ARTICLE IN PRESS

Chinese Journal of Aeronautics, (2018), xxx(xx): xxx–xxx

Chinese Society of Aeronautics and Astronautics & Beihang University

Chinese Journal of Aeronautics

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FULL LENGTH ARTICLE

Adaptive robust cubature Kalman filtering for satellite attitude estimation

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Received 22 March 2017; revised 22 May 2017; accepted 26 October 2017

KEYWORDS

Attitude estimation;
Cubature Kalman filter;
Multiple fading factors;
Optimal adaptive factor;
Robust filtering

Abstract This paper is concerned with the adaptive robust cubature Kalman filtering problem for the case that the dynamics model error and the measurement model error exist simultaneously in the satellite attitude estimation system. By using Hubel-based robust filtering methodology to correct the measurement covariance formulation of cubature Kalman filter, the proposed filtering algorithm could effectively suppress the measurement model error. To further enhance this effect and reduce the impact of the dynamics model error, two different adaptively robust filtering algorithms, one with the optimal adaptive factor based on the estimated covariance matrix of the predicted residuals and the other with multiple fading factors based on strong tracking algorithm, are developed and applied for the satellite attitude estimation. The quaternion is employed to represent the global attitude parameter, and three-dimensional generalized Rodrigues parameters are introduced to define the local attitude error. A multiplicative quaternion error is derived from the local attitude error to maintain quaternion normalization constraint in the filter. Simulation results indicate that the proposed novel algorithm could exhibit higher accuracy and faster convergence compared with the multiplicative extended Kalman filter, the unscented quaternion estimator, and the adaptive robust unscented Kalman filter.

1. Introduction

High-accuracy attitude estimation systems play an important role in earth-orientation and satellite control. The Extended Kalman Filter (EKF) is the most widely applied filtering algorithm for attitude estimation.[1] With the combination of the information from the kinematic model with that from measurement, the EKF can theoretically provide a relatively reliable estimation solution. However, in practical satellite attitude estimation applications, especially in on-orbit satellites, the attitude sensor measurement error is complicated because of the influence of the space environment, such as occasional maneuver, meteorites and space junk impact and pressure unbalance. Owing to various interference, the noise caused by jitter, vibration, etc. will cause a serious attitude error.[2,3] There errors cannot be directly dealt with using the traditional filtering algorithm, and are also difficult to be

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Peer review under responsibility of Editorial Committee of CJA.

Production and hosting by Elsevier

https://doi.org/10.1016/j.cja.2018.01.023
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eliminated by the general on-orbital calibration. Therefore, it is one of the main factors that affect high accuracy satellite attitude determination.[4–6]

One of the major problems for the satellite attitude determination via the Kalman Filter (KF) is having an algorithm which does not possess capability of the adaptation to the changing conditions of the state and measurement system. If the kinematic or measurement model used by the KF does not reflect the real information of attitude during various interference, the attitude estimator might diverge in a long term. Hence the KF algorithm that is employed as the attitude estimator must be strengthened robust by using an adaptive filtering approach.[7,8] Soken and Hajiyev[7] introduced robust unscented KF algorithms with the filter gain correction in the presence of measurement malfunctions for the attitude estimation process of a Pico satellite. The method works effectively if the measurements are not reliable. Zhong et al.[9] proposed a random weighting method in which the random weighting method and associated theory are established to resist the disturbances of the kinematic model's systematic error on system state estimation. However, these methods cannot work effectively if state and measurement outliers occur simultaneously.

To deal with these outliers, several nonlinear methods have been proposed in the literature.[10–13] By making use of the Huber technique to correct the measurement covariance equations of standard unscented filtering, a Huber-based unscented filtering is derived and applied to vision-based relative navigation.[10] Developing a robust filter in a batch-mode regression form and solving it via the iteratively reweighted least squares algorithm, Gandhi and Mili proposed a generalized maximum likelihood type KF which can detect and bound the influence of both the state and measurement outliers.[11] Also, based on the generalized maximum likelihood perspective on the KF, a robust derivative-free algorithm named outliers robust unscented KF is proposed to handle both the state and measurement outliers.[12] However, numerous iterations were required for the above proposed algorithm. On the other hand, a derivative-free nonlinear filter named the Adaptive Robust Unscented Kalman Filter (ARUKF) was proposed to track a maneuvering vehicle in Ref.[14], which can reduce the effect of the dynamics model error, the measurement model error, and the contaminated noise simultaneously. It is worth noting that this algorithm only needs fewer iterations.

To balance the contributions of the kinematic model information and the measurements to the state vector estimates, one effective adaptive filter method is to inflate the predicted state covariance through introducing a fading factor.[15–17] Yang and Gao[15] proposed an optimal adaptive factor based on the predicted residual vector, and had successfully applied the method in the field of geodesy. Another effective fading KF algorithm is strong tracking KF. In order to overcome the shortcomings of a single fading factor KF, Geng and Wang[16] proposed multiple fading factors KF to increase the predicted covariance component for the state parameters individually.

In this paper, the proposed attitude estimation approach, based on a filter developed by Arasaratnam et al.[18], is shown as an alternative to the Unscented Kalman Filter (UKF). This filter approach, which they call the Cubature Kalman Filter (CKF)[19], has several advantages over the EKF and UKF, including: (A) by using third-degree spherical-radial cubature rule to numerically compute Gaussian-weighted integrals, the probability distribution of the approximation nonlinear transformation is better than that of EKF and UKF; (B) it does not entail any free parameter; (C) with similar computational complexity as the EKF and UKF, the third-degree CKF will obtain more accurate and stable estimation results in high-dimension systems (more than three); (D) it also avoids that the requirement of system model must be differential in the EKF. In addition, the attitude kinematics equation based on quaternion description has more advantages than other description methods for satellite attitude updating.[20,21] However, the quaternion must obey a normalization constraint, which may lead to singular covariance. An alternative approach employed in this paper utilizes three-dimensional Generalized Rodrigues Parameters (GRPs) to represent the quaternion error vector, the updates are performed using quaternion multiplication, and then the normalization constraint will be maintained.[22] In this paper, two other adaptive robust filtering algorithms for attitude estimation systems are proposed to fight against the dynamics model error and the measurement model error that exist simultaneously in the attitude estimation system. The main contributions of this paper are summarized as follows: (A) the cost function of the predicted residuals and strong tracking robust nonlinear filtering algorithm is deduced in detail. These derivations provide a theoretical basis for introducing adaptive factors into nonlinear filtering frameworks, and explain the feasibility of the proposed algorithm. (B) Two different adaptive robust filtering algorithms, one with the optimal adaptive factor and the other with multiple fading factors, are developed. The derivation process and the calculation procedure of the two kinds of adaptive factors are the theoretical basis for the proposed algorithm. The entire adaptive robust cubature KF algorithm procedure is also given. (C) In order to satisfy the quaternion normalization constraint, a three-dimensional generalized Rodrigues parameters are introduced to represent a local attitude error. The robust adaptive cubature KF for satellite attitude estimation system is derived. (D) The proposed adaptive robust filtering algorithms are implemented on a nonlinear attitude estimation system in real time. The simulation results for several typical scenarios are satisfactory.

The organization of this paper proceeds as follows. Section 2 introduces the attitude kinematics equation of motion and star sensor measurement models by using quaternions. Then, the adaptive robust CKF including the combination of robust estimation methodology with the adaptive factor based on the estimated covariance matrix of the predicted residuals in CKF framework and the former combining with multiple fading factors CKF are developed in Section 3. Subsequently, a CKF is derived for satellite attitude estimation using quaternion update with the three-dimensional GRPs representation in Section 4. The effectiveness of the proposed filtering algorithm for satellite attitude estimation is investigated in Section 5. Finally, some conclusions are drawn in Section 6.

2. Attitude estimation system and observation model

In this section, the attitude kinematics equation of motion and star sensor measurement models using quaternions are briefly reviewed. The quaternion is a four-dimensional vector which is defined by $\boldsymbol{q} = [q_1,\ q_2, q_3, q_4]^{\mathrm{T}} = [\boldsymbol{\rho}^{\mathrm{T}}, q_4]^{\mathrm{T}}$, where $\boldsymbol{\rho}$ is the vector