Information Fusion 34 (2017) 70–79

Contents lists available at ScienceDirect

Information Fusion

journal homepage: www.elsevier.com/locate/inffus

Distributed fusion filters from uncertain measured outputs in sensor networks with random packet losses

R. Caballero-Águila[a], A. Hermoso-Carazo[b], J. Linares-Pérez[b,*]

[a] Departamento de Estadística e I. O., Universidad de Jaén, Paraje Las Lagunillas s/n, 23071 Jaén, Spain
[b] Departamento de Estadística e I.O., Universidad de Granada, Campus Fuentenueva s/n, 18071 Granada, Spain

ARTICLE INFO

Article history:
Received 18 March 2016
Revised 24 June 2016
Accepted 27 June 2016
Available online 28 June 2016

Keywords:
Sensor networks
Distributed filtering
Random parameter matrices
Correlated noises
Random packet dropouts

ABSTRACT

This paper addresses the distributed fusion filtering problem for discrete-time random signals from measured outputs perturbed by random parameter matrices and correlated additive noises. These measurements are obtained by a sensor network with a given topology, where random packet dropouts occur during the data transmission through the different network communication channels. The distributed fusion estimation is accomplished in two phases. Firstly, by an innovation approach and using the last observation that successfully arrived if a packet is lost, a preliminary distributed least-squares estimator is designed at each sensor node using its own measurements and those from its neighbors. Secondly, every sensor collects the preliminary filters that are successfully received from its neighbors and fuses this information with its own one to generate the least-squares linear matrix-weighted distributed fusion estimator. The accuracy of the proposed estimators, which is measured by the estimation error covariances, is examined by a numerical simulation example.

1. Introduction

The last decades have witnessed successful applications of sensor networks in a wide range of practical areas, including industrial control and monitoring, military surveillance, environment monitoring or target tracking, among others; therefore, it is not surprising that the estimation problem in sensor network systems has increasingly attracted attention and different kinds of estimation algorithms have been proposed, according to the communication scheme, the sensor node links and the available information. Based on different data fusion techniques, measurements from multiple sensors are combined to achieve more accurate signal estimators which improve those obtained through a single sensor. Centralized fusion algorithms in sensor network systems require a fusion centre that receives the measurements from all sensors, combines and processes all the information, and provides an unique signal estimator based on all the measured data of the network.

Recently, the focus of research has shifted to sensor networks with a given network topology, and centralized fusion methods are being replaced by distributed ones. In distributed estimation problems, the signal to be estimated is observed through a group of sensor nodes distributed over a region and communicated according to a specified network topology. The general setup is that each node can receive information from its adjacent sensor nodes and this information can be processed to get a signal estimator based not only on its own information but also on that from its neighbors. Hence, in distributed estimation problems there is not one single fusion center in the network but each node acts as both a sensor and a fusion center, and acquires information from its neighbors to generate distributed estimators based on both this information and its own one; the strategy of fusing this information is of fundamental importance and leads to different distributed estimation algorithm designs. The survey paper [1] can be consulted for more details on multi-sensor fusion estimation; in [2], a look over classical results and recent advances in multisensor fusion, as well as in consensus filtering to achieve a collective fusion over the network, is presented. Also, readers interested in recent advances in distributed filtering for stochastic systems over sensor networks may go through references [3] and [4], in which a detailed overview of this field is presented.

In a sensor network environment, the measured outputs may present multiplicative noise uncertainties due to several reasons, such as natural or human-made interference, excessive system noise, hardware or intermittent sensor failures; for instance, in situations involving sensor gain degradation, missing or fading measurements, the observation equations include multiplicative noises described by random variables taking values over the interval [0, 1]. Also, the transmission capacity is often limited in

* Corresponding author.
E-mail address: jlinares@ugr.es (J. Linares-Pérez).

http://dx.doi.org/10.1016/j.inffus.2016.06.008
1566-2535/© 2016 Elsevier B.V. All rights reserved.

unreliable networks and makes random communication delays and/or transmission packet dropouts be unavoidable in the communications between neighboring nodes. Since these random phenomena may potentially deteriorate the performance of the estimators, the estimation problem in systems including some of the aforementioned uncertainties is becoming a popular challenging research topic within the scientific community. For example, [5] and [6] are concerned with the problem of distributed fusion estimation over peer-to-peer sensor networks with random packet dropouts; the optimal distributed fusion filtering problem in systems with missing measured outputs, as well as random transmission delays and packet dropouts, is studied in [7] and [8]; recently, the distributed filtering problem for a class of multi-sensor stochastic uncertain systems with uncertainties caused by correlated multiplicative noises is addressed in [9]. The survey papers [10] and [11] and references therein can be consulted for further information.

In relation to the mentioned random uncertainties, it is worth noting that random parameter measurement matrices can be used to describe, for example, missing sensor measurements or multiplicative noises in the observation equations (see, e.g. [12] and [13]). Also, systems with random delays and packet dropouts, or systems with two-step random delays, can be transformed into systems with random parameter matrices (see, e.g. [14], [16] and [15]). Consequently, systems with random parameter measurement matrices provide an appropriate unified context for modeling the aforementioned network-induced random phenomena; this fact has encouraged an increasing interest in the signal estimation problem for such systems (see e.g. [17–23] and references therein). On the other hand, random matrices have also been used for the parameter estimation problem. In [24], a model with random measurement matrices is considered in the context of distributed parameter estimation over a coherent multiple access channel; an optimal inter-sensor collaboration scheme is designed for centralized parameter estimation under unknown network topologies and non-zero collaboration cost.

Furthermore, it should be noted that the classical assumption of independence between different sensor noises is somewhat conservative and can be restrictive in many real world problems in which correlation and cross-correlation of the noises may be present. For this reason, the latest research papers on signal estimation usually weaken this assumption and the estimation problem with correlated and cross-correlated noises has become an active research topic, not only in systems with deterministic matrices, but also in those with random parameter matrices (see, e.g. [19–22] for systems with random parameter matrices, and [25] and [26] for the case of deterministic matrices, among others).

Driven by the above considerations, the goal of this paper is to study the distributed filtering problem for a signal observed by a sensor network, when the measured outputs of the different sensors are perturbed by random parameter matrices and correlated additive noises. A peer-to-peer network topology is considered, with a fusion center which locally estimates the signal at each individual sensor node, using not only its own measurements but also those from its neighboring sensors according to the network topology. The information packets are transmitted between the neighboring sensors via unreliable communication channels, thus being subject to random packet losses. Different sequences of Bernoulli random variables with known probabilities are employed to describe the random packet dropouts in the different communication channels.

Under these assumptions, and without requiring the knowledge of the signal evolution model, the distributed estimation problem is addressed in two stages. Firstly, at each sensor node, a preliminary least-squares linear signal filter is obtained collecting the measurements from the neighboring sensors; when the current measurement is lost during transmission, the last successfully received one is used. After that, at the second stage, each node computes the least-squares matrix-weighted linear combination of the neighboring preliminary ones that successfully reach it.

The main contributions of the current research can be highlighted in the following threefold:

(1) *Information on the signal process:* our approach, based on covariance information, does not require the evolution model generating the signal process to design the proposed preliminary and distributed filtering algorithms; nonetheless, they are also applicable to the conventional formulation using the state-space model, even in the presence of state-dependent multiplicative noise, as it is shown in Section 4.
(2) *Signal uncertain measured outputs:* random measurement matrices and cross-correlation between the different sensor noises are considered in the measured outputs, thus providing a unified framework to address different network-induced phenomena, such as missing measurements or sensor gain degradation, along with correlated measurement noises.
(3) *Random packet losses:* the distributed estimation problem is developed in a peer-to-peer network where each node acts as both a sensor and a fusion center and the information packets are transmitted from the neighboring sensors via unreliable communications channels that can cause random packet dropouts.

A common denominator of the current research and other authors' previously published results is the use of covariance information and the innovation approach for the estimation. Nevertheless, the distributed filtering problem in partially connected networks has not been addressed in any of the authors' previous papers, so it is a novelty in itself and involves some additional troubles in comparison with our previous research. In fact, it is considered that the measurements for the estimation are obtained by a group of sensors distributed over a region, which are communicated according to a specific network topology. The main difficulties to address this problem, compared to previous papers, lie in the following two facts: a) The sensor network is not fully connected. Since this feature must be preserved during the filter design, some difficulties arise to guarantee the filter optimality. Actually, the use of zeros to weight those measurements from non-connected sensors is commonly handled by using generalized inverses, which leads to suboptimal approaches; in this paper, however, optimal estimators are designed by a new methodology that avoids the use of pseudo-inverses. b) The distributed error covariance matrices depend on random packet losses in the transmissions. However, these error covariances are upper-bounded by the preliminary ones, as it is shown in the numerical example.

The outlines of this paper are summarized as follows. In Section 2 we present the sensor network and the assumptions under which the distributed estimation problem will be addressed. The proposed distributer filter design is carried out in Section 3. More specifically, in Section 3.1 the observation model is rewritten in a compact form, for notational simplicity. In Section 3.2, a recursive algorithm for the preliminary least-squares linear filter is derived using an innovation approach. Section 3.3 describes how the proposed distributed filter is generated at each sensor node by a matrix-weighted linear combination of the neighboring preliminary ones that successfully reach the node, using the mean squared error as optimality criterion. The performance of the proposed estimators is illustrated by numerical simulations in Section 4. The paper concludes with some final comments in Section 5 and two appendices which include the derivation of the proposed preliminary and distributed filtering estimators, respectively.