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Brief paper

Adaptive control of uncertain nonlinear systems with quantized input signal ☆

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ABSTRACT

This paper proposes new adaptive controllers for uncertain nonlinear systems in the presence of input quantization. The control signal is quantized by a class of sector-bounded quantizers including the uniform quantizer, the logarithmic quantizer and the hysteresis quantizer. To clearly illustrate our approaches, we will start with a class of single-loop nonlinear systems and then extend the results to multi-loop interconnected nonlinear systems. By using backstepping technique, a new adaptive control algorithm is developed by constructing a new compensation method for the effects of the input quantization. A hyperbolic tangent function is introduced in the controller with a new transformation of the control signal. When considering multi-loop interconnected systems with interactions, a totally decentralized adaptive control scheme is developed with a new compensation method incorporated for the unknown nonlinear interactions and quantization error. Each local controller, designed simply based on the model of each subsystem by using the adaptive backstepping technique, only employs local information to generate control signals. Unlike some existing control schemes for systems with input quantization, the developed controllers do not require the global Lipschitz condition for the nonlinear functions and also the quantization parameters can be unknown. Besides showing global stability, tracking error performance is also established and can be adjusted by tuning certain design parameters. Simulation results illustrate the effectiveness of our proposed schemes.

1. Introduction

In quantized control systems, the control signal to the system is a piece-wise constant function of time and the system is interacted with information quantization. Due to its theoretical and practical importance in the study of digital control systems and networked control systems, there has been a great deal of interest in the development of quantized control systems. The main motivation for considering quantization in control systems comes from the observation that for many control systems, quantization is not only inevitable, but also useful. An important aspect is to use quantization schemes that have sufficient precision and require low communication rate. Much attention has been paid to quantized feedback control, in order to understand the required quantization density or information rate in stability analysis. The stabilization problem of linear or nonlinear systems with quantized control signals has been studied, see for examples Elia and Mitter (2001), Ishii and Francis (2002), Liberzon and Hespanha (2005) and Tatikonda and Mitter (2004), where the systems considered are completely known.

Uncertainties and nonlinearities always exist in many practical systems. Thus it is more reasonable to consider controller design for uncertain nonlinear systems. Quantized control of uncertain systems with known quantization parameters has been studied by using robust approaches in Liu, Jiang, and Hill (2012) and Persis (2009) and adaptive approaches in Hayakawaa, Ishii, and Tsumurac (2009a, b), Wang, Wen, Lin, and Wang (2017), Xing, Wen, Su, Cai, and Wang (2015), Xing, Wen, Zhu, Su, and Liu (2016), Zhou and Wen (2013) and Zhou, Wen, and Yang (2014). Adaptive control schemes for uncertain systems with logarithmic or hysteresis input quantization have been reported in Hayakawaa et al. (2009a, b), where the hysteresis type of quantization was originally introduced. However the stability condition in Hayakawaa et al.

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(2009a, b) depends on the control signal, which is hard to be checked in advance as the control signal is only available after the controller is put in operation. Since backstepping technique was proposed in Krstic, Kanellakopoulos, and Kokotovic (1995), it has been widely used to design adaptive controllers for uncertain systems (Zhou, Wen, & Zhang, 2004; Zhou, Zhang, & Wen, 2007). Adaptive backstepping control of uncertain nonlinear systems with quantized input have been studied in Xing et al. (2015, 2016), Zhou and Wen (2013) and Zhou et al. (2014). In Zhou and Wen (2013) and Zhou et al. (2014), a backstepping-based adaptive control scheme is presented for a class of uncertain strict-feedback nonlinear systems with hysteresis quantized input. Although the proposed method can avoid stability conditions depending on the control input, it requires the nonlinear functions to satisfy global Lipschitz conditions with known Lipschitz constants. This strict condition has been relaxed recently in Xing et al. (2015) by using am implicit adaptive controller. However in Xing et al. (2015), the unknown parameters are only contained in the last differential equation of the system and the control signal is implicitly involved in the proposed control law. That is, the control signal needs to satisfy the equation resulted from the control law. It is nontrivial to solve the equation to obtain the control signal explicitly. In Xing et al. (2016), a new quantizer is proposed based on logarithmic and uniform quantizers. By using such a quantizer, the resulting quantization error is bounded. However, in our paper, the quantization error depends on the input control signal and cannot be assumed bounded. Clearly, how to handle such a unbounded quantization error is difficult and challenging.

Due to difficulties in considering the effects of uncertain interconnections, extension of single-loop results to multi-loop interconnected systems is challenging, especially both input quantization and unknown interconnections are considered. In the control of uncertain interconnected systems, decentralized adaptive control strategy, designed independently for local subsystems and using locally available signals for feedback propose, is an efficient and practical strategy, see for examples Ioannou (1986) and Wen (1995). Research on decentralized adaptive control using backstepping technique has also received great attention, see for examples Jiang (2000), Wen (1994), Wen and Zhou (2007) and Wen, Zhou, and Wang (2009). In the presence of input quantization in unknown interconnected systems, the number of available decentralized control is still limited. Only paper (Wang et al., 2017) has addressed the issue of decentralized quantized control via output-feedback for interconnected systems. In Wang et al. (2017), the original system needs to be transformed to a form including only the output signal and the signals from filters. So interactions only exist in the equation for the output in the final control systems and the rest equations related to the filter signals do not involve interactions. In this paper, more general class of interconnected systems is considered in the sense that interactions exist in all the differential equations of the subsystems. Thus for such systems, it is more challenging to design appropriate controllers to account for the effects of unknown interactions.

In this paper, we propose new adaptive backstepping approaches to solve the tracking control problems of both single-loop uncertain nonlinear systems and multi-loop uncertain interconnected nonlinear systems, which are preceded by quantized input signal. The control signal is quantized by a class of sector-bounded quantizers including the uniform quantizer, the logarithmic quantizer and the hysteresis quantizer. Unknown parameters are contained in each differential equation of the system and their bounds are not required to be known. Based on backstepping approach, a new adaptive controller is developed by introducing a hyperbolic tangent function. By proposing a new transformation of the final control signal and using the property of the quantizer, the effects from the quantization input are effectively compensated so that the global Lipschitz conditions required for the nonlinearities in Zhou and Wen (2013) and Zhou et al. (2014) are relaxed. To handle unknown quantized parameters, new parameter updating laws are developed which do not require the knowledge on the bounds of such unknown parameters. When considering multi-loop interconnected systems with interactions allowed in every state equation, a totally decentralized adaptive controller design approach is developed together with a new compensation method constructed for the unknown nonlinear interactions and quantization error. A well defined smooth function is introduced in the decentralized adaptive controllers to compensate for the effects of unknown nonlinear interactions. Besides showing global stability of the systems, the tracking error can asymptotically converge to a residual, which can be made arbitrarily small by choosing suitable design parameters and thus adjustable. The main contributions of this paper are summarized as follows.

- The global Lipschitz condition for the nonlinear functions considered in a class of strict-feedback uncertain systems with input quantization is removed.
- A new adaptive control scheme is developed to achieve desired tracking performance for a larger class of nonlinear systems by constructing a new compensation method for the effects of the input quantization.
- Extension of single-loop results to multi-loop interconnected systems with both input quantization and unknown interconnections.
- A decentralized adaptive control scheme is developed together with constructing a new compensation method for the unknown nonlinear interactions.

To clearly illustrate our approach, we will start with single-loop uncertain nonlinear systems with input quantization. Then the obtained results are extended to a class of uncertain interconnected nonlinear systems with both input quantization and unknown interconnections.

2. Problem statement

2.1. Modeling of uncertain nonlinear systems

A class of uncertain nonlinear systems is considered in the following parametric strict-feedback form as in Krstic et al. (1995) and Marino and Tomei (1995).

$$\begin{aligned} \dot{x}_i &= x_{i+1} + \psi_i(\bar{x}_i) + \phi_i^T(\bar{x}_i)\theta \\ \dot{x}_n &= q(u(t)) + \psi_n(\bar{x}_n) + \phi_n^T(\bar{x}_n)\theta \\ y &= x_1(t), \quad i = 1, \ldots, n-1, \end{aligned} \tag{1}$$

where $x_i(t) \in \Re^1, i = 1, \ldots, n$, $u(t) \in \Re^1$ and $y(t) \in \Re^1$ are the states, input and output of the system respectively, $\bar{x}_i(t) = [x_1(t), \ldots, x_i(t)]^T \in \Re^i$, the vector $\theta \in \Re^r$ is constant and unknown, $\psi_i(\bar{x}_i) \in \Re^1$ and $\phi_i(\bar{x}_i) \in \Re^r$ are known nonlinear functions and differentiable, $q(u(t))$ represents a quantizer and takes the quantized values.

The control objective is to design a feedback control law for $u(t)$ ensure that the output $y(t)$ can track a reference signal $y_r(t)$ and all closed-loop signals are bounded.

Assumption 1. The reference signal $y_r(t)$ and its nth order derivatives are known and bounded.

Remark 1. The proposed scheme in Zhou and Wen (2013) and Zhou et al. (2014) requires the nonlinearities in the system to be globally Lipschitz continuous with known Lipschitz constants. Compared with Zhou and Wen (2013) and Zhou et al. (2014), this condition is now relaxed. Also in contrast to Xing et al. (2015), unknown parameters are contained in each differential equation of the system and their bounds are not required to be known. Thus the system considered in this paper is more general.