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Research Article

Robust fault tolerant control based on sliding mode method for uncertain linear systems with quantization

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ABSTRACT

This paper is concerned with the problem of robust fault-tolerant compensation control problem for uncertain linear systems subject to both state and input signal quantization. By incorporating novel matrix full-rank factorization technique with sliding surface design successfully, the total failure of certain actuators can be coped with, under a special actuator redundancy assumption. In order to compensate for quantization errors, an adjustment range of quantization sensitivity for a dynamic uniform quantizer is given through the flexible choices of design parameters. Comparing with the existing results, the derived inequality condition leads to the fault tolerance ability stronger and much wider scope of applicability. With a static adjustment policy of quantization sensitivity, an adaptive sliding mode controller is then designed to maintain the sliding mode, where the gain of the nonlinear unit vector term is updated automatically to compensate for the effects of actuator faults, quantization errors, exogenous disturbances and parameter uncertainties without the need for a fault detection and isolation (FDI) mechanism. Finally, the effectiveness of the proposed design method is illustrated via a model of a rocket fairing structural-acoustic.

1. Introduction

Controlling systems subject to actuator faults are a challenging issue, which are attracting more and more attention in the field of fault-tolerant control (FTC) systems [1]. Over the last few decades, the compensation of actuator faults has been an important and challenging research problem [2,3]. Most of the works proposed in the literature can be divided into two categories. The so-called passive approach consists in designing the same controller throughout the normal case as well as fault cases, e.g., [4–7]. It is simple to design and implement but the system stability and satisfactory performance cannot be guaranteed if any fault outside the predefined faulty set occurs. The latter approach is known as the active approach, and is aimed at selecting a precomputed control law or synthesizing a new control strategy online. Then the stability as well as the acceptable performance of the system can be maintained. Moreover, it is worth mentioning that the adaptive actuator failure compensation control scheme, as one of the effective active methods, has been extensively studied to compensate for unknown actuator failures [8–13].

While some FTC techniques and results have been well developed, one of the key challenges for FTC design is still how to deal with uncertainties in system matrices [14,15] and external disturbances [16–22]. A recent approach for dealing with uncertainties is based on the use of sliding mode method [24,23] to enhance the robustness of FTCs. However, the problem of FTC design based on SMC schemes is still in its early stage of development, and a few results have been reported in the literature [25–27]. The work by [25] shows that total failures can be dealt with by SMC schemes provided that there is exact duplication of actuators in the system. In [26], sliding mode controller is designed for a class of uncertain systems to deal with partial actuator degradation. Whereas a common assumption that the input matrix is of full column rank is made. It should be pointed out, in many practical systems [27,28], that the inherent redundancy should be exploited to deal with outage faults. Relying on a fault detection and isolation (FDI) mechanism, the literature in [27,29] proposes a novel scheme for FTC, in which sliding mode ideas are incorporated with control allocation to cope with the total failure of certain actuators.

On another research front, the quantized feedback control problem has become an active research topic in the field of automatic control owing to the wide applications of digital channels or computers in modern control systems [30]. Actually, data are quantized before transmission when measurements to be used for feedback are transmitted by a digital communication channel. In recent years, the theoretic works in [31–35] have been

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the few results on quantized feedback control design via sliding mode control schemes. Unfortunately, the above research does not study fault-tolerant problem. Due to actuator faults and quantization effects, traditional sliding mode controller cannot reach the specified sliding surface. Therefore, how to design a fault tolerant sliding mode control law to compensate for quantization errors is a challenging problem. To the best knowledge of the authors, the study of fault tolerant control via sliding mode method with both state and input quantization has not been reported.

The above considerations motivate the study in this paper. In the present work, the problem of designing a robust fault-tolerant sliding mode controller is studied. In order to compensate for both actuator faults and quantization effects, matrix full-rank factorization technique is made use of and a dynamic quantizer with a static adjustment policy of the quantization sensitivity is developed. The resulting closed-loop FTC system can be ensured to be asymptotically stable even in the presence of unmatched uncertainties, disturbances, quantization and actuator faults including outage. The main contributions of the paper include:

- A novel matrix full-rank factorization technique is incorporated with sliding manifold design under a special actuator redundancy assumption. Based on this, a sufficient condition for the existence of reduced-order sliding mode dynamics is derived, and an explicit parametrization of the desired sliding surface is also given.
- An adjustment range of quantization parameter for a dynamic quantizer for FTCs is given. Compared with the existing results [33–35], the fault tolerance ability becomes stronger by introducing flexible design parameters, no matter how small a lower bound of fault information is.
- Different from the References [27,29] relying on an FDI mechanism, an adaptive sliding mode controller is proposed to guarantee the closed-loop system asymptotic stability even the total failures of certain actuators occur.

The rest of the paper is organized as follows. After formulating the control problem some necessary preliminaries are presented in Section 2; in Section 3, we present the new adaptive sliding mode controller. One simulation example is given in Section 4, and finally the paper is concluded in Section 5.

The notations used throughout this paper are fairly standard. $\Re^n$ denotes the n-dimensional Euclidean space, $\Re^{m\times n}$ is the set of all $m\times n$ real matrices. In addition, I means the unit matrix with appropriate dimensions, and for a matrix M, M^T denotes its transpose, a block diagonal matrix with matrices $N_1, N_2, \ldots, N_m$ on its main diagonal is denoted as diag$\{N_1, N_2, \ldots, N_m\}$, $|x|_p$ represents the p-norm of the vector x, i.e., $|x|_p = (|x_1|^p + |x_2|^p + \cdots + |x_n|^p)^{1/p}$, $p \ge 1$. When $p=\infty$, $|x|_\infty = \max_{1\le i\le n}|x_i|$. For matrix $X \in \Re^{m\times n}$, $|X|_p$ is used to present the matrix p-norm, $|X|_p = \sup_{x\neq 0}|Xx|_p/|x|_p$. Specially, the notation $|\cdot|$ denotes the absolute value of a scalar, the standard Euclidean norm of a vector, or the induced norm of a matrix.

2. System description and problem statement

Consider a class of mismatched uncertain linear systems described by

$$\dot{x}(t) = (A + \Delta A(x,t))x(t) + B_2 u(t) + B_1 w(t). \tag{1}$$

where $x(t) \in \Re^n$ is the state vector, $u(t) \in \Re^m$ is the control input, and $w(t) \in \Re^q$ is the external disturbance. A, B_1, B_2 are known real constant matrices with appropriate dimensions. $\Delta A(x,t)$ represents the unmatched uncertainty of the linear system.

The FTC system considered in this paper is shown in Fig. 1.

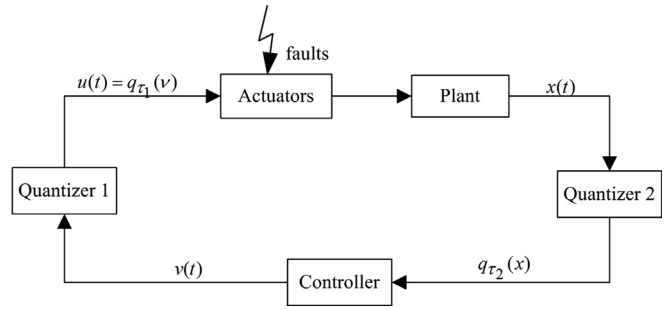

Fig. 1. Structure of the FTC system with quantization.

Remark 1. The fault tolerant control approaches in [16,11,9,8,12,3,28,13,36] are developed in a framework of disturbance-free ($w(t)=0$) or uncertainty-free ($\Delta A(x,t)=0$), which might be very restrictive in reality. Though the disturbances and parameter uncertainties are simultaneously considered in [10], they are both matched ones, i.e., $B_1 = B_2F_1, \Delta A(x,t) = B_2N(t)$. Different from above-mentioned references, this paper will take advantage of the robustness of SMC technique to deal with disturbances and mismatched parameter uncertainties.

2.1. Quantizer description

In the control strategies to be developed below, we will use quantized measurements of the form [33–35]

$$q_\tau(z) := \tau\left(\frac{z}{\tau}\right) := \tau \,\mathrm{round}\left(\frac{z}{\tau}\right), \quad \tau > 0, \tag{2}$$

where $z \in \Re^p$ is the variable to be quantized, τ denotes the quantizing level (the quantization sensitivity), $q_\tau(\cdot)$ is the uniform quantizer with respect to τ, and round(z/τ) means the element of z/τ to the nearest integer.

Define $e_\tau = q_\tau(z) - z$; from Fig. 1, the control input quantization $q_{\tau_1}(v)$ and state quantization $q_{\tau_2}(x)$ will be considered simultaneously. And the quantization errors are bounded by

$$\begin{aligned} |e_{\tau_1}| &= |q_{\tau_1}(v) - v| \le \Delta_1\tau_1, \\ |e_{\tau_2}| &= |q_{\tau_2}(x) - x| \le \Delta_2\tau_2. \end{aligned} \tag{3}$$

In this paper, a static quantizer $q_{\tau_1}(v)$ is used in the uplink channel to quantize the control input $v(t)$, and a dynamic quantizer $q_{\tau_2}(x)$ with a static adjustment of the quantization parameter τ_2 is utilized in the downlink channel to obtain quantized state signals. For a static quantizer, it is easy to be implemented in actual engineering due to its relatively simple structures. So the quantizer $q_{\tau_1}(v)$ is designed as a static one. The reason why designing a dynamic quantizer $q_{\tau_2}(x)$ with discrete adjustment of the quantization parameter is that it can drive the system trajectories onto the sliding surface, instead of just to some neighbor of the sliding surface. Further explanations of the two quantizers are located in [33]. For the dynamic quantizer, a quantizing level $\tau_2 = 0$ is added to handle the case that the system trajectories stay on the sliding surface. The additional definition is presented to have a completeness in the following: $q_{\tau_2}(x) \triangleq 0, \tau_2 = 0$.

2.2. Fault model

The faults to be considered in this paper cover actuator outage, loss of effectiveness and stuck. Let u_{ij}^F represents the signal from the ith actuator that has failed in the jth fault mode. Then, we describe the following fault model [5,12]:

$$u_{ij}^F = \rho_i^j u_i(t) + \sigma_i^j u_{si}(t).$$

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