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Distributed H_∞ filtering for a class of sensor networks with uncertain rates of packet losses

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ABSTRACT

In this paper, the distributed H_∞ filtering problem is discussed for a class of sensor networks with uncertain rates of packet losses. The packet losses occur randomly in measurements from local sensor and in transmission from the neighbor sensors are mutually independent but obey Bernoulli distribution. Different from the most results on packet losses, the rates of packet losses are assumed to be uncertain and norm-bounded. We aim to design a linear full-order filter such that the estimation error converges to zero asymptotically in the mean square while the disturbance rejection attenuation is constrained to a given level by means of the H_∞ performance index. By using the parameter-dependent Lyapunov function method, the sufficient conditions are obtained for ensuring the stochastic stability as well as prescribed H_∞ performance for the overall filtering error dynamics. These conditions are characterized in terms of the feasibility of a set of linear matrix inequalities (LMIs), and then the explicit expression is given for the desired filter parameters. Finally, one simulation example is employed to demonstrate the effectiveness of the proposed filter design technique in this paper.

1. Introduction

Over the past few decades, filtering or state estimation as one of the fundamental problems in control and signal processing, has received much attention ([1–3]). Comparing with other filters, the H_∞ filtering approach can provide a bound for the worst case estimation error without the need for knowledge of noise statistics, thus it has been widely applied into practical engineering. In recent years, H_∞ filter has become a hot research topic in control community ([4–6]).

Sensor network is an emerging technology of great interest to many academic units and research centers worldwide. A sensor network is composed of multiple sensor nodes that communicate with each other via a wireless network, and the data of each node are integrated. As usual, the sensor nodes are distributed spatially and coordinated to perform some definite global tasks. Due to the rapid developments of technologies in computing and communication, the sensor networks have been found to be intensively used in various contexts: infrastructure security, environment and habitat monitoring, industrial sensing, and traffic control, etc. ([7–9]). Recently,

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more and more scientists have come to do research on distributed filtering problems for sensor networks ([10–11]). In distributed filtering technology, all the sensors are connected by a topology network, and each sensor can receive not only the measurements form its own but also the information transmitted via internet form its neighbors. Hence, how to deal with the complicated coupling among the sensors becomes one of the most essential issues in designing the distributed filters. On this account, considerable research efforts have been made on sensor networks. In [12], a robust fault detection filter is designed for networked systems with distributed sensors. The estimation of spatially distributed processes by group of spatially distributed filters utilizing mobile sensors is considered in [13]. In [14], the distributed H_∞ filtering problem for a class of discrete-time Markovian jump nonlinear time-delay systems with deficient statistics of mode transitions is discussed. The distributed fuzzy filter is designed for a class of sensor networks described by discrete-time T–S fuzzy systems with time-varying delays and multiple probabilistic packet losses [15].

In a sensor network, the limited energy, computational power, and communication resources of the sensor nodes will inevitably lead to communication constraints in designing distributed estimators ([16–17]). For example, the information measured by sensors are usually in probability of being lost. Packet loss may occur during the data transmission because of the high maneuverability of the tracked target, intermittent sensor failures, or limited battery energy and so on. Note that such a packet loss phenomenon is a potential source of instability and poor performance in sensor networks due to the critical real-time requirement, thus has attracted considerable attention during the past few years. The distributed state estimation problem for a class of sensor networks with randomly varying nonlinearities and missing measurements is investigated in [18]. The H_∞ filter has been designed for the system with both randomly occurring sensor saturations and missing measurements [19]. A distributed fusion estimation method is presented for estimating states of a dynamical process observed by wireless sensor networks with random packet losses [20]. It should be pointed out that, most of the achievements mentioned above are of packet loss with certain rate. However, packet loss with uncertain rate is more practical, that is, the expectation of packet loss of a sensor network is not invariant due to the complexity of network environment. Moreover, plenty of samples for the expectation of packet loss are costly and time-consuming. A typical example is wireless sensor networks, where the reliability of the communication medium is greatly influenced by external environment, and the statistic on the expectation of packet loss is difficult to acquire. Therefore, it is meaningful to investigate the uncertain expectation of packet loss, especially packet losses both in local sensor and from the neighbor sensors in the design of the distributed estimators over sensor network, which giving rise to the main motivation for our current investigation.

In this paper, we aim to deal with the distributed H_∞ filtering problem for a class of sensor networks with random packet losses both in local system and from the neighbor sensors. All the sensors are connected by a fixed topology network, and the signal received by each sensor includes measurements from the local system and its neighboring nodes in probability of being lost. The packet losses are represented as a description of two independent Bernoulli-distributed stochastic processes. Different from the common studies on random packet loss process for sensor networks, the expectation of the packet loss rate is assumed to be uncertain in this paper, and the uncertainty is norm-bounded. By using the parameter-dependent Lyapunov functional approach, an easily implementable distributed filter design scheme is proposed to achieve the desired performance requirements.

This paper is composed of 5 sections as follows. In Section 2, the target plant described by a discrete-time linear system with a network of N sensors is introduced. The stochastic stability condition and H_∞ filtering design are given in Section 3. Furthermore, a simulation example is used in Section 4 to demonstrate the effectiveness of the presented filtering scheme in this paper. Finally, we summary the work and the contribution in Section 5.

1.1. Notations

In this paper, $\mathbb{R}^n$ and $\mathbb{R}^{n\times m}$ denote the n dimensional Euclidean space and the set of all $n\times m$ real matrices, respectively. $P>0$ means that matrix P is real symmetric and positive definite. $\|x\|$ denotes the Euclidean norm of the vector x. I and 0 denote the identity matrix and zero matrix with appropriate dimensions, respectively. The superscripts '-1' and 'T' stand for the inverse and transpose of a matrix, respectively. diag$\{\cdots\}$ stands for a block-diagonal matrix. The symbol $*$ denotes the symmetric part in a symmetric matrix. $E\{x\}$ and $E\{x|y\}$ stand for the expectation of the stochastic variable x and the expectation of x conditional on y, respectively.

2. Problem formulation

Consider the following linear discrete-time system:

$$\begin{cases} x(k+1)=Ax(k)+B\omega(k), x(0)=x_0 \\ z(k)=Mx(k) \end{cases} \tag{1}$$

together with N sensors subject to random packet loss described as follows:

$$y_i(k)=\alpha_i(k)C_ix(k), \quad i=1,2,\ldots,N \tag{2}$$

where $x(k)\in\mathbb{R}^{n_x}$ is the state vector, $z(k)\in\mathbb{R}^{n_z}$ is the signal to be estimated, $y_i(k)\in\mathbb{R}^{n_y}$ is the measurement output received by sensor i from system (1), and $\omega(k)\in\mathbb{R}^{n_\omega}$ is the exogenous disturbance input belonging $L_2([0,\infty),\mathbb{R}^{n_\omega})$. x_0 is the initial value. $\alpha_i(k)$ is Bernoulli distributed random variable (i.e. the values 0 and 1 stand for the failure and success of communication from plant to sensor i at time k. A, B and C_i are known constant matrices.

The N sensor nodes discussed in this paper are distributed in space and connected by a wireless network subject to a fixed topology, which characterized by a directed graph $Gr=\{\nu,\varepsilon,L\}$ of order N with the set of nodes (sensors) $\nu=\{1,2,\ldots,N\}$, set of edges $\varepsilon\subseteq\nu\times\nu$,