Desensitized cubature Kalman filter with uncertain parameters

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Abstract

In this study, a robust desensitized cubature Kalman filtering (DCKF) is proposed for nonlinear systems with uncertain parameters. Unlike the cubature Kalman filtering, the desensitized cost function is introduced by penalizing the posterior covariance trace with a weighted sum of the posteriori sensitivities. The sensitivity of the root square matrix is obtained by solving a Lyapunov-like linear equation, and the sensitivity propagation of the state estimate errors is presented. The effectiveness of the proposed DCKF is demonstrated by two numerical examples in which models with uncertain parameters are considered. © 2017 The Franklin Institute. Published by Elsevier Ltd. All rights reserved.

1. Introduction

Nonlinear state estimation plays an important role in a wide variety of applications, including estimation in navigation of aerospace vehicles [1], state of the chemical plant control [2], position and velocity of target tracking [3], and fusion of multi-sensor data [4]. A great deal of estimation methods such as extended Kalman filter (EKF), unscented Kalman filter (UKF),

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divided difference filter (DDF), and particle filter have been proposed to solve different practical problems. However, the existing nonlinear state estimation methods still suffer from high computational cost. For instance, the EKF is computationally intensive due to unstable calculation of Jacobians or Hessians [5–7]; the UKF and DDF may not converge or converge with high computational cost [8]; the particle filter suffers from expensive computational load [9]. Recently, a nonlinear filter, called cubature Kalman filter (CKF), for the Gaussian systems has been proposed based on the Bayesian framework [10,11]. The core idea of the CKF is using the cubature role to approximate the multidimensional integrals with \(2n\) deterministic cubature points, where \(n\) is the state vector dimension. In the CKF algorithm, the mean and the covariance of the state and the measurement vectors are calculated by propagating the cubature points through the nonlinear function. Compared with the EKF and the UKF, the CKF is usually applied in high-dimensional systems since it can produce higher accuracy and take less computational cost [10]. Subsequently, the CKF has been used in many applications including navigation [1], attitude estimation [12], chemical processing [13], and sensor data fusion [14,15], etc.

As a matter of fact, all above-mentioned filters assume that the parameters of the dynamic model are accurately known as a prior and the noises of the dynamic model are white with normal probability distributions [5]. It has been shown that the performances of these filters is highly sensitive to the uncertainties of the dynamic model, and deteriorate appreciably [16]. To solve this issue, Karlgaard and Shen extended a desensitized optimal control methodology [17], and proposed a robust filter to reduce the performance sensitivity of the filters with respect to uncertain model parameters. The desensitized Kalman filter is designed by introducing a weighted norm of the state error sensitivities to the cost function, and minimizing this cost function to obtain the desensitized state estimates [17]. The desensitized divided difference filtering [18] and the desensitized unscented Kalman filtering (DUKF) [19] were presented. For the DUKF, there is no continuous propagation for the sensitivities of the sigma points between the iterations, because a new set of sigma points is always resampled at the next iteration. Shen and Karlgaard skillfully designed a unique way to propagate the sensitivities of the state estimate errors and the priori/posteriori covariance matrices for the DUKF [19]. But for the CKF, the desensitized optimal control methodology is not introduced, and the sensitivity of the root square matrix in filtering should be redesigned to avoid the calculations of the vectorized formula and Kronecker product.

This paper proposes a robust cubature Kalman filter for dynamic systems with uncertain parameters. A desensitized cost function of the robust desensitized cubature Kalman filtering (DCKF) is designed by penalizing the posteriori covariance trace with a sensitivity-weighting sum of the posteriori sensitivities. Then, a gain matrix of the DCKF is obtained by minimizing the new cost function to amend the state estimation. The rest of this paper is organized as follows: Section 2 briefly introduces the recursive Bayesian framework and the CKF algorithm. Section 3 presents the propagation of the sensitivities and the DCKF is proposed naturally. Two numerical simulations about a vertically falling body model and a hovering helicopter model (HHM) are analyzed in Section 4. Conclusions are drawn in the end.

2. Cubature Kalman filter

Consider a discrete nonlinear system model with additive noises, which is given by

\[
x_k = f(x_{k-1}, c, u_{k-1}) + w_{k-1}
\]  

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