Quatérnion Kalman Filter Design Based on MEMS Sensors

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Abstract: Controlling UAV requires high-precision dynamic information input. However, mini UAV needs more demands because of its small volume. Using MEMS sensor can make the UAV become high-precision, low power consumption and inexpensive machine. Accelerometer and magnetometer can measure the acceleration of gravity and geomagnetic field that the vectors are uncorrelated, which can be considered as a vector in order to correct the gyroscope. Kalman filter based on quaternion has been adopted in this study in order to achieve the attitude measurement and error control of transporter.

Keywords: Kalman Filter, Data Fusion, MEMS Sensor

1 Introduction

The attitude angle information of local geographic coordinate frame is provided by the AHRS [1], which is very essential for the UAV’s navigation and control. The price of conventional mechanical and laser gyroscope is costly. For the reason of volume size and price limitation, it cannot be popularized in the minitype UAV. With the development of micro-electronics, the MEMS devices with high-precision, low power consumption, and small-size can satisfy aviation and astronomic demands[2-3]. Due to the characters of the low cost, small size, and convenience of AHRS applied in MEMS, it can be applied in many fields in the future.

The angle of pitch angle, roll angle and yaw angle can be calculated by measuring angular velocity and linear velocity, respectively. The MEMS gyroscope could measure rotational angular rate of a rigid body. Through analyzing integration of angular rates, rotation euler angle can be achieved. Nonetheless, there is severe zero bias error of the gyro and measurement errors in the angular rate gyroscope, which would lead to integral error in SINS(strapdown inertial navigation system) and difficulties of reaching the accuracy[4]. Meanwhile, accelerometer and magnetometer can calculate the uncorrelated vector -- acceleration of gravity and geomagnetic field, which can be used to correct the gyroscope as the attitude’s observation vector.

Kalman filter is more applying to data fusion of multiple sensors. It is a function of Kalman filter is applied to data fusion of multiple sensors, which can combine the attribute of multiple sensors and obtain more precise attitude information by updating prediction by using angular rate obtained through gyro measurement and observation by acceleration of gravity and magnetic field.
2  Attitude Angle Estimation base on Kalman Filter

The attitude angle can be achieved by calculating the integration of gyro angle rates during a short time. However, tiny measurement errors may change into many measurement errors through adding integral time. Accurate static information can be obtained by gyroscope with accelerometer and magnetic sensor. But it has a interruption of inertial forces, vibrations, or magnetic noises. Accelerometer and magnetic sensor could provide two uncorrelated estimations\[5\]. It can get attitude angle from integration of angular rates measured by the MEMS gyroscopes, which only performs well in high frequency region. But it is inevitably affected by gyro drifts. Without an additional observation for drifts correction, which is based on integration of angular rates would gradually diverge from the real attitude angle. The pitch angle and roll angle error can be observed by gravity direction vector. The yaw angle error can be observed by geomagnetic direction vector. So using gravity direction vector and geomagnetic direction vector as the observation vectors to correct the attitude angle.

Through analyzing integration of angular rates, a quaternion can be achieved. Secondly, to make the measurements of the accelerometers and magnetometer as a reference vector which are calculated through gravity field model and geomagnetic field model to correct the quaternion. The optimal estimate of quaternion can be achieved by this vector. Finally, the attitude angle can be achieved by this quaternion. The quaternion differential equation is expressions(1), where $\omega_x$, $\omega_y$, $\omega_z$ are the measured value of the 3-axis gyroscope.

\[
\begin{bmatrix}
q_0 \\
q_1 \\
q_2 \\
q_3
\end{bmatrix} =
\begin{bmatrix}
0 & -\omega_x/2 & -\omega_y/2 & -\omega_z/2 \\
\omega_x/2 & 0 & \omega_z/2 & -\omega_y/2 \\
\omega_y/2 & -\omega_z/2 & 0 & \omega_x/2 \\
\omega_z/2 & \omega_y/2 & -\omega_x/2 & 0
\end{bmatrix}
\begin{bmatrix}
q_0 \\
q_1 \\
q_2 \\
q_3
\end{bmatrix}
\]

(1)

The quaternions will gradually lose its standardization properties due to the calculation errors and other factors. To ensure the quaternion attitude matrix is orthogonal, quaternions need to be processed normally after each quaternion update cycle. The basic idea of the kalman filter is to process nonlinear problems by linear model. Then the linearized system is filtered [6]. The data of engineering survey are generally dissociation. Firstly, to conduct data discretization. The state equation after discretization is shown as follows:

\[
X(k | k-1) = Ax(k-1 | k-1)
\]

(2)

$A$ is a state transition matrix. $X(k|k-1)$ is the state estimates values of $k$ time in $k-1$
time. $\Delta t$ is the cycle of measurement. The output of the gyroscope and accelerometer are observation vector, as shown in equation (3):

$$ z(k) = H(k)x(k) + v_k $$

(3)

$H_k$ is the observation equation and $V_k$ is the measurement noise covariance matrix (Zero mean white noise as the measurement noise of the system).

Observation vector is jointly provided by accelerometers and magnetometers. The measured value of accelerated velocity relative to body axis system and geomagnetic field are two natural independent reference vectors. Thus quantity of state needs to be revised twice. Observations update equation is shown in equation (4)

$$ x_k = x_{k|k-1} + k_{x_k} (z_k - H_k x_{k|k-1}) $$

(4)

Suppose the errors of the system and observation noise are stable. In the process of filtering, the attitude angle is updated by using quaternion attitude angle differential equation. Attitude angle is corrected by using the measured value of accelerometers and magnetometers. In the process of filter, according to gravity and magnetic measurements, the variance error needs to be updated to calculate kalman gain in the next step, which is shown in formula (7). The variance prediction formula and gain filter matrix are shown in equation (5) (6):

$$ P_{k|k-1} = A P_{k-1} A^T + W Q W^T $$

(5)

$$ k_{x_k} = P_{k|k-1} H_k^T / (H_k P_{k|k-1} H_k^T + R) $$

(6)

$$ P_k = (1 - k_{x_k} H_k) P_{k|k-1} $$

(7)

3 Simulation and Analysis

A practical project is taken for a background to carry simulation for the system that composed by gyroscope and magnet compass. Simulation time is 300s, The sampling period of the sensor is 0.005s. Data transmission cycle is 1s. The mean square error of gyroscope drift white noise is 0.1°/s and that of accelerometer measurement noise is 0.0005g. The mean square error of magnetometer measurement noise is $10^{-7}$Gs.

This paper uses the local gravitational acceleration and magnetic field strength in NanJing. $g = [0 \ 0 \ -9.79494]^T$, Horizontal component of the magnetic field is $3.301 \times 10^{-6}$T. The vertical component is $3.684 \times 10^{-6}$T. The initial value of the variance is $p_{k-1} = \text{diag}(0.1, 0.1, 0.1, 0.1, 0.1)$.

The pitch angle and roll angle is set to close to 0° and yaw angle equal to 58°. In given conditions, the roll angle, pitch angle, and yaw angle are output by serial port. It is shown in Figure 1.
It can be seen from Figure 1 that the convergence speeds of pitch angle and roll angle are all rapid after the Kalman filter. It will become stable in a 2s-3s when filter starts working. As you can see in Figure 1, convergence speeds of yaw angle also is rapid. After gathering the data that real attitude data and filtered data in the static condition to calculate the attitude angle error respectively, we can get average values of the attitude angle error. It is shown in Table 1.

Table 1. Error of kalman filtering

<table>
<thead>
<tr>
<th>Error</th>
<th>Pitch angle</th>
<th>Roll angle</th>
<th>Yaw angle</th>
</tr>
</thead>
<tbody>
<tr>
<td>mean(°)</td>
<td>0.1135</td>
<td>0.1547</td>
<td>0.5261</td>
</tr>
<tr>
<td>RMSE (°)</td>
<td>0.2187</td>
<td>0.2833</td>
<td>0.9841</td>
</tr>
</tbody>
</table>

As you can see in Table 1, after performing Kalman filter, attitude angle doesn't drift with integration time. Drift error is limited in a certain range and fast convergence speed.

The validation testing showed yaw angle error range of ±0.5°, pitch angle error
range of ±0.2°, roll angle error range of ±0.2°. Cumulative error is limited to some extent and improve the attitude determination accuracy.

4 Conclusion

In this research, the core part is focusing on STM32F405, designing and implementing the quaternion kalman filter based on 3-axis MEMS gyroscope, accelerometer and magnetometer. The adopt quaternion kalman filtering algorithm have the features of high accuracy and fast convergence speed. The simulations reveal that attitude angle error is small and attitude angle doesn't drift with integration time. Cumulative error is limited effectively and improve the attitude determination accuracy Meanwhile, this system has the advantage of small volume, high precision and low cost, which will offer prospects the future application

References