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Design of robust nonfragile fault detection filter for uncertain dynamic systems with quantization

Jun Xiong[a,b], Xiao-Heng Chang[a,b,*], Xiaojian Yi[c,d]

[a] The School of Information Science and Engineering, Wuhan University of Science and Technology, Hubei, Wuhan 430081, China
[b] Engineering Research Center for Metallurgical Automation and Measurement Technology of Ministry of Education, Wuhan University of Science and Technology, Wuhan 430081, China
[c] The School of Mechatronical Engineering, Beijing Institute of Technology, Beijing 100081, China
[d] Department of Overall Technology, China North Vehicle Research Institute, Beijing 100072, China

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ABSTRACT

This paper investigates the fault detection problem for uncertain linear systems with respect to signal quantization. The measurement output transmitted via the digital communication link is considered to be quantized by a dynamic quantizer. Moreover, different from most of existing results on fault detection where the residual generator is assumed to be realized perfectly as the designed one, this study takes the inaccuracy and uncertainty on the implementation of residual generator into account. This paper pays much attention to designing a fault detection filter with quantization as the residual generator and formulates the design problem into the $\mathcal{H}_\infty$ framework. The objective is to guarantee the asymptotical stability and prescribed performance of the residual system. The S-procedure and a two-step approach are adopted to handle the effects of quantization and uncertainties on residual system. Corresponding design conditions of a robust fault detection filter and a robust nonfragile ones are derived in the form of linear matrix inequalities. Finally, the efficiency of the theoretical results is illustrated by the numerical example.

1. Introduction

Among the existing model-based fault detection and isolation (FDI) schemes, the so-called observer-based technique has received much attention both in the academic community and in industry since 1970's, and a great deal of significant results have been presented, such as [1–3] and references therein. The basic idea behind the development of the observer-based fault detection technique is to replace the process model by an observer which will deliver reliable estimates of the process outputs as well as to provide the designer with the needed design freedom to achieve the desired decoupling using the well-established observer theory. To achieve a successful fault detection, a residual generator which can produce a residual signal carrying the most important message for a successful fault diagnosis is needed. For the purpose of residual generation, researchers have proposed various methods to formulate different types of residual generators, to mention a few, fault detection filter (FDF), diagnostic observer (DO), parity relation based residual generator (PRRG), and so on [4–11]. Due to the fact that the practical plants are inevitably equipped with modeling errors and unknown disturbances, a central

* Corresponding author at: The School of Information Science and Engineering, Wuhan University of Science and Technology, Hubei, Wuhan 430081, China.
E-mail addresses: changxiaoheng@sina.com (X.-H. Chang), yixiaojianbit@sina.cn (X. Yi).

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issue related to the residual generation is the robustness of FDI system which aims to realize a suitable trade-off between the robustness against the other faults, unknown disturbances, and model uncertainties, and sensitivity for the faults of interests. To handle this problem, many powerful strategies and tools are borrowed from the advance robust theory, which produces a large number of meaningful results, for example [5,7,8,12–16].

However, in the above observer-based FDI results, a residual generator is usually assumed to be implemented perfectly and do not involve uncertainties. Opposite to this assumption, due to some constraints in its realization process, such as finite word length of the digital processors, quantization of the D/A and A/D converters, limited available memory of the microprocessor, and so on [17], there are more or less uncertainty and inaccuracy existing in the residual generator. Just as some results about nonfragile controller and filter [18–22], the uncertainty is bound to affect the dynamics of residual generator and further may have an effect on the performance of FDI system. Therefore, it is of great importance to investigate the residual generator design problem concerning parametric gain variations, i.e., nonfragile residual generator design problem.

It should be noted that almost all the above results, whether for linear or nonlinear systems, are not considered the effect of signal quantization, that is, all signals are transmitted through ideal communication channels. However, in practical applications, especially in networked control systems and digital signal processing systems [23–35], all signals should be transmitted via bandwidth-limited communication network where the quantization effects are unavoidable. It arises naturally a problem that whether the above results for FDI can be applied to this situation and maintain the desired performance as before. That deserves for further investigation because the signal quantization not only results in the coupling of the possible faults and quantization error, but also brings some changes in the FDI systems, which increases the difficulty of decoupling the fault of interests from the residual and the complexity of the design for residual generator. To solve this problem, recently, some researchers have devoted themselves into the study of FDI design for networked systems [36–39]. Stimulated by the recent research efforts on fault detection for networked systems, in this paper, by adopting the general dynamic quantizer proposed in [23], the effect of signal quantization will be considered in the design of a residual generator.

Motivated by above discussion, this paper studies the fault detection problem of uncertain discrete-time linear systems with quantized output signal. We focus our study on the application of robust theory and LMI technique to dealing with the robustness and sensitivity issues surrounding the design of residual generator for linear systems with model uncertainties and signal quantization. Selecting a suitable reference model, the residual generation problem is transformed into a $\mathcal{H}_\infty$ model matching problem (MMP). We first present a performance analysis condition for the residual system with model uncertainties and signal quantization, then based on this, the LMI design conditions for the robust FDF are provided. By extended these results to the case where a FDF is assumed to be equipped with uncertainties, we give the design of robust nonfragile FDF such that the corresponding residual system is asymptotically stable and preserves a desired performance. In summary, the main objective of this work is the development of a strategy to tackle the fault detection problem in dynamic systems with modeling errors and signal quantization, and the main contributions are expressed as follows.

(1) The fault detection problem is investigated for uncertain linear systems subject to measurement output quantization. The effect of signal quantization on residual system has been fully considered in the design of FDF.

(2) The nonfragile FDF with quantization is constructed. Different from existing results almost all of which design the ideal FDF under the assumption that the FDF could be implemented perfectly, we study the design problem of FDF with inaccuracy or uncertainty.

(3) All of the design conditions for the residual generators are given in terms of solutions to linear matrix inequalities (LMIs).

The rest of this paper is organized as follows. Section II is devoted to the model description and problem formulation. In Section III, two cases of the FDF design problem with quantization, i.e., whether the FDF is implemented perfectly or not, are considered, and sufficient conditions for robust FDF and nonfragile FDF are derived, respectively. Then we present a simulation example in Section IV to demonstrate the effectiveness of the proposed method. Finally, this paper is concluded in Section V.

Notations: In this paper, the notations and symbols are standard. The symbol $(*)$ means a symmetric term in a symmetric block matrix and $diag\{\cdots\}$ denotes a diagonal matrix. I and 0 are the abbreviations of the identity matrix and zero matrix with appropriate dimensions, respectively. The notation $\|\cdot\|$ represents the Euclidean norm. $l_2[0,\infty)$ is the space of square-summable vector functions over $[0,\infty)$. Moreover, the notation $He(A)=A+A^T$ is a special usage for simplification.

2. Problem formulation and preliminaries

In this paper, we investigate the FDF design problem for the general discrete-time system described as follows

$$\begin{aligned} x(k+1) &= (A+\Delta_A(k))x(k)+(B+\Delta_B(k))u(k)+(E+\Delta_E(k))d(k)+(E_f+\Delta_{Ef}(k))f(k) \\ y(k) &= (C+\Delta_C(k))x(k)+(D+\Delta_D(k))u(k)+(F+\Delta_F(k))d(k)+(F_f+\Delta_{Ff}(k))f(k) \end{aligned} \tag{1}$$

where $x(k)\in\mathcal{R}^n$ is the state variable, $u(k)\in\mathcal{R}^v$ is the control input, $y(k)\in\mathcal{R}^m$ is the measurement output, $d(k)\in\mathcal{R}^{k_d}$ is the unknown input vector (including external disturbance, uninterested fault as well as some norm-bounded unstructured model uncertainty), $f(k)\in\mathcal{R}^{k_f}$ is the fault to be detected and isolated. $A\in\mathcal{R}^{n\times n}$, $B\in\mathcal{R}^{n\times v}$, $E\in\mathcal{R}^{n\times k_d}$, $E_f\in\mathcal{R}^{n\times k_f}$, $C\in\mathcal{R}^{m\times n}$, $D\in\mathcal{R}^{m\times v}$, $F\in\mathcal{R}^{m\times k_d}$, and $F_f\in\mathcal{R}^{m\times k_f}$ are known system matrices. Without loss of generality, assume $d(k)$, $f(k)$ are l_2-norm