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Control synthesis problem for networked linear sampled-data control systems with band-limited channels

Guotao Hui [a], Huaguang Zhang [a,b,*], Zhenning Wu [a], Yingchun Wang [a]

[a] College of Information Science and Engineering, Northeastern University, Shenyang, Liaoning 110004, China
[b] State Key Laboratory of Synthetical Automation for Process Industries, Northeastern University, Shenyang, Liaoning 110004, PR China

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ABSTRACT

This paper addresses the control synthesis problem of networked linear sampled-data control systems (NLSCSs) with band-limited channels. First, since there exist packet dropouts when the information is transmitted through the band-limited channels, a novel compression compensation (C–C) method is proposed to ensure the integrity of transmission. Based on this method, a compound control strategy is established to deal with the data transmission synchronization problem under the band-limited channels. Then, a nonlinear switched system model with uncertainty is constructed, in which both the inter-sampler behavior and the packet dropouts behavior are considered. Furthermore, some more general stability results of the NLSCSs with band-limited channels are obtained by using a packet dropouts dependent Lyapunov functional method, and then the compound state feedback controller can be designed. Finally, an illustrative example is given to demonstrate the effectiveness of the proposed results.

1. Introduction

As a kind of networked control systems (NCSs) [27,42], networked linear sampled-data control systems (NLSCSs) (also called the linear sampled-data systems with unreliable feedback channels) have become the focus of study due to their attractive advantages, such as reduced system wiring, low weight, ease of system diagnosis and maintenance. However, the insertion of communication network will inevitably lead to some inefficiencies, such as the network-induced delay and packet dropouts, which result in instability and poor performance of control systems. Therefore, during the last decade, a great many of studies have been devoted to the analysis and synthesis of NLSCSs. Among the existing results on NLSCSs, some stability issues are investigated in [5,15,22,23,25,28,31,35–37,39,42,43], stabilizing and H_∞ controllers are designed in [2–4,7,8,11,14,17,19,20,24–27,30,32–35,38,40,41,46,47], fault detection and robust filtering are considered in [9,12,13,16,24,48], and guaranteed cost control is studied in [44].

In the work mentioned above, the bandwidth of network is large enough so that the data from sensor or controller can be lumped together into one network packet and be transmitted directly and simultaneously (called single-packet transmission). However, any communication network can only carry a finite amount of information per unit of time [10], which may limit its applications, for instance, the unmanned air vehicles (due to stealth requirements), underwater vehicles,

* Corresponding author. Address: Dept. of Electric Automation, Northeastern University, Shenyang, Liaoning, 110004, PR China. Tel./fax: +86 024 83687762.

E-mail addresses: hgt820112@163.com (G. Hui), hgzhang@ieee.org (H. Zhang), wuzn2003@hotmail.com (Z. Wu), drwangyc@gmail.com (Y. Wang).

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planetary rovers (environmental constraints) and so on. To handle such limitations, a multiple-packet transmission method was proposed in [29,42]. By using this method, the whole data of sensor or actuator are split into several packets and these packets will be sent out one by one, but they can not arrive at the controller or the plant simultaneously. It has been pointed out that the multiple-packet transmission method may be constructive to the analysis of some types of NCSs (both the plant and the controller in discrete-time domain), but it can not be carried out in NLSCSs with band-limited channels. The reasons are stated as follows [41,42]:

(a) It is difficult to determine the time when the controller carry out a calculation due to the existence of networked-induced delay.
(b) Due to the existence of packet dropouts, the data received by controller (or actuator) may be incomplete, and the dropping part may be variable during different sampling intervals. Hence, it is difficult to ensure that what percentage (or which part) is sufficient enough to trigger the calculation of the controller (or actuator).

Therefore the existing methods (single-packet transmission and multiple-packet transmission method) can not be applied directly to the study of the NLSCSs with band-limited channels.

Moreover, the current studies of the NLSCSs use single variable to analyze the network-induced delay and packet dropouts, for instance, the bounded time-varying delay, [1,2,44,45], or time-varying sampling period, [24,25], or the rates of packet dropouts [19,26,43]. However, the use of single variable to represent them will lead to a constraint which consists of the sampling period, the value of network-induced delay and the amount of the packet dropouts. Therefore, it is necessary to study them respectively. It is well known that only some stability results were provided in [22,23,43] under this condition. However, the control law was set in advance without considering the existence of the network. Motivated by this, the controller synthesis problem of the NLSCSs is studied in this paper, in which the two kinds of behaviors are taken into account respectively.

In this paper, we propose an effective method to study the NLSCSs under limited bandwidth condition. Firstly, a compression-compensation (C–C) method is proposed, which consists of three stages: data-packet-compressed stage, dimension-expanded stage, and signal-compensated stage. The idea of C–C method is inspired by the data compression and decompression technology in software science, for instance, the commonly used software WINRAR and ZIP. Its noticeable advantages are: (1) The limiting conditions (a) and (b) (see Paragraph 2) are removed. By using the C–C method, all the transmitted signals are in single-packet, which is true of no-limited bandwidth channels; and (2) Secure communication is built. The transmitted signal has been treated individually before transmission. Then the transmitted signal is not true but cryptographic, which is the same as the encrypted message in the communication theory [21]. Secondly, based on the C–C method, a nonlinear switched system model with uncertainty is proposed, where the uncertainty includes both the inter-sample behavior and packet dropouts behavior. In this paper, the inter-sample behavior is related to the range of delay, which is shorter than one sampling period. The arbitrary packet dropouts behavior is described as the number of successive packet dropouts, which takes arbitrary values in a bounded set. Finally, some more general stability results of the NLSCSs with band-limited channels are developed by using a packet dropouts dependent Lyapunov functional method, by which the compound state feedback controller can be designed directly. The effectiveness of the proposed results is demonstrated by a numerical example.

Notation 1. $\mathbb{Z}$ denotes the set of nonnegative integers. $\mathbb{Z}^+$ denotes the set of positive integer. I is the identity matrix of compatible dimensions. $\Re^n$ denotes the n-dimensional Euclidean space. The symbol $\|\cdot\|$ refers to the Euclidean norm for vectors and induced 2-norm for matrices. The symbol $|\cdot|$ means absolute values of real numbers or modulus of complex numbers. $*$ is used to complete symmetric matrices as in $\begin{bmatrix} A_{11} & A_{12} \\ A_{12}^T & A_{22} \end{bmatrix} = \begin{bmatrix} A_{11} & A_{12} \\ * & A_{22} \end{bmatrix}$.

2. The structure of NLSCSs with C–C method

The structure of NLSCSs with C–C method under bandwidth-limited channels is illustrated in Fig. 1, in which the sensor is clock-driven with sampling period h, and the rest of components are event-driven. The plant is described by the following continuous-time linear time-invariant system

$$\dot{x}(t) = Ax(t) + Bu(t), \tag{1}$$

where $x(t) \in \Re^n$ is the system state, $u(t) \in \Re^p$ is the control input. A and B are constant matrices with appropriate dimensions, which ensure the system (1) is controllable. The networked controller is a state feedback controller

$$u(kh) = Fx(kh), \tag{2}$$

where $k \in \mathbb{Z}$, and $F \in \Re^{p\times n}$ is the controller gain.

Throughout the paper, τ_{sc} and τ_{ca} are used to describe the sensor-to-controller delay and the controller-to-actuator delay respectively. Any controller delay can be absorbed into either τ_{sc} or τ_{ca}, without loss of generality. Furthermore, a maximum allowable network-induced delay $\tau_{\max}$ is set shorter than one sampling period. If the transmission delay $\tau = \tau_{sc} + \tau_{ca}$ satisfies $0 \leqslant \tau \leqslant \tau_{\max} < h$, the input signals $u(kh, \tau)$ are taken as successful transmission. Otherwise, the input signals $u(kh, \tau)$ are con-