Research on Key Technologies of Multi-rotor UAV High-precision Positioning and Navigation System

Yu Cao, Xiaofeng Zhang, Xiangjie Huang and Fei Wang
Beijing Institute of Technology, Zhuhai 519000, China

Abstract. For the continuous high-precision navigation and positioning needs of rotocraft UAVs based on industry applications, based on low-cost GNSS single-frequency positioning modules and MEMS inertial navigation, the design high-precision GNSS / INS integrated navigation module. At the same time using computer vision algorithms. Aiming at the requirement of high precision, the original data acquisition scheme that fully guarantees the accuracy of MEMS inertial navigation is designed. No one against the rotor for the high-frequency vibration problem of the mobile platform, the effect of IMU white noise parameters on the performance of MEMS inertial navigation and integrated navigation was analysed. The test results show that the IMU white noise parameters can effectively improve the combined navigation performance under high-frequency vibration conditions; the positioning accuracy of the module can reach centimetre level and be continuous and stable.

Key words. Integrated navigation, Kalman filtering, rotary-wing UAV, navigation and positioning, navigation system.

1. Introduction
The military interpretation of time-sensitive targets is a target with higher military value in a shorter period of time. Because it is extremely dangerous, it needs to be precisely attacked immediately. The ability to strike time-sensitive targets is mainly reflected in the speed and accuracy of the strike, which requires the weapon system to achieve aiming and positioning in a relatively short period of time. The rapid detection and tracking of the target and the high-precision positioning of the aircraft are the premise and foundation of fast and accurate positioning of time-sensitive targets. In modern warfare, unmanned reconnaissance aircraft have unique advantages and flexibility, and often bear the important tasks of battlefield reconnaissance and target surveillance. The precise positioning of military targets on the battlefield is an important prerequisite for grasping the battlefield situation, commanding decisions, and precise strikes. A lot of results have been achieved, but the research on the operational use of drones, especially dynamic target reconnaissance and positioning, is relatively lagging behind, and it cannot fully meet the operational requirements in terms of target positioning accuracy.

This paper designs a low-cost, high-precision, high-stability integrated navigation module for the special application scenarios of rotor drones, especially for the analysis and system optimization of the strong vibration of rotor drones. First, introduce the low-cost and high-precision integrated navigation module system design scheme; then, according to the special dynamic characteristics of the rotor UAV and its high-precision requirements, key performance optimization techniques are proposed; In the
experiment, the influence of IMU white noise parameters on the performance of MEMS inertial navigation and integrated navigation was analysed, and the positioning accuracy of the integrated navigation module on the rotor UAV was evaluated. Finally, the conclusion was given [1].

2. Computer vision positioning

2.1. Navigation and positioning principles

GPS uses a multi-satellite, high-orbit, ranging system, taking distance as a basic observation, and by simultaneously measuring the distance of four satellites, the position of the receiver can be solved. The receiver measures the time difference \( \tau \) between the time the satellite transmits the radio wave and the time the receiver receives the radio wave, and multiplies it by the speed of light \( c \) to obtain the distance \( \rho \), that is:

\[
\rho = c \times \tau = c \times (t_r - t_s)
\]  

(1)

In the formula: \( t_r \) is the time of the receiver, \( t_s \) is the time of the satellite transmitting radio waves. GPS uses the atomic time system uniformly. Because the satellite clock and receiver clock are not synchronized with the GPS atomic time, there are clock differences. Let them be \( \delta t_s \) and \( \delta t_r \), respectively, and the actual measured time difference includes the influence of the clock difference, as:

\[
\tau = (t_r - \delta t_r) - (t_s - \delta t_s)
\]

(2)

The satellite clock difference is measured by the GPS ground monitoring system and provided to the user through navigation messages, which can be considered to be known [2].

So, the actual measured distance should be (corrected with satellite clock difference added)

\[
\rho = c\tau = c(t_r - t_s) + c\delta t_r
\]

(3)

Because the distance observation \( \rho \) contains the error caused by the receiver clock difference, rather than the true distance \( \rho \) from the receiver to the satellite, it is called a pseudo range measurement. It is difficult for general users to measure the clock difference of the receiver with sufficient accuracy, and it can be solved together with the receiver's position coordinates as a parameter to be determined. Write the above formula as:

\[
\rho = \sqrt{(X - X_j)^2 + (Y - Y_j)^2 + (Z - Z_j)^2 + c\delta t_r}
\]

(4)

In the formula, \( X, Y, Z \) represents the rectangular coordinates of the first satellite in the Earth Protocol Coordinate System (WGS-84). They can be calculated by using the satellite position information given in the navigation message broadcast by the satellite, so they can be considered as known quantities. And \( (X, Y, Z) \) is the position coordinate of the receiver in the same coordinate system, and the clock difference with the receiver is the amount to be determined. There are 4 unknown parameters. Only 4 satellites need to be synchronized to obtain 4 pseudo range observations \( \rho_j (j = 1, 2, 3, 4) \). Composed of four equations, the receiver position \( (X, Y, Z) \) and clock difference \( \delta t_r \) can be solved by solving.
2.2. Visual navigation image filtering algorithm
Kalman filtering is a linear minimum variance estimation. The algorithm is recursive. The state space method is used to design filters in the time domain. It is suitable for estimating multidimensional random processes (stationary and non-stationary). It has both continuous and discrete. Similar algorithm, easy to implement on the computer. With the rapid development of computer technology, Kalman filtering theory is applied to various fields as the most important estimation theory. The design of integrated navigation system is one of the most successful aspects of its application. The following mainly introduces the Kalman filter equation of stochastic linear discrete systems. The equations of state and measurement of the system:

\[
X(t) = F(t)X(t) + G(t)w(t) \\
Z(t) = H(t)X(t) + v(t)
\]

Discretization provides:

\[
X_k = \Phi_{k,k-1}X_{k-1} + \Gamma_{k-1}W_k \\
Z_k = H_kX_k + V_k
\]

In the formula:

\[
\Phi_{k,k-1} = \sum_{n=0}^{\infty} \frac{(F(t_{k-1}))^n T^n}{n!}
\]

(7)

Where T is the iterative period; \( W_k, V_k \) is a white noise sequence with mean zero, \( W_k, V_k \) is independent of each other, and \( W_k, V_k \) is a constant value within the sampling interval. Its statistical characteristics are as follows:

\[
E[V_j V_j^T] = R_{ij} \delta_{ij} \quad E[W_i W_i^T] = Q_{ij} \delta_{ij}
\]

(8)

2.3. Modelling of positioning system based on visual navigation
According to the previous analysis, the error model of the GPS receiver output position is:

\[
\begin{align*}
Z_{L,i} &= -0.8122895Z_{L,i-1} - 0.1662947Z_{L,i-2} + \epsilon_{L,i} \\
Z_{K,i} &= -0.8461269Z_{K,i-1} - 0.1447292Z_{K,i-2} + \epsilon_{K,i} \\
Z_{H,i} &= -0.8537010Z_{H,i-1} - 0.1338772Z_{H,i-2} + \epsilon_{H,i}
\end{align*}
\]

(9)

For the speed error output by the GPS receiver, a first-order Markov process can be used to approximate the fit, which is expressed as follows:

\[
\begin{align*}
\dot{\delta V_{L}} &= -\frac{\delta V_{L}}{\tau_{L}} + \omega_{L} \\
\dot{\delta V_{K}} &= -\frac{\delta V_{K}}{\tau_{K}} + \omega_{K} \\
\dot{\delta V_{H}} &= -\frac{\delta V_{H}}{\tau_{H}} + \omega_{H}
\end{align*}
\]

(10)
3. Research on key technologies of multi-rotor UAV aerial survey system

3.1. Multi-rotor UAV RTK differential positioning technology research

The traditional multi-rotor UAV adopts satellite navigation system for positioning. When the transmission line is inspected at close range, it is susceptible to electromagnetic interference and collision accidents, which brings hidden safety hazards to UAV power grid inspection operations. The multi-rotor UAV RTK carrier phase differential technology is a real-time differential method for processing the carrier phase observations of the base station and the airborne receiver. Obtain the results of centimetre-level positioning accuracy (as shown in Figure 1).

3.2. Inertial navigation raw data collection

The high-frequency vibration peculiar to rotor drones is the real motion of this carrier. In order to collect high-frequency vibration information of rotor drones, it is necessary to ensure that the data sampling rate of inertial navigation is high enough. However, the update rate of the navigation solution is proportional to the amount of calculation. In order to ensure the real-time performance of the navigation module, the high-frequency inertial navigation data is down-sampled by averaging under the condition that the original navigation data sampling rate is sufficiently high. Performing low-frequency INS mechanical orchestration will not significantly affect the performance of integrated navigation. The integrated MCU calculates resource consumption and integrated navigation performance, collects MEMS inertial navigation data at the original sampling rate of 1 kHz, and then performs inertial navigation solution by averaging down-sampling to 50 Hz, enabling real-time high-precision integrated navigation on embedded platforms.

In the integrated navigation solution, only the time synchronization of the original data of GNSS and IMU (that is, the two data are marked with a common time scale) can meet the requirements of high precision. The random error of the crystal clock signal is small, but there is a large cumulative error. The accuracy of the time pulse signal 1PPS of the GNSS positioning module NEO-M8P is 30 ns, and the 1PPS clock error does not accumulate with time. Based on the characteristics of these two signals, this paper proposes a method that uses 1PPS signal to linearly compensate the crystal frequency drift, which can obtain accurate local time without error accumulation. Under the trigger of the MEMS inertial sampling pulse, the corresponding local time is recorded as the inertial navigation data sampling time, so as to achieve accurate synchronization of inertial navigation data and GNSS time. Figure 2 is a schematic diagram of INS data collection.
3.3. IMU white noise parameter adjustment

Allan analysis of variance for long-term static inertial navigation data is a standard way to evaluate the performance of inertial devices. Through the Allan variance curve, the random drift error noise of the IMU can be obtained, such as common white noise and zero offset noise. Taking the accelerometer as an example, Figure 3 is the Allan variance curve of the MEMS accelerometer, where the slope of the left side of the curve is \(-1/2\) represents the white noise of the accelerometer (that is, the random walk VRRW of the speed).

![Figure 2. Schematic diagram of INS data collection](image)

![Figure 3. Allan variance curve of MEMS accelerometer](image)
The white noise parameter calculated from the Allan variance curve is approximately equal to the data sheet. In the static test or low dynamic vehicle test environment, the white noise parameters obtained from Allan variance are substituted into the Kalman filter, and the integrated navigation module results are normally stable. However, for a carrier such as a rotor drone with severe vibration, using the above white noise parameters obtained from static data, the integrated navigation result calculated by Kalman filtering is abnormal. The analysis shows that this is because the micromechanical structure of the MEMS inertial navigation is affected by the severe high-frequency vibration of the rotor UAV carrier, and the measurement noise is significantly increased. Therefore, under the rotor UAV platform, it is necessary to conduct special test analysis on the noise parameters of the MEMS inertial navigation device, and fine-tune their corresponding parameters in the combined algorithm to optimize the performance of the combined navigation module [3].

3.4. Image matching

3.4.1. Matching method based on Gray area. The matching method based on the Gray area is to directly use the Gray information of the image to perform similarity measurement matching. Its performance mainly depends on the selection of the similarity measurement and search strategy. Such algorithms have been developed relatively mature. Commonly used similarity measurement algorithm There are: average absolute difference algorithm, average square difference algorithm, normalized cross correlation algorithm, sequential similarity detection algorithm, mutual information algorithm, fast Fourier transform, phase correlation algorithm, frequency domain correlation method, fuzzy information algorithm, image histogram And projection feature method, principal component analysis method, etc. The matching algorithm based on Gray area currently used in aircraft navigation mainly includes the average absolute difference algorithm and the normalized cross correlation algorithm. The principle of matching method based on Gray area is simple, There is no need for image segmentation and image feature extraction, but because grayscale information is easily disturbed by weather, illumination changes, noise, and various external factors, grayscale similarity is not as stable as the similarity of geometric features, and its ability to resist geometric deformation is poor. Matching positioning accuracy and reliability are difficult to guarantee. At the same time, it is necessary to detect the grayscale of all corresponding pixels in the two images the degree of similarity or difference, the amount of matching operation increases rapidly with the increase of the image size.

3.4.2. Feature-based matching method. The feature-based matching method first extracts features from the matching image, and determines the position of the measured image in the reference image using the corresponding similarity measure and relevant constraints. This type of algorithm can introduce a geometric distortion mechanism to estimate the matching images, so that the matching the algorithm has the ability to resist geometric distortion of the image, and effectively eliminates the mismatch caused by the local radiation distortion caused by the background, local environment or lighting. The feature-based matching method has been widely studied and is becoming more and more widely used in practical applications. The feature matching algorithm is key the steps mainly include image feature extraction and feature matching. In the image feature extraction stage, features are required to be easily detected, and are not sensitive to image noise and deformation. In the feature matching stage, due to changes in imaging conditions or different imaging sensors, the same feature reflects different Spectral characteristics, so feature selection and similarity measurement must consider these factors. Although the feature matching algorithm is somewhat robust to small noise, image rotation and scale differences, there is currently no one that can satisfy each Matching algorithm Generally used are based on different characteristics of the particular design and application environment using respective matching algorithm based on the current feature matching method can be divided into matching method based on feature points, lines, areas and the like.
3.4.3. Interpretation-based image matching method. The interpretation-based image matching method is based on the correct interpretation of the image. First, the model and the corresponding relationship between the model and the real-world objects or phenomena need to be established, and then the structural features or relationship features of the image are used for correlation search to establish the relationship between the nodes in the figure is sought to solve the matching problem with the help of semantic networks, frame theory and graph theory methods, but this matching method is far from mature. Because the imaging time and imaging conditions of the measured image and the reference image are different, it is estimated that After processing the corrected measured image and the reference image, there will still be different levels of Gray difference, geometric distortion, rotation and scale changes, etc., which can easily lead to incorrect matching.

To this end, the researchers have proposed a series of improved methods, such as incremental sign correlation, invariant moments and other algorithms. Logarithmic polar coordinates, circular projection, local invariant descriptors, invariant moments, Fourier-Mellin transformation and straight lines are used. Methods such as invariant moment of inclination histogram transform the image first, and then perform matching processing to overcome the effects of rotation and scale changes. In order to improve the accuracy of image matching and positioning, fast Fourier transform, phase correlation, least squares, Bayes, etc. are proposed. Matching method. To further improve the robustness of the image matching algorithm, researchers use various constraints such as multiple sub-regions and spatial geometric constraints, patio-temporal correlation, three-view constraints, peripolar geometric constraints, and multi-frame matching consistency decision to eliminate the wrong matching points to achieve a robust matching of the image.

4. System design
The drone operating system is deeply customized for the characteristics of power inspection operations. In order to be able to view the surrounding environment of the power grid in a wide range, the intelligent operating system can automatically plan routes, fully complete the refined tour and channel tour of transmission and transformation lines, and obtain orthophotos, 360° panoramic and Oblique photography 3D modelling image data (as shown in Figure 4). Through the intelligent control of the UAV, the defects and hidden dangers of the tower body and the channel environment can be clearly and accurately found, making the UAV power grid inspection operation safer and more reliable [4].

![Figure 4. UAV intelligent operating system functions](image)
5. Simulation research
The initial position of the aircraft is 20° north latitude, 110° east longitude, and the flight altitude is 500 m; the initial speed of the aircraft is 0 m/s, heading to the east. The maximum speed of the carrier is 186 m/s, which is similar to the maximum speed of the "Global Eagle" UAV 650 km/h, and the maximum flight altitude of the carrier is 16265.8 m, which is less than the practicality of the "Global Eagle" UAV the ceiling is 20000 m. Four dynamic targets are selected respectively, and the simulation time corresponding to each target positioning is 60 s. The target parameters are shown in Table 1.

Table 1. Target parameter settings

| Dynamic goal | Initial longitude / ° | Initial latitude / ° | Initial height / m | Initial speed / m / s | Acceleration / m / s² | Initial heading angle / ° |
|--------------|------------------------|----------------------|--------------------|-----------------------|------------------------|--------------------------|
| 1            | 111.15                 | 19.97                | 400                | 120                   | 0                      | 180                      |
| 2            | 111.32                 | 19.56                | 300                | 60                    | 5                      | 90                       |
| 3            | 110.60                 | 18.21                | 500                | 160                   | 0                      | 90                       |
| 4            | 110.37                 | 18.58                | 100                | 30                    | 7                      | 180                      |

According to the analysis in the previous section, UAV target positioning accuracy is related to platform stability accuracy, platform measurement accuracy, inertial device accuracy, and satellite navigation positioning accuracy. In order to obtain the required target positioning accuracy, the measurement of instrument parts should be selected and allocated reasonably positioning accuracy. Combined with the UAV high-precision target positioning algorithm, the position curve of the dynamic target relative to the platform can be obtained. As shown in Figure 5, it can be seen that the distance of the target from the platform is increasing, indicating that the carrier is gradually moving away from the target. The absolute value of the pitch angle relative to the platform is gradually decreasing, and the azimuth of the target relative to the platform tends to be 180°. The rate of change of the relative position of target 2 during 38 to 42 s becomes larger. This is because the carrier is not in the level flight phase during this period, but is in the acceleration pull-up phase, so the position of the target relative to the platform changes faster at this time [5].

![Figure 5. Relative position curve of dynamic target positioning](image)

6. Conclusion
This paper proposes a high-precision positioning solution for unmanned aerial vehicle dynamic targets, specifically studies the geometrical principles of target positioning for airborne optoelectronic platforms, designs a high-precision positioning algorithm for unmanned aerial vehicles, reasonably allocates errors in the positioning process, and constructs Simulation platform of high precision positioning system for UAV targets. The simulation results show that, according to the high-precision
positioning scheme of the UAV target, selecting a measuring device with appropriate accuracy, combined with the high-precision positioning algorithm of the UAV target, can achieve the higher accuracy of the UAV's own positioning accuracy and dynamic target positioning accuracy. It shows that the high-precision positioning scheme for UAV targets is feasible and has certain engineering application value.

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