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Robust unscented Kalman filter with adaptation of process and measurement noise covariances

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ABSTRACT

Unscented Kalman filter (UKF) has been extensively used for state estimation of nonlinear stochastic systems, which suffers from performance degradation and even divergence when the noise distribution used in the UKF and the truth in a real system are mismatched. For state estimation of nonlinear stochastic systems with non-Gaussian measurement noise, the Masreliez–Martin extended Kalman filter (EKF) gives better state estimates in relation to the standard EKF. However, the process noise and the measurement noise covariance matrices should be known, which is impractical in applications. This paper presents a robust Masreliez–Martin UKF which can provide reliable state estimates in the presence of both unknown process noise and measurement noise covariance matrices. Two numerical examples involving relative navigation of spacecrafts demonstrate that the proposed filter can provide improved state estimation performance over existing robust filtering approaches. Vision-aided robot arm tracking experiments are also provided to show the effectiveness of the proposed approach.

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1. Introduction

Kalman filter has been one of the most popular state estimation techniques for linear stochastic systems. This is partly due to its wide range of applications in industrial areas such as target tracking, spacecraft navigation and signal processing [1,2]. One main concern for Kalman filter is that it requires an accurate system model and exact noise statistics information. These limitations, however, are too strong to be always satisfied in real applications. The lack of exact information may induce large state estimation errors and even filter divergence. To overcome this problem, a number of robust filters have been proposed to mitigate the impact of the inaccurate information [3–17]. Typically, two strategies can be used to address the filtering problem with unknown noise statistics including estimating the noise statistics [8,10,14–16] and ignoring the noise statistics [13]. Although the H_∞ filter can guarantee bounded state estimation error, it can in fact be worse than those generated by the Kalman filter in a least-squares sense. The adaptation of noise covariances has been an important topic for developing robust Kalman filters. One of the methods for adaptation is to use a scale or a matrix factor as a multiplier to the process or measurement noise covariance matrices so that the adaptation against both the system uncertainty and the measurement malfunctions is possible.

For state estimation of nonlinear stochastic systems, extensions and generalizations have been proposed such as the robust extended Kalman filter (EKF) [18–21] and the Huber-based divided-difference filter [22,23]. In [18], the Masreliez–Martin method was used to develop a robust EKF in the case when the process noise has a Gaussian distribution and the measurement noise has a non-Gaussian distribution. In [19], an adaptive fading EKF was proposed by introducing a forgetting factor in the gain matrix. In [20], a robust EKF is proposed for the attitude estimation of small satellite. A forgetting factor is adopted in the gain matrix to compensate measurement uncertainties and faults. These results are extended to develop a robust EKF by using a matrix forgetting factor in [21]. Simulations results in [18–21] show that robust filters outperform the standard EKF when the noise covariances used in the robust filters and the truth are mismatched. Although it is straightforward and simple to develop robust EKF, the EKF suffers from its own drawbacks such as instability due to linearization and costly calculation of Jacobian matrices. Another alternative for state estimation of nonlinear stochastic systems is the particle filtering approach [24–28]. In [24], the particle Markov Chain Monte Calro (PMCMC) method has been developed for nonlinear non-Gaussian systems with unknown static parameters, which are MCMC algo-

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rithms that use a particle filter as a proposal mechanism. In [25], particle filter and smoother have been proposed for nonlinear systems by incorporating sequential parameter learning strategy. The key assumption for the proposed filter and smoother is the existence of a conditional sufficient statistic structure for the parameters. In [26], a generic approach has been developed called the sequential Monte Carlo (SMC^2) method. It should be pointed out that the SMC^2 is a sequential but not an on-line algorithm and the computational load increases with iterations owing to the associated cost of the MCMC steps. Nevertheless, the SMC^2 may offer several advantages over PMCMC in batch estimation scenarios [26]. In [27], nested particle filters have been proposed to approximate the posterior probability measure of the static parameters and the dynamic state variables of the system of interest. Unlike the SMC^2 scheme, the nested particle filters operate in a recursive manner and the computational complexity of the recursive steps is constant over time. In [28], the similarities and differences among the multiple try Metropolis (MTM) schemes and the particle Metropolis-Hastings (PMH) method have been investigated.

As stated in [29], it is easier to approximate a probability distribution than to approximate an arbitrary nonlinear transformation, the unscented Kalman filter (UKF) has been proposed for state estimation of nonlinear stochastic systems [29]. The main advantage of the UKF is that it does not use any linearization for calculating the state predictions and covariances. Many robust UKF variants have been proposed [30–40]. For instance, the H_∞ performance criterion has been combined with the UKF to improve the robustness against model errors and noise uncertainty in [30]. However, it is difficult to determine the performance level and the weighting matrices. In [31–34], several robust UKF algorithms have been proposed for nonlinear stochastic systems with measurement malfunctions. An adaptation scheme with multiple scale factors is used for adapting the measurement noise covariances so that only the data of the faulty sensor is scaled and any unnecessary information loss is prevented. Their applications in small satellite attitude estimation show that the fault can be detected accurately and the estimation performance can be improved greatly. In [35], the moving windowing approach is applied to develop an adaptive UKF where the historical innovation sequences are used to evaluate the measurement noise covariance. Simulation results show that the adaptive UKF outperforms the standard UKF when the precise knowledge of measurement noise statistics is unknown. It is shown that the performance can be further improved by estimating the measurement noise covariance using the present innovation [36]. It should be pointed out all the aforementioned work focus on adaptation of measurement noise covariance and the process noise parameters are not estimated. As a result they may be susceptible to unmodeled errors in the state propagation.

The case of unknown process noise covariance is often encountered in maneuvering target tracking and navigation systems [4], large state prediction errors may occur if the process noise covariance is not designed correctly. To this end, adaptation strategies have been proposed for process noise covariance in the UKF. For example, the robust UKF was developed for system fault detection in [37–39], where an adaptation scheme is carried out to detect the system fault. The application in nanosatellites attitude estimation shows that the robust UKF is fault tolerant against the sensor malfunctions. In [40], the fading factor is adopted to reduce the effect of the dynamics model errors and a robust estimation strategy is introduced to suppress the measurement model errors. Although the effect of the dynamic model error and the measurement error can be reduced simultaneously, the process and the measurement noise should be Gaussian distributions with known covariance matrices [37–40].

In this paper, we attempt to propose a robust UKF for nonlinear stochastic systems with Gaussian process noise and non-Gaussian measurement noise. The Masreliez–Martin EKF has been developed for such systems [18]. However, the process noise and the measurement noise covariance matrices should be known. To improve the estimation performance and practical usefulness, this paper aim to propose a robust UKF with adaptation of the process and the measurement noise covariance matrices. The fading factor is adopted to adjust the pre-designed process noise covariance and the innovation sequences are used to evaluate the measurement noise covariance. The simulation results are provided via relative navigation of spacecrafts. Experiments are also presented to evaluate the effectiveness of the adaptation strategies.

The rest of this paper is organized as follows. The problem of state estimation for nonlinear stochastic systems is formulated in Section 2. In Section 3, adaptation strategies are provided to estimate the process noise and measurement noise covariance matrices, which are used to develop a robust Masreliez–Martin UKF. In Section 4, two numerical examples are provided to illustrate the effectiveness of the proposed filter. In Section 5, experiments involving robot arm tracking are provided to show the effectiveness of the proposed adaptation strategies. Conclusion is drawn in Section 6.

2. Problem formulation

2.1. Problem formulation

Consider the following discrete-time nonlinear stochastic system

$$x_k = f(x_{k-1}) + w_{k-1} \tag{1}$$

$$z_k = h(x_k) + v_k \tag{2}$$

where $x_k \in \mathbb{R}^n$ and $z_k \in \mathbb{R}^m$ are the system state and the measurement vectors at time step k, respectively. f and h denote the system transition function and the measurement function, respectively. The process noise w_{k-1} is zero-mean white Gaussian with covariance matrix Q_{k-1} and the measurement noise v_k is represented by

$$p(v_k) = (1-\varepsilon)p_N(v_k) + \varepsilon q(v_k) \tag{3}$$

where $p(v_k)$ denotes the probability density function of v_k. $p_N(v_k)$ is the nominal Gaussian density function $\mathcal{N}(v_k, 0, R_{k,1})$ and $q(v_k)$ is the contaminating probability density $\mathcal{N}(v_k, 0, R_{k,2})$. The parameter $\varepsilon \in (0, 1)$ is called the degree of contamination.

The Masreliez–Martin EKF has been developed for nonlinear stochastic systems in the case when the process noise has a Gaussian distribution, and the measurement noise has a non-Gaussian distribution [18]. It should be pointed out that the process noise covariance Q_{k-1} and the nominal measurement noise covariance matrix $R_{k,1}$ are assumed to be known in the Masreliez–Martin EKF. However, the noise covariance matrices Q_{k-1}, $R_{k,1}$ and $R_{k,2}$ are generally unknown accurately in real world applications. Moreover, it is known that the UKF has been shown to generally perform better than the EKF and the UKF provides a derivative-free alternative to the EKF in the framework of Bayesian estimation.

To improve the performance and practical value of the robust Masreliez–Martin EKF, the aim of this paper is to develop a modified Masreliez–Martin UKF for the discrete-time nonlinear stochastic system (1)–(2) with unknown noise covariance matrices.

2.2. Background

For state estimation of nonlinear systems with Gaussian noise, Julier and Uhlmann presented a novel filter called the UKF in [29]. Unlike the EKF which approximates the nonlinear state and measurement equations using linearization, a set of carefully chosen

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