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

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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

M OST 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...
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 constrains 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 model is 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

\[ x(k+1) = Ax(k) + Bu(k) \]  \hspace{1cm} (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 \( \tau_{sc} \) and \( \tau_{ca} \), respectively) are upper bounded, i.e.,

\[
\tau_{sc} \triangleq \max_{k \geq 1} \{\tau_{sc,k} + \bar{\tau}_{sc}\} < \infty \quad (2a)
\]

\[
\tau_{ca} \triangleq \max_{k \geq 1} \{\tau_{ca,k} + \bar{\tau}_{ca}\} < \infty \quad (2b)
\]

where \( \tau_{sc,k}, \bar{\tau}_{sc}, \tau_{ca,k}, \bar{\tau}_{ca} \) 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

\[
N = \left\lfloor \frac{B_p}{B_c} \right\rfloor \quad (3)
\]

where \( \left\lfloor \frac{B_p}{B_c} \right\rfloor = \max\{\zeta \in \mathbb{N} : \zeta \leq \frac{B_p}{B_c}\} \).

The key point of the previously reported packet-based control approach is to realize that \( N \) in (3) is usually larger than \( \tau_{ca} \). 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 \( \tau_{ca} + 1 \). 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 $k - \tau_{sc,k}$

$$U^p(k|k - \tau_{sc,k}) = [u(k|k - \tau_{sc,k}) \ldots u(k + \tau_{ca}|k - \tau_{sc,k})].$$

(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 $u(k + \tau_{ca}|k - \tau_{sc,k})$ 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 overhead (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 $2^{16} = 65536$ 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 $\tau_{ca}$ 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]

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

(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 $U(k - \delta_k|k - \delta_k - \tau_{sc,k})$ at time $k$ at the controller side, where $k - \delta_k$ 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.,

$$\delta_k \triangleq \max_{0 \leq \alpha \leq \delta_k - 1} \left\| \frac{\Delta u(k)}{\|u(k + \alpha|k - \tau_{sc,k})\|} \right\| > \delta$$

(6)
where $\delta$ is the deadband set for FCSs, $\| \cdot \|$ denotes the Euclidean norm and $\Delta u_{ki} = u(k+1|k-\tau_{sc,k})-u(k+1|k-\tau_{sc,k}-\varpi)$. 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 $N-\tau_{ca}$ time steps, which also implies that $\varpi_k \leq N-\tau_{ca} - 1, \forall k$.

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

Algorithm 1 (Packet-Based Deadband Control)

S.1. Initiation. Set $k = 0$, $\varpi_k = 0$.

S.2. The sensor samples the plant and sends the sampled data packet to the controller.

S.3. At time $k$ at the controller side, if either 1) (6) is satisfied; or 2) $\varpi_k = N-\tau_{ca} - 1$, then send the current FCS to the actuator, update the register of the controller to be this FCS, and let $\varpi_{k+1} = 1, k = k+1$; otherwise let $\varpi_{k+1} = \varpi_k + 1, k = k+1$ and wait for the next time instant.

S.4. 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.

S.5. The appropriate control signal is selected from FCS by (7b) and applied to the plant. Go to S.2.

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

$$u^p(k) = u(k|k - \tau_{kp}^p), \quad \tau_{kp}^p \in \Omega^p$$  (7a)

where $\tau_{kp}^p$ denotes the round trip delay of the FCS being used at time $k$, $\Omega^p = [\tau_{sc} + \tau_{ca}]$ is the upper bound of the delay and consecutive data packet dropout for the round trip and $\Omega = \{2,3,\ldots,\bar{\tau}\}$. It is worth mentioning that $\tau_{kp}^p \geq 2$ 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

$$u(k) = u(k|k - \tau_k^c), \quad \tau_k^c \in \Omega$$  (7b)

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

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

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

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

$$u^p(k) = K_p^p \tau_{kp}^p \left( k - \tau_{kp}^p \right), \quad \tau_{kp}^p \in \Omega^p$$  (9a)

and

$$u(k) = K_c^c \tau_c \left( k - \tau_c \right), \quad \tau_c \in \Omega$$  (9b)

respectively, where the feedback gains $K_p^p, K_c^c$ with respect to the corresponding round trip delays $\tau_{kp}^p$ and $\tau_c$ 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

$$x(k+1) = Ax(k) + BK_p^p \tau_{kp}^p \left( k - \tau_{kp}^p \right), \quad \tau_{kp}^p \in \Omega^p$$  (10a)

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

$$x(k+1) = Ax(k) + BK_c^c \left( k - \tau_c \right), \quad \tau_c \in \Omega.$$  (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

$$x(k+1) = Ax(k) + (B + \Delta B_k)K_p^p \tau_{kp}^p \left( k - \tau_{kp}^p \right), \quad \tau_{kp}^p \in \Omega^p$$  (10c)
where $\Delta B_k$ satisfies
\[
(B + \Delta B_k)K_{\tau_k}P \left( k - \tau_k^w \right) = BK_{\tau_k}P \left( k - \tau_k^w \right)
\]
and $||\Delta B_k|| \leq \delta_B \Rightarrow ||B||$ 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 $K_{\tau_k}$, $i \in \Omega$. The closed-loop system in (10b) is stable if there exist $P_i = P_i^T > 0, Q_i = Q_i^T > 0, R_i = R_i^T > 0, S_i = \left( \begin{array}{cc} S_{11}^{ii} & S_{12}^{ii} \\ S_{21}^{ii} & S_{22}^{ii} \end{array} \right) \geq 0, \quad T_i^1, T_i^2$ with appropriate dimensions such that:

1. $\forall i \in \Omega$
\[
\Phi_i = \left( \begin{array}{cc} \Phi_{11}^{ii} & \Phi_{12}^{ii} \\ \Phi_{21}^{ii} & \Phi_{22}^{ii} \end{array} \right) \left( A - T_i \right)^T H_i < 0 \quad (11)
\]
\[
\Psi_i = \left( \begin{array}{cc} \lambda S_{11}^{ii} & \lambda S_{12}^{ii} \\ \lambda S_{21}^{ii} & \lambda S_{22}^{ii} \end{array} \right) \geq 0 \quad (12)
\]

2. $\forall i, j \in \Omega$
\[
P_i \leq \lambda P_j, Q_i \leq \lambda Q_j, R_i \leq \lambda R_j \quad (13)
\]

Define the following Lyapunov 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 $\tau_k^w \in \Omega$
\[
V_i(k) = V_i^0(k) + V_i^2(k) + V_i^2(k) \quad (16a)
\]
with
\[
V_i^0(k) = x^T(k)P_i x(k) \quad (16b)
\]
\[
V_i^2(k) = \sum_{m=\tau+1}^{k-1} \sum_{l=k+m-1}^{k-1} z^T(l)R_{\tau_k}z(l) \quad (16c)
\]
\[
V_i^2(k) = \sum_{l=k-\tau_k^w}^{k-1} x^T(l)Q_{\tau_k}x(l). \quad (16d)
\]

Define $\Delta V_i(k) = V_{i+1}(k+1) - V_i(k)$. Then along the trajectory of the system in (10b), we have
\[
\Delta V_i^2(k) = x^T(k+1)P_{\tau_k+1}x(k+1) - x^T(k)P_k x(k) \leq \lambda x^T(k+1)P_{\tau_k+1}x(k) + 2\lambda x^T(k)P_k x(k) + 2\lambda z^T(k)P_{\tau_k} z(k) + \lambda z^T(k)P_{\tau_k} z(k)
\]
\[
\Delta V_i^2(k) = \sum_{m=\tau+1}^{k-1} \sum_{l=k+m-1}^{k-1} z^T(l)R_{\tau_k}z(l) \quad (16e)
\]
\[
\Delta V_i^2(k) = \sum_{l=k-\tau_k^w}^{k-1} x^T(l)Q_{\tau_k}x(l) \quad (16f)
\]

Proof: Suppose at time $k, \tau_k^w = i \in \Omega$. Let
\[
z(l) = x(l+1) - x(l). \quad (14)
\]
We then obtain
\[
x(k) - x(k - \tau_k^w) = \sum_{l=k-\tau_k^w}^{k-1} z(l) = 0. \quad (15)
\]
and thus

$$\Delta V_3(k) \leq x^T(k)Q_3x(k).$$

Notice that

$$z(k) = (A - I)x(k) + BK_i x(k - \tau^i_k)$$

and

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

We then obtain

$$\Delta V_2(k) \leq x^T(k)[(\lambda - 1)P_t + Q_t + 2\lambda P_t(A - I)]x(k) + 2x^T(k)(\lambda P_tBK_t + (A - I)^T H_t B K_i)x(k - \tau^i_k) + x^T(k - \tau^i_k)(BK_i)TH_t BK_i x(k - \tau^i_k) - \frac{1}{\lambda} \sum_{l=k - \tau^i_k}^{k-1} z^T(l)R_l z(l)$$

where $H_t = \lambda P_t + \tau R_t$.

In addition, we have for any $T_1^i, T_2^i$ with appropriate dimensions

$$2 \left[ x^T(k)T_1^i + x^T(k - \tau^i_k)T_2^i \right] \times \left[ x(k) - x(k - \tau^i_k) - \sum_{l=k - \tau^i_k}^{k-1} z(l) \right] = 0$$

and for any $S_i$ with appropriate dimensions

$$\zeta^T_i(k)S_i\zeta_i(k) - \frac{1}{\lambda} \sum_{l=k - \tau^i_k}^{k-1} \zeta^T_l(k)S_i \zeta_i(k) = 0$$

where $\zeta_i(k) = [x^T(k) x^T(k - \tau^i_k)]^T$.

From (18)-(20), we obtain

$$\Delta V_i(k) \leq \zeta^T_i(k)\Xi_i \zeta_i(k) - \frac{1}{\lambda} \sum_{l=k - \tau^i_k}^{k-1} \zeta^T_l(k)\Psi_i \zeta_i(k - l)$$

where

$$\Xi_i = \begin{pmatrix} \Phi_i^{11} + \Pi_i^{11} & \Phi_i^{12} + \Pi_i^{12} \\ \Phi_i^{21} + \Pi_i^{21} & \Phi_i^{22} + \Pi_i^{22} \end{pmatrix}$$

$$\Pi_i^{11} = (A - I)^TH_t(A - I)$$

$$\Pi_i^{12} = (A - I)^TH_tBK_i$$

$$\Pi_i^{22} = (BK_i)^TH_tBK_i$$

and $\zeta_i(k, l) = [\zeta^T_i(k), z^T(l)]^T$. 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 $\lambda > 1$ and the feedback gains for the packet-based control approach $K_t, i \in \Omega^p$. The closed-loop system in (10a) is stable if there exist $P_t = P_t^T > 0, Q_t = Q_t^T > 0, R_i = R_i^T > 0, S_i = \begin{pmatrix} S_{11}^{iq} & S_{12}^{iq} \\ S_{21}^{iq} & S_{22}^{iq} \end{pmatrix} \geq 0, T_1^i, T_2^i$ with appropriate dimensions such that:

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

$$\Phi_i^{11} - \Phi_i^{12} (A - I)^TH_i$$

$$\Phi_i^{21} - \Phi_i^{22} (BK_i)^TH_i$$

$$\Psi_i \geq 0$$

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

$$P_t \leq \lambda P_j, Q_t \leq \lambda Q_j, R_i \leq \lambda R_j$$

where $\Phi_i^{11}, \Phi_i^{22}, H_i,$ and $\Psi_i$ are defined in Theorem 1 and

$$\Phi_i^{12} = (BK_i)^TH_i - T_1^i + (T_1^i)^T + iS_{22}^{iq}.$$  

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 NCSSs.

**Corollary 2:** If $K_t^P = K_t, i \in \Omega^p$ 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 $\Delta B_t K_t^r = \delta B_t K_t^r / \delta B_t R^p$, where $R^p = \max\{||K_t||_2 | i \in \Omega^p\}$. It is readily seen that $||\Delta B_t K_t^r / \delta B_t R^p|| \leq 1$. The comparison of the stability conditions between packet-based control and packet-based deadband control for NCSSs can then be revealed from the following theorem.

**Theorem 2:** Given $\lambda > 1$ and the feedback gains for the packet-based control approach $K_t, i \in \Omega^p$. The closed-loop system with the packet-based deadband control approach in (10c) is stable if there exist $P_t = P_t^T > 0, Q_t = Q_t^T > 0, R_i = R_i^T > 0, S_i = \begin{pmatrix} S_{11}^{iq} & S_{12}^{iq} \\ S_{21}^{iq} & S_{22}^{iq} \end{pmatrix} \geq 0, T_1^i, T_2^i$ with appropriate dimensions and a scalar $\gamma > 0$ such that:

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

$$\Phi_i^{11} - \Phi_i^{12} (A - I)^TH_i$$

$$\Phi_i^{21} - \Phi_i^{22} (BK_i)^TH_i$$

$$\Psi_i \geq 0$$

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

$$P_t \leq \lambda P_j, Q_t \leq \lambda Q_j, R_i \leq \lambda R_j$$

(28)
where \( \Phi_i^p \) and \( \Psi_i^p \) are defined in Corollary 1 and \( \Upsilon_i = [\lambda \delta_i^2 R_i^o \ 0 \ \delta_i^2 R_i^o H_i] \).

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 \( R_i^p = K_i, i \in \Omega \). 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 \( L_i = L_i^T > 0 \), \( W_i = W_i^T > 0 \), \( M_i = M_i^T > 0 \), \( X_i = (X_i^{11} \ X_i^{12} \ X_i^{21} \ X_i^{22}) \geq 0 \), \( Y_i \), \( \Psi_i \), \( \Phi_i \) with appropriate dimensions such that:

1) \( \forall i \in \Omega \)

\[
\Phi_i^o = \begin{pmatrix}
(\Phi_i^{11})^T & (\Phi_i^{12})^T & \lambda L(A - I)^T & \tau L(A - I)^T \\
* & * & \lambda L_i & \tau L_i \\
* & * & -\lambda M_i & 0 \\
* & * & \tau M_i & -\tau M_i
\end{pmatrix} < 0 \quad (29)
\]

\[
\Psi_i^o = \begin{pmatrix}
(\lambda X_i^{11})^T & (\lambda X_i^{12})^T & (\lambda Y_i^1)^T & (\lambda Y_i^2)^T \\
* & * & \lambda L_i & \tau M_i \\
* & * & -\lambda M_i & \tau L_i \\
* & * & L_i & -L_i
\end{pmatrix} \geq 0 \quad (30)
\]

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

\[
L_i \leq \lambda L_{ij}, M_i \leq \lambda M_{ij}, W_i \leq \lambda W_{ij}
\]

where

\[
\Phi_i^{11} = (\lambda - 1)L_i + W_i + 2\lambda(A - I)L_i + Y_i + (Y_i^2)^T + iX_i^{11}
\]

\[
\Phi_i^{12} = \lambda BV_i - Y_i^1 + (Y_i^2)^T + iX_i^{22}
\]

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

\[
\begin{pmatrix}
(\Phi_i^{11})^T & (\Phi_i^{12})^T & \lambda(B(A - I))^T & \tau(B(A - I))^T \\
* & * & \lambda(B(M))^T & \tau(B(M))^T \\
* & * & -\lambda F_i & 0 \\
* & * & \tau F_i & -\tau F_i
\end{pmatrix} < 0 \quad (32)
\]

Pre- and post multiply (32) and (12) by \( \text{diag}(F_i^1, F_i^2, F_i^3, F_i^4) \) and \( \text{diag}(F_i^{11}, F_i^{12}, F_i^{13}, F_i^{14}) \), respectively, and let \( L_i = L_i^T, M_i = M_i^T, W_i = W_i^T, Q_i = Q_i^T, R_i = R_i^T, X_i = \text{diag}(F_i^1, F_i^{11}), S_i = \text{diag}(F_i^2, F_i^{12}), Y_i = \text{diag}(F_i^3, F_i^{13}), j = 1, 2, V_i = K_i L_i^{-1} \). We then complete the proof.

It is noticed that (30) in Theorem 3 is no longer LMI conditions due to the term \( L_i M_i^{-1} L_i \). 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 \( i \in \Omega \)

\[
\mathcal{P}_i : \begin{cases}
\text{Minimize} \ & \text{Tr}(Z_i R_i + L_i P_i + M_i Q_i) \\
\text{Subject to} \ & (29), (31), L_i = L_i^T > 0, W_i = W_i^T > 0, \\
& X_i = (X_i^{11} \ X_i^{12} \ X_i^{21} \ X_i^{22}) \geq 0, \\
& \Psi_i^o \geq 0, \Theta_i^1 \geq 0, \Theta_i^2 \geq 0, \Theta_i^3 \geq 0, \Theta_i^4 \geq 0,
\end{cases}
\]

where

\[
\Psi_i^o = \begin{pmatrix}
(\lambda X_i^{11})^T & (\lambda X_i^{12})^T & (\lambda Y_i^1)^T & (\lambda Y_i^2)^T \\
* & * & \lambda L_i & \tau M_i \\
* & * & -\lambda M_i & \tau L_i \\
* & * & L_i & -L_i
\end{pmatrix}
\]

\[
\Theta_i^1 = \begin{pmatrix}
R_i & P_i \\
Q_i & \Theta_i^2 = \begin{pmatrix}
Z_i & I \\
* & R_i
\end{pmatrix}
\end{pmatrix}
\]

\[
\Theta_i^3 = \begin{pmatrix}
L_i & I \\
P_i & \Theta_i^4 = \begin{pmatrix}
M_i & I \\
* & Q_i
\end{pmatrix}
\end{pmatrix}
\]

If the solution of \( \mathcal{P}_i = 3n_i, \forall i \in \Omega \), 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:

\[
A = \begin{pmatrix}
0.98 & 0.1 \\
0 & 0.1
\end{pmatrix}, \quad B = \begin{pmatrix}
0.04 \\
0.1
\end{pmatrix}
\]

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 \( \delta = 0.1 \).
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:

$$K_P = \begin{pmatrix} K_P^1 \\ K_P^2 \end{pmatrix} = \begin{pmatrix} -0.6438 & -1.4748 \\ -0.5242 & -1.3079 \\ -0.4198 & -1.1549 \end{pmatrix}$$

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 $K_P^i$ 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 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.

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

$$x(k+1|k) = Ax(k|k-1) + Bu(k) + L (y(k) - Cx(k|k-1))$$  \hspace{1cm} (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:

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

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.
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


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

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