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Brief paper

Adaptive asymptotic tracking control of uncertain nonlinear systems with input quantization and actuator faults☆

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ABSTRACT

This paper studies the problem of adaptive tracking control for a class of uncertain nonlinear systems with input quantization, external disturbances and actuator faults. It is assumed that the upper bounds of disturbances and the time varying stuck faults, are unknown. Firstly, an intermediate control law is designed by a modified adaptive backstepping design procedure, where a damping term with the estimate of unknown bounds and a positive time-varying integral function are introduced in the intermediate control law. Then, a novel smooth function is introduced in the control law to eliminate the effect of quantization based on the intermediate control law constructed in the first step. It is shown that all the closed-loop signals are bounded and the output tracking error converges to zero asymptotically in spite of input quantization, disturbances and possibly infinite number of faults. Finally, simulation results demonstrate the efficiency of the proposed algorithm.

1. Introduction

In modern industrial applications, such as flight control systems, satellite systems and nuclear power systems, actuators and sensors are subjected to faults during operation, which may result in an unsatisfactory performance and even instability. To ensure system reliability and guarantee system stability in all situations, it is essential and significant to develop an efficient fault tolerant control (FTC) scheme to keep the stable and acceptable control performance when faults occur (Jiang, Staroswiecki, & Cocquempot, 2006; Tao, Joshi, & Ma, 2001; Yang & Ye, 2010). However, it is worth mentioning that the aforementioned results on fault-tolerant control were mainly developed for linear systems. In fact, it has been widely recognized that most practical industrial systems are nonlinear by nature (Krstic, Kanellakopoulos, & Kokotovic, 1995). Hence, it is more desirable and significant to design FTC methods for nonlinear systems. Recently, for a class of single-input single-output (SISO) nonlinear systems in parametric-strict-feedback form, some important results have been obtained based on the backstepping design technique (Cai, Wen, Su, & Liu, 2013; Tang, Tao, & Joshi, 2003; Wang & Wen, 2010; Wang, Wen, & Lin, 2015). Despite these efforts, however, to our best of knowledge, the fault-tolerant control considering the input quantization has not drawn any attention in the present literature.

The signal quantization, which can be seen as a map from continuous signals to discrete finite sets, has received a great deal of interests over recent decades in networked control systems. Lots of well known results on quantized control have been published in Brockett and Liberzon (2000), Elia and Mitter (2001), Fu and Xie (2005), Liberzon (2003), Liu, Jiang, and Hill (2012) and Lunze, Nixdorf, and Schroder (1999). Despite these efforts, there are few works devoted to adaptive control with quantized measurements (Hayakawaa, Ishii, & Tsumurac, 2009a,b). In Hayakawaa et al. (2009a), an adaptive quantized control for a class of linear systems is investigated. In Hayakawaa et al. (2009b), an adaptive quantized control for nonlinear systems is studied, where a sector bounded property on quantization errors is used to establish the results. It is noted that these approaches were relied on the control signals, which is difficult to obtain in practice. Recently, an adaptive quantized control scheme was presented for a class of strict feedback nonlinear systems based on backstepping technique

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(Zhou, Wen, & Yang, 2014). However, in order to obtain the stability condition, some restrictions on the quantization parameter has to be imposed, which is directly related to controller design parameters and some system parameters. In other words, to make the closed loop system stable, the quantization parameter may be very small. Meanwhile, all the nonlinear functions of the system must be known and satisfy the global Lipschitz continuity condition with known Lipschitz constants, the bounds of the partial derivative of the nonlinear functions with respect to system states must be known, and the unknown parameters are only considered in the last nonlinear function of the system and belong to a known compact convex set. As a matter of fact, these assumptions are too restrictive and not easy to satisfied in many practical systems.

Furthermore, the presented adaptive controllers (Zhou et al., 2014) do not produce the exact tracking in the presence of input quantization. Instead, only the boundedness of the tracking error was proven. As we known, asymptotic tracking has great potential in practical applications (Cai, de Queiroz, & Dawson, 2006; Zhang, Park, Shao, & Qi, 2014; Zhang, Xu, & Zhang, 2015; Zheng, Wen, & Li, 2013). It is therefore essential and challenging to investigate the asymptotic tracking problem for uncertain nonlinear systems with input quantization, actuator faults and disturbances, which always occur simultaneously in practical engineering. However, there is little work in the literature to consider asymptotic tracking design for uncertain nonlinear systems with input quantization, actuator faults and disturbances. Such an issue has not yet gained sufficient research attention and remains open, which motivates our present investigation work.

Motivated by these observations, in this paper, the problem of adaptive fault tolerant tracking controller for a class of uncertain nonlinear systems with input quantization and actuator faults is proposed. A combined backstepping and two step approaches are used in our controller design. Compared with existing results in the literature, the following contributions are worth to be emphasized: (1) By introducing a smooth function, a novel damping term with the estimate of unknown bounds and a positive time-varying integral function, the effects of input quantization, disturbances and actuator faults can be completely eliminated, a very coarse quantization can be achieved; (2) Unlike (Lin & Yu, 2016; Zhou et al., 2014) without considering actuator faults where the stabilization error is ultimately bounded, the output tracking error in this paper converges to zero asymptotically in spite of the input quantization, the external disturbances and the possibly infinite number of actuator faults; (3) In contrast with the existing results such as Cai et al. (2013), Tang et al. (2003) and Wang and Wen (2010) where the total number of faults is finite, the total number of faults is allowed to be infinite in this paper, which is more reasonable in practical applications; (4) The stability of the closed-loop system is global in the sense that the design parameters can be freely chosen and do not depend on the initial conditions of the controlled system.

2. System description and problem statement

Consider a class of uncertain nonlinear systems with input quantization in the following form:

$$\begin{aligned} \dot{x}_i &= x_{i+1} + \phi_i^T(\underline{x}_i)\theta,\ 1 \le i \le n-1, \\ \dot{x}_n &= \sum_{j=1}^{m} b_j q(u_j) + \phi_n^T(x)\theta + d(t), \\ y &= x_1 \end{aligned} \tag{1}$$

where $\underline{x}_i = [x_1, x_2, \ldots, x_i]^T \in \mathbb{R}^i$, $i = 1, 2, \ldots, n$, and $x = \underline{x}_n \in \mathbb{R}^n$ are the systems states, $y \in \mathbb{R}$ is the output of the system. $\theta \in \mathbb{R}^l$ and $b_j \in \mathbb{R}$ are unknown parameters. $\phi_i(\underline{x}_i) \in \mathbb{R}^l$, $i = 1, 2, \ldots, n$ are known nonlinear functions. $d(t) \in \mathbb{R}$ is unknown bounded time-varying additive disturbance. $q(u_j) \in \mathbb{R}$ denotes the quantized input with $u_j \in \mathbb{R}$ the control signal to be designed.

Remark 1. Since the unknown parameters appear in all the differential equations, the system (1) is more general than that in Zhou et al. (2014). In addition, to the best of our knowledge, the problem of adaptive asymptotic tracking control of the uncertain nonlinear system (1) with input quantization, actuator faults and external disturbances has not been addressed till now.

In this paper, the following hysteresis quantizer described in Zhou et al. (2014) is considered:

$$q(u_j) = \begin{cases} u_{i,j}\mathrm{sgn}(u_j), & \dfrac{u_{i,j}}{1+\delta_j} < |u_j| \le u_{i,j},\ \dot{u}_j < 0, \text{ or} \\ & u_{i,j} < |u_j| \le \dfrac{u_{i,j}}{1-\delta_j},\ \dot{u}_j > 0, \\ u_{i,j}(1+\delta_j)\mathrm{sgn}(u_j), & u_{i,j} < |u_j| \le \dfrac{u_{i,j}}{1-\delta_j},\ \dot{u}_j < 0, \text{ or} \\ & \dfrac{u_{i,j}}{1-\delta_j} < |u_j| \le \dfrac{u_{i,j}(1+\delta_j)}{1-\delta_j},\ \dot{u}_j > 0, \\ 0, & 0 \le |u_j| < \dfrac{u_{\min}}{1+\delta_j},\ \dot{u}_j < 0, \text{ or} \\ & \dfrac{u_{j,\min}}{1+\delta_j} \le |u_j| < u_{\min},\ \dot{u}_j > 0, \\ q(u_j(t^-)), & \dot{u}_j = 0 \end{cases} \tag{2}$$

where $u_{i,j} = \rho_j^{1-i} u_{j,\min}$ with integer $i = 1, 2, \ldots$ and $u_{j,\min} > 0$ denotes the size of the dead-zone for $q(u_j)$ and $0 < \rho_j < 1$, $\delta_j = (1-\rho_j)/(1+\rho_j)$. The constant $\rho_j \in (0, 1)$ is a measure of quantization density (Elia & Mitter, 2001), i.e., the smaller the ρ_j, the coarser the quantizer is. Since $\delta_j = (1-\rho_j)/(1+\rho_j)$, it is desirable that δ_j is close to 1.

Remark 2. It should be pointed that there are several features in the nonlinear quantized systems under consideration. First, the use of quantization makes the closed-loop quantized system a hybrid system. Second, the use of quantized signals introduces severe challenges to controller design as well as stability analysis. Therefore, the quantized state feedback control cannot be simply considered as a special case of the previously studied robust control problem (Krstic et al., 1995). As shown later, unlike the treatment for the state-feedback control problem without input quantization, a novel solution will be introduced.

Remark 3. From the definition of δ_j, it is easy to get $\delta_j \in (0, 1)$. The hysteretic quantizer parameter δ_j determines quantization levels of $q(u_j)$, the larger δ_j is, and the fewer quantization levels $q(u_j)$ will have. Therefore, how to ensure the control performance with fewer quantization levels is an interesting work. As shown later, by constructing a novel adaptive controller, the restrictive imposed in Zhou et al. (2014) that the nonlinearities of the system to be controlled should satisfy global Lipschitz conditions with known Lipschitz constants and their partial derivatives to be bounded are removed.

In order to propose a suitable control scheme, an important property that the hysteretic quantizer $q(u_j)$ can be decomposed into a linear part and a nonlinear part as follows (Zhou et al., 2014):

$$q(u_j) = u_j + f_j \tag{3}$$

where $f_j = q(u_j) - u_j \in \mathbb{R}$.