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Brief paper

Control strategy with adaptive quantizer's parameters under digital communication channels[☆]

Yugang Niu [a,1], Daniel W.C. Ho [b,c]

[a] Key Lab of Advanced Control and Optimization for Chemical Processed of Ministry of Education, East China University of Science & Technology, Shanghai 200237, China

[b] Department of Mathematics, City University of Hong Kong, 83 Tat Chee Avenue, Kowloon, Hong Kong

[c] School of Automation, Nanjing University of Science & Technology, Nanjing 210096, China

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ABSTRACT

A stabilizing controller designed without considering quantization may not be effectively implemented for the systems with quantized information due to quantization errors. Hence, an interesting issue is how to design the quantizer such that the desired system performance can be still attained by the above controller. In this work, a new control strategy with on-line updating the quantizer's parameter is proposed. This scheme may ensure the controlled system to attain the same dynamic performance, H_∞ disturbance attenuation level, as the one without signal quantization. A practical adjusting rule on quantizer's parameter is proposed such that the state-dependent parameter is available on both sides of encoder/decoder. Finally, some numerical examples have been provided to illustrate the present control scheme.

1. Introduction

In recent years, much attention has been paid to the study of networked control systems (NCSs), in which control loops are closed via digital communication channels. The insertion of communication networks brings some features, such as low cost, reduced weight, simple installation and maintenance, and increased system wiring. However, NCSs also yield some detrimental phenomena, e.g., quantization error, data packet losses, signal transmission delay, etc.

It is known that when system information, state/control signals, is transmitted by the digital communication channel, they are usually quantized before transmission. That is, the real value signals are mapped into piecewise constant signals taking values in a finite set. Apparently, these quantized signals will make the analysis and design of the control system become more complex due to quantization errors. Hence, many important results involving various quantization methods have been recently presented; see, e.g., Corradini and Orlando (2008); Elia and Mitter (2001); Fu and Xie (2005); Kameneva and Nesic (2009); Liu, Ho, and Niu (2012); Nair and Evans (2003); Sharon and Liberzon (2012) and Yun, Choi, and Park (2009). Especially, Gao and Chen (2008) proposed a new quantization dependent Lyapunov function approach to the problems arising from quantized feedback control. It is noted that a common feature in the aforementioned works is to investigate the effect of measurement quantization in the design of the controller such that the resultant closed-loop system attains the desired performance.

On the other hand, *many existed control laws* have been effectively designed for systems without involving signal quantization. If these existed control laws are directly applied to the system with quantized signals, the quantization effects may lead to the deterioration of system performance or even instability (Liberzon, 2003). Thus, the following two questions are frequently asked: (Q1) how can these existed control laws be effectively utilized in the case involving signal quantization? (Q2) What conditions should the quantizer satisfy so that the desired system performance, e.g., stability, can be still ensured?

Obviously, the above issues are interesting and significant. If these questions can be well addressed, many existing control laws may be utilized for the systems involving signal quantization. Recently, some corresponding works have been presented. Among

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E-mail addresses: acniuyg@ecust.edu.cn (Y. Niu), madaniel@cityu.edu.hk (D.W.C. Ho).

[1] Tel.: +86 21 64253794; fax: +86 21 64253325.

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them, Brockett and Liberzon (2000) proposed a hybrid control strategy combining with a suitable adjusting policy for the sensitivity of the quantizer such that, when the states were quantized, an existed state feedback control law could still ensure the stability of the closed-loop system as in the case without involving quantization. This approach was further extended to more general nonlinear systems in Liberzon (2003) and a discrete-time linear system in Zhai, Matsumoto, and Chen (2004), respectively. The key feature of the above control strategies is that the quantizer's parameters are adaptively updated at discrete instants of time and these switching events, determined by the values of the suitable Lyapunov function, resulted in a hybrid quantized feedback control policy. However, as pointed out in Zhai, Chen, and Imae (2006), the above adjusting strategies dependent on time cannot be applied to the system with disturbance input, e.g., H_∞ control system, due to the value of the disturbance input unavailable. In order to deal with the problem, Zhai et al. (2006) proposed a state-dependent strategy for adjusting the quantizer's parameters so that the system with quantized signals was asymptotically stable and achieved the same H_∞ disturbance attenuation level as the one without quantization, which was also extended to uncertain interconnected networked systems in Chen, Zhai, Gui, Yang, and Liu (2010).

With a zooming variable added to the quantization scheme, it is known that the dynamic quantizer can deal with both large and small variables in a simple way. These properties have been reflected in the design of quantized feedback control (see Remark 3.2 in Fu & Xie, 2009b) to avoid those saturation and dead-zone problems arising from quantization. A detailed discussion can also be found in the recent survey paper Jiang and Liu (2013) on dynamic quantizer which is used to enlarge the stability region for quantized nonlinear systems which cannot be achieved by static quantizer.

However, for the aforementioned state-dependent strategy, an interesting issue is how to make the quantizer's parameters available on both sides of encoder/decoder, since the value of state received by decoder is only a quantized one. This problem concerns how to implement the proposed scheme in practical applications and it motivates the present research. A practical adjusting rule will be proposed in this work, whose idea may also be utilized to handle the implementation problem in Chen et al. (2010) and Zhai et al. (2006) in which the above issue was not explicitly discussed.

In this work, the system in consideration may be subject to data packet losses, which is usually inevitable when the signals are transmitted via the network. It is known that the data packet dropout may be catastrophic and may deteriorate the performance of real time systems. Hence, many interesting results have been recently obtained in, e.g., Gao, Chen, and Lam (2008); Niu and Ho (2010); Quevedo, Ostergaard, and Nesic (2011); Sinopoli, Schenato, and Franceschetti (2008); Wu and Chen (2007); Xiong and Lam (2007) and You and Xie (2011). Moreover, Gao et al. (2008) proposed a novel delay system approach by the simultaneous consideration of quantization, delay, and packet dropout, which has emerged as an important and effective methodology for networked control analysis and synthesis. Especially, an estimating strategy was proposed in Niu and Ho (2010) to compensate the state losses. By adopting the similar estimating method as in Niu and Ho (2010), a robust controller without considering quantization is first designed in this work such that the resultant closed-loop system attains a prescribed H_∞ disturbance attenuation level. However, the desired system performance cannot generally be ensured by the above H_∞ controller, when the system's states are quantized before communicating to the controller. Hence, this work proposes a dynamic quantizer, whose parameter is adjusted on-line depending on system states, such that the desired H_∞ stability can be still achieved. Moreover, a practical adjusting rule on the state-dependent quantizing strategy is also given. It is shown that the quantizer's parameter is a piecewise constant, which is available on both sides of encoder/decoder. Due to its dependence on both the system state and the probability of packet dropout, the dynamic quantizer may effectively reflect the system dynamics and the effect of packet dropout.

Notations: $\mathbb{R}^n$ denotes the set of n-dimension real vectors, $\mathbb{N}^+$ denotes the set of positive integers, and Pr is the probability measure. $\mathcal{E}\{\cdot\}$ is the mathematical expectation. $\|\cdot\|$ denotes the Euclidean norm of a vector or the spectral norm of a matrix. $\lambda_{\min}(\cdot)$ denotes the minimum eigenvalue of a matrix. I is used to represent an identity matrix of appropriate dimensions. For a real symmetric matrix, $M > 0$ (< 0) means that M is positive-definite (negative-definite). Matrices, if not explicitly stated, are assumed to have compatible dimensions.

2. Problem formulation and preliminaries results

2.1. Problem formulation

Consider the discrete-time system of the form:

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

$$z(k) = Ex(k) \tag{2}$$

where $x(k) \in \mathbb{R}^n$ is the state, $u(k) \in \mathbb{R}^m$ is the control input, $z(k) \in \mathbb{R}^l$ is the controlled output, and $w(k) \in \mathbb{R}^p$ is the exogenous disturbance signal belonging to $L_2[0,\infty)$. A, B, D and E are known real matrices.

As discussed in Introduction, the existence of the feedback loop closed through a communication network will yield some detrimental phenomena. Among them is the data packet dropout due to the inevitable network congestion. In this work, it is assumed that the packet dropout may happen in the channel from the sensor to the controller and is modelled as the Bernoulli process $\theta \in R$ with the probability distribution as

$$\Pr\{\theta = 1\} = \bar{\theta}, \qquad \Pr\{\theta = 0\} = 1 - \bar{\theta} \tag{3}$$

where the known constant $\bar{\theta}$ represents the probability that any data packet will be lost.

A general consideration for the system (1)–(2) is how to design a controller to ensure its stability in the presence of packet dropout. In Section 2.2 later, an H_∞ controller is designed such that the system (1)–(2) is stochastically stable with a prescribed H_∞ disturbance attenuation level in the presence of packet dropout. And then, in Section 3, we will further consider how to design a dynamic quantizer such that the above H_∞ controller can still attain the same stability for case that the state signals are *quantized* before being communicated to the controller.

2.2. The H_∞ control with data packet loss

In this subsection, it is assumed that there only exists data packet dropout, i.e., without taking quantization into consideration. The following state compensator as in Niu and Ho (2010) is utilized to estimate the lost state:

$$\hat{x}(k) = (1-\theta)x(k) + \theta\hat{x}(k-1). \tag{4}$$

Thus, by means of the estimation from (4), the controller is constructed as:

$$u(k) = K\hat{x}(k) \tag{5}$$

where the gain matrix K will be given later.

By substituting (4)–(5) into (1), we obtain:

$$x(k+1) = [A + (1-\theta)BK]x(k) + \theta BK\hat{x}(k-1) + Dw(k). \tag{6}$$