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Fusion estimation using measured outputs with random parameter matrices subject to random delays and packet dropouts

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ABSTRACT

This paper investigates the centralized and distributed fusion estimation problems for discrete-time random signals from multi-sensor noisy measurements, perturbed by random parameter matrices, which are transmitted to local processors through different communication channel links. It is assumed that both one-step delays and packet dropouts can randomly occur during the data transmission, and different white sequences of Bernoulli random variables with known probabilities are introduced to depict the transmission delays and losses at each sensor. Using only covariance information, without requiring the evolution model of the signal process, a recursive algorithm for the centralized least-squares linear prediction and filtering estimators is derived by an innovation approach. Also, local least-squares linear estimators based on the measurements received by the processor of each sensor are obtained, and the distributed fusion method is then used to generate fusion predictors and filters by a matrix-weighted linear combination of the local estimators, using the mean squared error as optimality criterion. In order to compare the performance of the centralized and distributed fusion estimators, recursive formulas for the estimation error covariance matrices are also derived. A numerical example illustrates how some usual network-induced uncertainties can be dealt with the current observation model with random matrices.

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1. Introduction

In the last years, the use of sensor networks has experienced a fast development, since they usually provide more information than traditional single-sensor communication systems. So, the estimation problem in sensor network stochastic systems is becoming an important focus of research because of its countless practical applications, such as localization, target tracking, fault detection, environment observation, habitat monitoring, animal tracking, and communications. Different fusion estimation algorithms have been proposed for conventional systems where each sensor transmits its outputs to the fusion center over perfect connections (see e.g. [1–4], and references therein).

However, in a networked environment inevitably arise problems due to the restrictions of the physical equipment or uncertainties in the external environment that can worsen dramatically the quality of the fusion estimators designed without considering these drawbacks. Random observation losses, multiplicative noise uncertainties, sensor gain degradations and missing measurements are

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some of the random phenomena that motivate the need of designing new estimation algorithms. Furthermore, when the sensors send their measurements to the fusion center over imperfect communication networks, uncertainties as random delays or packet dropouts occurring during transmission can spoil the estimation performance. Therefore, it is not surprising that the design of new fusion estimation algorithms for systems with one of the aforementioned uncertainties (see e.g. [5–10] and references therein), or even several of them simultaneously (see e.g. [11–14] and references therein), has become an active research topic of growing interest.

Systems describing some situations with networked-induced random phenomena are special cases of systems with random parameter measurement matrices; for example, the networked systems with stochastic sensor gain degradation considered in [7], the systems with random observation losses in [8], missing measurements in [9] or with observation multiplicative noises in [10], all can be rewritten by using random parameter measurement matrices. Also, the original system with random delays and packet dropouts in [15] is transformed into an equivalent stochastic parameterized system and, in many papers, e.g. [16] and [17], systems with two-step random delays are transformed into systems with random parameter matrices.

The wide variety of real situations which can be described by systems with random parameter state transition and/or measurement matrices has encouraged the growth of interest on them and, as a consequence, a large number of results about the estimation problem in such systems have been obtained (see e.g. [18–23] and references therein). As can be observed from these references, many research efforts have been devoted to the centralized fusion estimation problem for systems with random parameter matrices and missing or randomly delayed measurements. However, although the centralized algorithms provide optimal estimators based on the measurements of all the sensors, they have an expensive computational cost when the number of sensors increases; moreover, they have other drawbacks such as bad robustness, poor survivability and reliability. In contrast, the distributed fusion method has less computation burden and more fault tolerance.

In this paper, we address the centralized and distributed fusion estimation problems in networked systems with random parameter matrices, from measurements subject to random delays and packet dropouts during the transmission. To the best of the authors knowledge, the simultaneous consideration of both uncertainties has not been investigated yet in the framework of random parameter matrices and, therefore, it constitutes an interesting research challenge.

More precisely, the current paper makes the following contributions: (1) Random measurement matrices are considered in the measurement outputs of the sensors, thus providing a unified framework to address some network-induced phenomena such as missing measurements or sensor gain degradation. (2) Besides the above network-induced phenomena, simultaneous random one-step delays and packet dropouts with different rates are supposed to exist in data transmissions from each sensor. Hence, the proposed observation model considers the possibility of simultaneous missing measurement outputs and random delays and packet dropouts after transmission, a realistic assumption in applications of networked systems where the noise is generated primarily and the unreliable network features can originate pure noise outputs before transmission. (3) Our approach, based on covariance information, does not require the evolution model generating the signal process. (4) Unlike most existing papers on random parameter matrices, where only centralized fusion estimators are obtained, in this paper both the centralized and distributed estimation problems are addressed under the innovation approach and recursive algorithms, very simple computationally and suitable for online applications, are proposed. (5) The estimators are obtained without the need of augmenting the state; so, the dimension of the designed estimators is the same as that of the original state, thus reducing the computational cost compared with the augmentation method.

The rest of the paper is organized as follows. In Section 2, we present the measurement model to be considered and the assumptions under which the centralized and distributed estimation problems are addressed. In Section 3, the innovation approach is used to derive a recursive algorithm for the centralized least-squares linear prediction and filtering estimators. In Section 4, local least-squares linear prediction and filtering algorithms are derived, and the proposed distributed estimators are generated by a matrix-weighted linear combination of the local estimators using the mean squared error as optimality criterion. A simulation example is given in Section 5 to show the performance of the proposed estimators. Finally, some conclusions are drawn in Section 6.

Notations. The notations used throughout the paper are standard. $\mathbb{R}^n$ and $\mathbb{R}^{m\times n}$ denote the n-dimensional Euclidean space and the set of all $m\times n$ real matrices, respectively. For a matrix A, A^T and A^{-1} denote its transpose and inverse, respectively. The shorthand $Diag(A_1,\dots,A_m)$ stands for a block-diagonal matrix whose diagonal matrices are $A_1,\dots,A_m$. $\mathbf{1}_n=(1,\dots,1)^T$ denotes the all-ones $n\times 1$-vector. I and 0 represent the identity and zero matrices of appropriate dimensions, respectively. If the dimensions of matrices are not explicitly stated, they are assumed to be compatible with algebraic operations. The notations $\otimes$ and $\circ$ represent the Kronecker and the Hadamard products, respectively. $\delta_{k,s}$ denotes the Kronecker delta function, which is equal to one if $k=s$, and zero otherwise. Finally, for any function $G_{k,s}$, dependent of the time instants k and s, we will write $G_k=G_{k,k}$ for simplicity; analogously, $K^{(i)}=K^{(ii)}$ will be written for any function $K^{(ij)}$, dependent on the sensors i and j.

2. Problem formulation

This paper aims to discuss the prediction and filtering estimation problems for discrete-time random signals from multi-sensor noisy measurements transmitted through different channel linked to local processors, using the centralized and distributed fusion estimation methods.

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