# Gradient Descent Algorithm for Small UAV Parameter Estimation System

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(Received 18 January 2017; revised 20 February 2017; accepted 5 March 2017)

**Abstract**: A gradient descent algorithm with adjustable parameter for attitude estimation is developed, aiming at the attitude measurement for small unmanned aerial vehicle (UAV) in real-time flight conditions. The accelerometer and magnetometer are introduced to construct an error equation with the gyros, thus the drifting characteristics of gyroscope can be compensated by solving the error equation utilized by the gradient descent algorithm. Performance of the presented algorithm is evaluated using a self-proposed micro-electro-mechanical system (MEMS) based attitude heading reference system which is mounted on a tri-axis turntable. The on-ground, turntable and flight experiments indicate that the estimation attitude has a good accuracy. Also, the presented system is compared with an open-source flight control system which runs extended Kalman filter (EKF), and the results show that the attitude control system using the gradient descent method can estimate the attitudes for UAV effectively.

**Key words**: gradient descent algorithm; attitude estimation; quaternions; small unmanned aerial vehicle (UAV)

**CLC number**: V249.3 **Document code**: A **Article ID**: 1005-1120(2017)06-0680-08

## 0 Introduction

In recent years, as unmanned aerial vehicles (UAVs) is progressing, small UAVs, thanks to their small size, simple structure, ease to operate, etc., have attracted increasing attentions[1]. The attitude measurement system of small UAV is the key component of autonomous flight, directly determining the stability and the position accuracy of UAV[2]. Benefited from the rapid development of micro-electro-mechanical systems (MEMS), the attitude estimation system is evolved into a low cost, light weight, easy integrated and portable attitude and heading reference system (AHRS)[3]. An AHRS is composed of tri-axis gyroscopes, tri-axis accelerometers and tri-axis magnetometers[4-5]. However, the MEMS sensor itself has a severe time-varying drifts[6]; the gyroscope has high dynamic performance, with big accumulated error over time; the accelerometer has no integral error, but in high dynamic condition, it will be disturbed by linear acceleration or rotational acceleration; the magnetometer is very susceptible to interference of ambient magnetic field. Therefore, neither gyroscope nor accelerometer nor magnetometer can independently provide accurate attitude estimation, and it is necessary to develop the appropriate attitude estimation algorithm to compensate sensor data errors[7].

At present, commonly used algorithms for attitude estimation system include Kalman filter (KF), Extend Kalman filter (EKF), complementary filter (CF), gradient descent (GD) algorithm and so on. KF has been widely used in UAV attitude system with expensive computing resources. It is difficult to establish a stable and

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**How to cite this article**: Guo Jiandong, Liu Qingwen, Wang Kang. Gradient descent algorithm for small UAV parameter estimation system[J]. Trans. Nanjing Univ. Aero. Astro., 2017,34(6):680-687.
http://dx.doi.org/10.16356/j.1005-1120.2017.06.680

reliable attitude equation, to determine the appropriate measurement noise and process noise covariance matrix. CF is not suitable for dynamic environment[8-9] due to its low precision and serious attitude drift.

We design an attitude estimation system by introducing the gradient descent method with self-designed STM32F4XX as the core controller, the MPU6050, LSM303D and L3GD20 as the attitude sensors. The embedded system is developed to verify the performance of the presented algorithm.

# 1 Gradient Descent Algorithm Design

The procedure of the algorithm is as follows: Firstly, the angular rate differential quaternion is calculated by using the angular rate output from the gyroscope and the quaternion differential equation. Secondly, the measured accelerometer and magnetometer data are preprocessed, based on the error function and its derivative of accelerometer and magnetometer. The gradient descent equation of attitude is obtained, and then the gradient descent method is utilized to compensate the quaternions error, and an accurate quaternions is derived. Lastly, the quaternions are obtained by integrating angular rate of gyroscope to the gradient descent method to solve the optimal quaternions of attitude. It realizes the compensated attitudes and improves the accuracy of attitude measurement.

## 1.1 Quaternion expression

Before describing the UAV attitude, the proper coordinate system must be established. The two coordinate systems commonly used in UAV attitude determination system are the body coordinate system marked with $b$ and the earth coordinate system marked with $e$. Usually, the center of gravity of the body is the origin of the body coordinate system, and $XYZ$ are the longitudinal, the lateral and the vertical axes, respectively. UAV rotating around $X$ axis generates the roll angle $\phi$, rotating around $Y$ axis the pitch angle $\theta$, rotating around $Z$ axis the yaw angle $\psi$. Neglecting the earth rotation, the ground coordinate system can be regarded as an inertial coordinate system. The transformation of the two coordinate systems can be represented by the transformation matrix

$$\boldsymbol{C}_e^b=\begin{bmatrix}\cos\theta\cos\psi & \cos\theta\sin\psi & -\sin\theta\\ \sin\theta\sin\phi\cos\psi-\cos\phi\sin\psi & \sin\theta\sin\phi\sin\psi+\cos\phi\cos\psi & \sin\phi\cos\theta\\ \cos\phi\sin\theta\cos\psi+\sin\phi\sin\psi & \cos\phi\sin\theta\sin\psi-\sin\phi\cos\psi & \cos\theta\cos\phi\end{bmatrix} \tag{1}$$

Since the Euler angle will present a singular point in the description of the attitude, the full position analysis cannot be achieved. However, the quaternion equation in the description of the attitude can avoid the singular point successfully with low computing cost and high real-time quality, satisfying the requirements of flight control system. The general form of the quaternion is given as[10]

$$q=q_1+q_2 i+q_3 j+q_4 k \tag{2}$$

Ignoring the influence of the earth rotation, the continuous and discrete domain of the equation of quaternion of the current and the previous estimation of orientation can be expression as[11]

$$\begin{aligned}\dot{q}_{\omega,t}&=0.5q_{\text{est},t}\otimes\omega_t\\ q_{\omega,t}&=q_{\text{est},t}+\dot{q}_{\omega,t}\Delta t\end{aligned} \tag{3}$$

where $\omega_t$ is the angular rate along the three directions in the body coordinate system relative to the inertial coordinate system, $q_{\omega,t}$ the current orientation quaternion, $q_{\text{est},t}$ the estimated quaternion, and $\Delta t$ the sample time. In initial condition with the known quaternion, the tri-axial angular rates measured by the gyroscopes can be used to update the quaternion and finally obtain the attitudes[12]. The transformation between the inertial coordinate system and the body coordinate system can be expressed by the quaternion as[13]

$$\boldsymbol{C}_e^b=\begin{bmatrix}q_0^2+q_1^2-q_2^2-q_3^2 & 2(q_1q_2+q_0q_3) & 2(q_1q_3-q_0q_2)\\ 2(q_1q_2-q_0q_3) & q_0^2-q_1^2+q_2^2-q_3^2 & 2(q_2q_3+q_0q_1)\\ 2(q_1q_3+q_0q_2) & 2(q_2q_3-q_0q_1) & q_0^2-q_1^2-q_2^2+q_3^2\end{bmatrix} \tag{4}$$

Combining the tri-gonometric transformation matrix and the quaternion transformation matrix, the relationship between the Euler and the quaternion is[14]

$$\phi=\arctan\left(\frac{2(q_2q_3+q_0q_1)}{q_0^2-q_1^2-q_2^2+q_3^2}\right)$$
$$\theta=-\arcsin(2(q_1q_3-q_0q_2))$$
$$\psi=\arctan\left(\frac{2(q_1q_2+q_0q_3)}{q_0^2+q_1^2-q_2^2-q_3^2}\right) \tag{5}$$

### 1.2 Quaternion compensation using the gradient descent method

The gradient descent method solves the minimum value of the expression in the direction of gradient descent. The expression is given as

$$x_{n+1}=x_n-\alpha\nabla F(x_n) \tag{6}$$

The gradient descent method adopts the first order convergence by solving optimal value in Eq. (6), where $\nabla F(x_n)$ is the gradient at $x_n$ and indicates the negative direction of the gradient, and $\alpha$ the sampling step in the gradient direction. The error function takes the direction of gradient as $\nabla F(x_n)/\|\nabla F(x_n)\|$. When the error function is infinitely approaching zero, it can be considered that Eq. (6) has reached the stable point, and the gradient iteration is completed. In this paper, the error function is a multivariate vector, and the independent variable is also a quaternion vector. Before the initialization of the algorithm, the quantized gyroscope, accelerometer and magnetometer outputs in body coordination are given as: $\boldsymbol{\omega}_b=[0\ \omega_x\ \omega_y\ \omega_z]$, $\boldsymbol{a}_b=[0\ a_x\ a_y\ a_z]$, $\boldsymbol{m}_b=[0\ m_x\ m_y\ m_z]$, and the local gravity vector and the earth magnetic field vector are expressed as: $\boldsymbol{g}_e=[0\ 0\ 0\ 1]$, $\boldsymbol{\rho}_e=[0\ \rho_x\ 0\ \rho_z]$.

#### 1.2.1 Error equation design

The error of the quaternion, obtained by integrating the gyroscope angular rate, is increasing over time. In order to reduce the drift error, the error function represented by the quaternion and the accelerometer can be solved by the gradient descent iteration[15]. The quaternion matrix error function can be obtained as

$$\boldsymbol{f}_g(\hat{q},\hat{a})=\begin{bmatrix}2(q_1q_3-q_0q_2)-a_x\\2(q_0q_1+q_2q_3)-a_y\\1-2(q_1^2+q_2^2)-a_z\end{bmatrix} \tag{7}$$

The value of the gravitational acceleration in the inertial coordinate system, which is rotated by the quaternion method into the body coordinate system, substracts the measured value of the current accelerometer. In order to obtain the optimum value of the error function, the gradient in Eq. (7) is given, and the Jacobian matrix is

$$\boldsymbol{J}_g(\hat{q})=\begin{bmatrix}-2q_2 & 2q_3 & -2q_0 & 2q_1\\2q_1 & 2q_0 & 2q_3 & 2q_2\\0 & -4q_1 & -4q_2 & 0\end{bmatrix} \tag{8}$$

Then the gradient formula of the accelerometer can be expressed as

$$\nabla\boldsymbol{f}_g(\hat{q},\hat{a})=\boldsymbol{J}_g^{\mathrm{T}}(\hat{q})*\boldsymbol{f}_g(\hat{q},\hat{a}) \tag{9}$$

Similarly, the error function of the magnetometer and the Jacobian matrix are expressed, respectively

$$\boldsymbol{f}_\rho(\hat{q},\hat{\rho},\hat{m})=\begin{bmatrix}2\rho_x(0.5-q_2^2-q_3^2)+2\rho_z(q_1q_3-q_0q_2)-m_x\\2\rho_x(q_1q_2-q_0q_3)+2\rho_z(q_0q_1-q_2q_3)-m_y\\2\rho_x(q_0q_2+q_1q_3)+2\rho_z(0.5-q_1^2-q_2^2)-m_z\end{bmatrix} \tag{10}$$

$$\boldsymbol{J}_\rho(\hat{q},\hat{\rho})=\begin{bmatrix}-2\rho_zq_2 & 2\rho_zq_3 & -4\rho_xq_2-2\rho_zq_0 & -4\rho_xq_3+2\rho_zq_1\\-2\rho_xq_3+2\rho_zq_1 & 2\rho_xq_2+2\rho_zq_0 & 2\rho_xq_1+2\rho_zq_3 & -2\rho_xq_0+2\rho_zq_2\\2\rho_xq_2 & 2\rho_xq_3-4\rho_zq_1 & 2\rho_xq_0-4\rho_zq_2 & 2\rho_xq_1\end{bmatrix} \tag{11}$$

The gradient formula of magnetometer is

$$\nabla\boldsymbol{f}_m=\boldsymbol{J}_\rho^{\mathrm{T}}(\hat{q},\hat{\rho})*\boldsymbol{f}_\rho(\hat{q},\hat{\rho},\hat{m}) \tag{12}$$

According to Eq. (6), defining the attitude quaternion $q_{\nabla,t}$, which is obtained from accelerometer and magnetometer by using the gradient descent method as

$$q_{\nabla,t}=q_{\nabla,t-1}-\mu_t\frac{\nabla\boldsymbol{f}}{\|\nabla\boldsymbol{f}\|} \tag{13}$$

where $\nabla\boldsymbol{f}=\begin{bmatrix}\boldsymbol{J}_g(\hat{q})\\\boldsymbol{J}_\rho(\hat{q},\hat{\rho})\end{bmatrix}^{\mathrm{T}}*\begin{bmatrix}\boldsymbol{f}_g(\hat{q},\hat{a})\\\boldsymbol{f}_\rho(\hat{q},\hat{\rho},\hat{m})\end{bmatrix}$, and $\mu_t$ is the sample step as

$$\mu_t=\eta\|\dot{q}_{\omega,t}\|\Delta t \qquad \eta>1 \tag{14}$$

where $\Delta t$ represents the sampling rate, and $\eta$ the measurement noise from the accelerometer and the magnetometer. Therefore, when $\nabla\boldsymbol{f}/\|\nabla\boldsymbol{f}\|$

is infinitely approaching zero, Eq. (13) achieves a stable point, which is the exact quaternion of attitude.

1.2.2 Algorithm fusion

The quaternion solved by Eq. (3) is $q_{\omega,t}$, and the accelerometer and magnetometer attitude quaternions is $q_{\nabla,t}$, and the estimated attitude quaternion is $q_{\mathrm{est},t}$. The fusion process is described by Eq. (15)

$$q_{\mathrm{est},t}=\alpha q_{\nabla,t}+(1-\alpha)q_{\omega,t}\quad 0\leqslant\alpha\leqslant 1 \tag{15}$$

where $\alpha$ and $(1-\alpha)$ are the weights applied to each orientation calculation. The right side of Eq. (15) consists of two parts: The former is suit for low speed state, and the latter is applied to high speed state. So $\alpha$ is a self-adapted value. An optimal value of $\alpha$ can be defined as the one that ensures the weighed divergence of $q_{\omega,t}$ equal to the weighted convergence of $q_{\nabla,t}$. Eq. (15) can be rearranged to define $\alpha$ as

$$(1-\alpha)\beta=\alpha\frac{\mu_t}{\Delta t} \tag{16}$$

where $\beta$ is an adjustable parameter, which is the divergence rate of $q_{\omega,t}$ and expressed as the magnitude of a quaternion derivative corresponding to the gyroscope measurement error. Since the convergence rate of the gradient descent method is related to the speed of motion, $\mu_t/\Delta t$ is relatively larger at this time, and $\beta$ is small, then

$$\alpha\approx\frac{\beta\Delta t}{\mu_t}\approx 0 \tag{17}$$

Substituting Eqs. (3), (17) into Eq. (15) yields the attitude fusion as

$$q_{\mathrm{est},t}=q_{\mathrm{est},t-1}+\left(\dot{q}_{\omega,t}-\beta\frac{\nabla \boldsymbol{f}}{\|\nabla \boldsymbol{f}\|}\right)\Delta t \tag{18}$$

In summary, the steps of the presented algorithm are as follows:

(1) The parameter, output from the attitude sensor and gyroscope, is normalized and the value of $\beta$ is determined.

(2) The angular rate differential quaternion is obtained through solving quaternion differential equation which utilizes the angular rate of the gyroscope.

(3) The error function and its derivative are developed involving the values measured by the accelerometer and the magnetometer.

(4) The gradient formula is developed using the error function in (3) and its derivatives, and then the gradient descent method is involved to obtain the optimum attitude quaternion.

(5) The angular rate of differential quaternion in (2) and the attitude quaternion in (4) are used to derive the fused quaternion.

(6) The latest attitude angle is updated with the fused quaternion in (5).

(7) Repeat the above steps to constantly update the attitude.

## 2 Hardware Platform Description

The attitude estimation system is designed with 32-bit ARM microcontrollers based on the Cortex-M4 kernel of STMicroelectronics as the main controller. Its frequency is up to 180 MHz with a single cycle multiplication and hardware division. Fig. 1 shows the proposed attitude and heading reference estimation system.

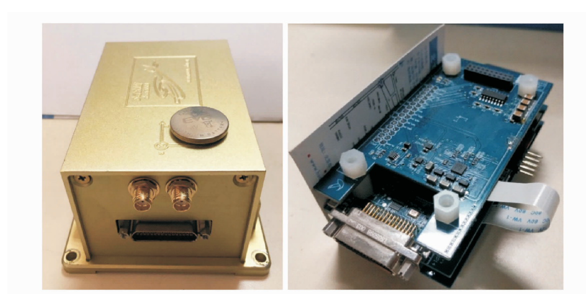

Fig. 1 Homemade prototype of AHRS (left) and its circuit component (right)

The estimation system structural diagram of the hardware design is shown in Fig. 2. The system is equipped with three types of MEMS sensors, MPU6050, LSM303D and L3GD20 respectively, which constitutes a low-cost, redundant-sensor, and a nine-axis attitude estimation system. All sensors providing digital outputs are collected by using SPI peripheral with time-sharing of sensor MCU. The estimated attitudes are sent to data log module using RS232 by wireless radio modem.

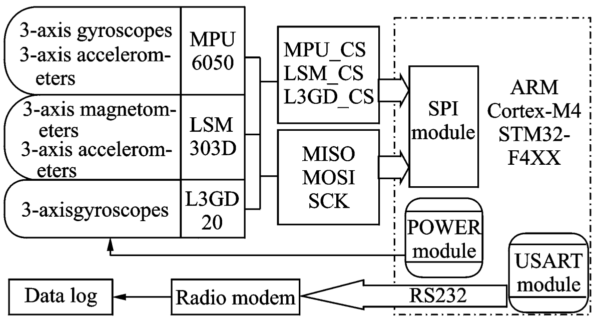


Fig. 2 Estimation system block diagram

## 3 Experimental Results and Analysis

To verify the proposed estimation algorithm, three kinds of experiments are carried out. The first test is implemented on a ground vehicle to validate the static accuracy, the second is implemented on a tri-axis turntable for movement performance testing, and the third uses a Hex-rotor equipped with a matured open-source attitude reference system to validate the robustness of the attitude estimation in real flight situations.

In the experiments, the frequency of data read from the three type sensors is 1 kHz. The full-scale range of the gyroscopes, accelerators and magnetometers are $\pm 1\ 000°/s$, $\pm 4$ g and $\pm 4$ Gauss. One step of the gradient descent calculation is within 0.95 ms, so the calculation cycle of the gradient descent algorithm is set as 1 ms by one timer.

### 3.1 Ground test

The ground test of the AHRS is to analyze the attitude estimation system data in the static state. Fig. 3 (a) shows the estimation output of the pitch angle when the system is placed horizontally, and Fig. 3 (b) shows the output of the roll angle, and Fig. 3 (c) shows the output of the yaw angle. Fig. 3 indicates that the pitch angle oscillates between 0.1° and 0.2° and no divergence during the horizontal test, which effectively eliminates the integral error of gyroscope. Also, the roll and the yaw angles exhibit good stability and accuracy in this condition. The outputs from the designed filter are considered as white noise in the system, with the average deviation of about 0.1°.

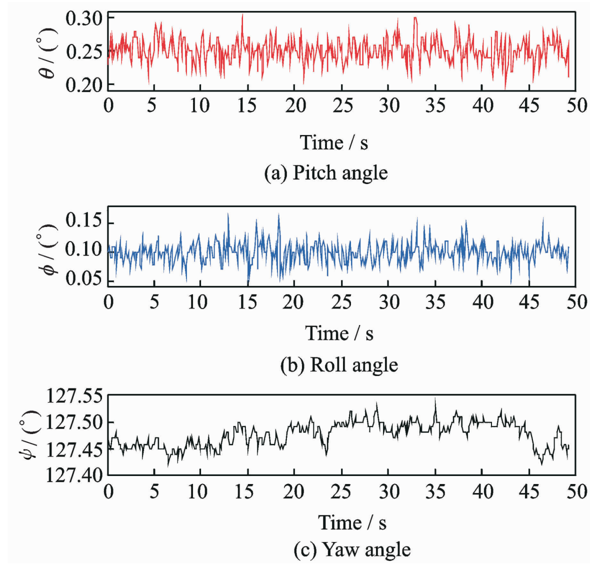


Fig. 3 Tri-axis attitude estimation in ground test

### 3.2 Tri-axis turntable experiment

The movement performance of the proposed algorithm is evaluated by a high-precision tri-axis turntable system as shown in Fig. 4. The system is initially fixed on the table with its $X$-$Y$-$Z$ axis aligned with the front-upper-right.

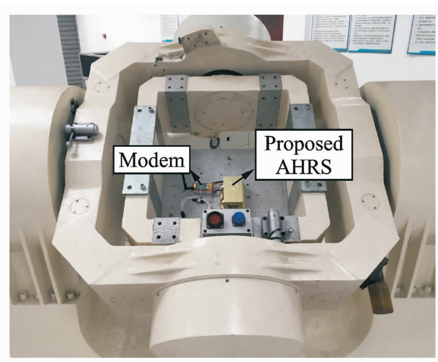


Fig. 4 Physical map of the tri-axis turntable testing

Since the turntable is able to obtain a position accuracy of $\pm 5''$ at a rate range from 0.001 to 400 (°)/s, its motion feedback is regarded as the reference. Since the turntable is ferrous material and the magnetometer is influenced by it, the accuracy of the pitch and the roll angles are evaluated in the turntable test.

Fig. 5 shows the pitch angle of the test in turntable condition. The red dash curve represents the orientation estimated by the proposed algorithm, and the blue solid curve is the turntable reference. In Fig. 5 (b), it can be observed that the proposed algorithm is able to estimate the attitude correctly within 1.0°, compared with the reference.

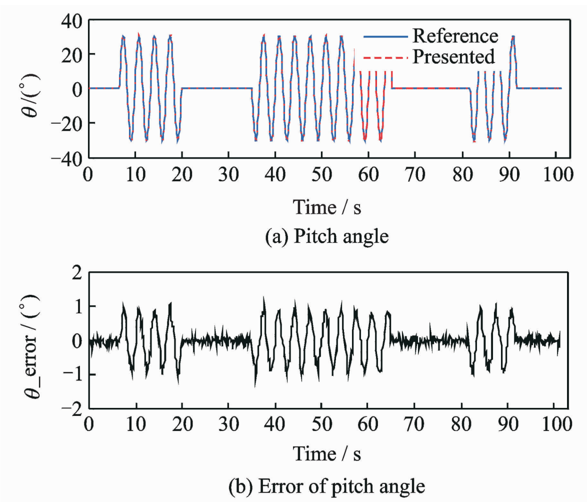


Fig. 5 Pitch angle by the proposed vs. the turntable reference

Fig. 6 shows the roll angle accuracy of the test situation. The presented method also tracks the roll motion in time, and the error is smaller than 1.2°, as show in Fig. 6 (b).

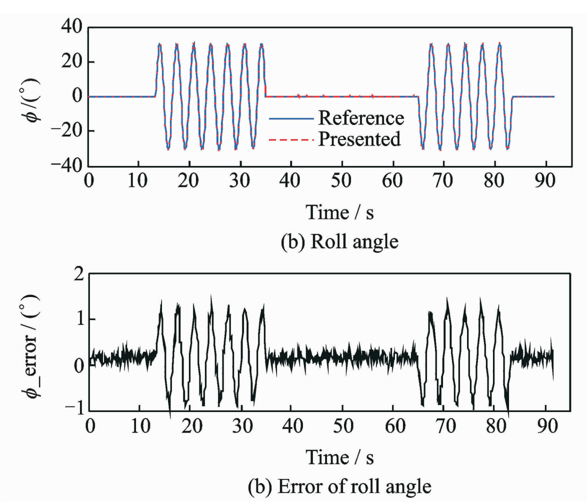


Fig. 6 Roll angle by the proposed vs. the turntable reference

Fig. 7 shows the performance of the coupled pitch and roll angle estimations in the movement situation. As shown in Fig. 7 (a), the pitch movement is a sine signal with an amplitude of 30°. Meanwhile, the roll remains zero. In Fig. 7 (b), the coupled estimated $\phi$ is within $\pm 0.5°$, produced by the proposed AHRS. The same accuracy is also reflected in roll movement vs. pitch zero, as show in Figs. 7 (c, d).

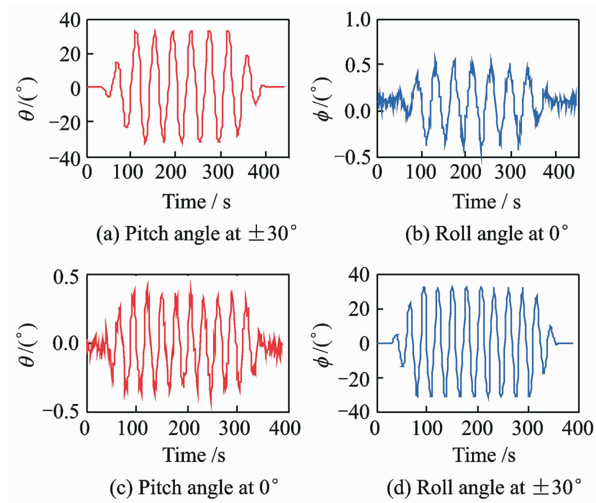


Fig. 7 The coupled performance of the pitch and the roll angles

### 3.3 Flight test

The flight test is implemented on a small Hex-rotor platforms, which is installed with the self-designed estimation system and the open-source flight controller. In order to analyze the accuracy of the attitude estimation system in real flight condition, the Pixhawk flight logs and the self-designed estimation system data are compared within time range as follows.

Fig. 8 shows the accuracy of the pitch angle, with high frequency motion and big angles given as ±20°. It can be seen that the two types of filters have a similar estimation accuracy. The presented algorithm can track the true motion in real time, compared with the open-source system with EKF. The same property of the roll angle is verified in Fig. 9. Fig. 10 shows the heading motion character. There are about 1.5° deviation between the two types of filters in the easily disturbed magnetic field.

It can be concluded from Figs. 8—10 that the attitudes estimated by the gradient descent method have no divergence, which effectively compensate the gyroscope integration errors. At the same time, the deviation of the pitch and the roll angles derived from the two systems are within 0.5°, and the deviation of heading is within ±1.5°. Therefore, the presented algorithm for attitude estimation system can meet the actual flight requirement of UAV.

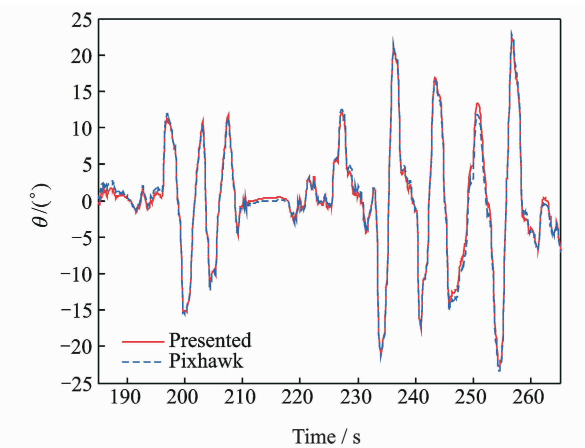


Fig. 8 Pitch angle in flight test

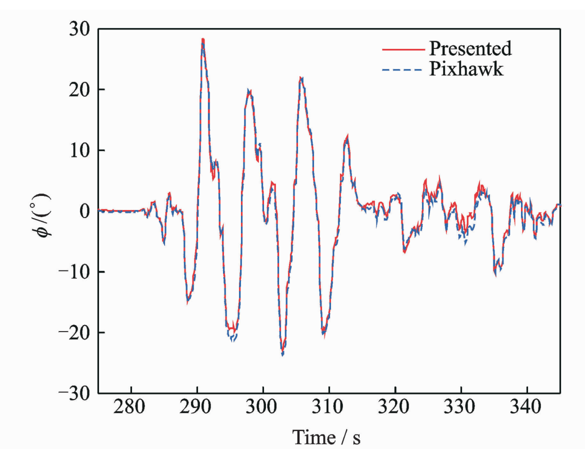


Fig. 9 Roll angle in flight test

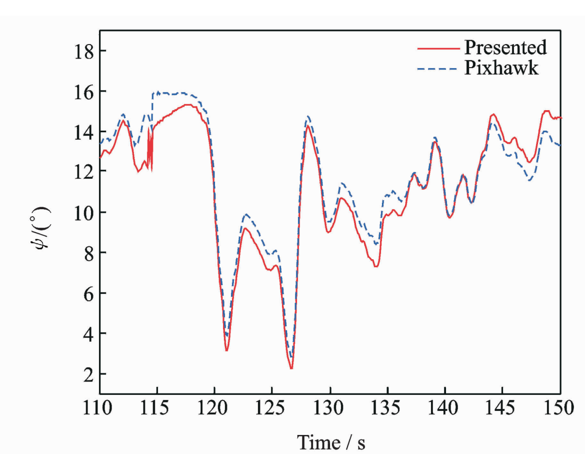


Fig. 10 Yaw angle in flight test

## 4 Conclusions

We have discussed the derivation process for the gradient descent algorithm with an adjustable parameter to decrease errors from accelerators in maneuver flight environment. A series of experiments are implemented to verify the property of the presented attitude estimation system, and the conclusions are drawn as:

(1) The quaternion attitude estimation algorithm based on gradient descent is developed, so that the accelerometer and the magnetometer data can be used and the error compensation for gyroscope measurement can be derived.

(2) Performance has been evaluated using a self-designed orientation sensor and reference system in ground, turntable and flight conditions, with low computing cost, high accuracy, and a less-than-1 ms running time.

(3) Performance is also benchmarked against the open-source EKF-based algorithm of orientation sensor, which satisfies the attitude control for small UAV.

## Acknowledgment

This research was supported by the Fundamental Research Funds for the Central Universities (No. 56XAA17075).

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