Advances in Engineering Research, volume 164
8th International Conference on Manufacturing Science and Engineering (ICMSE 2018)

Research on Application of UKF Filtering in MEMS Sensor Attitude Measurement System

Xingchao Zhang[1, a], Xuan Wang[1, b], Chengzhi Yang[1, c], Lu Wang[1, d] and Ye Zhao[1, e]

[1] Faculty of Electrical and Information Engineering, Oxbridge College, Kunming University of Science and Technology, Kunming 650106, China

[a]854027031@qq.com, [b]1171135925@qq.com, [c]1183589197@qq.com, [d]1156526528@qq.com, [e]544288582@qq.com

Keywords： MEMS (micro electro mechanical system), attitude measurement, attitude solution, TRAID, UKF

Abstract: Aiming at the problem that the traditional attitude measurement cannot meet the requirements of small and unmanned aerial vehicles in industrial and civil areas in terms of weight, volume, and power consumption and so on, a UAV attitude measurement system based on MEMS accelerometer, gyroscope and magnetometer was proposed. The Euler angle method were used to combine the quaternion method for attitude solution, The three-axis attitude determination (TRAID) algorithm was used to construct the measurement model, and the data fusion was carried out by the unexplained Kalman filter (UKF) algorithm, so as to realize the accurate attitude measurement in static and dynamic. The experimental results showed that the system static error was less than 1°, and the dynamic error was less than 1.3°. The system had higher measurement accuracy and could meet the practical application requirements.

Introduction

In recent years, attitude measurement was widely used in aerospace, human motion posture capture, robotics and other fields. In this paper, the attitude measurement of small unmanned aerial vehicle (UAV) was studied. Attitude angle is an important parameter of airframe attitude information, and its accurate measurement is of great significance to control aircraft flight and unmanned aerial vehicle detection. In order to ensure the continuous high-precision measurement of attitude information, traditional large aircraft usually have liquid-floating gyroscopes and electrostatic gyroscopes with high precision installed on the fuselage, and the zero-bias stability could reach 0.0015°/s [1, 2]. But due to the weight and volume of the device and the high cost, it couldn't be applied to a small UAV. Silicon micromachined gyroscope fabricated by MEMS sensor had the advantages of light weight, small size, low power consumption and small inertia [3, 4], which provided a good choice for UAV attitude measurement. However, the MEMS sensor also had disadvantages such as low precision and large drift, so that the gyroscope couldn't measure the angle for a long time. Therefore, Benoît Huyghe et al [5, 6] first measured the geomagnetic field and gravitational field with a magnetometer and accelerometer, and then calculated the object attitude angle through the direction cosine matrix. Thereinto, roll angle and pitch angle were calculated by using the object under static state only by the gravity characteristics. The heading angle was calculated by the characteristics of roll angle, pitch angle and constant geomagnetic vector measured by accelerometer. The advantage of this method was that there was no error accumulation in the static attitude angle measurement. The disadvantage was that the calculation of the object attitude angle was inaccurate due to the influence of gravity and other external forces in the dynamic state. Anthony Kim et al [7-9] proposed quaternion to represent the attitude angles to reduce the computational complexity. However, the problem of heading angle, roll angle and pitch angle distortion caused by external magnetic field distortion exists in the quaternion. The Euler angle was more intuitive and easy to understand, but the singular value problem exists in the attitude solution for a long time.

To summarize, the method of combining Euler angle and quaternion to calculate the attitude had been proposed in this paper. The three-axis attitude determination (TRAID) algorithm was used to construct the measurement model, and the data fusion was carried out with the Unscented Kalman Filter (UKF) algorithm, so that the accurate attitude measurement could be achieved when static and dynamic.

The Overall Design of the Measurement System

In this paper, the attitude measurement system applied to micro-aircraft was developed by using three-axis MEMS gyroscope, three-axis MEMS accelerometer, and three-axis MEMS magnetometer and so on. The system structure was shown in Fig.1. Under static conditions, the gravitational field and magnetic field near UAV were measured directly by accelerometer and magnetometer. Then, the direction cosine matrix was used to transform the navigation coordinate system and the body coordinate system, and the attitude angle was calculated. Under dynamic conditions, firstly, the direction cosine matrix observations of the carrier were obtained by TRIAD algorithm based on the output of accelerometer and magnetometer. Then the differential equation was established according to the output of the gyroscope and the quaternion was solved by using Runge-Kutta algorithm. Finally, the attitude of UAV was obtained by data fusion using UKF filtering algorithm.

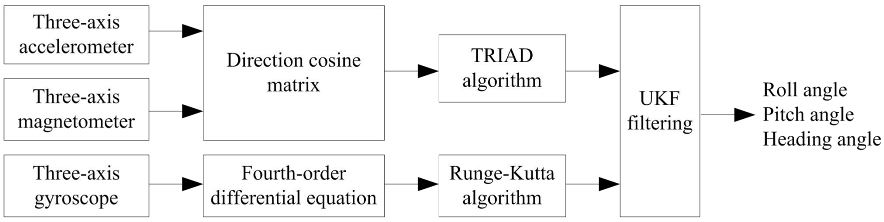

Fig.1.The configuration of the measurement system

Attitude Solution of Triad

The TRIAD algorithm based on a single vector observation was an algebraic method for determining the attitude matrix of an aircraft. Assuming that two non-parallel unit reference vectors are r_1、r_2 in the navigation coordinate system and b_1、b_2 in the body coordinate system. Under the two kinds of coordinate system, orthogonal coordinate system L and S which conform to the right-hand rule were respectively constructed, and then the unit vectors of each coordinate axis in the two orthogonal coordinate systems can be obtained, i.e.

$$l_1 = r_1,\ l_2 = \frac{r_1 \times r_2}{|r_1 \times r_2|},\ l_3 = l_1 \times l_2. \qquad s_1 = b_1,\ s_2 = \frac{b_1 \times b_2}{|b_1 \times b_2|},\ s_3 = s_1 \times s_2. \tag{1}$$

The unique orthogonal attitude matrix C could make the following function as $C = \sum_{i=1}^{3} s_i l_i^T$.

If $L = (l_1 \quad l_2 \quad l_3)$, $S = (s_1 \quad s_2 \quad s_3)$, then $C = SL^T$

The TRIAD algorithm establishes orthogonal basis based on the first set of vector (r_1, b_l). In this process, part of the information of the second set of vector (r_2, b_2) would be lost, and the attitude matrix obtained was different due to the selection of the reference vector.

If the measurement accuracy of the two sets of vectors was known, and in which the higher accuracy of the vector as a benchmark, the attitude solution accuracy was higher. Therefore, this paper used the magnetic field information as a reference vector for attitude solution.

UKF Filtering Algorithm

In the process of attitude solution, Kalman filtering was usually used for attitude estimation, but it only had higher accuracy for linear models [10]. If the model was non-linear, an extended Kalman filter (EKF) can be used. EKF used the Taylor expansion to expand the nonlinear function and retained the first order term [11], so that the nonlinear function was linearized, but the accuracy was only one order. Juiler et al [12] proposed unscented Kalman filter (UKF) .UKF used unscented transform (UT). According to the mean and variance of nonlinear function, its distribution was estimated, and the accuracy of filtering could reach more than second order [13, 14].

For a nonlinear system, the basic principle of UKF filtering was as follows.

$$x_{k+1} = F(x_k, u_k, v_k); \quad y_k = H(x_k, n_k). \tag{2}$$

Where x_k was the n_x-dimensional system state vector and y_k was the n_y-dimensional system observation vector. v_k was the system noise, and the covariance matrix was P_v. n_k was the observation noise, and the covariance matrix was P_n. Suppose V_k, n_k were Gaussian white noise, and were irrelevant to each other. The filtering algorithm can be obtained, i.e.

(1) Initialization

$$\hat{x}_0 = E[x_0]; \quad P_0 = E[(x_0 - \hat{x}_0)(x_0 - \hat{x}_0)^T]. \tag{3}$$

(2) Calculate sigma points (sampling points)

$$\chi_{k-1} = [\hat{x}_{k-1} \quad \hat{x}_{k-1} + \gamma\sqrt{P_{k-1}} \quad \hat{x}_{k-1} - \gamma\sqrt{P_{k-1}}]. \tag{4}$$

Where $k \in \{1,\ldots,\infty\}$,

(3) Time updating

$$\chi_{k|k-1} = F[\chi_{k-1}, u_{k-1}]. \quad \hat{x}_k^- = \sum_{i=0}^{2L} W_i^m \chi_{i,k|k-1}. \quad P_k^- = \sum_{i=0}^{2L} W_i^c [\chi_{i,k|k-1} - \hat{x}_k^-][\chi_{i,k|k-1} - \hat{x}_k^-]^T + R^v. \tag{5}$$

$$y_{k|k-1} = H[\chi_{k-1}]. \quad \hat{y}_k^- = \sum_{i=0}^{2L} W_i^m y_{i,k|k-1}. \tag{6}$$

(4) Measurement updating

$$P_{\bar{y}_k\bar{y}_k} = \sum_{i=0}^{2L} W_i^c [y_{i,k|k-1} - \hat{y}_k^-][y_{i,k|k-1} - \hat{y}_k^-]^T + R^n. \quad P_{x_k y_k} = \sum_{i=0}^{2L} W_i^c [\chi_{i,k|k-1} - \hat{x}_k^-][y_{i,k|k-1} - \hat{y}_k^-]^T. \tag{7}$$

$$K_k = P_{x_k y_k} P_{\bar{y}_k\bar{y}_k}^{-1}. \quad \hat{x}_k = \hat{x}_k^- + K_k(y_k - \hat{y}_k^-). \quad P_k = P_k^- - K_k P_{\bar{y}_k\bar{y}_k} K_k^T. \tag{8}$$

Where $\gamma = \sqrt{L + \lambda}$ was the scale factor, L was the dimensionality of the state, R^v was the system noise variance, R^n was the observed noise variance and W_i was the weight.

When the Euler angle was used to describe the attitude, the differential equation had singularity problem. That was, when the pitch angle $\theta = 90°$, attitude updating could not be performed. However, there was no such problem with the attitude differential equation established by the quaternions, and the equation was linear and the calculation was small. Therefore, the UKF filtering algorithm was used to improve Euler angle. In the time updating phase, the algorithm used Eq. 9 to convert the sampled Euler angles into quaternion to update the pose. And then, by using the Eq. 10 to convert the updated quaternion to the Euler angle form and carry out the remaining steps of the UKF filtering. After the improvement, the UKF algorithm based on Euler angles could work in full attitude without singularity problems.

$$Q=\begin{bmatrix}q_0\\q_1\\q_2\\q_3\end{bmatrix}=\begin{bmatrix}\cos\frac{\psi}{2}\cos\frac{\theta}{2}\cos\frac{\gamma}{2}+\sin\frac{\psi}{2}\sin\frac{\theta}{2}\sin\frac{\gamma}{2}\\\cos\frac{\psi}{2}\sin\frac{\theta}{2}\cos\frac{\gamma}{2}+\sin\frac{\psi}{2}\cos\frac{\theta}{2}\sin\frac{\gamma}{2}\\\cos\frac{\psi}{2}\cos\frac{\theta}{2}\sin\frac{\gamma}{2}-\sin\frac{\psi}{2}\sin\frac{\theta}{2}\cos\frac{\gamma}{2}\\-\sin\frac{\psi}{2}\cos\frac{\theta}{2}\cos\frac{\gamma}{2}+\cos\frac{\psi}{2}\sin\frac{\theta}{2}\sin\frac{\gamma}{2}\end{bmatrix}. \tag{9}$$

$$\begin{cases}\theta=\sin^{-1}(2\times(q_0\times q_1+q_2\times q_3))\\\gamma=\tan^{-1}\frac{-2\times(q_1\times q_3-q_0\times q_2)}{1-2\times(q_1^2+q_2^2)}\\\psi=\tan^{-1}\frac{2\times(q_1\times q_2-q_0\times q_3)}{1-2\times(q_1^2+q_3^2)}\end{cases}. \tag{10}$$

Where q_0, q_1, q_2 and q_3 were quaternions, and θ, γ and ψ were the pitch angle, roll angle and heading angle.

System Tests and Analysis

In order to verify the effect of UKF filtering algorithm, the measurement module was composed of gyroscope, accelerometer and magnetometer, and was tested. Firstly, the system was put on the three-axis turntable for static test. Test time was 35s, the sampling period was 0.1s, that is, 10 sampling points per second. Then the pitch angle, roll angle and heading angle curve of the system were shown in Fig.2 when the pitching angle was 40°, the roll angle was -50°and the heading angle was 100°. It could be seen from the figure that the error of roll angle and pitch angle was less than 0.5° and the error of heading angle was less than 1°during the test time. This paper described the design of the measurement system under static conditions with high measurement accuracy.

In order to verify the measurement accuracy of the attitude measurement system under the rotation condition, the dynamic test is carried out. Test time was 35s, the sampling period was 0.1s, that is, 10 sampling points per second. During the test, the attitude measurement system was respectively rotated around three axes, and the test results were shown in Fig.3. As could be seen from the figure, the error of the pitch angle and the roll angle was less than 1°, and the error of the heading angle was less than 1.3°in the test of time, which also had high measurement accuracy.

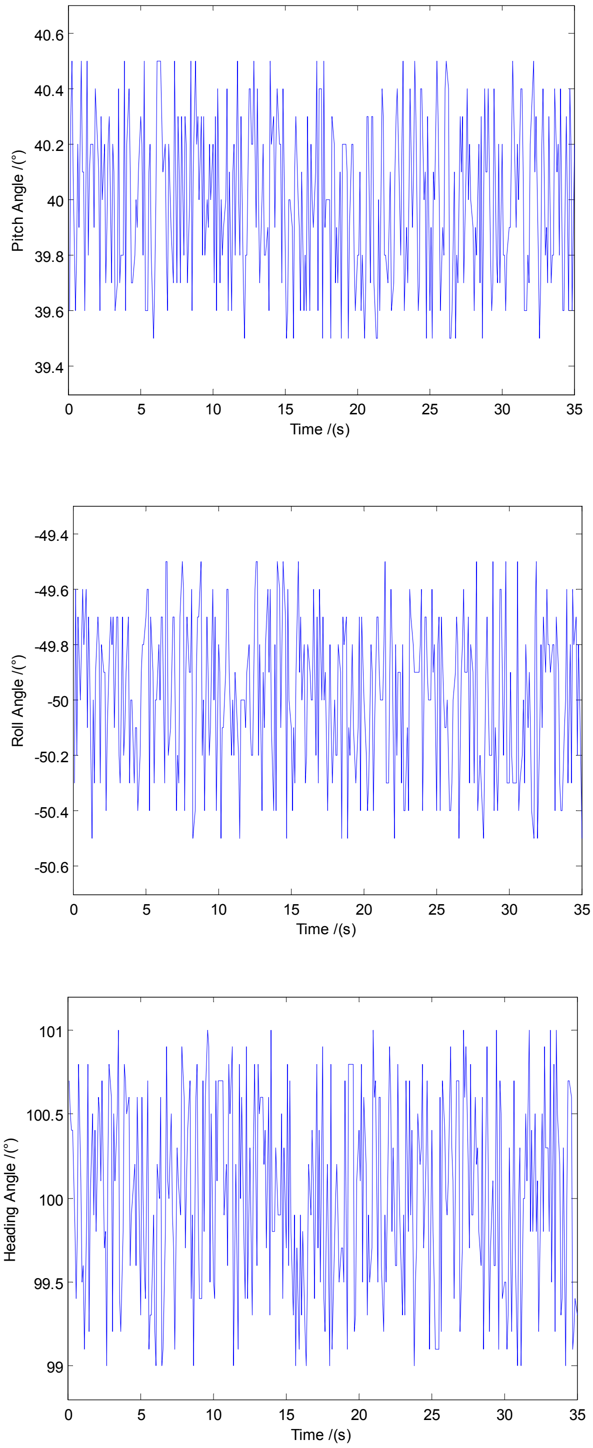

Fig.2.Static attitude angle curve

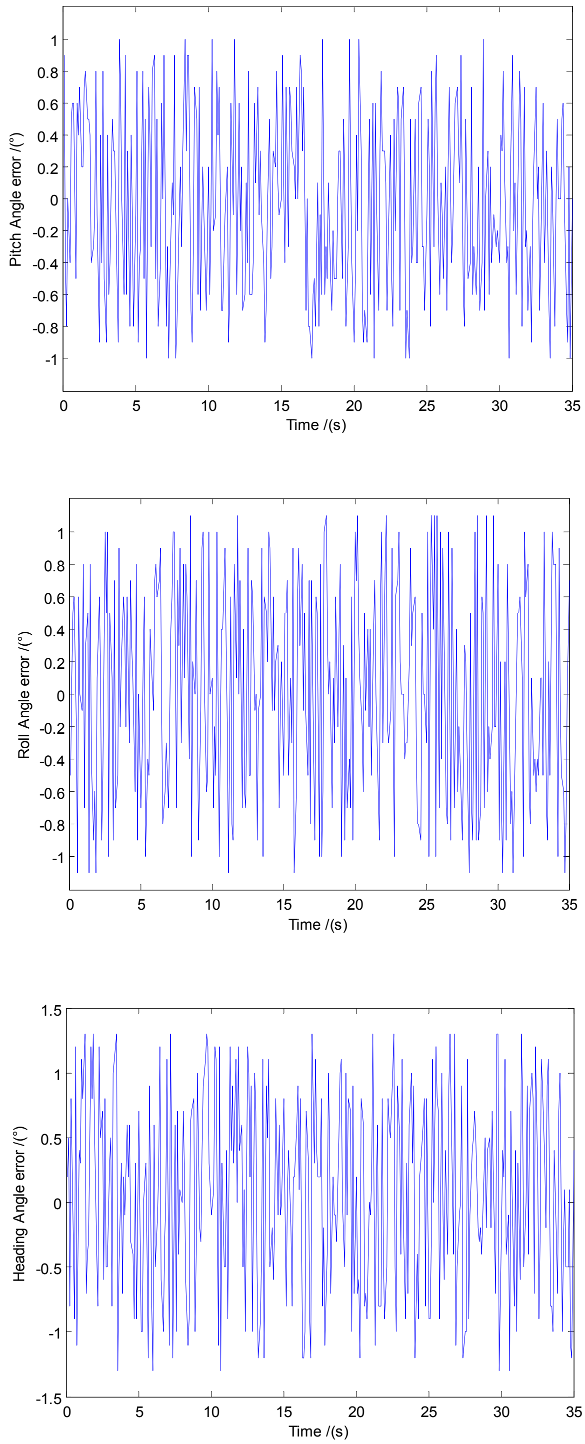

Fig.3.Dynamic attitude angle error curve

Conclusions

In this paper, a UAV attitude measurement system based on MEMS gyroscope, accelerometer and magnetometer was proposed, and the fourth-order Runge-Kutta algorithm was used for attitude solution. The accelerometer and the magnetometer were used to establish the measurement equation and data fusion by UKF filtering algorithm. The system test showed that the static error was less than 1° and the dynamic error was less than 1.3°. It had higher measurement accuracy and could meet the practical application requirements.

Acknowledgements

This work was financially supported by Yunnan Provincial Education Department Scientific Research Foundation of China under Grant 2015C106Y.

References

[1] Wang Shourong. Theory and Application of Silicon Miniature Inertial Devices [M]. Nanjing: Southeast University press,2000:172-173.(in Chinese)

[2] Liu Yu, Li Qiujun, Liu Jun. Rapid azimuth well logging based on piezoelectric gyroscope [J]. Journal of electronic measurement and instrument, 2007, 21(02):90-94. (in Chinese)

[3] Jiang Yanfeng. Micro Nano electronic devices [M]. Beijing: Chemical Industry Press, 2005:222-224. (in Chinese)

[4] Qian Huaming, Xia Quanxi, Que Xingtao, Zhang Qiang. MEMS Gyroscope Filtering Algorithm Based on Kalman Filtering [J]. Journal of Harbin Engineering University, 2010, 31(09):1217-1221.

[5] Benoît Huyghe， Jan Doutreloigne and Jan Vanfleteren． 3D Orientation Tracking Based on Unscented Kalman Filtering of Accelerometer and Magnetometer Data ［C］． IEEE Sensors Application Symposium，LA：IEEE Press，2009：148-152．

[6] Zhu Rong, Zhou Zhaoying. A MEMS-based attitude reference system [J] Measurement and Control Technology, 2002:21(10):6-8.(in Chinese)

[7] Anthony Kim，Golnaraghi M F． A Quaternion-Based Orientation Estimation Algorithm Using an Inertial Measurement Unit［C］. IEEE Position Location and Navigation Symposium，Plans: IEEE Press，2004: 268-272．

[8] Tatsuya Harada，Hiroto Uchino，Taketoshi Mori，et al． Portable Orientation Estimation Device Based on Accelerometer，Magnetometers and Gyroscope Sensors for Sensor Network [C]． IEEE Conference on Multisensory Fusion and Integration for Intelligent Systems， IEEE Press，2003: 191-196．

[9] Roman Kamnik， Simon Stegel， Marko Munih． Design and Calibration of Three-Axial Inertial Motion Sensor [C]．IEEE Conference on Power Electronics and Motion Control，Portoroz：IEEE Press，2006: 2031-2036．

[10] Daninel Roetenberg， Per J． Slycke， Peter H， Veltink． Ambulatory Position and Orientation Tracking Fusing Magnetic and Inertial Sensing． [J]． IEEE Transactions on Biomedical Engineering，2007，54(5) : 883-890．

[11] Abdelkrim Nemra， Nabil Aouf． Robust INS /GPS Sensor Fusion for UVA Localization Using SDRE Nonlinear Filtering [J]． IEEE Sensors Journal，2010，11(4) : 789-798．

[12] Simon Julier，Jeffrey Uhlmann，Hugh F． Durrant-Whyte． A New Method for the Nonlinear Transformation of Means and Covariances in Filters and Estimators [C]． IEEE Transactions on Automatic Control，USA: IEEE Press，2000: 477-482．

[13] Abhijit Kallapur，Mahendra Samal，Vishwas Puttige， et al． A UKFNN Framework for System Identification of Small Unmanned Aerial Vehicles [C]． IEEE Conference on Intelligent Transportation System，Beijing: IEEE Press，2008: 1021-1026．

[14] Hail Ersin Söken， Chingiz Hajiyev． UKF for the Identification of the Pico Satellite Attitude Dynamics Parameters and the External Torques on IMU and Magnetometer Measurements [C]．IEEE Conference on Recent Advances in Space Technologies，Istanbul： IEEE Press，2009: 547-552．