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Quantized $\mathcal{H}_\infty$ filtering for switched linear parameter-varying systems with sojourn probabilities and unreliable communication channels

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ABSTRACT

This paper addresses the problem of quantized $\mathcal{H}_\infty$ filtering for switched linear parameter-varying systems with both sojourn probabilities and unreliable communication channels. A more general model is developed, where both the mode-dependent logarithmic quantizer and channel noise are taken into consideration. With the sojourn probability-based switching law and parameterized Lyapunov functional, sufficient criteria promising stochastic stability of switched linear parameter- varying systems are derived. Finally, the results of the simulation show the effectiveness and feasibility of the proposed method.

1. Introduction

In the past few decades, linear parameter-varying systems (LPVSs) have become well-known for their advantages in modeling time-varying systems (TVSs), which have been widely studied and applied in various fields, such as industrial automation, networked control systems, aerospace systems, and robotics [12,29,30,42]. Note that the LPVS theory was originally developed to solve the control problems of linear TVSs. With the aid of the gain-scheduling approach, the criteria of the parameterized linear matrix inequality (PLMI) can be converted to linear matrix inequality (LMI) form. Therefore, it is of significance to study LPVSs. Recently, a great deal of effort has been devoted to research on LPVSs [13,14,38,44].

Switch systems (SSs) have been widely introduced in the research of subsystems that orchestrate switching. Subsystems are active in certain time intervals depending upon the switching law (SL). To date, SSs have been given considerable attention in both theory and practice [3,8,9,18,19,28,33,34,36,41]. In past decades, various approaches were proposed in the analysis and synthesis of SSs, such as average dwell time (ADT) [33], mode-dependent ADT [46], and persistent dwell time [1]. Nevertheless, in many physical applications [2,3,6,7,18,20,21,27], it is difficult to achieve the elements of SL. In this case, the existing SL may be useless in the stability analysis and control synthesis of SSs. To eliminate the aforementioned shortage, the sojourn probability (SP), namely, the probability of the state remaining in each subsystem, determines the SL. This

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system has been proposed for its advantages in terms of easy measurement. Up to now, increasing attention has been shifted toward SSs with SP information; see [1,25,26] and the references therein. Recently, to extend the application of SSs, scholars have drawn their attention to switched LPVSs. Note that switched LPVSs have shown superiority in designing the controller for time-varying switched systems. For example, the issue of $l_2 - l_\infty$ model reduction is considered in [43] and the filter design problem is discussed in [10]. However, as far as we know, there is no result focusing on the filter design issue of LPVSs based on the SP method.

On another research frontier, it is significant to consider factors including packet loss, quantization, and network-induced delay in the signal transmissions of networked control systems. In the practical communication channels, the signal transmissions are imperfect and some data cannot be received. Due to communication channel limits between controllers and actuators, the packet dropouts and data quantization will inevitably affect the performance and stability of systems. Fortunately, to eliminate the drawback of aforementioned systems, many effective methods are proposed in the literature [4,5,11,32,39,40,45,47]. To mention a few, [39] considers the logarithmic quantizer in $\mathcal{H}_\infty$ control design, and the signals in [24] are quantized before transmitting. On the other hand, the packet dropout may cause performance degradation, which plays a critical role in the communication constraints [16,17,23,37]. As a result, increasing attention has been devoted to mitigating the effect of packet loss. However, little attention has been allotted to the effect of both packet dropout and data quantization, not to mention channel noise.

From the above analysis, we focus on the study of quantized $\mathcal{H}_\infty$ filtering for switched LPVSs with SPs and unreliable communication channels. The main contributions of the paper are as follows. First, we derive a more general model for LPVSs, which is developed by using a mode-dependent logarithmic quantizer and the channel noise. Second, to facilitate the quantized controller design, the design conditions are expressed in the form of PLMI and are converted into an optimization problem with the aid of the gridding method. Last but not the least, the sufficient criteria are achieved by virtue of the SP-based switching law and parameterized Lyapunov functional. The simulation result is utilized to illustrate the effectiveness of the developed approach.

The remainder of the paper is organized as follows. In Section 2, the definitions of the preliminaries of the switched LPVSs are provided. The stability analysis and filter design problems are presented in Section 3. The simulation example is given in Sections 4 and 5 concludes the article.

2. Preliminaries

In this paper, we consider the following discrete-time-switched LPVSs over a probabilistic space:

$$\begin{cases} x(k+1) = A_{r_k}(\psi)x(k) + D_{r_k}(\psi)\omega(k) \\ y_0(k) = A_{y,r_k}(\psi)x(k) + D_{y,r_k}(\psi)\omega(k), \\ z(k) = A_{z,r_k}x(k) + D_{z,r_k}\omega(k) \end{cases} \tag{1}$$

where $x(k) \in \mathbb{R}^{n_x}$ is the state vector, $y_0(k) \in \mathbb{R}^{n_y}$ represents the nominal output measurement, $z(k) \in \mathbb{R}^{n_z}$ stands for the signal to be estimated, and $\omega(k) \in \mathbb{R}^{n_\omega}$ denotes the external disturbance signal, which belongs to $l_2[0, \infty)$. The parameter $\psi = \psi(k)$, where $\psi = [\psi_1\ \psi_2\ \dots\ \psi_s]$ means the vector of the a priori time-varying parameter (TVP), and belongs to a known compact set $\Theta = \{\psi :|\ \psi_j \mid\le \phi_j,\ j = 1, 2, \dots, s\}$, in which $\{\phi_j\}_{j=1}^{s} > 0$ and $\phi = [\phi_1\phi_2 \dots \phi_s]$. When $r_k = s$, the matrices (A_s, $A_{y,\,s}$, $A_{z,\,s}$, D_s, $D_{y,\,s}$, and $D_{z,\,s}$) are defined as the sth subsystem with constant matrices subject to compatible dimensions. Note that $r_k : [0, +\infty) \to \mathcal{N} = \{1, 2, \dots, N\}$ is the state-independent switching sequence.

By defining $\bar{y}_0(k)$ as the measurement received at the mode quantizer $q_s(\cdot)$, owing to the additive noises and packet dropouts of the network segments, one derives $\bar{y}_0(k) \neq y_0(k)$. In the sequence, the approximation between $\bar{y}_0(k)$ and $y_0(k)$ is constructed by adopting the stochastic process

$$\bar{y}_0(k) = \alpha(k)y_0(k) + \alpha(k)(1 - \beta(k))B_{r_k}(\psi)\upsilon(k), \tag{2}$$

where $\upsilon(k)$ is the additive channel noise of a mean square l_2 random disturbance and $B_{r_k}(\psi)$ is the known matrix of appropriate dimensions. It is noted that two random variables $\alpha(k)$ and $\beta(k)$ are mutually independent Bernoulli processes and take values of 1 and 0, where $\Pr\{\alpha(k) = 1\} = \alpha$, $\Pr\{\alpha(k) = 0\} = 1 - \alpha$, $\Pr\{\beta(k) = 1\} = \beta$, $\Pr\{\beta(k) = 0\} = 1 - \beta$ with α, $\beta \in [0, 1]$. Using the previous notation yields

$$\mathcal{E}\{\alpha(k)\} = \alpha,\ \mathcal{E}\{\beta(k)\} = \beta,\ \mathcal{E}\{\alpha(k)(1 - \beta(k))\} = \alpha(1 - \beta).$$

It can be seen from Fig. 1 that the signal $\bar{y}_0(k)$ from plant to the filter is assumed to be quantized by the quantizer that can be expressed as

$$y_f(k) = q_s(\bar{y}_0(k)) = \left[q_1(\bar{y}_0(k)^{(1)})\ q_2(\bar{y}_0(k)^{(2)})\ \cdots\ q_m(\bar{y}_0(k)^{(m)})\right]^{\mathsf{T}},$$

where $y_f(k)$ is the transmitted signal with quantization. Throughout this report, $q_j(\cdot)$ ($j \in [1, m]$) is logarithmically static and time invariant, and the set of quantization levels is estimated as

$$\mathcal{U}_s = \left\{\pm u_s^j, u_s^j = \kappa_s^{(i)} u_s^0, i = 0, \pm 1, \pm 2, \dots\right\} \cup \{0\},\ 0 < \kappa_s < 1, u_s^0 > 0.$$