Application Discussion of Airborne Beidou Navigation and Positioning System in Marine Aviation Magnetic Measurement of Unmanned Helicopter

Kefu Gao¹², Peng Jiang¹,*

1. Gnss Research Center, Wuhan University, Wuhan, 430079, China
2. Collaborative Innovation Center of Geospatial Technology, Wuhan, 430079, China
*Corresponding Author, Jiangp@whu.edu.cn

ABSTRACT. UAV marine aeromagnetic survey has the characteristics of simple operation and high efficiency. Unmanned Helicopter Marine magnetic measurements require accurate position and elevation of magnetic data. Based on this, the application of the airborne Beidou navigation and positioning system in the unmanned helicopter marine aviation magnetic force measurement is discussed. According to the actual working environment of the unmanned helicopter marine aviation magnetic force measurement and the requirement for positioning accuracy, the airborne single-frequency GPS positioning system is designed, and simulation tests and field tests are conducted. The GPS data is processed by using commercial software. The test results show that the airborne GPS positioning system meets the positioning accuracy requirements and can be applied to the unmanned helicopter marine aviation magnetic force measurement.

KEYWORDS: Positioning system, Beidou navigation, Unmanned helicopter

1. Introduction

Marine magnetic field information is not only an important material for sea geological survey and resource exploration, but also plays an important role in underwater magnetic target detection, geomagnetic matching navigation, anti-submarine exploration and other military applications (Jamoom M B et al. 2016) [1]. At present, according to different operating platforms, the marine magnetic force measurement is mainly divided into two kinds of work modes, that is on-board magnetic measurement and aeromagnetic measurement (Patricia A. 2016) [2]. The on-board magnetic measurement can acquire high-precision and high-resolution geomagnetic information and can be used for underwater magnetic target detection operations. However, due to the low operating efficiency, it can only meet the requirements for high-precision measurement operations in local key sea areas in China (Hsiao F Y et al. 2016) [3]. Aeromagnetic measurement can obtain large-area magnetic survey information in a short time, which has many features such as low operating cost, short time-consuming, low labor intensity, and high comprehensive efficiency. However, due to the high flight altitude and limited endurance, only large-scale geomagnetic information can be obtained. At the same time, it is difficult to meet the needs of offshore surveying operations. Aeromagnetic measurements and shipborne magnetic measurements complement each other to meet different mission requirements (Liu Z et al. 2017) [4]. The unmanned helicopter marine aviation magnetic force measurement work needs to obtain a dynamic position with a horizontal accuracy better than 2m and a dynamic elevation measurement with a precision better than 50cm for the positioning and correction of magnetic data (Guo F et al. 2017) [5]. Commercial GPS receivers are not suitable for installation in unmanned helicopters due to their large mass and volume and poor seismic performance. The single-frequency GPS receiver in this system is embedded in the industrial control computer PC104 and is suitable for marine magnetic measurement of unmanned helicopters. In a smaller range (<20km), the single-frequency GPS data obtained by the system is differentially processed and the latitude and longitude precision can reach the decimeter level, and the elevation accuracy is better than 50cm (Gumilar I et al. 2017) [6].

2. State of the Art

Since the 21st century, foreign terrestrial aeromagnetic measurement technology has been fully developed, a relatively complete measurement system has been established, and it has been successfully applied in the commercial field. However, drone marine aeromagnetic technology is more difficult. At present, only a few companies have the
technical strength. The aeromagnetic survey of domestic terrestrial drones started relatively late, but it has developed rapidly and has made considerable progress. In terms of terrestrial magnetic surveys, it has basically kept pace with foreign countries. However, there are still some gaps with foreign countries in marine magnetic surveys, magnetic sensors, and aerospace real-time compensation technologies (Ragauskas U et al. 2017) [7]. On October 16, 2009, China's first unmanned ground-based aeromagnetic exploration system made its first test flight in the Beizi Banner area of Qionghan Banner, Chifeng City, Inner Mongolia and achieved success. The system was led by the Institute of Remote Sensing of the Chinese Academy of Sciences, and was jointly sponsored by the Institute of Atmospheric Physics, the Institute of Electronics, the Institute of Geology and Geophysics of the Chinese Academy of Sciences, and the Modern Physics Center of Peking University. The payload is 30kg. In April 2011, through the optimization and upgrading of the original system, the “one-station and three-machine” flight control was successfully implemented (Malik R A et al. 2018) [8]. The Institute of Geophysical and Geochemical Exploration of the Chinese Academy of Geological Sciences took the lead in the development of a UAV-based aviation geophysical survey station exploration system. In the Dabaoshan integrated exploration area of Nenjiang County, Heilongjiang Province, a comprehensive drone magnetic measurement was conducted with a 180-meter flying height scale of 1:1 million and a 120-meter flying height scale of 1:50,000. The total flight line is 2980km, and high-quality measurement data have been obtained.

3. Methodology

3.1 Design of Airborne Beidou Navigation and Positioning System

The instruments used to measure the elevation of aircraft include: barometric altimeters, radio altimeters, airborne radars, and airborne laser altimeters. These instruments can only perform elevation measurements. GPS can also perform latitude and longitude measurements while taking elevation measurements to obtain the three-dimensional coordinates of the aircraft. Its working principle is as follows. GPS is mainly composed of three parts: space constellation, ground monitoring and user equipment. The space constellation consists of 24 GPS satellites. The user equipment mainly includes GPS receiver hardware and data processing software. GPS satellites transmit signals at the 1575.42 MHz and 1227.40 MHz frequencies to the ground. The GPS receiver receives the signal and solves it to find the distance between the satellite and the receiver. In the Earth Cartesian coordinate system, the following set of observational equations can be obtained:

\[ D_i = \sqrt{(X_i - X_0)^2 + (Y_i - Y_0)^2 + (Z_i - Z_0)^2 + c(T_i - T_0)} \] (1)

In the formula: \( D_i \) is the distance from each satellite to the receiver. \((X_i, Y_i, Z_i)\) is the coordinates of each satellite. \( c \) is the speed of satellite signal propagation. \( T_i \) is the clock difference of each satellite. The receiver coordinate value \((X_0, Y_0, Z_0)\) and the receiver clock difference \( T_0 \) are unknown. When the GPS receiver receives four or more satellites, the equations of equation (1) can be solved for the above unknowns, that is, the three-dimensional coordinates of the receiver are obtained.

The GPS positioning method can be divided into different locations according to reference points: single point positioning and differential positioning. The accuracy of single-point positioning is in meters, and the accuracy of differential positioning is in centimeters. This is because differential positioning can more effectively eliminate or reduce satellite orbit error, satellite clock error, receiver clock error, and ionosphere, tropospheric refractive error, etc., than single point positioning. Differential positioning is divided into code pseudo-range differential positioning and phase-detecting pseudo-range differential positioning according to different observations. The precision of phase-detecting pseudo-range differential positioning is higher than that of pseudo-range detection. According to different data processing methods, it is divided into real-time processing and post-test processing. Magnetic measurement does not require real-time data processing. Therefore, the airborne GPS positioning system adopts a phase-detecting pseudo-range dynamic differential post-processing working mode. The working mode diagram is shown in Figure 1.
The airborne GPS positioning system consists of two parts: a reference station and a rover. The reference station collects dual-frequency GPS data and stores dual-frequency observation data in text. The rover collects single-frequency GPS data and also stores single-frequency observation data in text format. Afterwards, both data are transferred to a PC and commercial software is used for differential processing. The design requirements of the airborne GPS positioning system are as follows: horizontal positioning accuracy requires 2m, elevation positioning accuracy requires 0.5m, and data update rate requirement is 10Hz.

According to the system design requirements, the base station uses a commercial dual-frequency GPS receiver LEICA SR530 Geodetic RTK Receiver, and its data update rate is up to 10Hz. Static positioning accuracy is 3mm+0.5ppm. The mobile station uses the airborne single-frequency GPS receiver designed by Novatel OEMV1 card. The OEMV1 card nominal differential positioning accuracy is 0.45m, and the highest data update rate is 20Hz. Single-frequency GPS receivers mainly include: single-frequency GPS antenna, OEMV1 card and PC104 IPC. OEMV1 card is embedded in the PC104 industrial computer, and single-frequency GPS antenna and PC104 IPC is installed in unmanned helicopters. System block diagram is shown in Figure 2.

By using the plug-and-play factor graph framework and combining the proposed optimal sensor subset selection mechanism, multi-sensor navigation needs are solved. At the same time, it meets the navigation accuracy requirements and system constraints. This section designs and analyzes the UAV full-source navigation solution to provide clear directions and ideas for follow-up work. UAVs are usually positioned and navigated by using an inertial/GPS integrated navigation system. Inertial/GPS integrated navigation has many advantages and can meet higher positioning accuracy requirements. However, because GPS has its inherent shortcomings, satellite signals are vulnerable to interference and deception. Therefore, in order to improve the autonomy of the UAV and ensure the accuracy of its navigation, it is necessary to design a reasonable full-source navigation architecture. The full-source navigation system architecture includes a full-source navigation system solution and an optimal sensor subset selection mechanism, a multi-source information fusion algorithm, a fault detection and system reconstruction module, and a navigation result evaluation.
module.

Judging from the overall plan for full-source navigation of drones, the key technical issues that need to be studied and solved are as follows. In the UAV multi-source information navigation system, each navigation sensor needs information fusion. However, some of the navigation sensors cannot achieve all-weather work, and integration with inertial navigation systems can cause intermittent fusion. Therefore, it is more necessary to rationally configure the UAV multi-source information fusion navigation system. In addition, because the frequency of the information update of each navigation sensor is not synchronized, it is difficult for the conventional filtering algorithm to achieve synchronization filtering fusion. For the problem that the measurement output of the navigation system is not synchronized, a new fusion algorithm needs to be proposed to realize the non-equal interval filtering problem of full-source navigation information fusion. In the UAV multi-source information navigation system, due to the introduction of multiple navigation devices, the probability of multi-source information navigation system failure has increased. When a sensor fails, it will affect the navigation results of the entire navigation system. Therefore, in order for the multi-source information navigation system to be able to effectively combine and provide high-precision navigation requirements, it is necessary to effectively detect and solve the faulty system.

### 3.2 Design of Multi-Source Information Fault Detection Scheme for Uav Navigation System Based on Marine Aviation Measurement

According to the above analysis of the design ideas and key technologies of the UAV full source navigation system, it is assumed that there are n available sensors for UAV full source navigation system. Optimal sensor subset selection for these sensors is conducted. First, the sensor's level is ordered. Second, the sensor is extended with a ternary tree. After comprehensive index analysis, the optimal sensor subset is obtained. The factor graph framework is constructed based on the optimal sensor subsets. Then based on the overall framework of the factor graph, the fusion algorithm of asynchronous information is performed. In the process of information fusion, it is necessary to perform fault detection on the working navigation sensors. The residual $\chi^2$ detection algorithm is used to detect hard faults. Then the m-step sliding residual $\chi^2$ detection algorithm is used to detect soft faults. If fault information is detected, the faulty sensor needs to be removed and the currently available sensor continues to perform optimal sensor subset selection. If no fault information is detected, the navigation is performed normally, and the evaluation result of the navigation result is calculated, and the evaluation result is given.

For ease of comparison, the position error of the navigation system is used as a measure of navigation accuracy. Among them, the average error value of longitude error is represented by $err_L$, and the unit is m. The average error of the latitude error is represented by $err_L$, and the unit is m. The average error of the height error is denoted by $err_H$ and its unit is m. In order to integrate positional accuracy into an index, the squared sum of longitude, twist, and height errors is averaged. After the root number processing is performed, a comprehensive location evaluation index $Err_p$ can be obtained, of which the unit is m, and the expression is:

$$Err_p = \sqrt[3]{\frac{1}{3}((err_L)^2 + (err_L)^2 + (err_H)^2)}$$

The calculation time cost is expressed by the simulation running time consumption and the unit is s. It should be noted that when comparing the time cost of calculation, it is necessary to compare the simulation environment, error setting, and track information. The high-altitude unmanned surveillance aircraft multi-source information autonomous navigation system consists of IMU, GNSS, CNS, TER, SAR, ADS and other systems. Of these navigation systems, only inertial navigation systems can operate without interruption around the clock. Other navigation systems may have signal interference, signal interruption or malfunction due to other reasons. Although the NSS system can work for a long time, it is subject to satellite launching countries, and the satellite signals are vulnerable to interference and attacks. Therefore, it is difficult to work without interruption all the time. The astronomical navigation system relies on star celestial bodies and only needs to capture the stars of visible stars. However, navigation and astronomy work is also limited when weather and time changes result in no visible stars. The terrain matching navigation system is equipped with a radar altimeter and needs to be used under the feature terrain. Although the radar altimeter emits a sharp pulse to the outside, its beam is very narrow, so the signal is highly concealed. The radial matching navigation system itself does not need to radiate information outward, and can withstand strong electromagnetic interference, but it needs to be used under the feature terrain. More information is available in the integrated navigation system. Therefore, the probability of navigation information failure will greatly increase, which seriously affects the performance of the integrated navigation system. In order to ensure the accuracy, stability and security of an unmanned aerial reconnaissance aircraft, it is necessary to study the fault detection algorithm of the system. The fault detection scheme in this paper adds a fault
detection algorithm to the fusion information fusion module and it is responsible for fault detection of the output information of each module.

4. Result Analysis and Discussion

In order to verify the positioning accuracy of this airborne single-frequency GPS positioning system, two tests were conducted in this paper: simulation test and field test. When dealing with test data, commercial software TTC is used. The ephemeris used is the precise ephemeris provided by IGS with an orbital accuracy of 5 cm. First, the observation data is preprocessed. Base station and rover observations are scanned. The satellites with very short observation time and the observation period are removed when the satellites are out of lock to improve the observation quality. Then the TTC software's integer ambiguity is used to process the observation data in the NTF mode. The purpose of the simulation test is to verify the nominal accuracy of the OEM board. The test site is located in the city of Qingdao. The baseline length is approximately 150 m. The observation time for each set of data in the simulation test is approximately 6 h. 4 sets of data are selected for analysis. Table 1 shows the dynamic three-dimensional root mean squared error (RMS) maxima for the four groups of data. The longitude and latitude RMS values of all epochs are less than 5 cm, and elevation RMS values are less than 10 cm, which is superior to the OEM board nominal positioning accuracy.

Table 1 All the Epoch Three Dimensional Rms Maximum Values of the Simulated Test Data Sets

<table>
<thead>
<tr>
<th>number</th>
<th>Maximum value of longitude RMS</th>
<th>Latitude RMS maximum</th>
<th>Maximum value of elevation RMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.012</td>
<td>0.013</td>
<td>0.043</td>
</tr>
<tr>
<td>2</td>
<td>0.012</td>
<td>0.013</td>
<td>0.036</td>
</tr>
<tr>
<td>3</td>
<td>0.025</td>
<td>0.031</td>
<td>0.065</td>
</tr>
<tr>
<td>4</td>
<td>0.016</td>
<td>0.024</td>
<td>0.043</td>
</tr>
</tbody>
</table>

The field experiment is to verify the positioning accuracy of the single-frequency GPS positioning system in the airborne environment. The test site is located in the Dongying seaside. The airborne single-frequency GPS receiver uses an unmanned helicopter as a moving carrier, and the moving speed is in the range of 6-15 m/s. Unmanned helicopter routes are set magnetic lines. During the flight, the GPS baseline length is in the range of 1~13 km. Each set of data for field trials is data for each voyage. The observation time is about 40 min. In the same experiment, four sets of data are selected for analysis. The maximum value of dynamic three-dimensional RMS is shown in Table 2. Figure 3 is a graphical analysis of a group selected. Figure 3(a) is a sequence of elevation values for all epochs of the set of data. Figure 3(b)~(d) is a three-dimensional RMS value sequence of all epochs.

Table 2 the Maximum Rms of All Epoch Three Dimensional Data in Field Trials

<table>
<thead>
<tr>
<th>number</th>
<th>Maximum value of longitude RMS</th>
<th>Latitude RMS maximum</th>
<th>Maximum value of elevation RMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.063</td>
<td>0.073</td>
<td>0.188</td>
</tr>
<tr>
<td>2</td>
<td>0.066</td>
<td>0.082</td>
<td>0.343</td>
</tr>
<tr>
<td>3</td>
<td>0.062</td>
<td>0.074</td>
<td>0.159</td>
</tr>
<tr>
<td>4</td>
<td>0.009</td>
<td>0.016</td>
<td>0.042</td>
</tr>
</tbody>
</table>

The RMS values of latitude and longitude of all the epochs in the field test data in Table 2 are all less than 10 cm, and the RMS values of elevation are less than 50 cm, satisfying the requirements of magnetic measurement work. Comparing the elevation change trend in Fig. 3(a) with the trend of the three-dimensional RMS value in Fig. 3(b)~(d), it can be seen that during the flight, the attitude of the unmanned helicopter during take-off and climbing changes greatly, resulting in a three-dimensional RMS value Larger. After an unmanned helicopter flies at a fixed altitude, the attitude is stable, and the three-dimensional RMS value tends to be stable and the amplitude decreases. Therefore, it can be inferred that the flight attitude of an unmanned helicopter is one of the main factors affecting the dynamic altitude accuracy.
During the simulation test, there is a requirement for a test degree with a large deviation in elevation value. One group is selected for analysis, as shown in Figure 4. Figure 4(a) shows this data. The elevation RMS value of some of the epochs exceeds 0.5m, which does not satisfy all epoch elevation values of the positioning group data. Figure 4(b) is the elevation RMS for all epochs. The position accuracy factor (PDOP value) of all epochs of this set of data is shown in FIG. 5. Comparing the moments with large amplitudes in Fig.4 and Fig.5, it can be seen that the moment when the elevation value has a large deviation, and the moment when the elevation RMS value is large coincides with the moment when the PDOP value is larger. It can be inferred that the observation quality of the satellite is one of the main factors that affect the positioning accuracy of dynamic differential positioning. The buildings around the test site are obstructed by the base station and the rover’s joint observation of satellite signals. In addition, satellites observed by both the base station and the roving station rise and fall, causing the observation satellite to lose lock, which will reduce the positioning accuracy. Therefore, in the field magnetic field measurement work, the site selection of the base station should ensure that the satellites jointly observed by the base station and the rover during the flight are not blocked, and the working time avoids time when the satellite is observed to rise or fall.

5. Conclusion

At present, land-based aeromagnetic surveys based on UAVs in China are basically mature and keep pace with the development of foreign countries, and have been successfully applied in engineering operations. The UAV marine aeromagnetic survey is still in the research stage, and it mainly focuses on the landing and landing UAV platform. The carrier-based UAV platform operation mode is still in the tracking and exploration stage. Therefore, the application of
the airborne Beidou navigation and positioning system in the unmanned helicopter marine aviation magnetic force measurement is discussed. Based on the background of the study and the previous literature, the following conclusions can be drawn from the accuracy test and the test results of the airborne GPS positioning system. The airborne single-frequency GPS positioning system can completely collect dynamic single frequency GPS data and save data files by using an unmanned helicopter as a motion carrier. TTC software is used to perform differential processing on observation data. The latitude and longitude positioning accuracy obtained is better than 10cm, and the height measurement accuracy is better than 50cm, meeting the system design requirements. Therefore, the airborne single-frequency GPS positioning system can be applied to the unmanned helicopter marine aviation magnetic force measurement.

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