GPS/SINS Navigation Method of Unmanned Aerial Vehicles Based on Vision Aids

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Abstract: - In this paper, the GPS/SINS of the UAV (Unmanned Aerial vehicle) integrated navigation is introduced and the problems of the GPS/SINS in the UAV navigation application are also analyzed.It proposes a GPS/SINS integrated navigation system based on vision AIDS. It design the GPS/SINS integrated navigation filter based on vision aids, and gives out the filter state equations and deduces filter observation equation. The the polar constraint between images and expounds the calculation method of camera displacement projection based on polar projection are introduced, and related simulations are made. The simulation experiments show that through introducing cameras shift information observed by the vision system, it can improve the observation of heading angle error in the integrated navigation, and solve the problem of heading angle error convergence in the UAV flying state of the GPS/SINS integrated navigation system, and it can improve the precision and speed of the UAV attitude angle estimation.

Key-Words: - GPS/SINS Navigation; UAV; Vision navigation; Simulation; Research

1 Introduction

UAV is a kind of wireless remote and automatic program control, automatic driving reusable spacecraft. Compared with manned aircraft, the UAV has the characteristics of simple structure, low cost, good concealment, strong survival ability, good mobility, etc. It is more suitable for big risk, and high difficult tasks. With the rapid development of micro-electro-mechanical technology, computer technology, and a variety of digital, light weight, small size, high precision of a new type of sensor are constantly emerging, the development of UAV is heading for micro miniaturization, intelligent, low cost and convenient use, etc.

Increasingly miniaturization of the development of UAV will be more independent, more flexible, more compact in the direction of development, its application field will be more widely, more and more UAV will be used in complex environments, such as cities, valleys, forests. As a result, increasingly complex flight environment puts forward the higher requirements of the UAV autonomous navigation system .In recent years, the rapid development of photovoltaic technology and automation technology, people try to use the camera to obtain images and convert them into digital signals, the whole process of realization of visual information processing by computer, such it has formed an emerging discipline, computer vision [1]. Computer vision is increasingly widely used in industrial production, medical and military and other fields. Computer vision not only can obtain abundant environmental information, but also it has the characteristics of independent, accuracy, reliability, and also has the advantages of the rich information. It has been widely used in the UAV autonomous navigation, motion estimation and obstacle detection, etc. How to make use of the visual system to improve the navigation ability of UAV is one of research hotspots now [2-3].

Computer vision need to deal with a large amount of image data, and the update frequency is low, it is difficult to meet the high dynamic motion state estimation of UAV. In addition, the visual system is a two-dimensional image of the three-dimensional world, although these images contain huge of information, but this is a description of the two-dimensional, it is still incomplete, it lacks information to describe the depth of the three-dimensional world. Therefore, in the practical application of computer vision in UAV navigation, it should needs to make information fusion of the data obtained by other sensors [4-7].

In the paper, it makes study of key technology of computer vision in UAV navigation, and improve the autonomy and accuracy of UAV navigation system, and improve the autonomous flight ability of UAV.

2 Design of integrated navigation system

GPS/SINS integrated navigation system of the UAV based on visual AIDS is formed by the GPS receiver, the micro inertial measurement unit and camera. Micro inertial measurement unit measures three axial acceleration and angular velocity of the carrier. GPS receiver outputs position and speed of carrier. The cameras and GPS keeps the synchronization collection. In the process of the UAV flight, the camera acquires image sequence of surroundings scenery and makes feature extraction of the sequence image. It obtained the image position of these feature points on the camera flat by matching and tracking image feature points obtained at the different moments .

According to the imaging position of the feature points, the relative rotation of the camera at the different moments, and the polar line constraint between the images of front and the rear frame, it obtained the normalized coordinates of the camera's optical center displacement on the image plane projection at that moment, which is the measured shift value of the camera in the image plane projection. According to the location information output by the GPS, the attitude information in the navigation system and the position relationships between camera coordinate system and carrier coordinates system, it can calculate the normalized coordinate of projection of camera shift on image plane of sequence images, that is the calculation value of camera shift on image plane of sequence images.

The GPS/SINS integrated navigation system based on visual aid is updated motion state according to the output value of the micro inertial measurement unit. Because of the initial motion error and micro inertial sensors measurement error, it is necessary to estimate the motion error of navigation system and make some modification. Through comparing the motion state of navigation system and output value of GPS, it can obtain the position error and velocity error of navigation system; Make the comparison of calculated value and measured value of projection of camera on image plane between different sequence images, it can obtain projection error of camera shift on the image plane. By observing the position error, velocity error, and the error of projection of camera displacement on the image plane, it can estimate the motion state error of integrated navigation system and it can correct the UAV motion state. The integrated navigation system Kalman filter is as below:

$$\begin{aligned}\dot{\boldsymbol{X}} &= \boldsymbol{A}\boldsymbol{X} + \boldsymbol{\varepsilon} \\ \boldsymbol{Z} &= \boldsymbol{H}\boldsymbol{X} + \boldsymbol{\upsilon}\end{aligned} \tag{1}$$

Where vector $\boldsymbol{X}$ represents filter states, which includes the position error, velocity error and platform disturbance angle of navigation system; Observation vector $\boldsymbol{Z}$ represents the position error, velocity error and projection error of camera shift on the image plane; $\boldsymbol{\varepsilon}$ represents noise vector of filter system ; $\boldsymbol{\upsilon}$ represents noise vector of filter $\boldsymbol{\upsilon}$ observation. The integrated navigation system is as shown in figure 1.

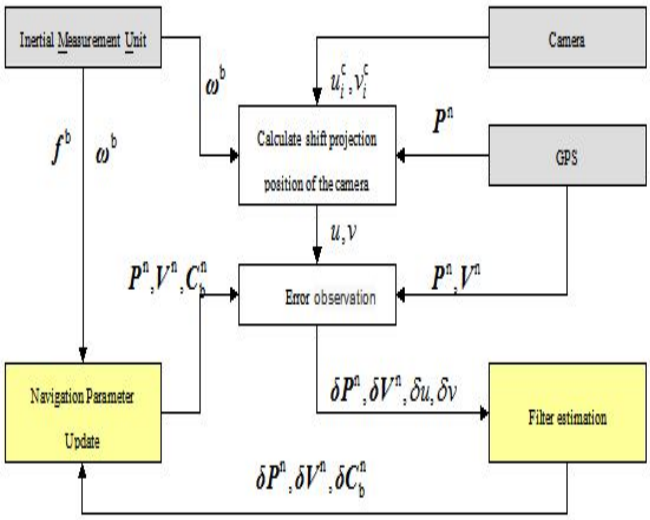


Figure.1 Structure of integrated navigation system

3 Error calculation of camera shift projection based on polar constraint

In the process of flight, the camera of the UAV can obtain sequence images of the surrounding environment. Through matching the feature points of two frames at different times and according to polar constraint it can calculatethe camera shift projection. Imaging position of space point M at different the moments in the camera is related with camera movements, whose relationship is shown in figure.2.

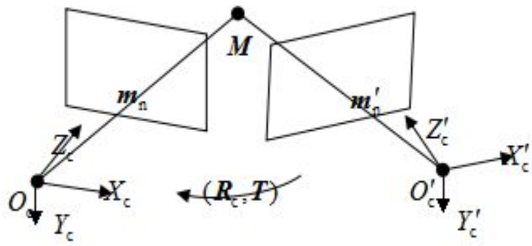


Figure.2 Epipolar line constraint of two pictures

In the figure the projection of spatial point M on camera image plane in the different moments are respectively $\boldsymbol{m}'$ 、 $\boldsymbol{m}$ ， which are represented by image plane normalized coordinates; The rotation matrix $\boldsymbol{R}_c$ and translation vector $\boldsymbol{T}$ represents the relationships between the cameras on the different moments.

According the polar line constraint between the two images, the below type can be obtained.

$$\tilde{\boldsymbol{m}}'_n(\boldsymbol{T} \times \boldsymbol{R}_c \tilde{\boldsymbol{m}}_n) = 0 \tag{2}$$

Among them, $\tilde{\boldsymbol{m}}_n$ and $\tilde{\boldsymbol{m}}'_n$ represent the homogeneous coordinates of the image points $\boldsymbol{m}_n$ and $\boldsymbol{m}'_n$; $\boldsymbol{R}_c$ represents the camera's rotating array at the different moments ; $\boldsymbol{T}$ represents the translation vector of camera at the different moments.

If we assume that the normalization of homogeneous coordinates of the camera shift $\boldsymbol{T}$ on the image plane is $[u_T \quad v_T \quad 1]^T$, each feature point of tracking at different moments is a correspondence point $[u_i \quad v_i \quad 1]^T \leftrightarrow [u'_i \quad v'_i \quad 1]^T$. Through the type of each corresponded point, we can get the below type.

$$[u'_i \quad v'_i \quad 1]\begin{bmatrix} 0 & -1 & v_T \\ 1 & 0 & -u_T \\ -v_T & u_T & 0 \end{bmatrix}\boldsymbol{R}_c\begin{bmatrix} u_i \\ v_i \\ 1 \end{bmatrix} = 0 \tag{3}$$

Among them, the rotation $\boldsymbol{R}_c$ of the camera is updated by gyro output. When a new frame comes, rotation matrix $\boldsymbol{R}_c$ is resettled to the unit matrix I , and the update equations are as follows:

$$\boldsymbol{R}_{ck+1} = \boldsymbol{R}_{ck}\boldsymbol{A}_k \tag{4}$$

$$\boldsymbol{A}_k = \boldsymbol{I} + [\boldsymbol{\sigma}\times] + \frac{[\boldsymbol{\sigma}\times]^2}{2!} \tag{5}$$

$$\boldsymbol{\sigma} = t\boldsymbol{C}_b^c\boldsymbol{\omega}_{ib}^b \tag{6}$$

Among them, $\boldsymbol{R}_{ck}$ represents rotation matrix of the camera coordinate system from the k period to last filter period of gyro sampling; $\boldsymbol{R}_{ck+1}$ represents rotation matrix of the camera coordinate system from k+1 period to last filter period of the gyro sampling; $\boldsymbol{\sigma}$ represents the rotation angle in camera coordinate system during gyro sampling period; $\boldsymbol{C}_b^c$ represents the direction cosine matrix from the coordinate system to the camera coordinate system ; $\boldsymbol{\omega}_{ib}^b$ represents gyro measurement values, namely, it is the projection vector of carrier relative to the rotation vector of the inertial coordinate system in the vector coordinate system ; t represents the gyro sampling interval.

As a result, in the type, only the projection coordinates $[u_T \quad v_T]^T$ of the camera shift $\boldsymbol{T}$ on the image plane are unknown. When the tracking feature points is greater than or equal to two points, the equations column of u_T and v_T can be represented through using the least two squares to solute projection coordinates $[u_T \quad v_T]^T$, that is the normalized coordinates of measured projection values of camera shift on the image plane .

At the same time, when the UAV is flying, GPS measures position $\boldsymbol{P}^{\mathrm{e}}$ of the UAV in the earth coordinate system. The position of the camera in the earth coordinate system can be determined according to $\boldsymbol{P}^{\mathrm{e}}$ and the position of the camera in the vehicle coordinate system, and the coordinates of the camera in the coordinate system of earth is as

$$\boldsymbol{P}_{\mathrm{c}}^{\mathrm{e}} = \boldsymbol{P}^{\mathrm{e}} + \boldsymbol{C}_{\mathrm{n}}^{\mathrm{e}} \boldsymbol{C}_{\mathrm{b}}^{\mathrm{n}} \boldsymbol{P}_{\mathrm{c}}^{\mathrm{b}} \tag{7}$$

Among them, $\boldsymbol{P}_{\mathrm{c}}^{\mathrm{b}}$ represents the coordinates of the cameras in the carrier system; $\boldsymbol{C}_{\mathrm{b}}^{\mathrm{n}}$ and $\boldsymbol{C}_{\mathrm{n}}^{\mathrm{e}}$ respectively represent the direction cosine matrix from the carrier coordinate system to the navigation coordinate system and the direction cosine matrix from the navigation coordinate system to the earth coordinate system , $\boldsymbol{C}_{\mathrm{n}}^{\mathrm{e}}$ can be obtained through the below type as follow:

$$\boldsymbol{C}_{\mathrm{n}}^{\mathrm{e}} = \begin{bmatrix} -\sin L\cos l & -\sin l & -\cos L\cos l \\ -\sin L\sin l & \cos l & -\cos L\sin l \\ \cos L & 0 & -\sin L \end{bmatrix} \tag{8}$$

Among them, L and l respectively represents the latitude and longitude of the location of the UAV .Make the difference of the camera position of the earth coordinate system in different moments, the shift of the camera in earth coordinate system $\boldsymbol{T}^{\mathrm{e}}$ can be obtained, in the camera coordinate system, it can be expressed as:

$$\boldsymbol{T}^{\mathrm{c}} = \boldsymbol{C}_{\mathrm{b}}^{\mathrm{c}} \boldsymbol{C}_{\mathrm{n}}^{\mathrm{b}} \boldsymbol{C}_{\mathrm{e}}^{\mathrm{n}} \boldsymbol{T}^{\mathrm{e}} \tag{9}$$

Among them, $\boldsymbol{C}_{\mathrm{b}}^{\mathrm{c}}$ respectively represents the direction cosine matrix from carrying system to the camera coordinate system ; $\boldsymbol{C}_{\mathrm{e}}^{\mathrm{n}}$ represents earth the direction cosine matrix from earth coordinate system to the navigation coordinate system, and $\boldsymbol{C}_{\mathrm{e}}^{\mathrm{n}} = \boldsymbol{C}_{\mathrm{n}}^{\mathrm{eT}}$.

According to the pinhole camera model , the projection normalized coordinates of displacement vector on the image plane is as

$$\hat{u}_{\mathrm{T}} = \frac{T_{\mathrm{x}}^{\mathrm{c}}}{T_{\mathrm{z}}^{\mathrm{c}}}$$

$$\hat{v}_{\mathrm{T}} = \frac{T_{\mathrm{y}}^{\mathrm{c}}}{T_{\mathrm{z}}^{\mathrm{c}}} \tag{10}$$

Among them, $[\hat{u}_{\mathrm{T}} \quad \hat{v}_{\mathrm{T}}]^{\mathrm{T}}$ represents the calculating projection displacement of the camera, T_x^c , T_y^c , T_z^c respectively represents three axial projection value of the camera shift in camera coordinate system. Thus, Thorough comparing with the calculated value and the measured value of shift projection of the camera , the shift of projection error of the camera on the image plane can obtained. It adopts $[\delta\boldsymbol{u} \quad \delta\boldsymbol{v}]^{\mathrm{T}}$ of normalized coordinates on the image plane, then,

$$\delta u = \hat{u}_{\mathrm{T}} - u_{\mathrm{T}}$$

$$\delta v = \hat{u}_{\mathrm{T}} - v_{\mathrm{T}} \tag{11}$$

4 Design of Integrated Navigation Filter

In the UAV flying, because there has the attitude estimation error, the shift vector of camera calculated by the type also exists error and thus it causes the error between the calculated value of shift projection of the camera and the actual measured value that is the shift projection error of cameras in section 2.

Because the UAV attitude estimation error will cause observation error of the shift projection of the camera, so when designing integrated navigation error state filter, it should consider projection shift error of camera got by visual system and do information fusion to improve the observability of integrated navigation system on the attitude error.

4.1 Filter state equation

System state for integrated navigation filter is as follow:

$$\boldsymbol{X} = [\boldsymbol{\varphi} \quad \delta\boldsymbol{V} \quad \delta\boldsymbol{P}]^{\mathrm{T}} \tag{12}$$

Among them, $\boldsymbol{\varphi} = [\phi_{\mathrm{N}} \quad \phi_{\mathrm{E}} \quad \phi_{\mathrm{D}}]^{\mathrm{T}}$ represents the platform imbalance angle;

$\delta \boldsymbol{V} = [\delta v_{\mathrm{N}} \quad \delta v_{\mathrm{E}} \quad \delta v_{\mathrm{D}}]^{\mathrm{T}}$ represents the speed error of the navigation system ; $\delta \boldsymbol{P} = [\delta L \quad \delta l \quad \delta h]^{\mathrm{T}}$ represents the location error of the navigation system; δL and δl respectively represent the error of latitude and longitude, the unit is angle points, δh represents the height error.

If we make no consideration on the rotation of the earth's and rotation navigation system related to the earth coordinate system, the filter state equation is as below:

$$
\begin{aligned}
&\delta \dot{L} = \frac{10800}{(r+h)\pi}\delta v_{\mathrm{N}} \\
&\delta \dot{l} = \frac{10800}{(r+h)\pi\cos L}\delta v_{\mathrm{E}} \\
&\delta \dot{h} = -\delta v_{\mathrm{D}} \\
&\boldsymbol{\delta \dot{V}} = \left[\boldsymbol{f}^{\mathrm{n}}\right]_{\times}\boldsymbol{\varphi} \\
&\dot{\boldsymbol{\varphi}} = 0
\end{aligned} \tag{13}
$$

$$
\begin{bmatrix} \dot{\boldsymbol{\varphi}} \\ \boldsymbol{\delta \dot{V}} \\ \boldsymbol{\delta \dot{P}} \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 \\ \boldsymbol{f}^{\mathrm{n}}\times & 0 & 0 \\ 0 & \boldsymbol{B} & 0 \end{bmatrix} \begin{bmatrix} \boldsymbol{\varphi} \\ \boldsymbol{\delta V} \\ \boldsymbol{\delta P} \end{bmatrix} + \boldsymbol{\varepsilon} \tag{14}
$$

Among them, L represents latitude; H represents high; R represents the radius of the earth; $\boldsymbol{f}^{n}$ represents the projection vector of the than force in navigation coordinate system.

If we take the system noise into consideration, the system equation can be written in matrix form just as follow:

$$
\boldsymbol{B} = \begin{bmatrix} \dfrac{10800}{\pi(r+h)} & 0 & 0 \\ 0 & \dfrac{10800}{\pi(r+h)\cos L} & 0 \\ 0 & 0 & -1 \end{bmatrix} \tag{15}
$$

In the type, $\boldsymbol{\varepsilon}$ represents noise vector of filter system.

4.2 Filter observation equation

The camera coordinate system and image plane normalized coordinate system has the relationship as follow:

$$
\begin{aligned}
u &= \frac{x^{\mathrm{c}}}{z^{\mathrm{c}}} \\
v &= \frac{y^{\mathrm{c}}}{z^{\mathrm{c}}}
\end{aligned} \tag{16}
$$

Taking differential on both sides, the relationship between the space point coordinates error and image plane projection normalized coordinates error can be obtained just as follow:

$$
\begin{bmatrix} \delta u \\ \delta v \end{bmatrix} = \begin{bmatrix} \dfrac{1}{z^{\mathrm{c}}} & 0 & -\dfrac{x^{\mathrm{c}}}{z^{\mathrm{c}}z^{\mathrm{c}}} \\ 0 & \dfrac{1}{z^{\mathrm{c}}} & -\dfrac{y^{\mathrm{c}}}{z^{\mathrm{c}}z^{\mathrm{c}}} \end{bmatrix} \begin{bmatrix} \delta x^{\mathrm{c}} \\ \delta y^{\mathrm{c}} \\ \delta z^{\mathrm{c}} \end{bmatrix} \tag{17}
$$

We make assumption that the shift of image of the camera in the navigation coordinate system is $\boldsymbol{T}^{\mathrm{n}}$ and takes the attitude error into consideration, when it is converted to the vector coordinate system , it is shown as follow,

$$
\begin{aligned}
\hat{\boldsymbol{T}}^{\mathrm{b}} &= \hat{\boldsymbol{C}}_{\mathrm{n}}^{\mathrm{b}}\boldsymbol{T}^{\mathrm{n}} \\
&= \boldsymbol{C}_{\mathrm{n}}^{\mathrm{b}}[\boldsymbol{I} + \boldsymbol{\Psi}]\boldsymbol{T}^{\mathrm{n}} \\
&= \boldsymbol{C}_{\mathrm{n}}^{\mathrm{b}}T^{\mathrm{n}} + \boldsymbol{C}_{\mathrm{n}}^{\mathrm{b}}[\boldsymbol{\varphi}]_{\times}
\end{aligned} \tag{18}
$$

Where $\boldsymbol{C}_{\mathrm{n}}^{\mathrm{b}}$ represents the direction cosine matrix from the navigation coordinate system to the vector coordinate system, $\boldsymbol{\varphi} = \left[\phi_{\mathrm{N}} \quad \phi_{\mathrm{E}} \quad \phi_{\mathrm{D}}\right]^{\mathrm{T}}$ represents the platform offset angle. The camera shift error in the vector coordinate system is as below:

$$
\begin{aligned}
\boldsymbol{\delta T}^{\mathrm{b}} &= \hat{\boldsymbol{T}}^{\mathrm{b}} - \boldsymbol{T}^{\mathrm{b}} \\
&= \boldsymbol{C}_{\mathrm{n}}^{\mathrm{b}}[\boldsymbol{\varphi}]_{\times}\boldsymbol{T}^{\mathrm{n}} \\
&= -\boldsymbol{C}_{\mathrm{n}}^{\mathrm{b}}[\boldsymbol{T}^{\mathrm{n}}]_{\times}\boldsymbol{\varphi}
\end{aligned} \tag{19}
$$

Make conversion of it to camera coordinate system,

$$\begin{aligned}\boldsymbol{\delta T}^{\mathrm{c}} &= \boldsymbol{C}_{\mathrm{b}}^{\mathrm{c}}\boldsymbol{\delta T}^{\mathrm{b}} \\ &= -\boldsymbol{C}_{\mathrm{b}}^{\mathrm{c}}\boldsymbol{C}_{\mathrm{n}}^{\mathrm{b}}[\boldsymbol{T}^{\mathrm{n}}]_{\times}\boldsymbol{\varphi}\end{aligned} \tag{20}$$

Where, $\boldsymbol{C}_{\mathrm{b}}^{\mathrm{c}}$ represents the direction cosine matrix from the vector coordinate system to the camera coordinate system. From the above formulas, the relationships between the projection error and the attitude error of the camera in the image plane is as below:

$$\begin{bmatrix}\delta u \\ \delta v\end{bmatrix} = \boldsymbol{M}\begin{bmatrix}\phi_{\mathrm{N}} \\ \phi_{\mathrm{E}} \\ \phi_{\mathrm{D}}\end{bmatrix} \tag{21}$$

$$\boldsymbol{M} = \begin{bmatrix}\frac{1}{T_{\mathrm{z}}^{\mathrm{c}}} & 0 & -\frac{T_{\mathrm{x}}^{\mathrm{c}}}{T_{\mathrm{z}}^{\mathrm{c}}T_{\mathrm{z}}^{\mathrm{c}}} \\ 0 & \frac{1}{T_{\mathrm{z}}^{\mathrm{c}}} & -\frac{T_{\mathrm{y}}^{\mathrm{c}}}{T_{\mathrm{z}}^{\mathrm{c}}T_{\mathrm{z}}^{\mathrm{c}}}\end{bmatrix}\boldsymbol{C}_{\mathrm{b}}^{\mathrm{c}}\boldsymbol{C}_{\mathrm{n}}^{\mathrm{b}}\begin{bmatrix}0 & T_{\mathrm{z}}^{\mathrm{n}} & -T_{\mathrm{y}}^{\mathrm{n}} \\ -T_{\mathrm{z}}^{\mathrm{n}} & 0 & T_{\mathrm{x}}^{\mathrm{n}} \\ T_{\mathrm{y}}^{\mathrm{n}} & -T_{\mathrm{x}}^{\mathrm{n}} & 0\end{bmatrix}\begin{bmatrix}\phi_{\mathrm{N}} \\ \phi_{\mathrm{E}} \\ \phi_{\mathrm{D}}\end{bmatrix} \tag{22}$$

In the formula, $\boldsymbol{T}^{\mathrm{n}} = [T_{\mathrm{x}}^{\mathrm{n}} \quad T_{\mathrm{y}}^{\mathrm{n}} \quad T_{\mathrm{z}}^{\mathrm{n}}]^{\mathrm{T}}$ and $\boldsymbol{T}^{\mathrm{c}} = [T_{\mathrm{x}}^{\mathrm{c}} \quad T_{\mathrm{y}}^{\mathrm{c}} \quad T_{\mathrm{z}}^{\mathrm{c}}]^{\mathrm{T}}$ are respectively the projection of camera displacement in the navigation coordinate system and the camera coordinate system; The matrix M describes the relationship between the error of the attitude angular and the error of the camera displacement projection in the image plane. Take the noise into Consideration, the observation equation of the filter is as below:

$$\begin{bmatrix}\delta u \\ \delta v \\ \boldsymbol{\delta V} \\ \boldsymbol{\delta P}\end{bmatrix} = \begin{bmatrix}\boldsymbol{M} & \boldsymbol{0}_{3\times3} & \boldsymbol{0}_{3\times3} \\ \boldsymbol{0}_{3\times3} & \boldsymbol{I}_{3\times3} & \boldsymbol{0}_{3\times3} \\ \boldsymbol{0}_{2\times3} & \boldsymbol{0}_{2\times3} & \boldsymbol{I}_{3\times3}\end{bmatrix}\begin{bmatrix}\boldsymbol{\varphi} \\ \boldsymbol{\delta V} \\ \boldsymbol{\delta P}\end{bmatrix} + \boldsymbol{v} \tag{23}$$

Thus we can know that the $[\delta u \quad \delta v]^{\mathrm{T}}$ includes the information of attitude error. Through the observation projection error ofcamera shift in image plane, it can directly observe the attitude error of the UAV, and enhance the observability of integrated navigation system for the attitude angle error.

4.3 Filtering correction of integrated navigation

The parameter calculating process of GPS/SINS integrated navigation based on visual aids mainly includes: the navigation parameter updating process, measuring process and the filter estimation process, as shown in figure.3 (In the page 8).

5. Verification of simulation

Through software Simulink, we establish the simulation environment and using the aircraft module in Aerosim toolbox to generate the theory movement parameters of the UAV , the output data of GPS receiver and inertial sensor measurement value, it set up the feature points and camera parameters of the environment . According to the motion, camera parameters and characteristics of location point of the UAV , it calculates the pixel coordinates of projection of the feature points on the image plane, and add output of random noise to analog cameras. Simulink simulation program interface is as shown in figure4.

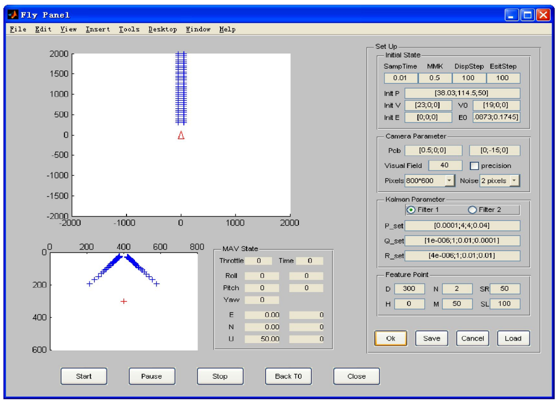


Figure.4 The interface of simulink program

It assumes that the inertial measurement unit output and the update frequency of the integrated navigation system motion state is 100 Hz, gyro constant deviation is 0.001 rad/s, the output noise is 0.01 rad/s, accelerometer constant deviation is 1 mg, and the output noise is 0.1 mg. GPS measurement update frequency is set as 1 Hz. Camera is located at the front, the UAV rolling axis is parallel to the optical axis, and the resolution is , horizontal viewing angle is 40°. There are 2 pixels of the error about the detection of feature points. We assume that there has two columns of feature points and the t projection of feature points on the image plane which is shown in figure 5.

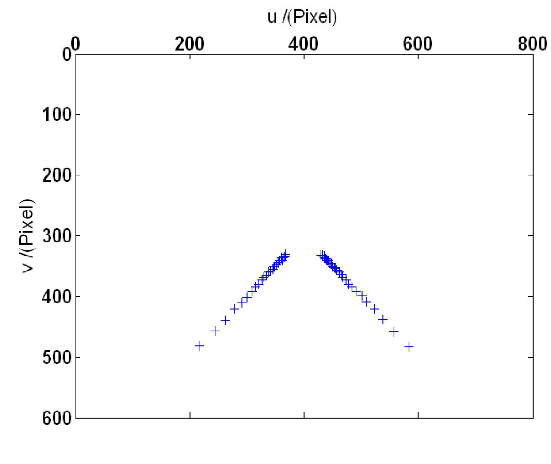


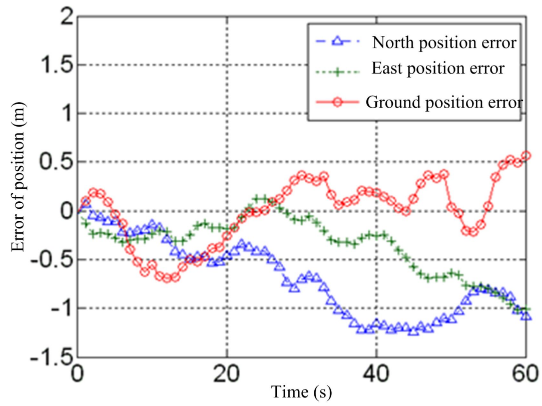
Figure.5 Projections of feature points on image plane

If we make assumption that the UAV initial flight height is 50 m, the initial velocity is 11 m/s.Initial velocity error of the integrated navigation is ; the initial platform imbalance angle is.

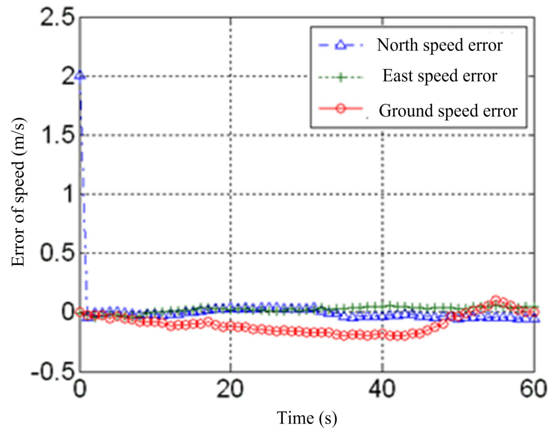
We establish Kalman filter according to GPS, inertial measurement unit and the output of the camera, it set the initial state of motion of integrated navigation to estimate motion error. Finally, according to the estimation error of motion state, it can correct motion state of integrated navigation system and compares it with theoretical motion state. In Kalman filter ,the initial parameters of the covariance matrix are as follows:

$$\boldsymbol{P}_0 = diag\{(0.01')^2,(0.01')^2,(2\mathrm{m})^2,(2\mathrm{m/s})^2,(2\mathrm{m/s})^2,(2\mathrm{m/s})^2,$$
$$(0.2\mathrm{rad})^2,(0.2\mathrm{rad})^2,(0.2\mathrm{rad})^2\}$$
$$\boldsymbol{Q} = diag\{(0.001')^2,(0.001')^2,(1\mathrm{m})^2,(0.1\mathrm{m/s})^2,(0.1\mathrm{m/s})^2,(0.1\mathrm{r}$$
$$(0.01\mathrm{rad})^2,(0.01\mathrm{rad})^2,(0.01\mathrm{rad})^2\}$$
$$\boldsymbol{R} = diag\{(0.002')^2,(0.002')^2,(1\mathrm{m})^2,$$
$$(0.1\mathrm{m/s})^2,(0.1\mathrm{m/s})^2,(0.1\mathrm{m/s})^2,(0.1)^2,(0.1)^2\}$$

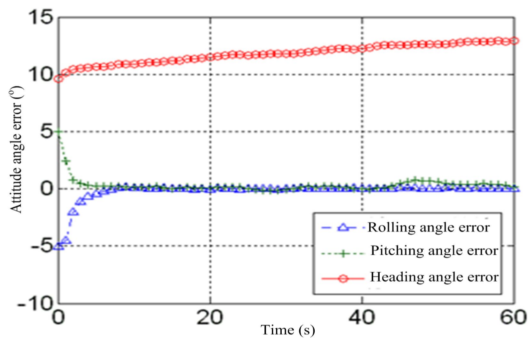
In order to test the improvement of the attitude angle estimated by the visual system, it first establish the GPS/SINS integrated navigation error filter. It compares the output of the GPS and inertial navigation system to estimate the error state of the inertial navigation and make the correction of the motion. Then, the motion state estimation results are compared with the theoretical motion state . The UAV maintains the level of flight state, through the 60s simulation experiments, the error of the GPS/SINS integrated navigation system of the UAV is shown as in Figure .6.



a) Position error



b) Speed error



c) Attitude angle error

Figure.6 Error of GPS/SINS integrated navigation system for UAV

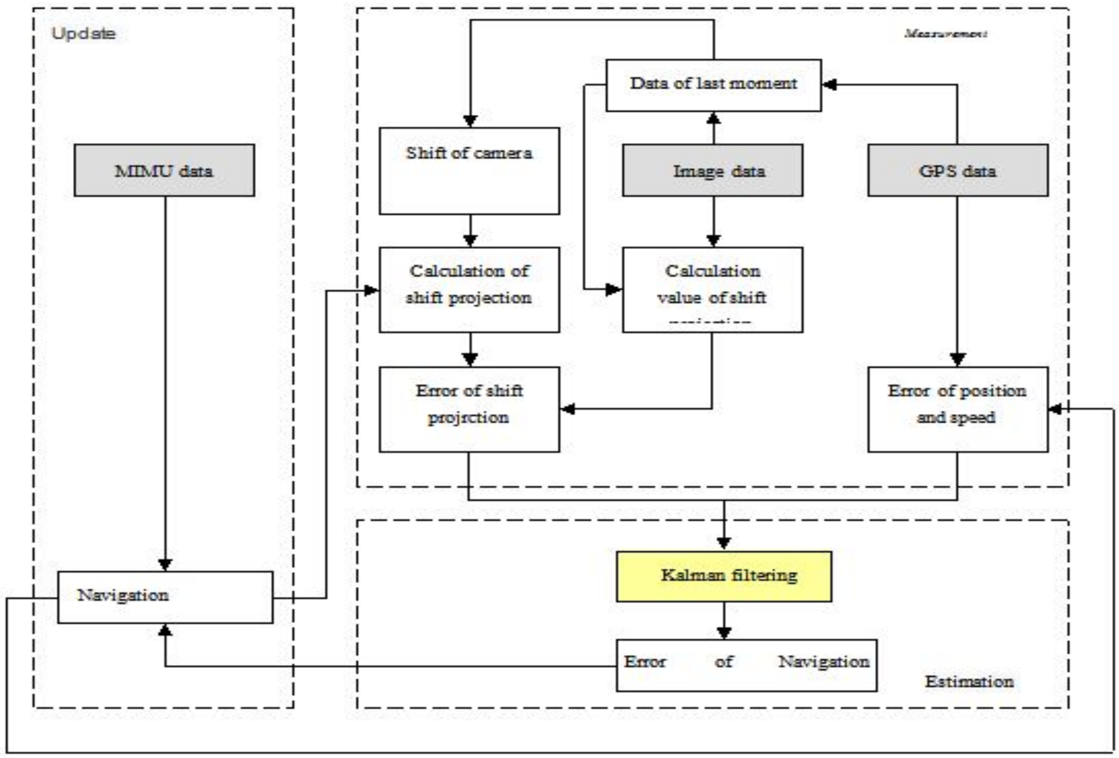


Figure.3 The updata process of integrated navigation data

Figure 6 shows the results of the GPS/SINS integrated navigation in the condition of the UAV flying. Among them, figure 6 (a) gives out three position error components of the integrated navigation, the unit is m; Figure 6 (b) presents three velocity error components of the integrated navigation, the unit is m/s; Figure 6 (c) shows three euler angle error of the integrated navigation . As can seen from the figure 6 (a) and figure (6 b), the position and velocity error can be observed directly, the speed error will immediately be converged after filtering, after convergence, its speed estimation accuracy is about 0.1m/s, and the position error and accuracy of velocity error convergence are related to GPS measurement error;

Figure 6 (c) shows that, after the beginning of the filter, two horizontal attitude angle are rapidly converged, and the horizontal attitude angle error convergence from the original 10° to 0° fast, and the converging scope is less than 1° after 10 s;

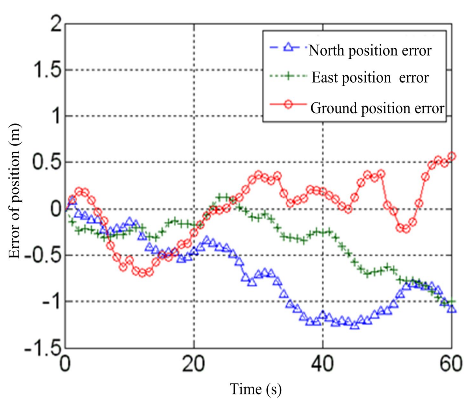
The course angle error does not converge after the beginning of the filtering, but it can increase with time affected by the error of gyro constant .

Figure.6 shows that, under the condition of the UAV flying, in the GPS/SINS integrated navigation, other error states can be quickly converged except the heading angle error;

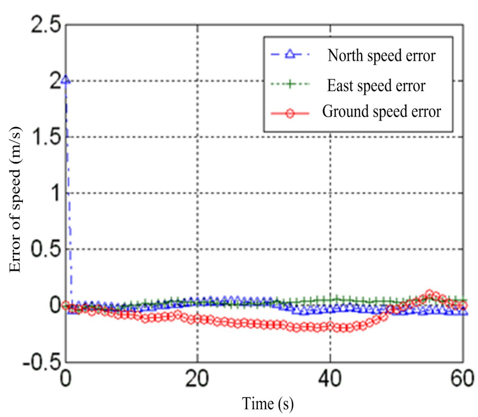
Since the heading angle error can not be observed, after the filter the error is not convergent. Due to the error of inertial sensor, heading angle error will be increased with time.

We can set up the filter of the GPS / SINS integrated navigation of UAV based on the visual aids, according to the the feature points which is tracked by vision system, it observes position error of the camera shift projection to improve the observability of the attitude angle.

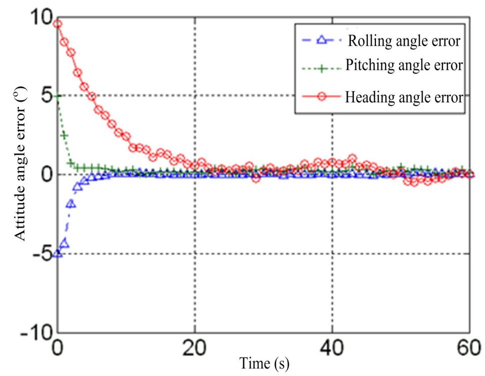
In the same simulation conditions, in simulation experiment, the GPS/SINS integrated navigation system error of the UAV based on visual aids after 60 seconds is as shown in figure .7.



a) Position error



b) Speed error



c) Attitude angle error

Figure.7 Error of vision-aided GPS/SINS integrated navigation system for UAV

Figure.7 shows the results of the GPS/SINS/Vision integrated navigation based on visual aids in the flying state of UAV.

Among them, figure 7 (a), figure 7 (b) and figure 7 (c) respectively show the error components of three position of integrated navigation , the error components of three speed and three euler Angle error of integrated navigation.

As can be seen from figure 7 (a) and figure 7 (b), the convergence situation of position error and velocity error of GPS/SINS integrated navigation based on visual aids are same as the result of the GPS/SINS integrated navigation. Figure 7 (c) shows that, after beginning of the filter, the two level attitude angle is rapidly convergent, and the convergence precision is 1°after 10s;

The initial error of angle, which is about 10°, it is also rapidly convergent after the filtering, and when it is 20s, it is converged to 2° and estimated accuracy maintains about 2°.

The GPS/SINS integrated navigation and the simulation experiments of the GPS/SINS integrated navigation based on visual aids show that in the condition of the UAV flying, because of position error and velocity error can be observed directly, the estimation of two methods of integrated navigation of the position error and velocity error are basically the same, whose precision after the stability may be related to GPS measuring accuracy.

The difference of two kinds of integrated navigation is the estimation for attitude.The error of heading angle in GPS/SINS integrated navigation system is large.

And the visual measurement information is introduced in GPS/SINS integrated navigation based on visual aids.

Through the visual system it can measure the shift information of the airborne camera to improve the observability of the integrated navigation system and enhance the observation of the attitude angle error of integrated navigation system. Especially in the state of the UAV flying, it can change the UAV heading angle error unobservable to observable thus to improve the estimation accuracy of the UAV heading angle by the integrated navigation system .

Due to two horizontal attitude angle error does not exist the unobservability problem, comparing with GPS / SINS integrated navigation GPS /SINS integrated navigation based on the visual aids can not improves two horizontal attitude angle too much.

6. Conclusion

In this paper, the GPS/SINS of the UAV integrated navigation is introduced and the problems of the GPS/SINS combination in the UAV navigation application are also analyzed.

It proposes a GPS/SINS integrated navigation system based on visual AIDS. It designs the GPS/SINS integrated navigation filter based on visual aids, and gives out the filter state equations and deduces filter observation equation .The polar constraint between images and expounds the calculation method of camera displacement projection based on polar projection are introduced. Finally it makes related simulations.

The simulation experiments show that through introducing cameras shift information observed by the vision system, it can improve the observation of heading angle error in the integrated navigation, and solve the problem of heading angle error convergence in the UAV flying state of the GPS/SINS integrated navigation system, and it also can improve the precision and speed of the UAV attitude angle estimation.

Conflict of interest

The authors confirm that this article content has no conflict of interest.

Acknoeledgements

Declared none.

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