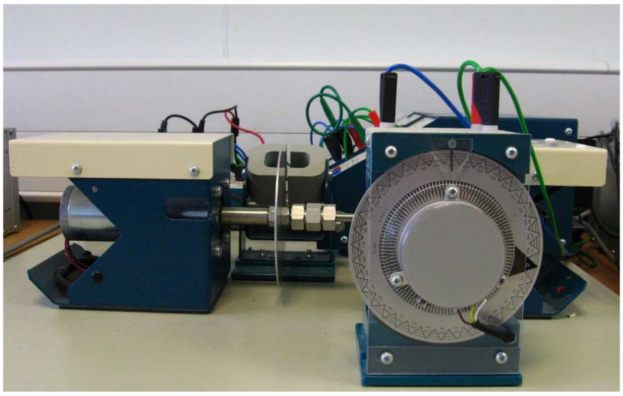

Fig. 6. DC servo plant in the University of Glamorgan.

Fig. 7. Network controller in the Chinese Academy of Sciences.

In [38], the DC servo system at sampling period 0.04 s is identified to be of the form in (1) with the following system matrices:

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

and the measurement equation being

$$y(k) = Cx(k)$$

with

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

The system states are obtained using a state observer of the following form with $L = [6\ 6\ 6]^T$:

$$x(k+1|k) = Ax(k|k-1) + Bu(k) + L\left(y(k) - Cx(k|k-1)\right) \tag{33}$$

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

In the experiment, the round trip delay between UK and China is found to be typically upper bounded by 0.32 s which is 8 sampling periods. For the implementation of the packet-based deadband control approach, an FCS containing 20 forward control signals is used, with the feedback gains being the following, designed using Corollary 3:

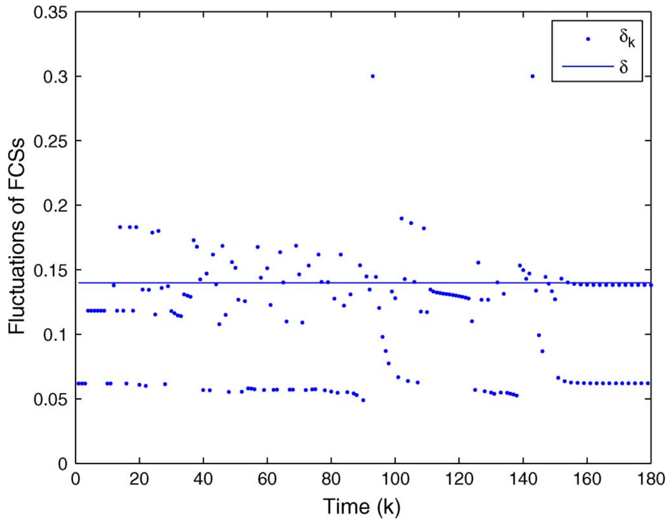

Fig. 8. Using deadband to reduce data transmissions in NCSs.

$$K = \begin{pmatrix} K_2 \\ K_3 \\ K_4 \\ K_5 \\ K_6 \\ K_7 \\ K_8 \\ K_9 \\ K_{10} \\ K_{11} \\ K_{12} \\ K_{13} \\ K_{14} \\ K_{15} \\ K_{16} \\ K_{17} \\ K_{18} \\ K_{19} \\ K_{20} \\ K_{21} \end{pmatrix} = \begin{pmatrix} -0.0643 & 0.0039 & 0.0249 \\ -0.0589 & 0.0035 & 0.0221 \\ -0.0547 & 0.0032 & 0.0202 \\ -0.0527 & 0.0030 & 0.0191 \\ -0.0495 & 0.0025 & 0.0180 \\ -0.0494 & 0.0029 & 0.0177 \\ -0.0485 & 0.0032 & 0.0175 \\ -0.0466 & 0.0027 & 0.0168 \\ -0.0458 & 0.0029 & 0.0165 \\ -0.0460 & 0.0027 & 0.0164 \\ -0.0459 & 0.0030 & 0.0164 \\ -0.0456 & 0.0031 & 0.0164 \\ -0.0445 & 0.0026 & 0.0158 \\ -0.0440 & 0.0024 & 0.0154 \\ -0.0439 & 0.0025 & 0.0153 \\ -0.0437 & 0.0025 & 0.0152 \\ -0.0429 & 0.0022 & 0.0149 \\ -0.0430 & 0.0023 & 0.0149 \\ -0.0434 & 0.0026 & 0.0150 \\ -0.0437 & 0.0028 & 0.0151 \end{pmatrix}.$$

Using a deadband of $\delta = 0.14$, it is seen from Fig. 8 that only around 25% of the FCSs are sent to the actuator. In other words, the deadband control strategy used here reduces around 75% of the control data transmissions.

On the other hand, with the feedback gains defined above and the packet-based deadband control approach in Section II, the output response of the DC servo system which is remotely controlled via the Internet is illustrated in Fig. 9. The results show that the output responses converge quickly which proves the effectiveness of both the packet-based deadband control approach and stabilized controller design method.

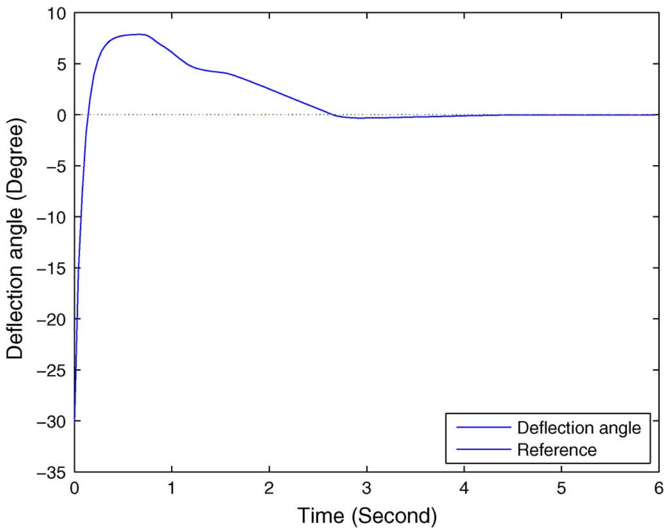

Fig. 9. Experimental response using the packet-based deadband control approach.

V. Conclusion

Within the recently reported packet-based control framework for NCSs, a packet-based deadband control approach is proposed, with also a stabilized controller design method obtained using time delay switched system theory. This approach exploits more fully of the packet structure in the network being used in NCSs, by sending a larger forward control sequence and then setting a deadband on the sequences which allows transmission only in the presence of a sufficiently large change between the current sequence and the one last sent. The performance of the proposed packet-based deadband approach and the stabilized controller are verified using both numerical and experimental examples, which illustrate the effectiveness of the approaches in the sense that it effectively reduces the data transmission in NCSs and in the meanwhile maintains the system performance at a satisfactory level. Further improvements will focus on: 1) reducing the conservativeness of the LMI-based stability and stabilization results; and 2) describing the communication constraints in a stochastic way to represent the reality better.

References

[1] *Networked Control Systems: Theory and Applications*, F.-Y. Wang and D. Liu, Eds., 1st ed. New York: Springer, 2008.

[2] J. Baillieul and P. J. Antsaklis, "Control and communcation challenges in networked real-time systems," *IEEE Proc.*, vol. 95, no. 1, pp. 9–28, Jan. 2007.

[3] P. Antsaklis and J. Baillieul, "Special issue on technology of networked control systems," *IEEE Proc.*, vol. 95, no. 1, pp. 5–8, Jan. 2007.

[4] D. Muñoz de la Peña and P. D. Christofides, "Output feedback control of nonlinear systems subject to sensor data losses," *Syst. Control Lett.*, vol. 57, no. 8, pp. 631–642, 2008.

[5] I. G. Polushin, P. X. Liu, and C.-H. Lung, "On the model-based approach to nonlinear networked control systems," *Automatica*, vol. 44, pp. 2409–2414, 2008.

[6] W.-A. Zhang and L. Yu, "Modelling and control of networked control systems with both network-induced delay and packet-dropout," *Automatica*, vol. 44, no. 12, pp. 3206–3210, 2008.

[7] C. Lin, Z. Wang, and F. Yang, "Observer-based networked control for continuous-time systems with random sensor delays," *Automatica*, vol. 45, no. 2, pp. 578–584, 2009.

[8] N. Vatanski, J.-P. Georges, H. Aubrun, E. Rondeau, and S.-L. Jämsä-Jounel, "Networked control with delay measurement and estimation," *Control Eng. Practice*, vol. 17, no. 2, pp. 231–244, 2009.

[9] J. Ren, C.-W. Li, and D.-Z. Zhao, "Linearizing control of induction motor based on networked control systems," *Int. J. Autom. Comput.*, vol. 6, no. 2, pp. 192–197, 2009.

[10] D. Yue, Q.-L. Han, and J. Lam, "Network-based robust H_∞ control of systems with uncertainty," *Automatica*, vol. 41, no. 6, pp. 999–1007, 2005.

[11] H. Gao and T. Chen, "New results on stability of discrete-time systems with time-varying state delay," *IEEE Trans. Autom. Control*, vol. 52, no. 2, pp. 328–334, Feb. 2007.

[12] Y.-L. Wang and G.-H. Yang, " H_∞ control of networked control systems with time delay and packet disordering," *IET Control Theory Appl.*, vol. 1, no. 5, pp. 1344–1354, 2007.

[13] H. Gao, X. Meng, and T. Chen, "Stabilization of networked control systems with a new delay characterization," *IEEE Trans. Autom. Control*, vol. 53, no. 9, pp. 2142–2148, Sep. 2008.

[14] Z. Wang, F. Yang, D. W. C. Ho, and X. Liu, "Robust H_∞ control for networked systems with random packet losses," *IEEE Trans. Syst. Man Cybern. B, Cybern.*, vol. 37, no. 4, pp. 916–924, Apr. 2007.

[15] M. Liu, D. W. C. Ho, and Y. Niu, "Stabilization of Markovian jump linear system over networks with random communication delay," *Automatica*, vol. 45, no. 2, pp. 416–421, 2009.

[16] X. Meng, J. Lam, and H. Gao, "Network-based H_∞ control for stochastic systems," *Int. J. Robust Nonlinear Control*, vol. 49, no. 3, pp. 295–312, 2009.

[17] Z. Wang, D. W. C. Ho, Y. Liu, and X. Liu, "Robust H_∞ control for a class of nonlinear discrete time-delay stochastic systems with missing measurements," *Automatica*, vol. 45, no. 3, pp. 684–691, 2009.

[18] P. Mhaskar, N. H. El-Farra, and P. D. Christofides, "Predictive control of switched nonlinear systems with scheduled mode transitions," *IEEE Trans. Autom. Control*, vol. 50, no. 11, pp. 1670–1680, Nov. 2005.

[19] D. Xie, X. Chen, L. Lü, and N. Xu, "Asymptotical stabilisability of networked control systems: Time-delay switched system approach," *IET Control Theory Appl.*, vol. 2, no. 9, pp. 743–751, 2008.

[20] L. Zhang and D. Hristu-Varsakelis, "Communication and control co-design for networked control systems," *Automatica*, vol. 42, no. 6, pp. 953–958, 2006.

[21] D. B. Daĉić and D. Neŝić, "Quadratic stabilization of linear networked control systems via simultaneous protocol and controller design," *Automatica*, vol. 43, no. 7, p. 1145, 2007.

[22] S. Yksel and T. Baar, "Communication constraints for decentralized stabilizability with time-invariant policies," *IEEE Trans. Autom. Control*, vol. 52, no. 6, pp. 1060–1066, Jun. 2007.

[23] X.-M. Tang and J.-S. Yu, "Feedback scheduling of model-based networked control systems with flexible workload," *Int. J. Autom. Comput.*, vol. 5, no. 4, pp. 389–394, 2008.

[24] Y. Mostofi and R. M. Murray, "To drop or not to drop: Design principles for Kalman filtering over wireless fading channels," *IEEE Trans. Autom. Control*, vol. 54, no. 2, pp. 376–381, Feb. 2009.

[25] Y.-B. Zhao, G. P. Liu, and D. Rees, "A predictive control based approach to networked Hammerstein systems: Design and stability analysis," *IEEE Trans. Syst. Man Cybern. B, Cybern.*, vol. 38, no. 3, pp. 700–708, Jun. 2008.

[26] Y.-B. Zhao, G. P. Liu, and D. Rees, "Improved predictive control approach to networked control systems," *IET Control Theory Appl.*, vol. 2, no. 8, pp. 675–681, 2008.

[27] Y.-B. Zhao, G. P. Liu, and D. Rees, "Design of a packet-based control framework for networked control systems," *IEEE Trans. Control Syst. Technol.*, vol. 17, no. 4, pp. 859–865, Jul. 2009.

[28] P. Otanez, J. Moyne, and D. Tilbury, "Using deadbands to reduce communication in networked control systems," in *Proc. Amer. Control Conf.*, 2002, vol. 4, pp. 3015–3020.

[29] F.-L. Lian, J. K. Yook, D. M. Tilbury, and J. Moyne, "Network architecture and communication modules for guaranteeing acceptable control and communication performance for networked multi-agent systems," *IEEE Trans. Ind. Inf.*, vol. 2, no. 1, pp. 12–24, Feb. 2006.

[30] F.-L. Lian, J. R. Moyne, and D. M. Tilbury, "Performance evaluation of control networks: Ethernet, ControlNet, and DeviceNet," *IEEE Control Syst. Mag.*, vol. 21, no. 1, pp. 66–83, Jan. 2001.

[31] W. Stallings, *Data and Computer Communications*, 6th ed. Englewood Cliffs, NJ: Prentice-Hall, 2000.

[32] Y. He, "Delay-dependent robust stability and stabilization based on free-weighting matrices," (in Chinese) Ph.D. dissertation, Inst. Inf. Sci. Eng., Central South University, Changsha, China, 2004.

[33] X.-M. Sun, J. Zhao, and D. J. Hill, "Stability and L_2-gain analysis for switched delay systems: A delay-dependent method," *Automatica*, vol. 42, no. 10, pp. 1769–1774, 2006.
[34] Y. He, Q. Wang, C. Lin, and M. Wu, "Delay-range-dependent stability for systems with time-varying delay," *Automatica*, vol. 43, no. 2, pp. 371–376, 2007.
[35] X. He, Z. Wang, and D. Zhou, "Robust H_∞ filtering for networked systems with multiple state delays," *Int. J. Control*, vol. 80, no. 8, pp. 1217–1232, 2007.
[36] L. E. Ghaoui, F. Oustry, and M. AitRami, "A cone complementarity linearization algorithm for static output-feedback and related problems," *IEEE Trans. Autom. Control*, vol. 42, no. 8, pp. 1171–1176, Aug. 1997.
[37] Y. Moon, P. Park, W. Kwon, and Y. Lee, "Delay-dependent robust stabilization of uncertain state-delayed systems," *Int. J. Control*, vol. 74, no. 14, pp. 1447–1455, 2001.
[38] W. Hu, "Design of networked control systems and global web-based control laboratory," Ph.D. dissertation, Faculty Adv. Technol., Univ. Glamorgan, Pontypridd, U.K., 2008.

Yun-Bo Zhao received the B.Sc. degree in mathematics from Shandong University, Shandong, China, in 2003, the M.Sc. degree in systems theory from the Institute of Systems Science, Chinese Academy of Sciences, China, in 2007, and the Ph.D. degree from the University of Glamorgan, Pontypridd, U.K., in 2008.

He has held postdoctoral positions in INRIA-Grenoble, France and the University of Glamorgan, respectively. He is currently a Research Associate with the University of Glasgow. His research interests include networked control systems, multi-agent systems, and systems biology.

Guo-Ping Liu (M'97–SM'99) received the B.Eng. and M.Eng. degrees in electrical and electronic engineering from the Central South University of Technology, Changsha, China, in 1982 and 1985, respectively, and the Ph.D. degree in control engineering from UMIST, Manchester, U.K., in 1992.

He is a chair of control engineering with the University of Glamorgan, Pontypridd, U.K. He has been a Professor with the University of Glamorgan since 2004, a Hundred-Talent Program Visiting Professor of the Chinese Academy of Sciences since 2001, and a Changjiang Scholar Visiting Professor of Harbin Institute of Technology since 2008. He has more than 400 publications on control systems and authored/coauthored 6 books. His main research areas include networked control systems, modelling and control of fuel cell vehicles, advanced control of industrial systems, nonlinear system identification and control, and multiobjective optimisation and control.

Dr. Liu is the Editor-In-Chief of the International Journal of Automation and Computing and a Fellow of IET.

David Rees received the B.Sc. (Honors) degree in electrical engineering from the University of Wales, College Swansea, U.K., in 1967 and the Ph.D. degree from the Council of National Academic Awards, U.K., in 1976.

He is currently part-time Reader in the Faculty of Advanced Technology, University of Glamorgan, Pontypridd, U.K. He has published over 200 Journal and Conference publications. He was the joint editor of *Industrial Digital Control Systems* (Peter Peregrinus, 1988), and has contributed to numerous monographs; the latest is three chapters in *Dynamic Modelling of Gas Turbines-Identification, Simulation, Condition Monitoring and Optimal Control* (Springer, 2004). His current research interests include nonlinear modelling, system identification and networked control systems.

Dr. Rees was a recipient of an IEE Premium Award in 1996. He is Fellow of the Institution of Engineering and Technology and a past Chairman of the IEE control Applications Professional Group.

1. Packet-based deadband control for internet-based networked control systems

Accession number: 20103613211642
Authors: Zhao, Yun-Bo (1); Liu, Guo-Ping (2, 3); Rees, David (2)
Author affiliation: (1) Department of Aerospace Engineering, University of Glasgow, Glasgow, G12 8QQ, United Kingdom; (2) Faculty of Advanced Technology, University of Glamorgan, Pontypridd CF37 1DL, United Kingdom; (3) CTGT Centre, Harbin Institute of Technology, Harbin 150001, China
Corresponding author: Zhao, Y.-B.(yzhao@eng.gla.ac.uk)
Source title: IEEE Transactions on Control Systems Technology
Abbreviated source title: IEEE Trans Control Syst Technol
Volume: 18
Issue: 5
Issue date: September 2010
Publication year: 2010
Pages: 1057-1067
Article number: 5288548
Language: English
ISSN: 10636536
CODEN: IETTE2
Document type: Journal article (JA)
Publisher: Institute of Electrical and Electronics Engineers Inc., 445 Hoes Lane / P.O. Box 1331, Piscataway, NJ 08855-1331, United States
Abstract: A packet-based deadband control approach is proposed for networked control systems (NCSs). Compared with previously reported packet-based control approaches to NCSs, the approach proposed in this paper takes full advantage of the packet-based data transmission in NCSs, and thus considerably reduces the use of the communication resources in NCSs whilst maintaining the system performance at a satisfactory level. A stabilized controller design method is obtained using time delay switched system theory, which has not been achieved in previously reported packet-based control approaches. The proposed deadband control strategy and the stabilized controller design method are verified using a numerical example as well as practical experiments based on an Internet-based test rig for NCSs. © 2010 IEEE.
Number of references: 38
Main heading: Controllers
Controlled terms: Control system analysis - Control system stability - Delay control systems - Internet - System stability
Uncontrolled terms: Communication resources - Control approach - Data transmission - Dead band control - Internet based - Internet-based networked control systems - Networked control systems - Numerical example - Packet-based - Stabilized controller design - Switched system - Test rigs
Classification code: 732.1 Control Equipment - 731.4 System Stability - 731.1 Control Systems - 723 Computer Software, Data Handling and Applications - 718 Telephone Systems and Related Technologies; Line Communications - 717 Optical Communication - 716 Telecommunication; Radar, Radio and Television
DOI: 10.1109/TCST.2009.2033118
Database: Compendex

Record 1 of 1
Title: Packet-Based Deadband Control for Internet-Based Networked Control Systems
Author(s): Zhao, YB (Zhao, Yun-Bo); Liu, GP (Liu, Guo-Ping); Rees, D (Rees, David)
Source: IEEE TRANSACTIONS ON CONTROL SYSTEMS TECHNOLOGY **Volume:** 18 **Issue:** 5 **Pages:** 1057-1067 **DOI:** 10.1109/TCST.2009.2033118 **Published:** SEP 2010
Times Cited in Web of Science Core Collection: 26
Total Times Cited: 28
Usage Count (Last 180 days): 0
Usage Count (Since 2013): 11
Cited Reference Count: 38
Abstract: A packet-based deadband control approach is proposed for networked control systems (NCSs). Compared with previously reported packet-based control approaches to NCSs, the approach proposed in this paper takes full advantage of the packet-based data transmission in NCSs, and thus considerably reduces the use of the communication resources in NCSs whilst maintaining the system performance at a satisfactory level. A stabilized controller design method is obtained using time delay switched system theory, which has not been achieved in previously reported packet-based control approaches. The proposed deadband control strategy and the stabilized controller design method are verified using a numerical example as well as practical experiments based on an Internet-based test rig for NCSs.
Accession Number: WOS:000283187100006
Language: English
Document Type: Article
Author Keywords: Deadband control; Internet-based test rig; networked control systems; packet-based control; stability
KeyWords Plus: H-INFINITY CONTROL; PREDICTIVE CONTROL; TIME-DELAY; NONLINEAR-SYSTEMS; STABILITY; DESIGN; COMMUNICATION; STABILIZATION; PERFORMANCE; LOSSES
Addresses: [Zhao, Yun-Bo; Liu, Guo-Ping; Rees, David] Univ Glamorgan, Fac Adv Technol, Pontypridd CF37 1DL, M Glam, Wales.
[Liu, Guo-Ping] Harbin Inst Technol, CTGT Ctr, Harbin 150001, Peoples R China.
Reprint Address: Zhao, YB (reprint author), Univ Glasgow, Dept Aerosp Engn, Glasgow G12 8QQ, Lanark, Scotland.
E-mail Addresses: yzhao@eng.gla.ac.uk; drees@glam.ac.uk; gpliu@glam.ac.uk
Author Identifiers:

Author	ResearcherID Number	ORCID Number
Liu, Guo-Ping	O-3511-2014	0000-0002-0699-2296
Zhao, Yun-Bo	F-1699-2010	

Publisher: IEEE-INST ELECTRICAL ELECTRONICS ENGINEERS INC
Publisher Address: 445 HOES LANE, PISCATAWAY, NJ 08855-4141 USA
Web of Science Categories: Automation & Control Systems; Engineering, Electrical & Electronic
Research Areas: Automation & Control Systems; Engineering
IDS Number: 667IS
ISSN: 1063-6536
29-char Source Abbrev.: IEEE T CONTR SYST T
ISO Source Abbrev.: IEEE Trans. Control Syst. Technol.
Source Item Page Count: 11

Funding:

Funding Agency	Grant Number
National Natural Science Foundation of China	60934006

Manuscript received April 07, 2009; revised July 30, 2009; accepted September 02, 2009. Manuscript received in final form September 18, 2009. First published October 16, 2009; current version published August 25, 2010. Recommended by Associate Editor Z. Wang. The work of Y.-B.Zhao and G.-P.Liu was supported in part by the National Natural Science Foundation of China under Grant 60934006.

Close
Web of Science™
Page 1 (Records 1 -- 1)
[1]
Print