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An adaptive cubature Kalman filter algorithm for inertial and land-based navigation system

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ABSTRACT

Aimed at the problem of nonlinear and time-varying noise characteristics in inertial and land-based integrated navigation system, a cubature Kalman filter algorithm based on maximum a posterior estimation and fading factor has been proposed, and the fuzzy control theory is used to make it better to track the time-varying noise characteristics. Nonlinear measurement model of the land-based navigation system has been established. Online identification and adaptive adjustment of the measurement noise features has been realized by means of the designed noise estimator, which can effectively improve the estimation precision and inhibit filtering divergence. The simulation results show that the method proposed by the paper has a higher filtering accuracy compared with the traditional cubature Kalman filter. The horizontal positioning accuracy is improved by about 40%, and the horizontal velocity accuracy is improved by about 60%. The new algorithm can enhance the applicability of the land-based navigation system in required navigation performance.

1. Introduction

Land-based radio navigation system is an important means of navigation, which can provide continuous two-dimensional positioning to dynamic users in some area. Land-based radio navigation can be divided into two categories: short-range and long-range. Short-range includes Very-high-frequency Omnidirectional Range (VOR), Distance Measuring Equipment (DME), etc. Long-range includes Loran-C etc. All of them can be used for navigation in different route. The position and velocity of the airborne receiver can be estimated by measuring the pseudorange and pseudorange rate of the receiver every time in the radio navigation system.

With the development of technology, traditional aviation system is making the transition to Future Air Navigation System (FANS) [1]. At the same time, this development put forward higher requirements to related technology of the current aviation system, especially for the navigation system. The navigation system should provide Required Navigation Performance (RNP) when the plane is flying in a certain area under FANS. Based on the currently existing construction and distribution of land-based stations, inertia and land-based integrated navigation is becoming a major operation mode. And it's navigation performance is next only to INS/GPS integrated navigation system [2,3]. Under this mode, land-based navigation information can be applied to correct INS. Therefore,the precision of the navigation system would be ensured for long-term work [4].

Many methods have been proposed to solve the problem of integrated navigation upon land-based navigation system. The most common approach is based on the Kalman filter [5,6]. However, in the actual land-based radio navigation and positioning, the system model is nonlinear. Linear filtering method is obviously inaccurate, so the navigation precision will be affected seriously.

Aiming at the problem of nonlinear equations, algorithm based on extended Kalman filtering (EKF) was proposed in [7]. However, EKF need linearization of the nonlinear system model and the method is applicable when the system noise is Gaussian noise.

In recent years, with the gradual development of filtering technology, Unscented Kalman Filter (UKF) and Cubature Kalman Filter (CKF), etc. have appeared [8,9]. CKF was proposed by Canadian scholar Arasaratnam in 2009 [10]. The core is to capture the statistic characteristics of random variables after the nonlinear transformation according to basic cubature points generated by the spherical-radial cubature rule.

Compared with EKF, CKF has no need for linearization of the nonlinear model and calculation of the Jacobian matrix, which can

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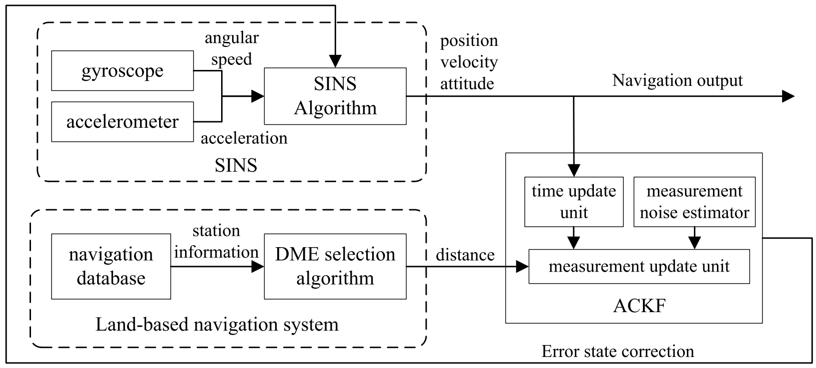

Fig. 1. Structure diagram of inertial and land-based integrated navigation system.

solve the problem of poor positioning accuracy and error divergence caused by linear truncation [11]. Compared with UKF, CKF has stronger adaptability. Cubature points of CKF symmetrically appear in a lower dimensional subspace, and each weight of them is equal. Therefore, CKF is regarded as a powerful tool to figure out the nonlinear estimation problem in the integrated navigation system.

However, a priori statistical properties of the noise should be accurately known as well as EKF algorithm when we design cubature Kalman filter. In the practical application, on the one hand, the priori statistical properties of the noise restricted by testing samples are unknown and inaccurate. On the other hand, when the system is in the actual operation environment, the statistical characteristics of the noise become complex and have time-varying characteristics because of various uncertain factors. Thus, traditional CKF methods don't have adaptive ability to deal with time-varying noise estimation. Especially the system model exists uncertainty, unknown noise statistics becomes time-varying and serious disturbances occur in the practical environment. Then, it's likely to lead to the degradation of the filtering precision and even worse, the divergence with the incorrect priori information of the noise statistics.

Recently, various different techniques have been proposed to solve the problem above, such as the H_∞ filter algorithm, the Adaptive Kalman Filter (AKF) algorithm and the multiple model method. The H_∞ filter algorithm is robust but has low accuracy [12]. Ge et al. [13] introduced the strong tracking filter to improve the tracking performance of the SCKF which has better ability to deal with the inaccuracy model and abrupt state change, but the influence of the unknown noise statistic is not considered. The AKF algorithm utilizes the innovation and residual information to estimate and modify the statistic of the system noise, which can reduce state estimation error and improve the system accuracy. There are numerous adaptive algorithms, including the covariance matching method, the maximum likelihood method, the correlation test method [14,15]. Chen et al. propose an Adaptive Extended Kalman Filter (AEKF) on INS/WSN integration system for mobile robot indoors [16]. Liu Yu et al. propose an Adaptive Gaussian Sum Squared-root Cubature Kalman Flter (AGSSCKF) for the state estimation problem [17]. In multiple model method, more than one filter runs parallel under different models in order to cover real noise characteristics, but the computational load may increase [18].

Therefore, as a combination of AKF and CKF, this paper proposes an Adaptive Cubature Kalman Filter (ACKF) algorithm based on maximum a posterior estimation and fading factor, and the fuzzy control theory is also used to make it better to track the time-varying noise characteristics. Then, the algorithm is applied to nonlinear and time-varying noise estimation in the inertial and land-based integrated navigation system. The algorithm regards CKF as the basic theoretical frame, which can estimate and modify the model parameters and noise statistics of system by maximum posterior estimation theory. Compared with the traditional CKF, it has the ability to adapt to the time-varying noise, and compared with existing algorithm, it is easy to implement as the simple recurrence formula of the noise statistic estimator. Nonlinear measurement model of inertial and land-based integrated navigation system has been established. Finally, a simulation has been given to prove the algorithm. The simulation results show that the method could effectively improve estimation precision and inhibit filtering divergence, which can enhance the applicability of land-based navigation system in required navigation performance.

2. System model for integrated navigation system

The structure diagram of the inertial and land-based integrated navigation system is shown in Fig. 1. The angular speed and acceleration of carrier is measured by the navigation sensor. The position, velocity and attitude can be get by using the navigation algorithm. As we use DME among the land-based navigation system, the distance between carrier and the selected station can be obtained from it. The inertial and land-based integrated navigation system adopts distance combination model, which regards INS as reference system, and the land-based navigation system as auxiliary system. The accuracy and reliability could be influenced by INS and land-based navigation system. Because of the time-varying characteristic of measurement noise, it is greatly needed to make use of an improved filtering algorithm to acquire a good state estimation, which is an adaptive cubature Kalman filter algorithm proposed in section 3. The filter consists of three units: the time update unit, the measurement noise estimator and the measurement update unit. System models are described as follows.

2.1. DME selection algorithm

DME is the main type of short-range land-based radio navigation system, which can be used to the navigation of continental air route, terminal and non-precision occasions. The ground stations are used in the Land-based radio navigation system, so the navigation database needs to be applied. The database stores all of the station information in the flight coverage. As the plane is close to a station, we can tune to the frequency of the station. Thus, we could use the information of nearby stations and ranging signals to calculate the position of the plane. When the land-based navigation system work in DME/DME mode, it is necessary to select two stations. Then two issues should be considered: antenna blind area and station intersection angle, which are shown in Fig. 2 and Fig. 3.

There is a blind area in the upper space of the station antenna, so the plane can't receive normal signal when it is in this area. The higher the altitude is, the greater the blind area radius is. α is set