An Improved Method for Measuring the Height of Quad-rotor Aircraft

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ABSTRACT: The air pressure sensor provides high-precision height information by temperature compensation, but it is easily interfered by environment, and the precision is decreased by the height. This paper presents a new approach for measuring the height of quad-rotor aircraft, using the air pressure sensor, GPS and accelerometer data. The proposed algorithm which is based on discrete Kalman filtering results in eliminating interference from environmental change on the air pressure sensor. The algorithm was tested extensively in simulations and experiments, the results show that this method can get more accurate height information, and fully meet the demands of flight control of quad-rotor aircraft.

Keywords: quad-rotor aircraft; pressure sensors; discrete Kalman filter; height measurement

1 INTRODUCTION

With the development of the inertial measurement unit, the attitude control and trajectory tracking of quad-rotor aircraft are gradually resolved, making the aircraft achieve autonomous flight. The height measuring unit is required to provide real-time and accurate flight altitude, especially in low altitude. Therefore, how to use the limited airborne equipment on the four-rotor aircraft to obtain accurate and reliable information is the key to the research.

GPS can provide positioning information for the four-rotor aircraft, but its long response time and error range can’t meet the real-time requirements and the accuracy. If the number of star searches not satisfies the requirement, it will seriously affect the accuracy of height information; the pressure sensor has advantages of small volume, low power consumption, characteristics of short response time, high reliability, high measurement accuracy and wide measuring range which are widely used in the four-rotor aircraft, but the pressure highly susceptible to the environmental wind and measured from the data contains all kinds of noise, and the error after damping treatment of the aircraft will appear less. Therefore, combining GPS with different characteristics of the pressure sensor and accelerometer inertia unit can get high accuracy from the aspect of height information.

In this paper, we first establish a reasonable and accurate motion model for the pressure sensor, GPS and inertial sensor unit, and then we carry out the data fusion with the discrete Kalman filtering algorithm. Finally, we compare the measured height of radio module to demonstrate the feasibility of this method.

2 DATA PROCESSING AND MODELING OF AIR PRESSURE SENSOR

In the gravity field, the atmospheric pressure decreases with altitude, and the height information of the aircraft can be obtained by using this principle. The relationship between the standard and height is expressed as follows:

\[
\begin{align*}
\beta & \neq 0, H = \frac{T_b}{\beta} \left( \frac{P_H}{P_b} \right)^{-\beta R / g} - 1 + H_b \\
\beta & = 0, H = -\frac{RT_b}{g} \ln \left( \frac{P_s}{P_n} \right) + H_b
\end{align*}
\]  

(1)
In this formula, $P_H$ represents the corresponding pressure value when the height is $H$; $P_b$ and $T_b$ respectively represent the air pressure and temperature when the surface height is $H_b$; $\beta$ represents the vertical temperature gradient; $G$ represents the gravity acceleration; $R$ represents the air specific gas constant.

In practical use, the pressure and temperature are easily affected by the environment which could result in height error. From the formula of partial derivatives, we can conclude: The relationship between temperature and height is proportional, but the atmospheric pressure and height is inversely. Therefore, the wind interference will lead to a lower measured pressure; as a result, the height of information is higher than the actual height. We need to handle this problem.

Read raw data from the pressure sensor and use the average filter:

$$\begin{align*}
    p &= \frac{1}{n} \sum_{i=1}^{n} p_i \\
    t &= \frac{1}{n} \sum_{i=1}^{n} t_i
\end{align*}$$

The measurement equation is as follows:

$$H_{\text{baro}} = h_b + h' + \lambda_1$$

In this formula, $h_b$ represents the true altitude; $h'$ represents the error of system; $\lambda_1$ represents the noise of measurement.

3 DATA PROCESSING AND MODELING OF GPS’

GPS is the global positioning system. The localization principle is based on the measurement of the intersection to determine the location of the intersection method. But the accuracy of the GPS developers to the civilian use is far less than the accuracy of its own military use, and the frequency of its update can’t meet the real-time requirements of aircraft. This research selects the Ublox-GPS module and carries on the low-pass filter processing to the GPS height information. The GPS signal is analyzed by Fourier analysis of the height measurement data collected at 50Hz frequency, and the cutoff frequency is 0.15. The spectrum diagram is as Figure 1.

The measurement equation is as follows:

$$H_{\text{GPS}} = h_g + \lambda_2$$

In this formula, $h_g$ represents the true altitude, and $\lambda_2$ represents the noise of measurement.

4 DATA PROCESSING AND MODELING OF ACCELEROMETER

The accelerometer is measured by the linear acceleration of the vertical ground motion to measure the height of the flight. We respectively use the strap-down type and the three-direction line acceleration sensor along the three axes of the aircraft-fixed connection, which calculate the three directions of the line acceleration.

In this study, the sensor with three axes and three-axis accelerometer, which can directly measure the acceleration of the vertical direction, is used for MPU6000. The integral equation is as follows:

$$\begin{align*}
    V &= \int a \, dt + \varepsilon_1 \\
    h &= \int V \, dt + \varepsilon_2 = \int \left( \int a \, dt + \varepsilon_1 \right) \, dt + \varepsilon_2
\end{align*}$$

In this formula, $a$ represents the t moment of acceleration; $V$ represents speed; $h$ represents altitude; $\varepsilon_1$ and $\varepsilon_2$ represent the error of system. Due to the height of the accelerometer measurements that will have a cumulative error over time, it is required to combine with other high sensors.

The measurement equation of accelerometer is shown as follows:

$$a_v = a' + \lambda_3$$

In this formula, $a'$ represents the actual vertical acceleration, and $\lambda_3$ represents the measurement noise.

5 SOFTWARE FLOW-CHART OF DATA FUSION ALGORITHM

In this flow chart, $H_{\text{baro}}$ represents the altitude of barometer; $H_{\text{GPS}}$ represents the altitude of GPS; $H$ represents the height value resulting from the data fusion.
6 IMPLEMENTATION OF THE DISCRETE KALMAN FILTERING ALGORITHM

The principle of Kalman filter is the linear minimum variance estimation, and the estimation criterion is based on the minimum variance. This study uses adaptive KF to realize mutual compensation of the height from GPS and pressure sensors.

(1) The establishment of system state equation and measurement equation

The height \( h \), vertical velocity \( V_z \) and acceleration \( a' \) are regarded as the state variables. The state equation of this system is shown as follows:

\[
\begin{bmatrix}
    \dot{h} \\
    \dot{V_z} \\
    \dot{a'}
\end{bmatrix} =
\begin{bmatrix}
    0 & 1 & 0 \\
    0 & 0 & 1 \\
    0 & 0 & 1
\end{bmatrix}
\begin{bmatrix}
    h \\
    V_z \\
    a'
\end{bmatrix} +
\begin{bmatrix}
    0 \\
    0 \\
    1
\end{bmatrix} \dot{w}
\]

(7)

According to the aforementioned analysis of the height, we establish a system of measurement equation as follows:

\[
\begin{bmatrix}
    h \\
    V_z \\
    a'
\end{bmatrix} =
\begin{bmatrix}
    1 & 0 & 0 \\
    0 & 0 & 1 \\
    0 & 0 & 0
\end{bmatrix}
\begin{bmatrix}
    \lambda_1 \\
    \lambda_2 \\
    \lambda_3
\end{bmatrix}
\]

(8)

(2) Design of Kalman filter

State equation and observation equation of discrete Kalman filter are as follows:

\[
X(k + 1) = AX(k) + Bu(k)
\]

(9)

\[
Z(k) = H_k X_k + v(k)
\]

(10)

In the formula, the noise of the system \( u(k) \) and the observation noise \( v(k) \) are not related to the Gauss white noise, and the corresponding covariance is respectively \( Q(k) \) and \( R(k) \). \( E\{u(k)\} = 0 \); \( E\{u(k)u(k)^T\} = Q(k)\delta_{kj} \); \( E\{v(k)\} = 0 \); \( E\{v(k)v(k)^T\} = R(k)\delta_{kj} \).

The system sampling frequency is 50Hz, so the state transition matrix is \( A = \begin{bmatrix} 1 & 0.02 & 0.00008 \\ 0 & 1 & 0.02 \\ 0 & 0 & 1 \end{bmatrix} \), the noise matrix is \( B = \begin{bmatrix} 1.3333 \times 10^{-2} \\ 0.00008 \\ 0.05 \end{bmatrix} \) and the measurement matrix is \( H = \begin{bmatrix} 1 & 0 \\ 1 & 0 \\ 0 & 1 \end{bmatrix} \). Therefore, according to the principle of Kalman filter:

a) The prediction equation of \( k+1 \) moment is as follows:

\[
X(k + 1|k) = AX(k)
\]

(11)

b) The state update equation is as follows:

\[
X(k + 1) = X(k + 1|k) + K_{k+1}(Z(k + 1) - H_{k+1}X(k + 1|k))
\]

(12)

c) The gain equation is as follows:

\[
K_{k+1} = P_{k+1|k}H_{k+1}^T(H_{k+1}P_{k+1|k}H_{k+1}^T + R_{k+1})^{-1}
\]

(13)

d) The estimation error variance is as follows:

\[
P_{k+1} = (I - K_{k+1}H_{k+1})P_{k+1|k}
\]

(14)

e) The error covariance update is as follows:

\[
P_{k+1} = AP_kA^T + BQ_kB^T
\]

(15)

7 SIMULATION RESULTS

To verify the validity of this study, a simulated test was carried out in MATLAB. The variance of \( w \) was 100; the variance of \( \lambda_1 \) was 200; the variance of \( \lambda_2 \) was 80; the variance of \( \lambda_3 \) was 0.01. Because of the high error of GPS, it is not suitable to be used directly for data fusion. Therefore, the adaptive factor \( \sigma \) is used to determine the influence of the current environment on the height of the barometer.

Given the initial state of the filter as follows:

\[
P(0) = 10 \times
\begin{bmatrix}
    1 & 0 & 0 \\
    0 & 1 & 0 \\
    0 & 0 & 1
\end{bmatrix}
\]

(16)

The algorithm simulation curve is shown in Figures (2) to (4):
8 CONCLUSION

From the simulation results, we can conclude that the height of the pressure sensor is close to the real height in the case of the outside environment. However, the height of GPS with poor accuracy is highly variable. When there is wind that forms the external environment, the height of the pressure sensor is increased, but the GPS height is decreased. Due to the addition of the adaptive factor, the fusion height will be adjusted according to the trend of the GPS fusion results, with the maximum close to the true height value. The error is relatively serious when the sampling points are in the range of 2,300-2,800.

Therefore, the discrete Kalman filter with the addition of the adaptive factor can get more accurate height information, which satisfies the precision requirement of the four-rotor aircraft.

REFERENCES


Figure 2. Barometer height, GPS height, fusion height and radio altitude.

Figure 3. Fusion height and radio altitude.

Figure 4. The error between the fusion height and the radio altitude.


