

# Inertial/celestial integrated navigation algorithm for long endurance unmanned aerial vehicle<sup>1</sup>

FANG TING<sup>2,3</sup>, HUANG XIAOMING<sup>2</sup>

**Abstract.** In recent years, unmanned aerial vehicle (UAV) technology has been widely used in military and civil fields because of many advantages, such as low cost and no need of personal operation, among them, the most strategic value is long endurance UAVs. The strapdown inertial navigation system proposed in this paper was an inertial navigation algorithm for such long endurance UAVs. Simulation analysis and practical application of the algorithm were carried out to verify the feasibility of the algorithm in specific applications. In addition, the characteristics of pure inertial navigation system without correction and the reasons for the occurrence of navigation error were analyzed, so as to provide a reference for modular design of integrated navigation system.

**Key words.** Long endurance unmanned aerial vehicle (UAV), strapdown inertial navigation system (SINS), integrated navigation system.

## 1. Introduction

The development of UAVs makes our production, life and other fields have undergone great changes. Whether it is in agriculture or military applications, it is hoped that UAVs can have longer time navigation. However, high-altitude long endurance UAVs has higher requirements for navigation, such as higher accuracy and autonomy, which is difficult to achieve for traditional single navigation systems [1]. It can be seen from the analysis that both celestial navigation and inertial navigation system have their own characteristics. After combining them, they can give full play to the advantages of the two, realize complementary advantages, and eventually build a strong anti-interference, high precision navigation system [2]. The success of high-altitude long endurance UAVs is inseparable from a stable and reliable navigation system. Compared with other types of UAVs, its particularity of operating environment makes it more demanding for navigation system [3]. For the

---

<sup>1</sup>School of Electrical and Information Engineering, Anhui University of Technology, Maanshan, Anhui, 243000, China

<sup>2</sup>Corresponding author

high-altitude photography, measurement and control, and reconnaissance tasks conducted by aerial high-altitude (HALE) unmanned aerial vehicle, it is necessary to equip with optical/electronic detection equipment and provide accurate positioning accuracy and a stable working environment for the equipment [4].

In addition to aerial reconnaissance and control class UAVs, when the HALE UAV is engaged in similar work such as geographical mapping, it also requires navigation systems to provide very high precision for these devices, so as to guarantee high resolution images and other information in the process of geographical mapping [5]. In the long standing environment, the internal and external environment of UAVs is relatively complex, and there is a great deal of interference. Therefore, the UAV navigation system must be highly reliable and have high anti-interference capability [6]. In view of this special demand, the UAV navigation sensor, whether it is configuration or system structure, has a higher demand. Therefore, the algorithm of relative integrated navigation has certain application value.

## 2. State of the art

The UAV technology of our country is relatively advanced in the world. From the initial development so far, it has experienced forty years. A series of different purposes, different properties of the drone reconnaissance aircraft, and general UAVs have been successfully developed, which are now widely used in various industries [7]. The UAV technology of our country is relatively mature, and the UAVs have excellent performance, which are loved by domestic and overseas users. One of the most typical representatives of the long endurance UAV is Xianglong UAV. Its continued sailing time has reached more than 10 h, which is prominent in the same type of UAVs [8].

After decades of development, the current methods of celestial navigation used by UAVs mainly include direct and indirect sensitive horizon. The latter uses the principle of starlight refraction to make a higher progress [9]. The existing indirect sensitive horizon method has to be realized on the basis of orbital dynamics. But for long endurance UAVs, their kinematic characteristics do not meet the conditions of use [10]. In this case, it is necessary to design a strapdown inertial navigation algorithm that can be used in engineering practice. According to different installation methods of measurement devices, the inertial navigation system can be divided into two types, platform type and strapdown inertial navigation system [11]. Because inertial platform is relatively large in volume and quality, it results in higher cost of platform inertial navigation system. In addition, because of its complicated structure, the failure rate is relatively high, and its reliability is difficult to be effectively guaranteed. The development of inertial sensors has led to strapdown inertial navigation gradually replacing platform type systems. With the development of modern computer information technology, an inertial/satellite integrated navigation system has come into being in order to satisfy the rapid development of UAV industry.

### 3. Methodology

#### *3.1. The basic principle of strapdown inertial navigation*

Strapdown inertial navigation system (SINS) used in UAVs is an inertial accelerometer, such as accelerometer and gyroscope, which is fixed on UAV platform. These sensors are used to carry out the UAV body coordinate system, as well as acceleration and angular increments. The accelerometer calculates the projection of the acceleration component in the inertial coordinate system in the body coordinate system. What are measured by the gyro include the projection of the UAV in the body coordinate system and the angular rate of rotation relative to the inertial space. The coordinate system of UAV is relative to the navigation coordinate system, which is the required navigation information. According to the situation, the Northeast terrain coordinate system is adopted. In order to obtain the strapdown matrix, it is necessary to convert the volume of the body coordinate system relative to the inertial coordinate to that of the geographic coordinate system. The strapdown attitude can be used to calculate the relative information of the body, and the relative information can be transformed from the relative coordinate system to the geographical coordinate system.

An example of long endurance unmanned aerial vehicle that could be equipped with the strapdown inertial navigation is shown in Fig. 1.



Fig. 1. Long endurance unmanned aerial vehicle

The working principle of strapdown inertial navigation system is that when the initial conditions are determined, the attitude, position and velocity of the vector

are computed by the measured results of the inertial component, and the navigation parameters in the navigation coordinate system are converted into the navigation parameters. For only a simple inertial navigation system, the accurate navigation parameters cannot be obtained if the accuracy of the inertial period is low. In the case of integral action, there will be cumulative errors. Therefore, it is necessary to combine it with visual navigation or satellite navigation, and the Kalman filter is used to correct the initial and parameter errors in inertial navigation to ensure the accuracy of navigation parameters. The principle of strapdown inertial navigation system is shown in Fig. 2.

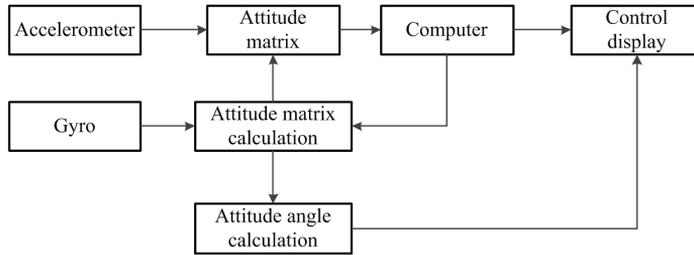


Fig. 2. Scheme of strapdown inertial navigation system

The design scheme of the UAV navigation development contains many contents, including the measuring information of simulated gyroscope and accelerometer, the output of the GPS module design, trajectory generation module planning, the design of strapdown inertial navigation module and the design of visual measurement module [12]. The first step is to simulate the track according to the actual situation of the planning, and obtain the UAV attitude, velocity, acceleration and angular speed and position of the ideal information. In addition, the error is added to the real error model to simulate the outputs of inertial devices, satellite systems and visual system measurements. Finally, the outputs of the inertial navigation system are calculated. Then, according to the needs of UAV navigation, the appropriate data fusion method is chosen, and the corresponding sensor output is called to estimate the parameters of the strapdown inertial navigation system. The error correction is also included in the calculation result, which includes the deviation of the sensing element. Finally, the output of the combined system is shown, and finally the simulation design of the UAV integrated navigation system is completed.

### ***3.2. Design of linked inertial navigation algorithm***

The attitude of UAV is solved by using strapdown navigation system, which is to solve the attitude differential equation by using the angular increment information produced by inertial component. Finally, the angle information rotation relationship between the machine system and the navigation system is obtained by using the calculated results. By calculating the attitude matrix values, the attitude information in different directions of the UAV can be obtained, and the attitude information matrix can be updated by using the continuous output of the inertial components, so that the attitude update can be carried out. Whether it is speed, posture, or po-

sition, the navigation parameter information must have a reference standard when it is expressed. On the other hand, the output information of inertial devices such as inertial sensors in inertial navigation systems is relative to the inertial coordinate system. Therefore, the definition of the common coordinate system must be carried out. In the process of navigation, the types of coordinate systems used by UAVs are very large. According to this demand, the department of geography is chosen as the navigation system of unmanned aerial vehicle during flight. Based on the needs of the research, the conversion of the full text and the analysis of the coordinate system are carried out in this paper.

A rigid body acts as a fixed point at one point of the body and rotates on an axis, so that it can rotate to achieve any gesture. The rotation process of the quaternion can be expressed as follows:

$$q = \cos \frac{\theta}{2} + \sin \frac{\theta}{2} \cdot \mathbf{n} = \cos \frac{\theta}{2} + \sin \frac{\theta}{2} \cos \alpha \cdot i + \sin \frac{\theta}{2} \cos \beta \cdot j + \sin \frac{\theta}{2} \cos \gamma \cdot k. \quad (1)$$

In formula (1),

$$q_0(0) = \cos \frac{\theta_0}{2} \sin \frac{\varphi_0}{2} \cos \frac{\gamma_0}{2} - \sin \frac{\theta_0}{2} \sin \frac{\varphi_0}{2} \sin \frac{\gamma_0}{2},$$

$$q_1(0) = \sin \frac{\theta_0}{2} \cos \frac{\varphi_0}{2} \cos \frac{\gamma_0}{2} - \cos \frac{\theta_0}{2} \sin \frac{\varphi_0}{2} \sin \frac{\gamma_0}{2},$$

$$q_2(0) = \cos \frac{\theta_0}{2} \cos \frac{\varphi_0}{2} \sin \frac{\gamma_0}{2} + \sin \frac{\theta_0}{2} \sin \frac{\varphi_0}{2} \cos \frac{\gamma_0}{2},$$

$$q_3(0) = \cos \frac{\theta_0}{2} \sin \frac{\varphi_0}{2} \cos \frac{\gamma_0}{2} + \sin \frac{\theta_0}{2} \cos \frac{\varphi_0}{2} \sin \frac{\gamma_0}{2}.$$

In the upper form,  $q$  represents the displacement vector of the rigid body and has a directionality. Symbol  $\theta$  represents the angle of rotation of a rigid body with an axis, and  $\alpha, \beta, \gamma$  represent the angles between the motion direction of the rigid body and coordinate axes, respectively. In addition, in order to facilitate full text coordinate conversion, the subscripts are interpreted as follows: geographic coordinate system - subscript  $t$ , earth coordinate system - subscript  $e$ , inertial coordinate system - subscript  $i$ .

It is assumed that the rotation angle speed of UAV is  $\omega$ . When the quaternion differential equation and its own coordinate system are in line with the coordinate system of the UAV, the attitude calculation formula of the UAV can be obtained:

$$\dot{q} = \frac{1}{2} q \cdot \omega. \quad (2)$$

Formula (2), since the true value corresponding to the quaternion can be seen as

0, can be rewritten and the corresponding matrix is obtained

$$\begin{bmatrix} \dot{q}_0 \\ \dot{q}_1 \\ \dot{q}_2 \\ \dot{q}_3 \end{bmatrix} = \frac{1}{2} \begin{bmatrix} 0 & -\omega_x & -\omega_y & -\omega_z \\ \omega_x & 0 & \omega_z & -\omega_y \\ \omega_y & -\omega_z & 0 & \omega_x \\ \omega_z & \omega_y & -\omega_x & 0 \end{bmatrix} \begin{bmatrix} q_0 \\ q_1 \\ q_2 \\ q_3 \end{bmatrix} \quad (3)$$

The calculation of the angular rate in formula (3) is

$$\omega_{tb}^b = \omega_{ib}^b - \omega_{it}^b = \omega_{ib}^b - C_t^b (\omega_{eb}^t + \omega_{ie}^t) \quad (4)$$

By solving the differential equations of the quaternion, the real-time attitude of the UAV can be obtained by using the result of the calculation, and the strapdown attitude matrix  $T$  ( $C_b^t$ ) is obtained in the form

$$T = \begin{bmatrix} q_0^2 + q_1^2 - q_2^2 - q_3^2 & 2(q_1q_2 - q_0q_3) & 2(q_1q_3 + q_0q_2) \\ 2(q_1q_2 + q_0q_3) & q_0^2 - q_1^2 + q_2^2 - q_3^2 & 2(q_2q_3 - q_0q_1) \\ 2(q_1q_3 - q_0q_2) & 2(q_2q_3 + q_0q_1) & q_0^2 - q_1^2 - q_2^2 + q_3^2 \end{bmatrix}. \quad (5)$$

The Picard solution method is selected for the solving the quaternion may be written as

$$\dot{q}(t) = \frac{1}{2} \Omega_b q(t). \quad (6)$$

It is further converted into an iterative form

$$q(t) = \left\{ \cos \frac{\Delta\theta_0}{2} \cdot I + \frac{1}{\Delta\theta_0} \sin \frac{\Delta\theta_0}{2} \Delta\Theta \right\} q(0), \quad (7)$$

$$q(n+1) = \left\{ \cos \frac{\Delta\theta_0}{2} \cdot I + \frac{1}{\Delta\theta_0} \sin \frac{\Delta\theta_0}{2} \Delta\Theta \right\} q(n). \quad (8)$$

The solution of the differential equation can be calculated. The attitude angle is calculated by using strapdown matrix, and the following parameters are included

$$\theta = \sin^{-1} T_{32}, \quad (9)$$

$$\gamma = \tan^{-1} \left( -\frac{T_{31}}{T_{33}} \right), \quad (10)$$

$$\varphi = \tan^{-1} \left( -\frac{T_{12}}{T_{22}} \right). \quad (11)$$

$$\text{Here } \gamma = \begin{cases} \gamma & T_{33} > 0, \\ \gamma + 180^\circ & T_{33} < 0, \gamma < 0, \\ \gamma - 180^\circ & T_{33} < 0, \gamma > 0, \end{cases} \quad \psi = \begin{cases} \varphi & T_{22} > 0, \psi > 0, \\ \varphi + 360^\circ & T_{22} > 0, \psi < 0, \\ \varphi + 180^\circ & T_{22} < 0. \end{cases}$$

On this basis, the most important information about the navigation, including pitch, roll and yaw can be obtained. With the rotation of the earth, the angular

velocity component of the geographic system in three directions is calculated as

$$\begin{cases} \omega_{ieE}^t = 0, \\ \omega_{ieN}^t = \omega_{ie} \cos L, \\ \omega_{ieU}^t = \omega_{ie} \sin L. \end{cases} \quad (12)$$

With the UAV movement, the change of angular velocity between the geographical coordinate system and the earth coordinate system can be expressed as

$$\begin{cases} \omega_{etE}^t = -\frac{V_N^t}{R_m+h}, \\ \omega_{etN}^t = \frac{V_E^t}{R_n+h}, \\ \omega_{etU}^t = \frac{V_E^t}{R_n+h} \tan L. \end{cases} \quad (13)$$

Thus, the sum of the angular velocity components between the geographical coordinate system and the earth coordinate system can be calculated. And the tracking angle rate of sins is obtained:

$$\begin{cases} \omega_{itE}^t = -\frac{V_N^t}{R_m+h}, \\ \omega_{itN}^t = \omega_{ie} \cos L + \frac{V_E^t}{R_n+h}, \\ \omega_{itU}^t = \omega_{ie} \sin L + \frac{V_E^t}{R_n+h} \tan L. \end{cases} \quad (14)$$

In the above formula,  $R_m$  represents the radius of curvature on the meridian of the earth ellipsoid,  $R_n$  represents the radius of curvature of the earth reference meridian, and  $\omega_{itE}^t, \omega_{itN}^t, \omega_{itU}^t$  represent the matching information of the white noise measured by the gyro in all directions of the earth. Symbol  $\varepsilon$  represents the platform equivalent error rotation caused by gyro drift,  $\phi$  denotes the attitude deviation of the UAV mathematical platform written in the corresponding variables in the geographic system and  $L$  denotes latitude information. Finally,  $V$  represents the speed vector of the UAV in all directions.

The output measured by the accelerometer on the UAV is not the data of the aircraft system relative to the navigation system, so the geographic system  $t$  is needed as the navigation system of the UAV. By using the matrix  $C_b^t$ , the relative information of the machine system relative to the inertial system is converted into the comparative information relative to the geographic system

$$f^t = C_b^t f^b. \quad (15)$$

In the upper form,  $f^t$  represents the comparative information of the geographic system,  $C_b^t$  represents the transformation matrix, and  $f^b$  represents the comparative information of the machine system.

The formula (15) is unfolded and we can obtain the formula as follows

$$\begin{bmatrix} f_E^t \\ f_N^t \\ f_U^t \end{bmatrix} = \begin{bmatrix} T_{11} & T_{12} & T_{13} \\ T_{21} & T_{22} & T_{23} \\ T_{31} & T_{32} & T_{33} \end{bmatrix} \begin{bmatrix} f_E^b \\ f_N^b \\ f_U^b \end{bmatrix}. \quad (16)$$

In summary, the basic equation of inertial navigation system can be obtained

$$\dot{V}_{et} = f - (2\omega_{ie} + \omega_{et}) \times V_{et} - g. \quad (17)$$

The formula (17) is unfolded and we can obtain the formula as follows.

$$\begin{aligned} \begin{bmatrix} \dot{V}_E^t \\ \dot{V}_N^t \\ \dot{V}_U^t \end{bmatrix} &= \begin{bmatrix} f_E^t \\ f_N^t \\ f_U^t \end{bmatrix} - \\ &- \begin{bmatrix} 0 & -(2\omega_{ieU}^t + \omega_{etU}^t) & 2\omega_{ieN}^t + \omega_{etN}^t \\ 2\omega_{ieU}^t + \omega_{etU}^t & 0 & -(2\omega_{ieE}^t + \omega_{etE}^t) \\ -(2\omega_{ieN}^t + \omega_{etN}^t) & 2\omega_{ieE}^t + \omega_{etE}^t & 0 \end{bmatrix} \cdot \\ &\cdot \begin{bmatrix} V_E^t \\ V_N^t \\ V_U^t \end{bmatrix} + \begin{bmatrix} 0 \\ 0 \\ -g \end{bmatrix}. \end{aligned} \quad (18)$$

### 3.3. Flow arrangement of linked inertial navigation algorithm

By inertial navigation, a very accurate horizontal attitude can be provided. On this basis, the platform type astronomical positioning can further obtain the accurate two-dimensional position information through the height difference method. The study of inertial celestial navigation is the analysis of integrated navigation based on the whole platform model. When using celestial navigation positioning, in order to avoid the accuracy of positioning due to the lack of height information, the pressure altimeter is usually used for auxiliary positioning to ensure the observability of the height channel. Through the combination of navigation system design, the autonomy and navigation precision of the navigation system can be guaranteed.

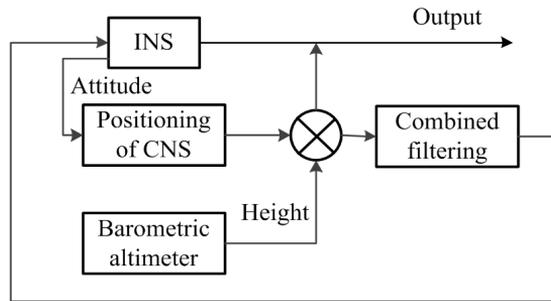


Fig. 3. Scheme of inertial/astronomical position combination

In the design of strapdown inertial navigation algorithm, the initial velocity, attitude and location information must be calculated or given. Each of these initial parameters contains both the true initial information and the initial error. By using the initial information alignment method in inertial navigation, the initial attitude

misalignment angle can be determined, and the integrated navigation can also be estimated under static conditions. After the initial state of UAV operation is determined, the strapdown inertial navigation algorithm can be used to calculate. The flow of the design using this algorithm is shown in Fig. 4.

#### 4. Result analysis and discussion

Based on the above mentioned UAV integrated navigation system algorithm and related design, the simulation research was carried out. The simulation time was 84 h, and the acceleration time of the accelerometer and gyroscope in the UAV navigation system was 0.01 s. The initial attitude was a stationary condition, and the velocity was 0. The initial parameters are as follows:

(1) Initial position: latitude and longitude were 105.63 and 45 degrees, and the height was 1 km.

(2) Initial error: the deviation of initial position and velocity was zero, and the deviation of pitch angle was 0.2 degrees.

(3) Gyro error: measurement noise and Changzhi drift were 0.05 and 0.5 degree/h, respectively.

(4) The error of accelerometer: noise measurement and bias error were  $10^{-5}$  g and  $10^{-4}$  g, respectively.

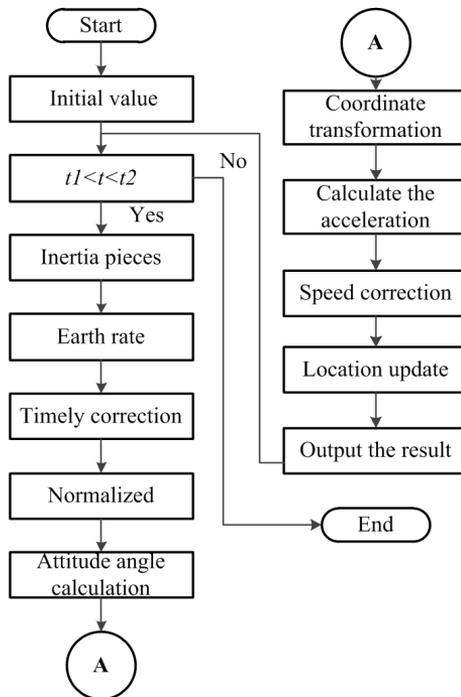


Fig. 4. Strapdown inertial navigation system algorithm

In simulation, the period of Kalman filtering information fusion was 1 s, and the output frequency of INS CNA data was 1 Hz. In order to facilitate the analysis, it was assumed that the positioning accuracy and altimeter measurement accuracy of CNS were 300 m and 50 m, respectively. The initial value of the filter is shown in Table 1.

Table 1. Working initial value of Kalman

Error term	Horizontal attitude	Heading angle	Speed	Latitude and longitude	Height
Initial value	360 °	1800 °	0.6 m/s	100 m	100 m

During the flight of the UAVs, the gyro and accelerometer were set to 0.01 s. After the take-off, the UAVs climbed 7 times in succession. Finally, the UAVs finally climbed to the highest position, and maintained the current position for 800 s flat flight. After the flat flighted, they gradually were downhill and landing. The test time was a total of 2500 s. The sensing elements used throughout the flight included micro accelerometers and mechanical gyroscopes. Under static conditions, the navigation simulation results of UAV Based on sins are shown in Figs.5-8.

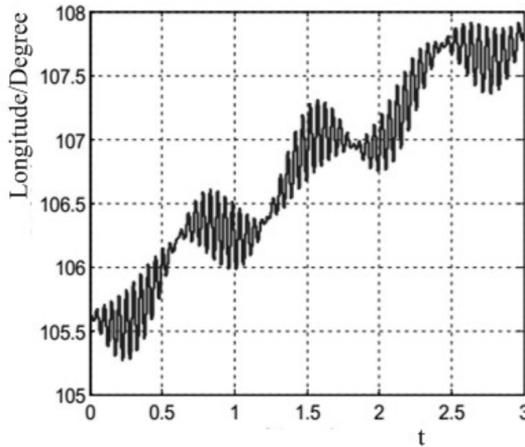


Fig. 5. Longitude error characteristic curve

In the stationary state, the accuracy of celestial navigation and positioning of UAV was simulated and analyzed, and the inertial navigation system was simulated by computer. The selected inertial navigation system was equivalent to gyro drift 0.1 degrees/h and acceleration zero bias to  $10^{-4} g$ . The error of inertial attitude angle was not taken into account, and the observation error of celestial navigation sensitive phase was . Under the simulation condition, since the inertial navigation system provided the horizontal datum for the astronomical positioning under the

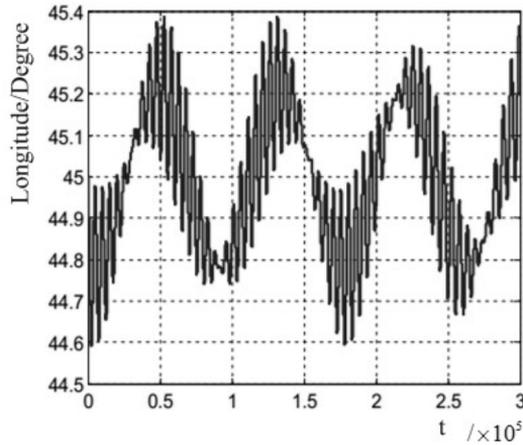


Fig. 6. Latitude error characteristic curve

airborne environment, it was necessary to take full account of the accuracy of the astronomical positioning, which was affected by the inertial attitude error angle. The error was the superposition effect of steady state and random error. Through the synthetic analysis of the simulation curves, it can be seen that the results obtained by the strapdown inertial navigation system are consistent with the error propagation equations under static conditions. The conclusions are as follows:

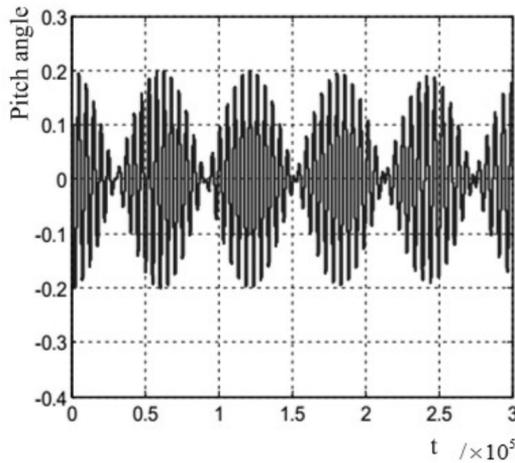


Fig. 7. Pitch angle error characteristic curve

If the initial errors of gyro, accelerometer and navigation parameters are considered at the same time, the height, accuracy, direction, velocity and other positional parameters of the UAV will be divergent, and the deviation of angle and latitude will occur. In addition, position information, posture, and speed all oscillate in three directions. The oscillation errors can be divided into positional oscillation,

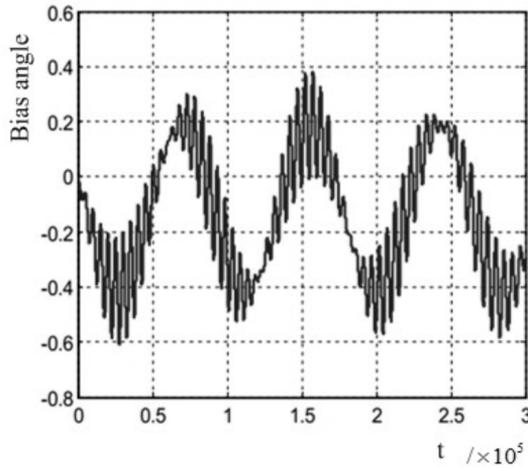


Fig. 8. Bias angle error characteristic curve

earth oscillation and Foucault oscillation, and their periods are 84.4 min, 24 h and 51 h respectively. The Foucault oscillator is the longest in the cycle time. As the dimension changes, the value of the dimension determines the length of the cycle directly. At the equator, the Foucault oscillation period is 0. But at the poles of the earth, Foucault oscillations degenerate and eventually degenerate into earth oscillations. Finally, the oscillation law of navigation parameters can be summed up as follows. There are earth oscillation and Schuler oscillation existing in navigation information such as heading angle, precision and dimension. The oscillation of the earth Schuler oscillation plays an obvious inhibitory effect. In the horizontal direction of the velocity and attitude information is the existence of Foucault and Schuler oscillation, and Foucault oscillation has a significant inhibitory effect on Schuler oscillation.

## 5. Conclusion

High altitude long endurance UAVs are now more and more popular, but they have very high precision and autonomy requirements for navigation systems. The traditional single navigation system is difficult to meet its performance requirements. Therefore, according to the actual demand, the strapdown inertial navigation algorithm was proposed in this paper on the basis of the advantages of celestial navigation and inertial navigation system. On this basis, the simulation and application analysis of related algorithms were carried out. Through analysis, the scheme of integrated navigation system for unmanned aerial vehicle (UAV) which is oriented to engineering practice planning was successfully carried out. The design of time inertial navigation algorithm was studied according to the system principle. Finally, the simulation of the algorithm was improved under static conditions, and the feasibility and efficiency of the algorithm were verified. The specific analysis was carried

out by the measured data. Through the analysis of the measured results, it can be seen that the error of this algorithm is relatively small, which effectively solves the autonomy problem of the traditional GPS integrated navigation system and can be widely used in engineering practice, and it plays a very active role in promoting the development of UAV at high altitude and long endurance in China, which has a very strong application value

## References

- [1] I. K. NIKOLOS, K. P. VALAVANIS, N. C. TSOURVELOUDIS, A. N. KOSTARAS: *Evolutionary algorithm based offline/online path planner for UAV navigation*. IEEE Transactions on Systems, Man, and Cybernetics, Part B (Cybernetics) *33* (2003), No. 6, 898–912.
- [2] A. CESETTI, E. FRONTONI, A. MANCINI, P. ZINGARETTI, S. LOGHI: *A vision-based guidance system for UAV navigation and safe landing using natural landmarks*. Journal of Intelligent and Robotic Systems *57* (2010), Nos. 1–4, 233–257.
- [3] I. K. NIKOLOS, K. P. VALAVANIS, N. C. TSOURVELOUDIS, A. N. KOSTARAS: *Evolutionary algorithm based offline/online path planner for UAV navigation*. IEEE Transactions on Systems, Man, and Cybernetics, Part B: Cybernetics *33* (2003), No. 6, 898–942.
- [4] Y. KUROKI, G. S. YOUNG, S. E. HAUPT: *UAV navigation by an expert system for contaminant mapping with a genetic algorithm*. Expert Systems with Applications *37* (2010), No. 6, 4687–4697.
- [5] J. ZHANG, Y. WU, W. LIU, X. CHEN: *Novel approach to position and orientation estimation in vision-based UAV navigation*. IEEE Transactions on Aerospace and Electronic Systems *46* (2010), No. 2, 687–700.
- [6] A. G. SHEM, T. A. MAZZUCHI, S. SARKANI: *Addressing uncertainty in UAV navigation decision-making*. IEEE Transactions on Aerospace and Electronic Systems *44* (2008), No. 1, 295–313.
- [7] J. ZHANG, W. LIU, Y. WU: *Novel technique for vision-based UAV navigation*. IEEE Transactions on Aerospace and Electronic Systems *47* (2011), No. 4, 2731–2741.
- [8] J. Y. CHEN: *UAV-guided navigation for ground robot tele-operation in a military reconnaissance environment*. Ergonomics *53* (2010), No. 8, 940–950.
- [9] S. T. GOH, O. ABDELKHALIK, S. A. ZEKAVAT: *A weighted measurement fusion kalman filter implementation for UAV navigation*. Aerospace Science and Technology *28* (2013), No. 1, 315–323.
- [10] Y. GUI, P. GUO, H. ZHANG, Z. LEI, X. ZHOU, J. DU, Q. YU: *Airborne vision-based navigation method for UAV accuracy landing using infrared lamps*. Journal of Intelligent & Robotic Systems *72* (2013), No. 2, 197–218.
- [11] E. MICHAELSEN, J. MEIDOW: *Stochastic reasoning for structural pattern recognition: An example from image-based UAV navigation*. Pattern Recognition *47* (2014), No. 8, 2732–2744.
- [12] F. LINDSTEN, J. CALLMER, H. OHLSSON, D. TÖRNQVIST, T. B. SCHÖN, F. GUSTAFSSON: *Geo-referencing for UAV navigation using environmental classification*. IEEE International Conference on Robotics and Automation (ICRA), 3–8 May 2010, Anchorage, Alaska, USA, (2010), Publ: Curran Associates, Inc., 1420–1425.

Received August 7, 2017

