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Kalman filter applied in underwater integrated navigation system

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Abstract: For the underwater integrated navigation system, information fusion is an important technology. This paper introduces the Kalman filter as the most useful information fusion technology, and then gives a summary of the Kalman filter applied in underwater integrated navigation system at present, and points out the further research directions in this field.

Key words: Kalman filter; underwater integrated navigation system; information fusion technology

1 Introduction

Underwater navigation system, fewer sources of information, hidden highly in terms of military and civilian, with long working hours and complex environment, has a great demand and application prospects. Using a single navigation method is difficult to achieve the accuracy requirements of navigation and positioning, but the integrated navigation technologies can improve the accuracy and reliability of underwater navigation and positioning. The so-called underwater integrated navigation system is known as the subsystem. In this paper, the underwater integrated navigation system information fusion technologies were analyzed.

2 Underwater integrated navigation system profile

The study of underwater integrated navigation system included the Inertial Navigation System (INS) and auxiliary navigation system. INS as a underwater integrated navigation system was a navigation equipment. Aided navigation system for underwater integrated navigation included underwater terrain aided navigation system, underwater landform assisted navigation system, marine gravity-assisted navigation system and marine magnetic assisted navigation system. Underwater integrated navigation system is a multi-sensor system, the information has the diversity and complexity, such as the information was provided by the various navigation systems, the effective integration of navigation and positioning accuracy are not high. Therefore, the information fusion technology is the key technology of the underwater integrated navigation system. Information fusion technology can be basically divided into random class and artificial intelligence class. Random class includes the weighted average method, Kalman filtering techniques, Bayesian estimation methods, statistical decision, cluster analysis method, wavelet transform method and DS evidential reasoning; Artificial intelligence class includes fuzzy control technology and neural network technology. The Kalman filtering technique is currently the most widely used underwater integrated navigation information fusion

3 Kalman filter

Kalman filter was proposed by Rudolph E. Kalman in 1960, is a computer-implemented real-time recursive

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estimation algorithm from the parameters of the prior valuation and new observational data according to a certain recursive formula, the state parameters can be updated.

3.1 Mathematical description of the conventional Kalman filter

For integrated underwater navigation system, the general form of the Kalman filter is:

$$X_k = \phi_{k,k-1} X_{k-1} + \Gamma_{k-1} W_{k-1} \tag{1}$$

$$L_k = A_k X_k + V_k$$

where, X_k and X_{k-1} are the state vectors of the moment k and $k-1$ respectively, $\phi_{k,k-1}$ is the state transition matrix, W_{k-1} and Γ_{k-1} are the moment of the system noise and the noise coefficient matrix of $k-1$ respectively, L_k, A_k and V_k are the moments of the observation vector, observation matrix and observation noise of k, respectively. W_{k-1} and V_k are the mean and variance, respectivdy, which are not related to the Gaussian white noise sequence:

$$E\{W_k\} = 0,\ E\{W_k W_j^{\mathrm{T}}\} = Q_k \delta_{kj},\ E\{V_k\} = 0 \tag{2}$$

$$E\{V_k V_j^{\mathrm{T}}\} = R_k \delta_{kj},\ \mathrm{cov}(W_i V_j) = 0$$

State mean square step prediction equation is:

$$\hat{X}_{k/k-1} = \Phi_{k/k-1} \hat{X}_{k-1} \tag{3}$$

$$P_{k/k-1} = \Phi_{k/k-1} P_{k-1} \Phi_{k/k-1}^{\mathrm{T}} + \Gamma_{k-1} Q_{k-1} \Gamma_{k-1}^{\mathrm{T}}$$

Gain equation is:

$$K_k = P_{k/k-1} A_k^{\mathrm{T}} (A_k P_{k/k-1} A_k^{\mathrm{T}} + R_k)^{-1} \tag{4}$$

State variance of the valuation equation is:

$$\hat{X}_k = \hat{X}_{k/k-1} + K_k (L_k - A_k \hat{X}_{k/k-1}) \tag{5}$$

$$P_k = (1 - K_k A_k) P_{k/k-1}$$

where, Q_k and R_K stand for the system noise and measurement noise covariance matrix, K and P_k gain matrix for the covariance matrix of the state valuation.

3.2 Kalman filter technique

Kalman filter theory originally proposed only applies to the linear system, and requires the observation equation to be linear, integrated navigation system is a nonlinear model, Bucy and Sunahara work on the Kalman filter in the nonlinear. The expansion of the system and the nonlinear observer widen the scope of the Kalman filter theory. Extended Kalman filter (EKF) is a most widely used non-linear filtering method. However, when the system model is uncertainty or interference, signal statistical properties are not completely known, these uncertainties make the estimation accuracy reduce greatly of extended Kalman filter, and in some severe cases, these can lead to filter divergence. With the continuous development and updating of the underwater integrated navigation technology, the numerical stability of the Kalman filter and the increasing high demand for computational efficiency become practicality and effectiveness. Potter proposed the square root filtering algorithm and Bierman UD factorization filter can improve the stability and reliability of the Kalman filter. With the continuous development of modern adjustment theory, robust control theory to introduce filtering, robust filtering theory, which are more representative of the robust Kalman filter, the filter can effectively enhance the underwater integrated navigation system fault-tolerant performance and navigation accuracy.

4 Kalman filter integrated navigation system of underwater

In recent years, the application of Kalman filtering techniques in the integrated navigation system of underwater achieved great development, the emergence of new technologies include: the federal extended Kalman filter, the unscented Kalman filter and the adaptive Kalman filtering technique.

4.1 Federal extended Kalman filter

Underwater integrated navigation system is a multi-sensor data fusion system, the use of Kalman filtering technique for information fusion are two ways: the centralized Kalman filtering and the dispersion of Kalman filter. The centralized Kalman filter focus on handling all the subsystems. Theoretically, the centralized Kalman filter gives the optimal estimation of the state, but it can not guarantee to overcome the shortcomings of the filter poor real-time and fault-tolerant performance, and be unable to give full play to the value of the underwater integrated navigation system. Decentralized filtering is an effective method of solving large-scale system state estimation and fault tolerance, a large number of decentralized filtering methods, proposed by Carlson Federal filtering theory is applied to underwater integrated navigation system. The design ideas of the federal extended Kalman filter is the first distributed processing, and then the global integration, resulting in the establishment of the Global Estimates on the basis of all observations. Federal Kalman filter can be reduced due to the uncertainty of the initial position of filter divergence, so that the probability of the convergence of the filter is significantly improved, thereby improving the navigation performance.

Federal Kalman filter of Hartman[2] for underwater navigation system has a high positioning accuracy. Federal extended Kalman filter of Wang[3] is used to SINS/DVS/TCM2/GPS underwater integrated navigation system, positioning underwater integrated navigation system of federal Kalman filter observation equation and measurement equation and simulation results show that the use of federal extended Kalman filter underwater navigation information fusion technology exports the navigation accuracy to meet the performance indicators of the precision reliability of underwater vehicle, thus improves the long-distance underwater vehicle time of stable navigation. Federal extended Kalman filter of Liu[4] for SINS / GNS / DVS underwater integrated navigation system further validates that it can effectively improve the navigation accuracy.

4.2 Unscented Kalman filter

Unscented Kalman filter (UKF) in the study of robot navigation based on the unscented transform was proposed by Juliter. The basic idea of unscented transform is to calculate the various statistics in the filtering process. This method is based on the current statistics information to select multiple points, respectively, to predict the next step, re-use certain weights on the predictive value of the unscented transform calculation, and forecast the mean and variance. Unscented Kalman filter is an approximation of the probability distribution function of the nonlinear system, rather than the nonlinear function approximation, so its calculation of the amount of extended Kalman filter. This method ensures that the calculation of predictive value can accurately pass the required information, the accuracy can be at least the accuracy of the second order extended Kalman filter for nonlinear equations.

The above-mentioned characteristics of the Unscented Kalman filter is widely used in the integrated navigation system in recent years in underwater integrated navigation. Unscented Kalman filter of Merwe[5] is used in the integrated navigation system of underwater robot to get a higher accuracy than the extended Kalman filter. Unscented Kalman filter of Xu Jianfeng[6] for submarine geomagnetic-assisted navigation system gets the higher precision navigation and positioning, and this method is used in other underwater integrated navigation systems. Unscented Kalman filter of Wang[7] for terrain-aided navigation system for underwater vehicle, effectively reduces the underwater vehicle navigation and positioning errors, and improves the stability and accuracy of the underwater integrated navigation system.

4.3 Adaptive Kalman filter

Due to the complexity of the sea conditions, the measurement noise statistical properties of underwater integrated navigation system change in the actual work environment, the initial priori values can not represent the noise in the actual work. After a lot of trial and error of the inertial navigation system, the noise statistics of the experimental system can be obtained, but the actual work measurement noise statistics are still unknown. In view of this situation, adaptive Kalman filtering technique is used for underwater integrated navigation system. During the filtering, it can also be brought about by the observational data, online estimation and correction of model parameters, the noise statistical properties improve the precision of the filter, and thus achieve the high navigation and positioning accuracy.

Yan Dengyang[8] resolved federal Kalman filter to calculate the large amount of system measurement noise varies with the actual work environment of the different characteristics of the proposed fuzzy adaptive Kalman filtering technique for underwater inertial/geomagnetic integrated navigation system, enhanced the robustness of the system model that was unknown or under uncertainty output precision, and improved the accuracy of navigation. Xu[9] proposed a fuzzy model of the adaptive Kalman filter based on the T-SFIMMA for submarines underwater integrated navigation system, real-time tracking and automatic conversion of the system model.

4.4 Three kinds of Kalman filter

1) In the filtering algorithm, the federal Kalman filter, unscented Kalman filtering and adaptive Kalman filter to nonlinear problems of underwater integrated navigation system are linearized, the system state must satisfy the Gaussian distribution. To solve the non-Gaussian distribution of the Underwater Navigation System model, if it is still simple state of use of characteristics of the mean and variance, the performance of the filter is deteriorated. The status of these three kinds of Kalman filter are generally not suitable for non-Gaussian model. To solve the non-Gaussian model, these three kinds of Kalman filter and other filters should combinate for processing. In addition, the unscented Kalman filter and extended Kalman filter are similar, they require a relatively large amount of computation.

2) In the form of a filter, the federal Kalman filter with multiple filter information fusion processing can improve the convergence of the filter, but it is a complex equipment, the disadvantage is that the cost is relatively high. Unscented Kalman filter and adaptive Kalman filter using a single filter, the requirements of the equipment are relatively simple.

3) In the real-time filter, adaptive Kalman filter can be continuously online estimation and correction of real-time model parameters and noise. Due to the presence of multiple filters, federal Kalman filter is slow in the processing of data. Unscented Kalman filter not only adds the time iteration, but also updates the Sigma set of sample points, especially in high-dimension, the number of samples of Sigma sets is large, so the computational speed is slower.

5 Prospects

Recently, Kalman filtering technique has its own advantages of dealing with the problem of nonlinear filtering of the underwater integrated navigation system and overcoming the uncertainty of model, and has achieved certain theoretical results, but with the continuous development of modern science and technology, and the continuous development of the oceans by mankind, yet to do further researches:

1) Underwater integrated navigation system in a category or categories of problems can only solve one Kalman filtering technique, but it needs to solve many problems. It can be resolved in order to get an underwater integrated navigation system information integration best practices from the following aspects. First, the Kalman filtering technique combined with other information fusion technologies. By combining the advantages of all kinds of information fusion technologies have played each other, improve the navigation and positioning accuracy of the underwater integrated navigation system. Second, the lack of analysis of Kalman filtering techniques and further developed Kalman filtering technique that based on Kalman filtering techniques for underwater integrated navigation system should be studied. Three underwater navigation technologies continuously evolve and improve the status and role of underwater navigation, underwater integrated navigation system is no longer a combination of two or three navigation systems, but with a variety of navigation systems, this system will have more problems, the technical requirements for information fusion will be more to study the underwater integrated navigation system and to adapt to multiple combinations of Kalman filtering techniques for future research and difficult problem.

2) Application of other methods of information fusion technologies. Kalman filter, for example, Bayesian estimation is the basis of the Kalman filter, Bayesian estimation theory is an important branch of mathematical probability theory, the basic idea is to seek through a combination of random variables a priori information

and the new observation sample take a posteriori information. In fact, all forms of Kalman filtering techniques are some of the special form of Bayesian estimation, in-depth study of the application of Kalman filtering techniques in the integrated navigation system of underwater should be based on Bayesian estimation. Also the mathematical methods of probability theory and numerical analysis applications to information fusion technology further improve the accuracy and reliability of underwater integrated navigation system.

3) Other information fusion technologies. Integrated navigation system of underwater uses a Kalman filter, we can consider other information fusion techniques applied to integrated navigation system of underwater with some special circumstances, Bikaerman filter can get a higher accuracy.

4) Theory with the actual situation. Most of the information fusion technology researches in the underwater integrated navigation system are in the phase of theoretical research and few actual work, the data used by many researches is through simulation, lacking the actual reference value. In future studies of this situation, we must combine our research and engineering practice of underwater integrated navigation up to identify problems in practice, solve problems, and find an underwater integrated navigation which can provide the optimal accuracy and reliability of the information fusion technology.

6 Conclusion

Three kinds of Kalman filter underwater integrated navigation system are introduced, and compare their advantages and disadvantages, and then points out the development trend of information fusion technology, it may be integrated navigation system of underwater information fusion technology to provide reference.

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