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Optimal recursive estimation for networked stochastic uncertain systems with fading measurements and time-correlated channel noises

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HIGHLIGHTS

- Time-correlated measurement noises, correlated multiplicative noises and fading measurement are considered.
- An equivalent model with finite-step correlated virtual noises and multiple measurement delays is developed.
- Correlation functions among noise, state, measurement, and innovation are analyzed.
- Linear minimum variance optimal linear estimators are presented using an innovation analysis approach.

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ABSTRACT

This paper is concerned with the optimal linear estimation problem for discrete-time stochastic system with time-correlated channel noises, correlated multiplicative noises and fading measurements. The time-correlated channel noises are described by a seemingly ARMA (autoregressive moving average) model. By an equivalent transformation, the original system is transformed into the same-dimension system with finite-step correlated virtual noises and multiple measurement delays. The statistical properties of correlation functions among noise, state and measurement are analyzed. Further, the optimal linear state estimators including filter, predictor and smoother are derived by using an innovation analysis approach. A simulation example shows the effectiveness of the proposed algorithms.

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1. Introduction

In the networked control systems (NCSs), all kinds of complex problems often appear in data communication because of the unreliability of the network. It also puts forward higher requirements for the estimation and control algorithms in order that the algorithms can be applicable to a wide range in NCSs [1].

In most estimation algorithms, the noises are assumed to be uncorrelated generally, i.e., the process and measurement noises are white [2,3]. However, in practical applications, many cases will lead to the correlated noises, such as the presence of the same background noises or interference sources in the environment. Therefore, the optimal state estimation for systems with correlated noises has been one of the most significant research frontiers in NCSs in recent years. According to the range of the noise correlation time, it consists of three types: correlated noises in simultaneousness (i.e., the process

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and measurement noises are correlated at the same instant) [4–12], finite-step correlated noises (i.e., the process and measurement noises are auto-correlated and/or cross-correlated within a finite time interval) [13–27] and time-correlated noises (i.e., the process and measurement noises are auto-correlated and/or cross-correlated in the whole time) [28–34].

Under the condition of correlated noises in simultaneousness, the estimation problems for systems with random transmission delays and lost measurements are studied in [5–7], respectively. In [8,9], the particle filter and cubature information filter of nonlinear systems are derived under assuming correlated noises in simultaneousness. In the case that the process and measurement noises are correlated at the same time and the noise variances are uncertain, the measurement fusion and state fusion estimators are addressed in [10–12], respectively.

The estimation problems of the finite-step correlated noises in NCSs were also hot topics in last few years. In [13–18], the minimum-variance estimators and distributed fusion estimators for NCSs with packet dropouts, transmission delays and multiplicative noises are designed, under the assumptions of one-step auto-correlated and/or two-step cross-correlated noises, respectively. In the case of multi-step auto-correlated process noises, the recursive optimal filter is derived in [19–21] for the discrete-time systems with missing measurements and multiplicative noises, respectively. An optimal filter is derived for systems with stochastic nonlinearities, missing measurements, and finite-step auto-correlated and cross-correlated noises [22]. However, the filters are only designed in [19–22], but multi-step predictor and smoother are not reported. Recursive estimation problems are also addressed for the networked descriptor systems with packet dropouts and one-step auto-correlated measurement noises and correlated process noises in simultaneousness [23]. In [24], the results in [23] are extended to tackle the more general arbitrary finite-step auto-correlated and cross-correlated noises. For systems with stochastic parameters, packet dropouts or fading measurements, and finite-step correlated noises, optimal linear estimators are proposed in [25,26], respectively. Assuming that the state-space model is unknown, the least-squares linear filter and smoother are derived for systems with multi-step cross-correlated noises [27].

It is well known that the system noises are finite-step correlated when the process noise and measurement noise are based on a moving average (MA) model [14–26]. Sometimes, the system noises have an autoregressive model with the order of n (AR(n)), which will result in the time-correlated noises. In recent literature [28–34], the optimal and suboptimal estimation problems are investigated, where the measurement noises are modeled as AR(1). However, the autoregressive moving average (ARMA) model has a more general form for the colored noise. It is true that the AR or MA model is a special case of ARMA model when the coefficient parameters of its MA or AR process are zeros. ARMA is one of the most important time series model. It is widely used in the fields of meteorology, hydrology, economy and so on [35].

Meanwhile, another active research topic in NCSs is the estimation problem over fading measurements. The essence of packet dropouts in NCSs can be seen as a special case of the fading measurements. The main causes of fading measurements are the following aspects: (1) The aging of the sensor will often lead to random fading of the signal. (2) When the signal is transmitted through a communication medium, part of the energy will randomly be converted into heat energy or be absorbed by the communication medium, which results in the fading of the signal.

In [36,37], the unscented Kalman filter with sufficient conditions for convergence is derived for the stochastic nonlinear systems with multiple fading measurements. However, the process and observation noises are assumed to be uncorrelated. The recursive unbiased filter is designed for systems with random parameter matrices, multiple fading measurements and correlated noises [38]. However, one-step auto- and two-step cross-correlated noises are only discussed. Under the condition that the process and measurement noises are white, the state estimation problem for discrete time-invariant linear systems with fading wireless channels is studied in [39].

These considerations in above literature motivate us to build the optimal linear estimators for NCSs with fading measurements and time-correlated noises as shown in Fig. 1. By an equivalent transformation, the original system with time-correlated noises is transformed into a new system with finite-step correlated virtual noises and multiple measurement delays. Then, based on an innovation analysis approach, we derive the optimal linear estimators and corresponding estimation error covariance matrices for the state. Compared with the existing results, the main contributions are three aspects: (1) The existing results mainly focus on MA or AR noises. However, the time-correlated noises in this paper follow a seemingly ARMA model. So the noises considered in this paper are more general. (2) Through the direct innovation analysis, the proposed method avoids the state augmentation. (3) The optimal linear estimators including filter, predictor and smoother as well as the corresponding error covariance matrices are presented.

The topics covered in this paper are summarized as follows. In Section 2, the problem considered is formulated. Section 3 discusses system transformation and some auxiliary lemmas. In Section 4, the optimal linear estimators (filter, predictor and smoother) are derived using an innovation analysis approach. In Section 5, a simulation in target tracking is presented to show the effectiveness of the proposed estimators. At last, we summarize the results presented in this paper in Section 6.

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