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Recursive approach to networked fault estimation with packet dropouts and randomly occurring uncertainties

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ABSTRACT

In this paper, we discuss the fault estimation problem for a class of time-varying networked systems in the simultaneous presence of randomly occurring uncertainties, stochastic nonlinearities and packet dropouts. The phenomena of the randomly occurring uncertainties and packet dropouts are characterized by utilizing mutually independent random variables with known occurrence probabilities. The stochastic nonlinearities are also considered which can cover many known nonlinearities as special cases. The major focus is on the design of the fault estimation algorithm such that, for all randomly occurring uncertainties, stochastic nonlinearities and packet dropouts, an optimized upper bound of the estimation error covariance is derived at each time step and the explicit form of the estimator gain is provided. As a by-product, the unknown system state is estimated simultaneously. It should be noted that a new compensation scheme is introduced to improve the estimation performance by properly using the statistical property of the imperfect measurements. In addition, the monotonicity of the trace of such an optimal upper bound with respect to the missing probability is revealed from theoretical perspective. Finally, the usefulness of the proposed estimation compensation scheme is demonstrated by a simulation example.

1. Introduction

During the past two decades, a large number of advance results have been reported to deal with the problems of the fault detection and isolation (FDI) for many practical engineering systems under high reliability requirements [1–6]. An important issue surrounding the investigation of the FDI is to estimate the fault signal firstly and then provide a residual generation scheme for fault detection or compensate the unknown fault for synthesizing the fault-tolerant control systems. Therefore, the fault estimation problem has received increasing research attention and a variety of fault estimation approaches have been given in the literature, see e.g. [7–10] and the references therein. To be more specific, a sliding mode observer scheme has been given in [7] to deal with the fault estimation problem for dynamical systems with time-varying coupling strength, and the faults have been reconstructed based on the equivalent output error injection signal. In [8], the H_∞ fault estimation problem has been studied for a class of linear discrete periodic systems with the information scheduler, where the desired fault estimation algorithm has been presented in terms of the Riccati matrix difference equation approach. Very recently, the estimation problems of randomly occurring faults over finite-horizon have been tackled in [9] for nonlinear time-varying systems with different sources of disturbances via the recursive Riccati difference equation approach and in [10] for nonlinear time-varying systems with fading measurements by means of the recursive matrix inequality method.

As is well known, the nonlinearities and uncertainties contribute the complexities of the system modeling, and hence it is necessary to handle them carefully when analyzing the complex dynamical systems under increasing performance requirements [9,11–18]. For example, the fault signal has been estimated in [9] for a class of time-varying systems with stochastic nonlinearities characterized by the statistical characteristics, and it can be seen that a novel performance requirement against different sources of disturbances has been introduced. To cope with the uncertainties, the H_∞ fault estimation scheme has been developed in [19] for a class of linear *uncertain* time-varying systems with known inputs in view of the Krein-space theory. It is worth pointing out that an auxiliary system has been introduced in [19] where the parameter uncertainties have been tackled as the disturbance terms, and a new H_∞ performance index involving the known inputs has been provided in order to better reflect the effect of the known inputs onto the whole system performance. Recently, the so-called randomly occurring uncertainties have been modeled by the Bernoulli distribution in [20,21] and some analysis methods have been given

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for discrete uncertain nonlinear systems by means of the linear matrix inequality technique. However, it should be noticed that the fault estimation problem suffers from more complexities if both the randomly occurring uncertainties and the stochastic nonlinearities are taken into account, and this is necessary to properly characterize the resulted effects onto the fault estimation performance which constitutes the focus of our present research.

On another research frontier, the study of the networked control systems (NCSs) has received increasing research attention due to its advantages such as enabling the execution of several tasks over long distance, increasing the flexibility of control system design, and reducing the complexity and the overall cost [22–27]. Nevertheless, accompanying with the developments of the NCSs, the network-induced phenomena (e.g. packet dropouts, communication delays, signal quantization, uncertain sampling periods) are inherently inevitable which would degrade the whole system performance [28–34]. Hence, a great number of results have been reported for the analysis and design of NCSs with network-induced phenomena [35,36]. For instance, based on the non-uniform sampled outputs, a novel fault estimation approach has been developed in [37] for NCSs subject to non-uniform uncertain sampling periods. Note that the packet dropout (often called missing measurement) frequently occurs and, therefore, the fault estimation problem with packet dropouts has gained persistent research attention [10,38–40]. In [39], the authors have designed a sliding-mode observer to estimate the rotor speed and the unknown load torque for the networked dc motor system with packet dropouts. Recently, the problems of FDI and fault estimation have been studied in [40] for NCSs with data packet dropouts and communication delays by developing a novel residual matching scheme, where the simultaneous estimation of fault and system state has been given. It is worthwhile to note that, compared with the fruitful results on fault estimation problems for time-invariant networked systems subject to packet dropouts with identical missing probabilities [41], the corresponding results on time-varying fault estimation problems with individual missing probabilities are still in early stages probably due to the increasing complexities. In addition, the problem of the joint estimation of fault and system state for *time-varying* networked systems with randomly occurring uncertainties and packet dropouts has not been thoroughly studied, not to mention the case when both different sensors having individual missing probability and the algorithm performance evaluation are conducted simultaneously. Hence, the fundamental question that this paper will answer is how to design the fault estimation algorithm for addressed time-varying systems with network-induced phenomena and evaluate the algorithm performance.

Inspired by the above discussions, we aim to develop the fault estimation scheme for the addressed time-varying networked systems and conduct the algorithm evaluation issue in order to meet the increasing performance requirements correspondingly. For the addressed problem, the phenomena of the randomly occurring uncertainties and packet dropouts are characterized by several random variables obeying the Bernoulli probability distribution with known occurrence probabilities. In particular, the measurements may experience the packet dropouts during the signal transmissions and different sensors are allowed to have individual missing probability, which is more general. Moreover, the relationship between the upper bound of the estimation error covariance and the missing probability is revealed, i.e., the monotonicity of the trace of the estimation error covariance with respect to the missing probability is shown. The major advantages of this paper lie in: (1) the addressed time-varying networked system is comprehensive which could cover the randomly occurring uncertainties, stochastic nonlinearities as well as packet dropouts in a same framework; (2) a compensation scheme is provided by utilizing the statistical information of the packet dropouts when designing the fault estimation algorithm; (3) the proposed fault estimation approach is capable of estimating the unknown system state as a by-product; and (4) the developed fault estimation algorithm is of a recursive form applicable for online implementations. Finally, the simulations show that the presented fault estimation scheme is capable of attenuating the adverse effects from packet dropouts and maintaining the desired performance.

The reminder of this paper is organized as follows. In Section 2, the considered system model is given and the addressed problem is formulated. In Section 3, we provide a new fault estimation algorithm which can handle the stochastic nonlinearities, randomly occurring uncertainties and packet dropouts simultaneously. In the same section, the state estimation is also obtained as a by-product. In Section 4, the algorithm performance evaluation is provided. An illustrative example is used in Section 5 to demonstrate the usefulness of the main results. Finally, the conclusion is provided in Section 6.

Notations: The notations used throughout the paper are fairly standard. $\mathbb{R}^n$ represents the n-dimensional Euclidean space. For the matrix X, X^T is the transpose. $\text{diag}\{X_1, X_2, \ldots, X_N\}$ represents a diagonal matrix with $X_1, X_2, \ldots, X_N$ in the diagonal. $\mathbb{E}\{x\}$ denotes the mathematical expectation of the random variable x. I and 0 stand for an identity matrix and a zero matrix with appropriate dimensions, respectively. The Hadamard product is defined as $\left[A \circ B\right]_{n\times n} = \left[a_{ij} \times b_{ij}\right]_{n\times n}$. Moreover, the matrices are assumed to be compatible for algebraic operations if their dimensions are not explicitly stated.

2. Problem formulation and preliminaries

In this paper, we consider the following class of discrete time-varying networked systems:

$$\bar{x}_{k+1} = (\bar{A}_k + \alpha_k \Delta\bar{A}_k)\bar{x}_k + g(\bar{x}_k, \xi_k) + \bar{F}_k f_k + \bar{B}_k \varpi_k, \tag{1}$$

$$\bar{y}_k = \Xi_k \bar{C}_k \bar{x}_k + \bar{h}(\bar{x}_k, \varsigma_k) + \upsilon_k, \tag{2}$$

where $\bar{x}_k \in \mathbb{R}^n$ is the system state, $\bar{x}_0$ is the initial state with mean $\breve{x}_0$, $\bar{y}_k \in \mathbb{R}^m$ is the measurement output, ξ_k and ς_k are zero-mean white noises, $f_k \in \mathbb{R}^f$ is the additive fault, $\Xi_k = \text{diag}\{\beta_{1,k}, \beta_{2,k}, \ldots, \beta_{m,k}\}$ characterizes the random link failure case, ϖ_k is the zero-mean process noise with covariance Q_k, and υ_k is the zero-mean measurement noise with covariance $S_k > 0$. Here, $\bar{A}_k, \bar{B}_k, \bar{C}_k$ and $\bar{F}_k$ are known and bounded matrices with appropriate dimensions.

The real-valued matrix $\Delta\bar{A}_k$ represents the norm-bounded parameter uncertainty:

$$\Delta\bar{A}_k = \bar{H}_k \mathcal{F}_k \bar{N}_k \tag{3}$$

where $\bar{H}_k$ and $\bar{N}_k$ are known real constant matrices, and $\mathcal{F}_k$ is an unknown matrix satisfying $\mathcal{F}_k \mathcal{F}_k^T \le I$.

The random variables $\alpha_k \in \mathbb{R}$ and $\beta_{i,k} \in \mathbb{R}$ ($i = 1, 2, \ldots, m$), which account for the phenomena of the randomly occurring uncertainties and packet dropouts respectively, satisfy the Bernoulli distribution taking the values of 0 or 1 with