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Linear estimation for networked control systems with random transmission delays and packet dropouts

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ABSTRACT

In networked control systems, random delays and packet dropouts are inevitable during data transmissions due to the limited communication capacity. The phenomena of random delays and packet dropouts of both sides from a sensor to an estimator and from a controller to an actuator are modeled via employing two groups of Bernoulli random variables. By defining some new variables, the original system with random delays and packet dropouts is equivalently transformed into a stochastic parameterized system. The optimal linear filter, predictor and smoother in the linear minimum variance sense are presented via the orthogonality projection approach. They depend on the probabilities of the stochastic parameters. The solutions to the optimal linear estimators are given by three equations including a Riccati, a Lyapunov and a simple difference. The stability of the proposed estimators is analyzed. At last, a sufficient condition for the existence of the steady-state estimators is given for time-invariant systems. Two examples are provided to verify the effectiveness of the proposed algorithms.

1. Introduction

Over the past decades, the research on control and estimation problems for networked control systems or sensor networks has attracted considerable attention due to the wide applications in target tracking, transportation, communication, control, and so on [2–4,7–38]. In networked systems, data packets are transmitted in both the sensor-to-estimator (S-E) channel and the controller-to-actuator (C-A) channel. Due to the limited communication capability, random delays and packet dropouts are almost inevitable in data transmissions. Therefore, the research on modeling, estimation and control problems of networked systems is difficult and challenging [6,27].

In networked systems, transmission delays and packet dropouts are usually random in nature and can be described by stochastic parameters [5]. The design problems of the controllers for networked control systems have been reported in many literatures, see, e.g., [2,18,25,29–31,35]. Since we aim at designing the estimators in this paper, we mainly discuss the research status of estimation problems in networked systems. For systems with random delays, Ray et al. [11] present a full-order linear filter with the Kalman-like form. However, the optimal linear filter is not with the given form since there is the one-step correlated measurement noise. Therefore, it is really suboptimal. Zhang et al. [36] design the optimal and suboptimal filters via an innovation reorganized approach. In Su et al. [17], the full- and reduced-order l_2–l_∞ filters are designed for Takagi–Sugeno fuzzy delayed systems. The robust estimators are also studied in [26,33]. However, packet dropouts are not taken into account in the aforementioned references.

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For systems with multiple packet dropouts, a steady-state suboptimal H_2 filter is presented based on a unified stochastic parameterized model via the linear matrix inequality (LMI) approach [12]. Furthermore, the linear minimum variance optimal linear estimators are presented via the innovation analysis approach [20] and H_∞ filter is also designed via the LMI approach [38]. In [22], a recursive linear unbiased minimum variance filter is designed for systems with finite packet dropouts. However, it is only involved for the case of packet dropouts in the S-E channel in the references [12,38,22]. Recently, the estimation problems with packet dropouts in both S-E channel and C-A channel are studied via the projection method [7,21] and the LMI approach [13], respectively. The mean square stability of estimators is also analyzed in [37]. The aforementioned results are all dependent on the packet dropout rates. In fact, the information of time stamps of data packets is available and can be used. Sinopoli et al. [15] present a Kalman filter with intermittent observations. It depends on the knowledge whether a packet at each time is received or lost. However, the proposed filter does not have the steady-state property since the filtering gain depends on the stochastic parameters. However, the multiple random delays are not taken into account in the aforementioned references.

The aforementioned results are separately focused on random delays or packet dropouts. However, random delays and packet dropouts almost exist in networked control systems simultaneously. Then, a key issue is how to establish a suitable model to describe them simultaneously. Recently, the estimation problems with both random delays and packet dropouts have been reported, see, e.g., [3,8,10,12,14,23,24,34], including the stochastic filter dependent on the knowledge whether a packet is received or lost [14], Robust H_∞ filters for nonlinear networked systems [3,34], the optimal and adaptive filters [8,10], and distributed fusion estimators for multi-sensor or multi-channel systems [9,28]. In [23], a packet at the sensor side is retransmitted several times to avoid packet dropouts as far as possible, however, which can lead to the network congestion. Two kinds of optimal linear filters with/without time stamps have been designed for systems with measurement transmission delays and losses in [24] where a packet is only transmitted once and a packet at most is used once for updating the estimate. However, the single-side case in the S-E channel is only involved. So far, the both-side case in the S-E channel and C-A channel is not yet considered, which is more general in networked control systems. This motivates our work in this paper.

In the present paper, we consider the optimal linear estimation problem for networked control systems with bounded transmission delays and multiple packet dropouts of both sides in the S-E channel and C-A channel. Two groups of Bernoulli distributed random variables are employed to describe the phenomena of the random delays and packet dropouts. By defining a group of new variables, the system with random delays and packet dropouts is transformed into the stochastic parameterized system with the known statistical probabilities. Optimal linear estimators dependent on the probabilities are obtained in terms of three difference equations including a Riccati, a Lyapunov and a simple difference governed by the distributions of the stochastic parameters. The designed estimators can be easily implemented since they are linear and simple. The stability of the estimators is analyzed. It is worthwhile to note that the results in this paper cannot be obtained by the simple extension from the single-side case in the S-E channel of [24]. The filtering gain of the obtained filter is affected by the control input since there are random delays and packet dropouts. This is different from the standard Kalman filter with a deterministic control input [1] where the filtering gain is not affected by the control input. So the proposed filter does not have the steady-state property in general when the control input is time-varying. However, here we do not consider the design problem of the controller and consider it to be known. At last, a sufficient condition of the existence for the steady-state filter is given for time-invariant systems.

2. Problem formulation

Consider the discrete time-varying linear stochastic system (see Fig. 1):

$$x(t+1) = \Phi(t)x(t) + B(t)\tilde{u}(t) + \Gamma(t)w(t) \quad (1)$$

$$z(t) = H(t)x(t) + D(t)\tilde{u}(t) + v(t) \quad (2)$$

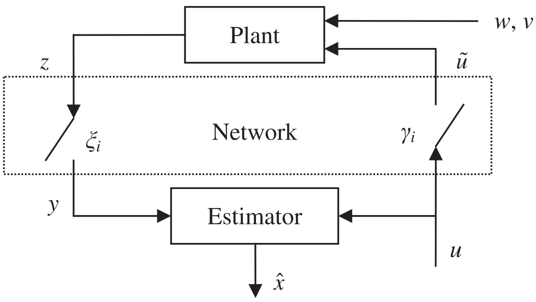

Fig. 1. NCS schematic with random delays and packet dropouts.