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Brief paper

Decentralized adaptive tracking control for a class of interconnected nonlinear systems with input quantization ☆

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ABSTRACT

In this paper, a decentralized output-feedback adaptive control scheme is proposed for a class of interconnected nonlinear systems with input quantization. Both logarithmic quantizers and improved hysteretic quantizers are studied, and a linear time-varying model is introduced to handle the difficulty caused by quantization. The proposed scheme allows the parameters of the quantizers to be freely changed during operation, and can guarantee global stability of the overall closed-loop system regardless of the coarseness of the quantizers and the existence of interactions among subsystems. Moreover, with the aid of a kind of high-gain K-filters, it is shown that all tracking errors converge to a residual set which can be made arbitrarily small by adjusting some design parameters. Simulation results are presented to illustrate the effectiveness of the proposed scheme.

1. Introduction

Motivated by great interest for applications in complex engineering systems such as electric power systems and chemical reactors, decentralized adaptive control for uncertain interconnected systems has long been an active issue in the control community. Different from centralized controllers, decentralized controllers are designed independently for subsystems and use only local signals for feedback, which brings challenge to the design and analysis in face of uncertain interactions among subsystems. In the early stage of the research, decentralized adaptive control schemes were developed mainly based on the certainty equivalence principle (Ioannou & Kokotovic, 1985; Shi & Singh, 1992; Wen & Hill, 1992). Since the middle 1990s, the research has been accelerated with the development of backstepping design (Krstic, Kanellakopoulos, & Kokotovic, 1995) and considerable achievements have been made; see, for instance, Jiang (2000), Li, Tong, and Li (2015), Wang and Lin (2015), Wen (1994) and Zhou and Wen (2008) and the references therein for more details.

On the other hand, signals in modern control systems are often quantized before being transmitted through communication channels and recent years have witnessed an increasing amount of attention in quantized control. A quantizer can be regarded as a map from a continuous region to a discrete set of numbers, making the control signal or the measurement of the system to be controlled a piecewise constant function of time. Quantization introduces strong nonlinear characteristics, which may degrade system performance or even result in instability. Aiming at understanding the required quantization resolution and mitigating the effect of quantization errors, much attention has been paid to quantized control of systems whose models are completely known or suffer from uncertainties composed of disturbances only (Ceragioli, Persis, Claudio, & Frasca, 2011; De Persis, 2005; Fu & Xie, 2005; Liberzon, 2014; Liberzon & Hespanha, 2005).

In practice, it is often required to consider systems with general uncertainties such as unknown parameters and uncertain nonlinearities. In Corradini and Orlando (2008), De Persis (2009) and Liu, Jiang, and Hill (2012a,b), such uncertainties were studied for quantized control systems via robust control approaches, under the assumption that the bounds of the uncertainties are known. As we know, adaptive control is also useful to handle uncertainties and specially suitable for those without bound knowledge. Considering input quantization, adaptive control schemes were

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developed for uncertain linear and nonlinear systems in Hayakawa, Ishii, and Tsumura (2009a,b), respectively, but the resulting stability conditions depend on control signals and are hard to be checked in advance. In Zhou, Wen, and Yang (2014), an adaptive backstepping control scheme was proposed for a class of strict-feedback systems and global stability was guaranteed by choosing the parameters of the quantizer and the controller to satisfy a derived inequality, which relaxes the stability conditions in Hayakawa et al. (2009a,b). A drawback of Zhou et al. (2014) lies in that the system nonlinearities are required to be globally Lipschitz. This restriction was later removed in Xing, Wen, Su, Cai, and Wang (2015). However, the same as Hayakawa et al. (2009a,b), and Zhou et al. (2014), the scheme in Xing et al. (2015) requires the measurement of full states. Recently, adaptive quantized control via output-feedback was studied in Xing, Wen, Zhu, Su, and Liu (2016) for a class of nonlinear systems. Nevertheless, to the best of our knowledge, existing adaptive quantized control schemes generally assume that the parameters of quantizers are constant (Xing et al., 2015, 2016; Zhou et al., 2014) or changeable but satisfy some inequalities involving control signals (Hayakawa et al., 2009a,b). In other words, these schemes do not consider the more general case that the parameters of quantizers may be freely changed during operation, which is an important issue from both theoretical and practical viewpoints. For example in tracking control, when the tracking error is small, the quantizer may be adjusted to be coarser by changing its parameters to decrease the communication burden; on the other hand, when the tracking error is large, the quantizer may be adjusted to be finer to improve the tracking performance. Moreover, existing adaptive quantized control schemes are mainly focused on controlling single-input single-output systems without interactions with other systems, and decentralized adaptive quantized control for interconnected systems needs to be further investigated.

In this paper, a decentralized output-feedback adaptive backstepping control scheme is proposed for a class of interconnected nonlinear systems with input quantization. Both logarithmic quantizers and hysteretic quantizers are studied. The proposed scheme has the following features:

- Unlike existing adaptive quantized control schemes, in this paper the parameters of quantizers are allowed to be freely changed during operation according to system performance and communication burden. To handle the difficulty caused by quantization, we introduce a linear time-varying model to describe quantizers and estimate the bounds of the resulting time-varying terms. With the aid of such efforts, our controllers need no information about the parameters of quantizers.
- An improved hysteretic quantizer is introduced, which can enhance the ability to reduce chattering in comparison with the hysteretic quantizer in Zhou et al. (2014).
- Instead of the traditional K-filters employed in the existing output-feedback adaptive quantized control scheme (Xing et al., 2016), we construct a kind of high-gain K-filters to estimate the unmeasured states, which is shown to be effective to improve the tracking performance.
- The proposed scheme is totally decentralized and the effect of interactions among subsystems is successfully compensated for by introducing a smooth function. It is proved that the overall closed-loop system is globally stable regardless of the coarseness of quantizers.

The rest of this paper is organized as follows. In Section 2, the control problem is introduced. In Section 3, the adaptive controllers design is presented, followed by the stability analysis in Section 4. Section 5 gives the simulation results to illustrate the effectiveness of the proposed scheme. Finally, we conclude in Section 6.

2. Problem formulation

Consider an interconnected nonlinear system consisting of N single-input single-output subsystems in output-feedback form, given by

$$
\begin{aligned}
&\dot{x}_i = A_i x_i + \varphi_i(y_i)\theta_i + b_i\eta_i(y_i)Q_i(u_i) + f_i(y_1,\ldots,y_N,t),\\
&y_i = x_{i,1}, \quad i = 1,\ldots,N,\\
&A_i = \begin{bmatrix} 0 & \\ \vdots & I_{n_i-1} \\ 0 & \cdots 0 \end{bmatrix} \in \mathbb{R}^{n_i\times n_i}, \qquad b_i = [0\cdots 0\ \bar{b}_i^{\mathrm{T}}]^{\mathrm{T}} \in \mathbb{R}^{n_i},
\end{aligned} \tag{1}
$$

where $x_i = [x_{i,1},\ldots,x_{i,n_i}]^{\mathrm{T}} \in \mathbb{R}^{n_i}$, $Q_i(u_i) \in \mathbb{R}$ and $y_i \in \mathbb{R}$ are the states, input and output of the ith subsystem, respectively; I_{n_i-1} is the $(n_i-1)\times(n_i-1)$ identity matrix; $\theta_i \in \mathbb{R}^{\iota_i}$ and $\bar{b}_i = [b_{i,m_i},\ldots,b_{i,0}]^{\mathrm{T}} \in \mathbb{R}^{m_i+1}$ with $b_{i,m_i} \neq 0$ are unknown constants; $\varphi_i(y_i) \in \mathbb{R}^{n_i\times\iota_i}$ and $\eta_i(y_i) \in \mathbb{R}$ with $\eta_i(y_i) \neq 0$ are known smooth functions; $f_i \in \mathbb{R}^{n_i}$ are unknown interactions among subsystems; and $\rho_i := n_i - m_i > 1$. The states $x_{i,2},\ldots,x_{i,n_i}$ are unmeasured and each subsystem is preceded by a quantizer falling into the following two types:

- Logarithmic quantizer (Hayakawa et al., 2009a,b):

$$
Q_i(u_i) = \begin{cases} (1+\delta_i)p_{i,j}, & \text{if } p_{i,j} \le u_i < p_{i,j+1},\\ 0, & \text{if } 0 \le u_i < p_{i,1},\\ -Q_i(-u_i), & \text{if } u_i < 0. \end{cases} \tag{2}
$$

- Hysteretic quantizer:

$$
Q_i(u_i) = \begin{cases} p_{i,j}, \ \text{if } \dfrac{p_{i,j}}{1+\delta_i} < u_i \le p_{i,j}, \quad Q_i^- \ge p_{i,j},\\ \text{or } p_{i,j} \le u_i < \dfrac{p_{i,j}}{1-\delta_i}, \quad Q_i^- \le p_{i,j},\\ (1+\delta_i)p_{i,j},\\ \text{if } p_{i,j} < u_i \le \dfrac{p_{i,j}}{1-\delta_i}, \quad Q_i^- \ge (1+\delta_i)p_{i,j},\\ \text{or } \dfrac{p_{i,j}}{1-\delta_i} \le u_i < p_{i,j+1}, \quad Q_i^- \le (1+\delta_i)p_{i,j},\\ 0, \ \text{if } 0 \le u_i \le \dfrac{p_{i,1}}{1+\delta_i},\\ \text{or } \dfrac{p_{i,1}}{1+\delta_i} < u_i < p_{i,1}, \quad Q_i^- = 0,\\ -Q_i(-u_i), \quad \text{if } u_i < 0. \end{cases} \tag{3}
$$

In (2) and (3), $\delta_i = \frac{1-\epsilon_i}{1+\epsilon_i}$ and $p_{i,j} = a_i\epsilon_i^{1-j}$ with $0 < \epsilon_i < 1$, $a_i > 0$ and $j = 1, 2, 3, \ldots$. The parameter a_i determines the size of the dead-zone for $Q_i(u_i)$, and ϵ_i is a measure of quantization density. The smaller the ϵ_i is, the coarser the quantizer is. In (3), $Q_i^-(t)$ is the latest value of Q_i before the time instant t and $Q_i^-(0) := 0$. Mathematically, $Q_i^-(t) = 0$ for $t \in [0, T_{i,1}]$ and $Q_i^-(t) = Q_i(u_i(T_{i,h}))$ for $t \in (T_{i,h}, T_{i,h+1}]$, where $T_{i,h}$ $(h = 1, 2, 3, \ldots)$ with $0 \le T_{i,1} < T_{i,2} < T_{i,3} < \cdots \le +\infty$ denotes the time instants when $Q_i(u_i)$ makes transitions. The maps of (2) and (3) for $u_i \ge 0$ are plotted in Figs. 1 and 2, respectively.

Remark 1. Compared with the logarithmic quantizer (2), the hysteretic quantizer (3) has additional quantization levels and can reduce chattering because whenever its output makes a transition from one value to another, some dwell time will elapse before a new transition can occur. Similar discussion can be found in Hayakawa et al. (2009b).

Remark 2. The hysteretic quantizer (3) can be considered as an improved version of the hysteretic quantizer in Zhou et al. (2014). The latter involves $\dot{u}_i$ and its output may make transitions at every point of quantization levels if the sign of $\dot{u}_i$ changes frequently,