Actively Compensating for Data Packet Disorder in Networked Control Systems

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

Abstract—Data packet disorder often occurs in networked control systems (NCSs), which, however, has not been taken into account in most literature to date. In this brief, the cause and effect of data packet disorder are analyzed, and an active compensation scheme is proposed to compensate for it. The proposed scheme is flexible to admit all the existing control approaches to be used and also derives a novel closed-loop system model of NCSs, which enables more reasonable and effective theoretical analysis of NCSs. The effectiveness of the proposed active compensation scheme is illustrated by a numerical example.

Index Terms—Active compensation, comparison rule, data packet disorder, networked control systems (NCSs), time stamp.

I. INTRODUCTION

THE RAPID development in network technology and embedded computing devices has allowed the remote and distributed connection of cluster of control devices, which forms a class of control systems called networked control systems (NCSs). In NCSs, data are exchanged through a communication network, which inevitably introduces communication constraints to the control systems. Despite the advantages of the remote and distributed control that NCSs brings, the communication constraints in NCSs generally degrade the system performance or even destabilize the system at certain conditions, which therefore present a new challenge for conventional control theory [1]–[5].

Among all the communication constraints, the delays of transmitting the data packets containing either the sampled data in the sensor-to-controller channel or the control signals in the controller-to-actuator channel play a dominant role in NCSs. This so-called "network-induced delay" in NCSs has therefore attracted considerable attention, mainly from the time delay system (TDS) community [6]–[8]. In these kinds of studies, NCSs with network-induced delay are typically modeled as conventional TDSs, which then enables conventional approaches in TDSs to be applied to NCSs. However, it is

observed that network-induced delay in NCSs is greatly influenced by the changes of the network load, which is generally time varying and unpredictable, thus enabling network-induced delay to be arbitrarily variable within a certain range of delays. As far as arbitrary network-induced delay is concerned, a situation often occurs where a data packet sent earlier may arrive at the destination node later or vice versa, that is, data packet disorder. Theoretical analysis (Section II) and a simulation example (Section V) reveal the negative effects of data packet disorder, which, however, has been absent from the literature to date. This fact thus motivates this work for a better understanding of data packet disorder in NCSs and, furthermore, an active compensation scheme for it.

The key idea of the active compensation scheme proposed in this brief lies in the use of time stamps for data packets being used in NCSs and a comparison rule defined at the actuator side. The scheme is deployed by taking advantage of the packet-based transmission of data in NCSs, a remarkable characteristic that distinguishes NCSs from conventional TDSs. Under the active compensation scheme, the control actions applied to the plant are always based on the latest system information available, and thus, the effect of data packet disorder can effectively be eliminated. It is also worth mentioning that using this scheme all the existing control approaches to NCSs can still be used without any modification, thus enabling this scheme to be flexible and unified. Furthermore, the derived system model successfully considers the communication constraints including network-induced delay, data packet dropout, and data packet disorder simultaneously, which cannot be achieved by using the aforementioned conventional approaches from TDS theory [6]–[9].

II. DATA PACKET DISORDER AND RELATED WORK

In NCSs, the plant is controlled over some communication network by the controller. Due to the communication network inserted into the control system, network-induced delay is inevitable in NCSs, denoted by $\tau_{sc}(t)$ and $\tau_{ca}(t)$ for the delays in the sensor-to-controller channel and controller-to-actuator channel, respectively (called "sensor-to-controller delay" and "controller-to-actuator delay", respectively, hereafter). The plant dynamics, in general, is described by the following differential equation:

$$\dot{x}(t) = f(x(t), u(t)) \tag{1}$$

where u is the control input to the plant. In this brief, the sensor is assumed to be time driven, whereas the controller and the actuator are event driven, as assumed in [9]. "Time driven" for the sensor in this brief implies an independent constant time
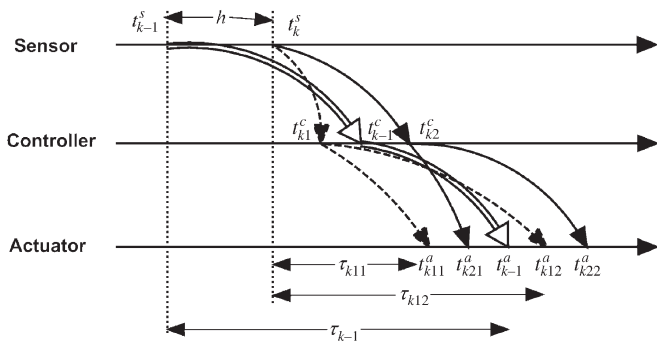
Fig. 1.   Illustrating how data packet disorder occurs.

interval h between which the plant dynamics is sampled, and the "event-driven" controller and actuator are trigged by newly arrived data (sampled data or control signals) but not at specific time instants.

A. Data Packet Disorder

Let us consider the typical data transmission process in NCSs illustrated in Fig. 1 and define "round-trip delay" for a sampled data packet to be the time interval from sampling the system states to the control signal based on this sampled data being applied to the plant. Generally, round-trip delay mainly consists of two transmission delays, i.e., sensor-to-controller delay and controller-to-actuator delay, whereas in this brief, all the other potential delays such as the computation delay of the controller are considered to be part of the round-trip delay, that is, the round-trip delay is the total delay in the system.

As mentioned earlier, the time-driven sensor sends its sampled data every h seconds, as illustrated in Fig. 1 at time instants t_{k-1}^s and t_k^s, respectively. However, due to the arbitrary network-induced delay, the sampled data packet sent at time instant t_{k-1}^s does not necessarily arrive at the actuator earlier than its subsequent data packet sent at time instant t_k^s. This occurs when, for example, in Fig. 1, $\tau_{k-1} - \tau_{k11} > h$. Based on this analysis, Proposition 1 readily follows.

Proposition 1: Given a constant sampling period h and arbitrarily variable network-induced delays, data packet disorder occurs if and only if

$$\Delta\tau_m = \tau_{\max} - \tau_{\min} > h \qquad (2)$$

where $\tau_{\max}$ and $\tau_{\min}$ are the upper and lower bounds of the round-trip delay.

Proof: On one hand, data packet disorder occurs when the round-trip delays for the sampled data packet sent at time instants t_{k-1}^s and t_k^s in Fig. 1 are $\tau_{\max}$ and $\tau_{\min}$, respectively, provided (2) holds. On the other hand, if $\Delta\tau_m \leq h$, then the data packet sent at time instant t_k^s will never arrive at the actuator earlier than the one sent at time instant t_{k-1}^s, that is, no data packet disorder occurs. ∎

Remark 1: If data packet disorder occurs in an NCS, then we can conclude that (2) holds for this NCS. On the contrary, if (2) holds for an NCS, Proposition 1 implies that data packet disorder will inevitably occur for a certain data packet after the NCS runs for a sufficient long time, but it does not mean that every data packet will experience disorder in this case. From this point of view, it is readily seen that Proposition 1 is still valid in the presence of data packet dropout.

Remark 2: It is necessary to point out that, although the assumption of small network-induced delay, i.e., less than one sampling period, is common in the literature on NCSs, this assumption is often for theoretical simplifications but hardly represents the reality. An example can be seen in [10] where a servo system is remotely controlled over the Internet using a test rig whose controller and plant are located, respectively, at the Chinese Academy of Sciences, Beijing, China, and at the University of Glamorgan, Pontypridd, U.K. The plant is sampled every 0.04 s, and the typical round-trip delay is between 0.20 and 0.32 s, that is, between five and eight sampling periods. According to Proposition 1, data packet disorder will inevitably occur in this case.

B. Related Work

If no special treatment is taken, the existence of data packet disorder will produce a situation where older information is used instead of the latest information available. Take Fig. 1 as an example where we assume the sampled data packet sent at time instant t_k^s arrives at the actuator at time instant t_{k11}^a (data packet disorder occurs in this case). According to conventional approaches without compensating for data packet disorder, the control signal based on sampled data at time instant t_k^s will be used between t_{k11}^a and t_{k-1}^a, whereas after t_{k-1}^a, the control signal based on older sampled data at time instant t_{k-1}^s will be used. This is obviously unreasonable and seriously degrades the system performance.

A possible solution for data packet disorder is the so-called "networked predictive control" or "packet-based control" for NCSs, which was first proposed by Liu *et al.* [11] and then improved by Zhao *et al.* [12], [13]. This approach takes advantage of the packet-based transmission of the network being used in NCSs, which enables a sequence of forward control signals to be sent simultaneously in a single data packet, provided that the size of the data packet in NCSs is large enough. This forward control sequence can then be used to compensate for data packet disorder by appropriately selecting the forward control signal with respect to the current network conditions. However, although this kind of solution is effective, the requirement of sending a sequence of forward control signals simultaneously in a single data packet may not always be available in NCSs, which thus restricts the application of this approach to certain conditions.

From the perspective of conventional TDS theory, there are still no effective approaches to deal with this issue to date. For example, in [9] (and also in [14]) the following closed-loop system model for NCSs with a linear plant model was obtained:

$$\dot{x}(t) = Ax(t) + Bu(t) \qquad (3a)$$

$$u(t) = Kx(i_k h), t \in [i_k h + \tau_k, i_{k+1}h + \tau_{k+1}), \ k \geq 1 \qquad (3b)$$

where $i_k h$ and $i_{k+1}h$ were the sampling time instants, and the relationship $i_{k+1} > i_k$ was not required, that is, no compensation scheme for data packet disorder was considered. In [8], a similar model was considered, and even if the authors noticed that data packet disorder may occur, they unfortunately assumed $i_{k+1} > i_k$ artificially without providing any supportive design method. Similar situations can also be found in recently reported results, for example, in [6], [7], [15], and [16].
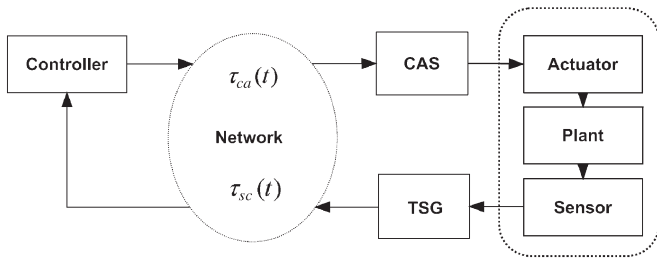
Fig. 2.   Schematic structure of the active compensation scheme for NCSs.

III. ACTIVELY COMPENSATING FOR DATA PACKET DISORDER IN NCSs

In this section, an active compensation scheme for data packet disorder in NCSs is presented. As mentioned earlier, the derived system model considers the communication constraints in NCSs including network-induced delay, data packet dropout, and data packet disorder simultaneously, compared with previously reported results where data packet disorder is excluded.

The schematic structure of the active compensation scheme for NCSs is illustrated in Fig. 2, which is seen to be distinct from conventional control systems in two aspects: the time stamp generator (TSG) at the sensor side and the control action selector (CAS) at the controller side.

As implied by the name, TSG is used to label each sampled data packet with a "time stamp" that contains the information of the corresponding sampling time instant of the sampled data packet. This time stamp remains in the control data packet after the control signal is calculated based on the sampled data, thus enabling the sampling time instant based on which each control data packet is calculated to be known by the CAS module in Fig. 2. This information is then used by CAS to actively compensate for data packet disorder.

CAS consists of a register and a logic comparator. The register is used to store only a single step of the control signal with the corresponding time stamp, as mentioned earlier. When a control data packet arrives, the logic comparator' compares the time stamps of both the newly arrived control data packet and the one already in the register of CAS, and only the latest control data packet is stored after the comparison process and then applied to the plant. This way, the introduction of CAS can effectively deal with data packet disorder in NCSs with the help of TSG. For example, suppose in Fig. 1 that the control data packet based on sampled data at time instant t_k^s arrives at the actuator at time instant t_{k11}^a. Then, at time instant t_{k-1}^a when the control data packet based on sampled data at time instant t_{k-1}^s arrives, CAS knows that the newly arrived control data packet is calculated based on older sampled data and will thus discard this control data packet, and the register of CAS remains unchanged. Thus, CAS avoids the existence of the aforementioned situation where an older control action instead of the latest available one is applied to the plant, that is, CAS successfully eliminates the effect of data packet disorder in NCSs.

Suppose the kth control data packet that arrives at the actuator successfully is based on the i_kth sampled data packet, and its corresponding round-trip delay is τ_k. Then, the sampled data packet based on which the kth "effective" control data

packet is applied to the plant after the comparison process can be determined by the following comparison rule:

$$P_{i_k^*} = \begin{cases} P_{i_{k-1}^*}, & \text{if } i_{k-1}^* > i_{k'} \\ P_{i_{k'}}, & \text{otherwise} \end{cases} \tag{4}$$

where the control data packet $P_{i_{k-1}^*}$, which is based on sampled data at time instant $i_{k-1}^* h$, is already in the register of CAS, and $P_{i_{k'}}$, which is based on $i_{k'}$, just arrives at CAS.

Based on the aforementioned analysis, the algorithm of the active compensation scheme can now be summarized as follows.

Algorithm 1 (Active Compensation Scheme):
S1. The sensor samples the system dynamics.
S2. TSG labels the sampled data with the time stamp and sends the sampled data packet over the network to the controller.
S3. The controller receives the sampled data packet and calculates the corresponding control signal, which is then sent to the actuator with the time stamp in S2.
S4. CAS compares the time stamps of the newly arrived control data packet and the one already in the register of CAS by (4). The latest control data packet is then sent to the actuator and also stored in the register.
S5. The control action from CAS is applied to the plant.

Using the proposed active compensation scheme, data packet disorder in NCSs can now effectively be dealt with. From the schematic structure in Fig. 2 and Algorithm 1, it is readily seen that this scheme additionally inserts two modules, namely TSG and CAS, into the control system but does not modify the original control components in the system, that is, the sensor, the controller, and the actuator. This design approach therefore enables all the existing conventional control approaches to be applied to this control structure without any modification, and data packet disorder can effectively be dealt with. This flexibility enables the proposed scheme to be readily deployed in practice.

Remark 3: It is noticed that data packet disorder may occur in both sensor-to-controller and controller-to-actuator channels, and the proposed active compensation scheme can effectively deal with data packet disorder no matter in which channel data packet disorder occurs. However, the existence of data packet disorder in the sensor-to-controller channel makes it unnecessary to calculate the control signal at certain time instants. For example, in Fig. 1, if the sampled data packet sent at time instant t_k^s arrives at the controller at time instant t_{k1}^c, then the calculation of the control signal based on sampled data at time instant t_{k-1}^s (which arrives at the controller at time instant t_{k-1}^c) is unnecessary since this control action will definitely not be used by the actuator (it will be discarded by CAS). To deal with this issue, a sampled data selector (SDS) similar to CAS can be deployed at the controller side. SDS also consists of a register and a logic comparator like CAS, which can be used in a similar way to determine the latest sampled data. The controller will work as normal if the newly arrived sampled data packet contains the latest system information; otherwise, the controller will be idle. This way, the use of SDS is able to reduce both the computation burden of the controller and the communication burden in the controller-to-actuator channel without affecting the deployment of the active compensation scheme.

IV. MODELING AND FURTHER DISCUSSION

In this section, we show that the active compensation scheme derives a unified model for NCSs that can simultaneously take the communication constraints, including network-induced delay, data packet dropout, and data packet disorder, into account. We further point out that the active compensation scheme also reduces the communication constraints in NCSs, which is thus beneficial for the control performance.

A. Unified Model for NCSs

With the active compensation scheme proposed in the last section, the control law for the plant in (1) can be obtained as follows:

$$u(t) = g\left(x\left(i_k^* h\right)\right), \qquad t \in \left[t_k^*, t_{k+1}^*\right), \ k \geq 1 \qquad (5)$$

where i_k^* is defined in (4), τ_k^* is the round-trip delay with respect to i_k^*, and $t_k^* \triangleq \tau_k^* + i_k^* h$.

Compared with the system model in (3), where the sequence of the sampling time instants $\{i_k h : k = 1, 2, \ldots\}$ can be decreasing, in the aforementioned system model, we can guarantee that the sequence of the sampling time instants $\{i_k^* h : k = 1, 2, \ldots\}$ is increasing, which implies that the effect of data packet disorder is effectively eliminated in this model.

It is worth mentioning that the control law in (5) has already taken data packet dropout into account since there is no more constraint on the increasing sequence $\{i_k^* h : k = 1, 2, \ldots\}$. Therefore, the system model in (1) and (5) can be regarded as a unified model for NCSs, which simultaneously considers the communication constraints, including network-induced delay, data packet dropout, and data packet disorder.

B. Further Discussion: Reduced Communication Constraints

It is observed that the active compensation scheme for data packet disorder not only effectively eliminates the negative effects of data packet disorder but also modifies the characteristics of the communication constraints to the system. This can be observed in the following two aspects.

1) Reduced Delay Increase Rate: With the active compensation scheme, it is noticed that, at $t_k^* + h$, the worst case would be using the control signal at time t_k^*, which implies that no new control signals arrive during $(t_k^*, t_k^* + h)$. On the other hand, using a new control signal at $t_k^* + h$ can only decrease the actual delay τ_k^* from the worst case. In view of this fact, we have the following relationship:

$$\tau_{t_k^* + h} \leq \tau_k^* + h \qquad (6)$$

where $\tau_{t_k^* + h}$ denotes the round-trip delay of the system at time $t_k^* + h$. This fact further implies that the actual delay to the system cannot grow too fast, i.e., during any time interval (t_1, t_2), the actual delay can only increase by as much as $\Delta \triangleq t_2 - t_1$. This constraint on the delay increase rate does not exist in conventional models for NCSs and can potentially be used to derive less conservative controller design methods for NCSs.

2) Reduced Delay Bound: It is well known that burst traffic often occurs in Internet-based data transmission, which implies that, in practice, network-induced delay with large lower and upper bounds usually varies for the most time within a narrow range of relatively small delays. For such a case, designing a controller with respect to these large bounds is clearly conservative. Fortunately, it is noticed that the active compensation scheme can effectively reduce the actual delay bound, since it discards those data packets with a sudden change in delay. For example, in the NCS test rig used in [10], the round-trip delay is bounded in two to eight sampling periods, while for most of the time (more than 80%), the delay is constrained to two values, i.e., four and five sampling periods. Using the active compensation scheme, the delay bound can be effectively narrowed to three to six sampling periods, which is certainly beneficial for the control performance, since now we can design the controller for a narrow delay bound.

From the aforementioned analysis, it is seen that the active compensation scheme is more like a communication protocol rather than a control strategy, since this scheme has effectively reduced the communication constraints but does not affect the control structure itself. In this sense, while the use of this scheme could contribute greatly to improve the system performance, as shown in the next section, the analysis of the control performance such as stability, stabilization, robustness, etc., can still be done separately based on the unified model in (1) and (5), for which there are plenty of results in the literature [6]–[8]. Therefore, we exclude such analysis in this brief.

V. NUMERICAL EXAMPLE

Consider the following continuous-time linear system borrowed from [17], which has also been studied in, for example, [8] and [9]:

$$\dot{x}(t) = \begin{pmatrix} 0 & 1 \\ 0 & -0.1 \end{pmatrix} x(t) + \begin{pmatrix} 0 \\ 0.1 \end{pmatrix} u(t). \qquad (7)$$

In the following simulation, we use the same state feedback gain as designed in [17], that is, $K = [-3.75 \ -11.5]$, and the plant is sampled with a constant period $h = 0.04$ s. The lower and upper bounds of the round-trip delay are first set as $\tau_{\min} = 0.24$ s and $\tau_{\max} = 1.6$ s, respectively, and both channels are assumed to have the same upper and lower bounds (0.12 and 0.8 s, respectively).

According to the analysis in Section II, data packet disorder inevitably occurs in this case, and without compensation, old information might be used instead of the latest information available. However, with the active compensation scheme proposed in Section III, it is seen in Fig. 3 that the sampling time instants based on which the control actions are applied (that is, $i_k^* h$) are nondecreasing, which implies that data packet disorder has effectively been dealt with.

The system state responses of both with the active compensation scheme and without it are illustrated in Fig. 4, which proves the effectiveness of the proposed approach. Another case is also considered in Fig. 5, where the upper bound of the round-trip delay is increased to $\tau_{\max} = 2.4$ s with $\tau_{\min}$ remaining unchanged. In this case, it is seen that the system is still stable in
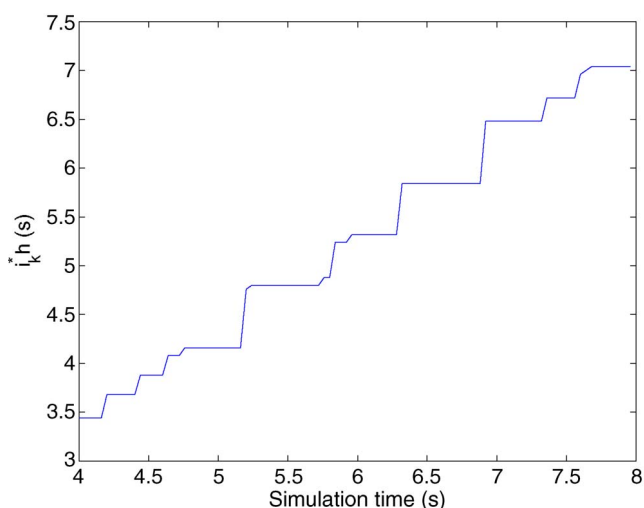
Fig. 3.   Relationship between simulation time t and $i_k^* h$ in (5), which shows data packet disorder has been effectively dealt with.
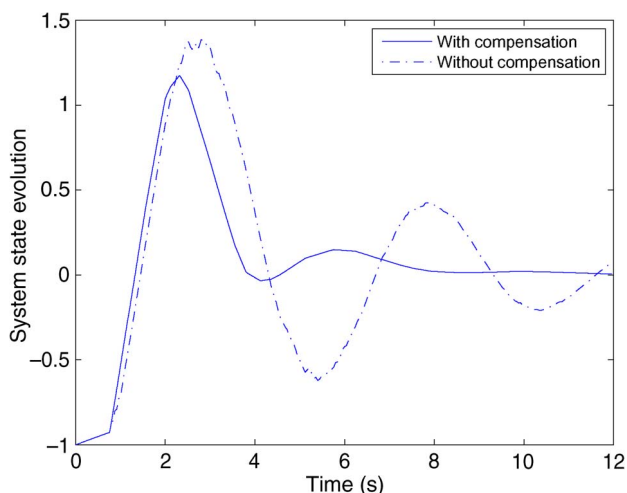

Fig. 4.   Active compensation scheme results in better system performance where $\tau_{\max} = 1.6$ s.
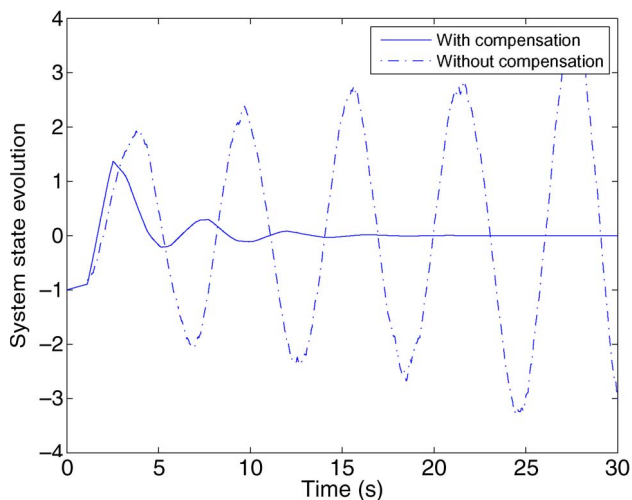

Fig. 5.   Active compensation scheme maintains the stability of the closed-loop system where $\tau_{\max} = 2.4$ s.

the presence of the active compensation scheme while unstable without it.

VI. CONCLUSION

Network-induced delay in NCSs has widely been explored in literature to date, while unfortunately, the effect of data packet disorder is often neglected, despite its frequent presence in NCSs. In this brief, the cause and effect of data packet disorder in NCSs have been investigated in detail, and an active compensation scheme has also been proposed to deal with the negative effect. The derived novel model for NCSs within this framework provides the foundation of a more reasonable and effective theoretical analysis of NCSs. The effectiveness of the proposed approach has been illustrated by a numerical example. Future research will be focused on controller design and performance analysis within the framework of data packet disorders.

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