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Adaptive sampling rate control for networked systems based on statistical characteristics of packet disordering

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ABSTRACT

This paper investigates an adaptive sampling rate control scheme for networked control systems (NCSs) subject to packet disordering. The main objectives of the proposed scheme are (a) to avoid heavy packet disordering existing in communication networks and (b) to stabilize NCSs with packet disordering, transmission delay and packet loss. First, a novel sampling rate control algorithm based on statistical characteristics of disordering entropy is proposed; secondly, an augmented closed-loop NCS that consists of a plant, a sampler and a state-feedback controller is transformed into an uncertain and stochastic system, which facilitates the controller design. Then, a sufficient condition for stochastic stability in terms of Linear Matrix Inequalities (LMIs) is given. Moreover, an adaptive tracking controller is designed such that the sampling period tracks a desired sampling period, which represents a significant contribution. Finally, experimental results are given to illustrate the effectiveness and advantages of the proposed scheme.

1. Introduction

1.1. Motivation

Packet disordering, meaning that a packet sent earlier may arrive at the destination node after some packets sent later or vice versa, is an increasingly common phenomenon in communication networks. Packet disordering is introduced into networked control systems (NCSs) since information is exchanged or transmitted via network media in NCSs [1,2]. More importantly, it can impact end-to-end application performances significantly, irrespective of its causes. In User Datagram Protocol (UDP)-based applications that are highly sensitive to delay, e.g., IP telephony, an out-of-order packet (a packet that arrives late at the destination node) that arrives after the elapse of playback time is treated as lost thereby decreasing the perceived quality of voice [3]. For delay sensitive NCS applications wherein UDP is chosen usually and information is exchanged or transmitted via network media, out-of-order packets inevitably existing in communication are treated as lost thereby degrading the reliability of communication networks, which might have adverse impact on control performances of NCSs. However, we know that wireless-based industrial applications, such as packaging, manufacturing, wood machining or plastic extrusion, have a strict requirement of reliability. For instance, normal channel load, Radio Frequency (RF) conditions and recommended Quality of Service (QoS) of network, the expected application-level packet loss is very small (less than 1 in 100,000) [4]. Hence, we advocate that packet disordering should be explicitly taken into account, and an alternative solution should be explored for NCSs to reduce such effect and to improve system performances. In this context, we propose an adaptive sampling rate control scheme for NCSs with packet disordering.

So far, the majority of NCSs research efforts have focused on controller design to provide sufficient stability conditions in the presence of packet disordering [5–10]. Significant works have also been reported on how to describe packet disordering, such as comparing the sampling instants of received signals [5], identifying packet disordering by displacements of packets [6,7], and comparing transmission delay [8]. Based on those, a so-called active compensation scheme, wherein late packets are discarded, has been used in [6–10]. In the sense of stabilizing the NCSs, this type of methodology is effective.

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However, in the above-mentioned literature, there still exist two underlining shortcomings, which can be briefly summarized in the following. One is that active control techniques for avoiding heavy packet disordering have not been investigated. The measurement studies done by [3,11–14] showed the impact of packet disordering on end-to-end application performances and predicted the increasing trend of out-of-order deliveries. It should be pointed out that heavy packet disordering would bring challenges for the methods in [6–10] wherein the degree of packet disordering is ignored. The other is that statistical characteristics shown by packet disordering have not been analyzed in the aforementioned literature so far, such that the existing methods are either highly inefficient or not optimal in real networked control system applications. These motivate the present study.

1.2. Control strategy

To overcome these shortcomings, we fully analyze the statistical characteristics of packet disordering and investigate an adaptive sampling rate control method. Moreover, we also show that adjusting sampling rate based on statistical characteristics of packet disordering is an alternative solution to reduce packet disordering. To illustrate the possible existence of a correlation between packet disordering and sampling rate, [2] a measurement setup and UDP flows across an IP backbone network were generated. And the experiments in [2] have shown that delivering data at the higher rates is more prone to packet disordering due to the small sending time interval though there are many other reasons which cause packet disordering. It seems likely that parallelism at the link layer will permit some packets to overtake those sent earlier but queued on a parallel link, causing this behavior [2]. Hence the sampling rate should be appropriately reduced if heavy packet disordering occurred within network communications, otherwise much more packets may arrive out of order leading to bad network performances. Thus, there is an obvious conflict between the two demands of high sampling rate and light packet disordering, while ensuring stability and desired control performances of NCSs.

Our strategy is to design an adaptive controller in order to enable the sampling period to tend to a desired sampling period under the control actions. The so-called desired sampling period means a sampling interval under which networks can be under a good and steady condition at operation (light packet disordering) and the desired control performance can be guaranteed as well. The suggested scheme tries to improve QoS of networks, such that control performances of NCSs are improved. Hence, the proposed sampling rate control method is a tradeoff between QoS of networks and control performances of systems. Moreover, the statistical characteristics of packet disordering are used for stability analysis and control of NCSs. The established technology route for NCSs is depicted in Fig. 1. Different from the conventional NCSs, a Packet Disordering Calculator (PDC) is added to the closed-loop systems. PDC is responsible for computing displacement values of packets, disordering density and disordering entropy. As the sensor takes measurements of the plant state at each t_k time instant (t_k denotes the kth ($k=0,1,\ldots$) sampling time instant), the information about the sampling period is additionally appended. Once the packet arrives at the controller node, the data are used to calculate control action (state feedback). After that, the achieved control action is sent to the PDC via the network. The actuator selects the newest control signal and then uses it to control the plant, as well as act on the sampling rate together with disordering entropy.

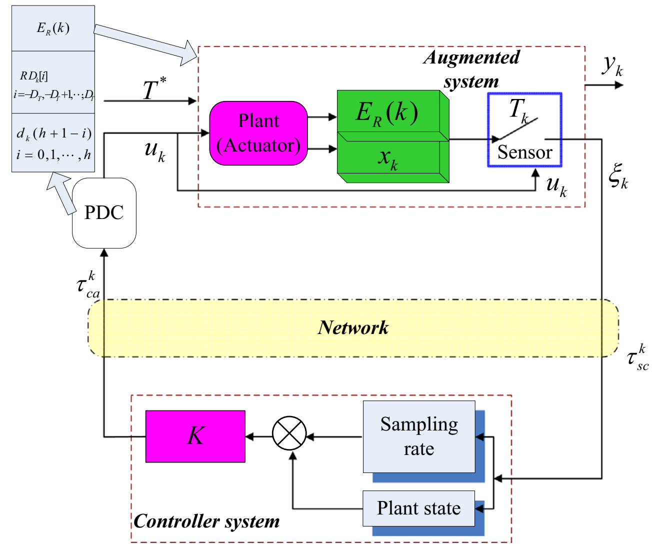

Fig. 1. Architecture of NCS with the sampling rate adaptive control scheme.

1.3. Main contributions

The main contributions of this work are threefold. First, a sampling rate algorithm based on computed disordering entropy is proposed, which extends the existing results [5–10] wherein the stability analysis and synthesis of NCSs with packet disordering are investigated under the condition of the constant sampling rate. Second, an adaptive tracking controller used to cooperatively control the sampling rate and the plant is designed, such that the sampling period tracks the desired sampling period and the system can be stabilized. To our knowledge, designing a controller to drive the sampling rate to a desired value has not been investigated up to now. In addition, Bernoulli statistical characteristic shown by disordering entropy is utilized during constructing the augmented model of systems and investigating the stability of NCSs, which is the third contribution of this paper. Experimental results are given to demonstrate the effectiveness of the proposed approach.

This paper is organized as follows. The problem statement is presented in Section 2. Section 3 is dedicated to stability analysis and controller design of NCSs. Section 4 presents the adaptive tracking controller design. Experimental verification is performed in Section 5. Conclusions are stated in Section 6.

Notation: We use "$*$" to represent a term that is induced by symmetry, diag($\cdots$) stands for a block-diagonal matrix, and Ln($\cdot$) stands for $\log_e(\cdot)$. $\|\boldsymbol{A}\|_2$ for a matrix $\boldsymbol{A}$ denotes the 2-norm, which is the maximum singular value of $\boldsymbol{A}$. Prob($\cdot$) stands for the probability operator, and $\mathbf{E}(\cdot)$ stands for the mathematical expectation operator.

2. Problem statement

A state equation of system under zero input is first considered

$$\dot{\boldsymbol{x}}(t)=\boldsymbol{A}\boldsymbol{x}(t) \tag{1}$$

where $\boldsymbol{x}(t)$ is the state vector, $\boldsymbol{A}$ is some constant matrix of appropriate dimensions. Since a digital controller and zero-order hold transformation are usually applied in typical control systems communicating over networks, it is quite natural to analyze NCSs from the discrete-time point of view [15,16]. Then, system (1) is discretized as

$$\boldsymbol{x}_{k+1}=e^{\boldsymbol{A}T_k}\boldsymbol{x}_k \tag{2}$$

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