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UKF-based nonlinear filtering over sensor networks with wireless fading channel

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ABSTRACT

Stochastic stability of UKF-based nonlinear filter for general nonlinear system over a wireless sensor network with fading channel is studied. In the process of signal transmission, sensor data may be fluctuant or even dropout due to fading channel. By considering signal fluctuation and transmission failure simultaneously, we establish sufficient conditions of statistical convergence property that ensure the stability of the unscented Kalman filter. It is shown that the mean error covariance with respect to fading process is bounded and converges to a steady state value. Moreover, for scalar measurement and Rayleigh fading channel, "explicit expressions" for sequences which can be used as upper bounds on the expected error covariance will be got. Numerical examples are given to illustrate the effectiveness of the developed techniques.

1. Introduction

Wireless sensors and actuators have become an interesting alternative with the rapid evolution of wireless sensor networks, such as [6,19,3,7]. A large number of wireless sensors and actuators, which are capable of sensing, collecting and processing information, have the advantages of easy maintenance, expansion, convenience and high efficiency and so on. They can be placed where wires cannot go, or where power sockets are not available. However, wireless sensor networks are more vulnerable to the influence of the external environment compared with cable communication. Depending on the application, the wireless channel can be constant or time-varying caused by moving machines, people, vehicles and so forth. Therefore, using wireless communication channel will result in either slow or fast fading due to several effects such as variations in multi-path interference and shadowing, which frequently lead to communication delay and more network packet loss [25]. When the estimator is implemented across unreliable communication channels in wireless multi-hop sensor networks, the nature of the networks, such as channel fading [17], packet loss [10], communication delay [9], asynchronous sampling and so on, cannot be ignored. As a result, these bring new challenges to the design of the estimator.

Early interesting results on estimation of systems with wireless communication channel can be found in Sinopoli et al. [26] for observation losses of linear time-invariant system (over a single communication link) undergoing a Bernoulli process γ_k. The existence of a threshold has been shown such that, if the observation arrival rate lies below this threshold, then the expected error covariance becomes unbounded, see also [18,11,12]. Afterwards these results were extended in various espects, such as: to time-homogeneous Markovian observation loss processes of linear system with a single link in Huang

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and Dey [8], Xie and Xie and other references [27,28,31,4], to extended Kalman filter (EKF) of nonlinear system by Reif with intermittent observations [11], which model the arrival of the observations as a random process and a maximum dropout interval, to unscented Kalman filter (UKF) for nonlinear system underdoing i.i.d. observation losses by Li and Xia [13]. Instead of the expected value of the covariance matrix, different critical packet dropout probabilities have been obtained by using other criteria [8,4,23]. In these literatures, stability of the estimation error covariance matrices in the mean sense has been analyzed by a modified discrete-time Riccati recursion effectively. Recently, to counter the effect of random packet loss, the paper [24] proposes a linear coding method to preprocess the measured output.

For continuous fading distributions, an analysis of the expected error covariance for scalar systems can be found in [15,5] where the expected error covariance is always bounded. In [15], KF over fading channels is studied under the assumption that the receiver can decide whether to accept or to reject each noisy packet. The work [5] follows the line of research in [2] and proves that the mean error covariance of the remote KF is bounded and convergent, where the probability of transmission failure is assumed to be zero. And the authors provide concrete results on how to obtain deterministic and asymptotically convergent bounding sequences on the average error covariances which are hard to compute analytically. In [29], the authors consider the stability of the time-varying KF connected to the plant through fading channels subject to both transmission failure and signal fluctuation. Lower and upper bounds for the mean error covariance matrix are provided in the form of a modified Lyapunov iteration and a modified Riccati iteration. Furthermore, fading channels can be partially compensated for through control of bit-rates and the power levels used by the radio amplifiers, see, e.g., [20–22]. Unfortunately, to the best of the authors' knowledge, the nonlinear filter design for nonlinear dynamical system with fading observations has not been fully investigated, not to mention the case that the coexistence of transmission failure and signal fluctuation. For nonlinear system, the UKF is a fast growing area playing a crucial role in many fields. And the stability is the essential condition for the UKF working well [30].

Motivated by this, we focus on the UKF-based state estimation for nonlinear dynamic system over wireless sensor network. Due to that the coexistence of transmission failure and signal fluctuation is natural in wireless communication channels, both of them are considered. The main contribution of this paper is studying the stability of the modified UKF with faded observations. By using elements of stochastic stability theory, it is shown that the mean error covariance of the modified UKF with respect to fading process remains bounded and also converges to a steady state matrix. The result obtained depends upon the fading channel gain and the transmission failure rate. Moreover, for special case of scalar observations and specific fading distribution, we provide "explicit bounding matrix sequences" that overbounds the mean error covariance matrix and also converges to a steady state value. As pointed out by Dey [5], these bounds provide a simple way to compute realistic bounds on the expected error covariance, and it will be quite useful when one wants to minimize the mean error covariance for such sensor network. The present paper expands upon our recent conference contribution [14] and gives "explicit expressions" for sequences which can be used as upper bounds on the expected error covariance for the special case.

The remainder of the paper is organized as follows: Section 2 describes the effect of fading channel and the problem of the UKF with faded observations. In Section 3, we establish sufficient conditions for boundedness of the estimation error covariance. For special cases of scalar observations and Rayleigh distribution, we provide "explicit bounding matrix sequences" that over bound the mean error covariance matrix and also converge to a steady state value. In Section 4, we give two examples to illustrate the effectiveness of the developed techniques. In Section 5, we state our conclusion and give directions for future work.

2. Problem formulation

Consider the following uncontrolled discrete-time nonlinear model:

$$\begin{aligned} x_{k+1} &= f(x_k, u_k) + w_k \\ z_k &= h(x_k) + v_k \end{aligned} \tag{1}$$

where, $k \in \mathbf{N}$ is discrete-time, $\mathbf{N} = \{0, 1, \ldots\}$. $x_k \in \mathbf{R}^n$ represents the state vector, $u_k \in \mathbf{R}^m$ represents the control, and $z_k \in \mathbf{R}^q$ represents the observation. $w_k \in \mathbf{R}^w$ and $v_k \in \mathbf{R}^v$ are the process noise and the observation noise vectors, respectively, $\mathbf{R}^n$ denotes the n-dimensional Euclidean space. Assume that the nonlinear function f and h are continuously differentiable, and the initial distribution of x_0 is Gaussian with mean zero and covariance matrix P_0. Moreover, x_0 is uncorrelated with w_k and v_k. w_k and v_k are assumed to be uncorrelated zero-mean Gaussian white noise sequence. $E[w_k w_j^T] = Q_k \delta_{kj}$, $E[v_k v_j^T] = R_k \delta_{kj}$. Q_k and R_k are positive definite matrices.

In this article, we are interested in estimating the state of the nonlinear model (1) by using the unscented Kalman filtering approach.

2.1. Effect of channel fading

In this part we will describe that how to model the effect of a wireless fading communication channel on the observations. To remotely estimate the state, the nonlinear system is observed by a wireless sensor which yield discrete-time