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Research Article

Simultaneous fault detection and control design for switched systems with two quantized signals

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ABSTRACT

The problem of simultaneous fault detection and control design for switched systems with two quantized signals is presented in this paper. Dynamic quantizers are employed, respectively, before the output is passed to fault detector, and before the control input is transmitted to the switched system. Taking the quantized errors into account, the robust performance for this kind of system is given. Furthermore, sufficient conditions for the existence of fault detector/controller are presented in the framework of linear matrix inequalities, and fault detector/controller gains and the supremum of quantizer range are derived by a convex optimized method. Finally, two illustrative examples demonstrate the effectiveness of the proposed method.

1. Introduction

Due to the rapid growth in communication technology, more and more digital communication networks for the exchange of information are employed [1]. Although they bring huge advantages such as high resource utilization and simple installation, they also bring us some new problems. As one of the typical issues, signal quantization has been considered for the networks with limited capacities. Recently, numbers of works have focused on quantized control and quantized filtering [2–6]. So far, existing quantization policies can be categorized into two types, i.e., static and dynamic. The parameters of static quantizers stay invariant when the systems evolve [7,8]. On the other hand, dynamic quantizers are always time varying and have memory, and the parameters of dynamic quantizers expand or contract (zoom) the quantizer range according to the recent quantizer input [9,10].

For several years, there have been strong interest and intensive research activities in the area of fault detection [12–14]. Comparing with the design problem separated as the detection unit and the control unit, the simultaneous fault detection and control (SFDC) problem. Problem unifies the control and the detection units into a single unit, and it leads to far less overall complexity. It has recently leaded to a vast amount of research into the analysis and synthesis of SFDC problem. In [11], a mixed $\mathcal{H}_2/\mathcal{H}_\infty$ optimization problem was formulated to solve the SFDC problem. A robust integrated controller/diagnosis in aircraft application was investigated in [15]. In [16], the controller and fault detector in feedback control loops were derived. The fault sensitivity performance index in the given frequency range was solved in [17].

Considering the aforementioned discussion, the SFDC problem for switched systems has been proposed in the literature. Dynamic observer for the system was designed in [18]. SFDC problem switched system based on state-dependent switching law was considered in [19]. However, to the best of authors' knowledge, the SFDC problem for switched systems, which contain two quantizers in the control channel and in the output channel, respectively, has not been investigated yet. Furthermore, the existing methods for switched systems are not suitable to solve this quantized error and guarantee a better performance. Therefore, a new technique needs to be developed to synthetically consider the detection objective and the control objective for switched systems with two quantized signals. Moreover, in practice, many complicated systems are controlled by communication networks, and the sensor measurement signal and the control signal are transmitted through a remote and possible wireless network. In such case, the sensor information and the control information need to be quantized before being transmitted. Thus, the SFDC problem for switched system with the transmission requirements in two channel has practical implications. As the significance in theory and practice, the SFDC problem for switched systems with two quantized signals should

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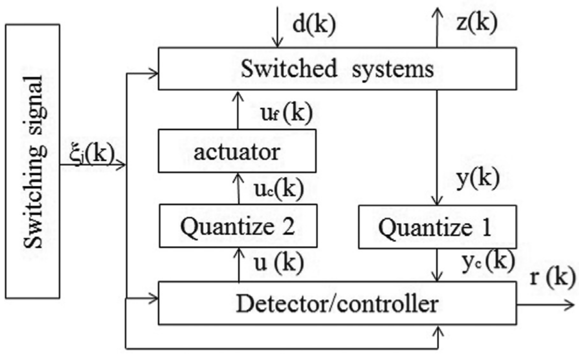

Fig. 1. Scheme for simultaneous fault detection and control with two quantized signals.

be directly investigated.

In this paper, SFDC problem for switched systems with two quantized signals is investigated, as depicted in Fig. 1, where two quantizers in both the forward and the backward channels are considered. For actuator faults, a detector/controller and switching signal are designed, respectively. Moreover, robust performance for SFDC design is derived. Meanwhile, the supremum of quantizer ranges is obtained, respectively. The main contributions in this paper are listed as follows: (i) taking two quantized signals and quantized errors into account, weighted $\mathcal{L}_2$ performance is established, and fault detector/controller gains can be derived by solving convex LMI conditions. (ii) The supremums of two quantizer ranges are obtained, and then are used to distinguish the applicability of our proposed method.

The rest of this paper is organized as follows. Section 2 describes the design objectives. Sufficient conditions to capture the system performance and the fault detector/controller design approach are proposed in Section 3. Section 4 gives a numerical example. Conclusions of this paper are given in the last section.

Notation: For a matrix A, A^T denotes its transpose. For a symmetric matrix, $A>0$ ($A\geq 0$) and $A<0$ ($A\leq 0$) denote positive-definiteness (positive semi-definite matrix) and negative-definiteness (negative semi-definite matrix), respectively. The Hermitian part of a square matrix M is denoted by $He(M){:=}M+M^T$. X_i represents a matrix in which all elements are one with appropriate dimensions. The symbol $*$ within a matrix represents the symmetric entries. 0 and I denote the zero matrix and unit matrix with appropriate dimensions.

2. Problem formulation

Consider the SFDC systems as Fig. 1, where the switched system is described by:

$$\begin{aligned} x(k+1) &= \sum_{j=1}^{N}\xi_j(k)(A_jx(k)+B_{j1}u_f(k)+B_{j2}d(k)),\\ y(k) &= \sum_{j=1}^{N}\xi_j(k)C_jx(k),\\ z(k) &= \sum_{j=1}^{N}\xi_j(k)(E_jx(k)+F_{j1}u(k)+F_{j2}d(k)) \end{aligned} \tag{1}$$

where $x(k)\in\mathcal{R}^n$ is the state, $y(k)\in\mathcal{R}^m$ is the measured output, $z(k)\in\mathcal{R}^{m_z}$ is the performance output, $u_f(k)\in\mathcal{R}^{n_u}$ is the control input, and $d(k)\in\mathcal{R}^d$ is the disturbance input, assumed to belong to $l_2[0\ \infty)$. The switching signal $\xi_j(k)$: $Z^+\to\{0,1\}$ specifies that jth subsystem is activated when $\xi_j(k)=1$ at each time step k, and $\sum_{j=1}^{N}\xi_j(k)=1$, $k\in Z^+$. N is the number of subsystems, and denote $\mathcal{N}=\{1\cdots N\}$. The matrices A_j, B_{j1}, B_{j2}, C_j, E_j, D_{j1} and D_{j2} ($j\in\mathcal{N}$) have appropriate dimensions, and switch with ξ_j at certain discrete time.

2.1. Quantizer description

As depicted in Fig. 1, $u(k)$ and $y(k)$ are quantized, respectively, before the control input $u(t)$ and the measurement signals $y(k)$ are transmitted.

In this paper, a dynamic quantizer introduced in [20,21] is employed in the form of

$$q_{\mu(k)}(k)=\mu(k)q\left(\frac{g(k)}{\mu(k)}\right)$$

where $g(k)$ is assumed as the signal to be quantized, and quantizer $q_{\mu(k)}(k)$ is composed of parameter $\mu(k)>0$ and the static quantizer $q(\cdot)$. The parameter $\mu(k)$ can be seen as the '*zoom*' variable according to the variation of $g(k)$. Since $g(k)$ is smaller, the quantizer decreases $\mu(k)$ (i.e. zoom in), and obtains smaller range and smaller quantized errors; whereas, the quantizer increase $\mu(k)$ (i.e. zoom out), and obtains a quantizer with larger range and larger quantized errors. Thus, the parameter $\mu(k)$ is updated depending on $g(k)$. The static quantizer $q(\cdot)q(\cdot)$ is a piecewise constant function $q(\cdot)$: $\mathcal{R}^l\to\mathcal{D}$, where $\mathcal{D}$ is a finite subset of $\mathcal{R}^l$. This leads to a partition of $\mathcal{R}^l$ into a finite number of quantization regions of the form $\left\{\frac{g(k)}{\mu(k)}\in\mathcal{R}^l\colon\ q\left(\frac{g(k)}{\mu(k)}\right)=i,\ i\in\mathcal{D}\right\}$. And the static quantizer $q(\cdot)$ has properties as

$$\begin{aligned} &\left|q\left(\frac{g(k)}{\mu(k)}\right)-\frac{g(k)}{\mu(k)}\right|\leq\Delta\quad\text{if}\ \left|\frac{g(k)}{\mu(k)}\right|\leq M,\\ &\left|q\left(\frac{g(k)}{\mu(k)}\right)-\frac{g(k)}{\mu(k)}\right|>\Delta\quad\text{if}\ \left|\frac{g(k)}{\mu(k)}\right|>M, \end{aligned}$$

where Δ and M are known as the quantized errors bound and the range of $q(\cdot)$, respectively.

Therefore, in this paper, control input $u(k)$ and measurement output $y(k)$ with quantization are given by

$$u_c(k)=q_{\mu_1(k)}(k),\quad y_c(k)=q_{\mu_2(k)}(k), \tag{2}$$

where $q_{\mu_1(k)}(k)=\mu_1(k)q_1\left(\frac{u(k)}{\mu_1(k)}\right)$, $q_{\mu_2(k)}(k)=\mu_2(k)q_2\left(\frac{y(k)}{\mu_2(k)}\right)$, and satisfy

$$\begin{cases} \left|q_1\left(\frac{u(k)}{\mu_1(k)}\right)-\frac{u(k)}{\mu_1(k)}\right|\leq\Delta_1 & \text{if}\ \left|\frac{u(k)}{\mu_1(k)}\right|\leq M_1\\ \left|q_1\left(\frac{u(k)}{\mu_1(k)}\right)-\frac{u(k)}{\mu_1(k)}\right|>\Delta_1 & \text{if}\ \left|\frac{u(k)}{\mu_1(k)}\right|>M_1, \end{cases}$$

$$\begin{cases} \left|q_2\left(\frac{y(k)}{\mu_2(k)}\right)-\frac{y(k)}{\mu_2(k)}\right|\leq\Delta_2 & \text{if}\ \left|\frac{y(k)}{\mu_2(k)}\right|\leq M_2\\ \left|q_2\left(\frac{y(k)}{\mu_2(k)}\right)-\frac{y(k)}{\mu_2(k)}\right|>\Delta_2 & \text{if}\ \left|\frac{y(k)}{\mu_2(k)}\right|>M_2. \end{cases}$$

Remark 1. This kind of dynamic quantizer is composed of the parameter $\mu(k)>0$ and the static quantizer $q(\cdot)$, and has been proposed in [22–25]. In this paper, we extend the discussion in [25] to switched systems with two quantizers, and the SFDC problem has been considered. Since the quantized errors cannot be ultimately eliminated, these errors will be considered to develop the system performance. Besides, the supremums of quantizer