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H_∞ filtering for multiple channel systems with varying delays, consecutive packet losses and randomly occurred nonlinearities

Xiu-Ying Li, Shu-Li Sun *

Department of Automation, Heilongjiang University, Harbin 150080, PR China

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ABSTRACT

In this paper, we deal with the H_∞ filtering problem for a class of multiple channel network-based systems. The system under consideration contains random varying delays, consecutive packet losses, as well as sector-bounded nonlinearities with random occurrence. A group of mutually independent stochastic variables satisfying Bernoulli distributions is introduced to model the addressed system. A linear full-order filter is designed such that, in the presence of all admissible time delays, packet losses and random nonlinearities, the dynamics of the filtering error is guaranteed to be exponentially stable in the mean square sense, and the prescribed H_∞ disturbance rejection attenuation level is also achieved. Sufficient conditions are established for the existence of the desired filters. The explicit expression of the desired filter gains can be obtained by solving the feasibility of a linear matrix inequality (LMI). The illustrative examples are given to demonstrate the effectiveness of the proposed method.

1. Introduction

With the rapid development of computer and communication technology, networks have been increasingly used in industry due to their flexibility in modularization and economic efficiency. In most industrial process, the plant, the controller and other components are often connected over network media, where signals are transmitted through networks in the form of data packets, which is known as the so-called networked control systems (NCSs). Because of the wide applications of NCSs in manufacturing plants, traffic, communication, aviation, and space flight, etc., a great deal of attention has been paid to this area. Many results for control and filtering problems have been investigated in the literatures, see [1–7] and the references therein. Much of recent work on NCSs has been done on H_∞ design which has gained persistent attention from the early 1980s [8–12]. As for H_∞ filtering, it means that design an estimator for a given system such that the L_2 gain from the exogenous disturbance to the estimation error is less than a given level γ. In contrast with the well-known Kalman filter, the H_∞ filter does not make any assumptions on the statistics properties of the process and measurement noises, which are not always available in application. So H_∞ filtering is more adaptive to the actual environment.

During the transmission through the network link from the sender to the receiver, the data packets will be lost unavoidably due to the unreliable medium and network congestion. There are several ways to deal with the data losses in network communication protocols. For example, the lost data will need to be resend in the TCP/IP which will cause more communication delay and is not acceptable for some control systems. For the real-time data transmission in NCSs, the UDP/IP is widely used because of

* Corresponding author.
E-mail address: sunsl@hlju.edu.cn (S.-L. Sun).

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the short communication delay. Thus, the transmission delays and packet losses are important issues in NCSs, which occur randomly in nature. Besides the Markovian modeling method [13,14], another popular approach to describing packet loss or transmission delay phenomenon is the Bernoulli distribution model, e.g., see [15,16] for packet loss and [17,18] for transmission delay, respectively. Different from separately considering packet losses or time delays problem, latest references have focused on dealing with packet loss and random varying delay in a unified framework [19,20]. However, in practical engineering, real systems often have multiple channels. Although there are few results when considering the cases that the individual sensor has different packet missing probability [21,22] or time delay probability [23] of different channel, most of the relevant literature has been based on the hypothesis that all the sensors have the same packet loss rates or/and time delay rates. To date, the H_∞ filtering problem for the NCSs with multiple channels where the packet loss rates and delay rates of different sensors are simultaneously different has not been fully investigated.

On the other hand, nonlinearities are recognized to exist universally in practical systems. Filtering for nonlinear dynamical systems is an important research area. Because the Takagi–Sugeno (T–S) fuzzy model has been proven to be a conceptually simple and powerful tool to approximate complex nonlinear systems [24], many researchers have paid attention to the fuzzy filtering method. For more details on the subject, see [25,26] and the references therein. It is worth mentioning that, in a networked environment, a number of practical systems are influenced by additive nonlinear disturbances, such as random failures and repairs of the components, changes in the interconnections of subsystems, sudden environment changes, etc., which also occur in a random way. The additive exogenous disturbances to the system model caused by environmental changes are named as randomly occurred nonlinearities (RONs) [27]. Take an aircraft engine system as an example [28]; the aircraft in air is in some way disturbed by uncontrolled external forces, such as wind gusts, gravity gradients, or structural vibrations, which may enter the systems in many different ways and can be modeled as the RONs. Among various type of nonlinearities, the sector-nonlinearity that covers Lipschitz conditions and norm-bounded conditions is quite general and can characterize the quantization and saturation functions in NCSs [29]; thus, it has been extensively studied in the existing literatures, e.g., see [30–32] etc. It is well known that nonlinearity and randomness are the two main causes that have resulted in the complexity of considerable systems. To the best of our knowledge, H_∞ filtering problem for multi-channel network-based systems with varying delays, consecutive packet losses and randomly occurred nonlinearities has not been properly addressed yet despite its potential in practical applications. This motivates our current work.

The main contributions of this paper can be summarized as follows. (1) A fairly comprehensive model is proposed to describe the measurement output transmission of the multiple channel network-based systems by introducing two diagonal matrices. For different sensors, the probabilities of the occurrence of random packet losses and transmission delays phenomena may differ from each other. The situation considered widely that all channels have the same packet loss rate or/and time delay rate is included here as a special case. (2) By employing the Lyapunov stability theory combined with the stochastic analysis approach, a linear full-order filter is designed such that, in the presence of all admissible time delays, packet losses and randomly occurred nonlinearities, the dynamics of the filtering error is guaranteed to be exponentially stable in the mean square sense, and the prescribed H_∞ disturbance rejection attenuation level is also achieved. (3) To reduce the design conservativeness, a sufficient condition of obtaining the H_∞ filter matrices is given in LMI form by introducing the slack variable to separate the Lyapunov matrices and the filter matrices which are coupled together.

The rest of this paper is organized as follows. In Section 2, we first give the model of multi-channel network-based systems with varying delays, consecutive packet losses and randomly occurred nonlinearities by using some Bernoulli distributed stochastic variables and then formulate the H_∞ filter design problem under consideration. In Section 3, the sufficient conditions of exponential stability in the mean square and H_∞ performance analysis are presented. The main results for the equivalent LMI constraints of the H_∞ filter design are provided in Section 4. Illustrative examples are given in Section 5 and we draw conclusions and provide some future directions in Section 6.

1.1. Notation

The following notation will be used in this paper. $\mathfrak{R}^n$ denotes the n dimensional Euclidean space. I and 0 denote the identity matrix and zero matrix with suitable dimensions, respectively. Prob$\{\cdot\}$means the occurrence probability of the event "$\cdot$". $E\{x\}$ stands for the expectation of the stochastic variable x. Superscript T is the transpose operator. I^+ is the set of positive integer. If A is a matrix, $\lambda_{max}(A)$ ($\lambda_{min}(A)$) means the largest (smallest) eigenvalue of A. The notation $X \geq Y (X > Y)$, where X and Y are symmetric matrices, means that X–Y is positive semi-definite (positive definite). $l_2[0,\infty)$ is the space of square summable vectors. diag$_n\{A_i\}$ stands for the block-diagonal matrix diag$\{A_1, A_2, \cdots, A_n\}$ and the notation vec$_n\{x_i\}$ denotes $[x_1, x_2, \cdots x_n]$ where x_i is a scalar or a matrix. The asterisk $*$ in a matrix is used to denote the terms induced by symmetry.

2. Problem formulation

The considered problem is shown in Fig. 1, in which the plant is described by the discrete-time system of the following form:

$$\begin{aligned} x_{k+1} &= Ax_k + \sum_{i=1}^{d} \alpha_{i,k} f_i(x_k) + Dw_k, \\ \tilde{y}_k &= Cx_k + v_k, \\ z_k &= Lx_k. \end{aligned} \tag{1}$$

where $x_k \in \mathfrak{R}^n$ is the state, $\tilde{y}_k \in \mathfrak{R}^r$ is the measured multi-channel output, $z_k \in \mathfrak{R}^m$ is the signal to be estimated; $w_k \in \mathfrak{R}^q$