

Unmanned Aerial Vehicle Landing Method Based on BeiDou Relative Navigation Technology

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Abstract—Unmanned aerial vehicle (UAV) technology is rapidly developing and application, and UAV recycling is the key link in the application according to statistics, 80% of UAV failures occurred in the process of landing. Traditional UAV recycling methods have been unable to meet the modern UAV use. With the rapid development and application of BeiDou Navigation Satellite System (BDS) in China, using BDS to realize automatic control of UAV becomes a new hot research topic. This paper presents a UAV landing recycling scheme based on BDS relative navigation technology and studies its key technologies. Adding MEMS inertial information to assist BDS improves its accuracy and enhances the feasibility and practicability of the scheme. The dynamic to dynamic positioning experiment verifies the reliability of key technologies and shows that the relative positioning technology proposed in this paper meets the requirements of automatic landing of UAVs and proves that the automatic landing of UAVs is feasible.

Keywords—unmanned aerial vehicle; dynamic to dynamic relative positioning positioning; MEMS inertial information assist; BeiDou satellite navigation system.

I. INTRODUCTION

The UAV system has developed rapidly in recent years, and has been widely used in various industries and directions of military and civilian use. But the UAV recycling is one of the key links in UAV use, whether the recycling methods is flexible and flexible accuracy and reliability are high, equipment and operation is simple has become an important indicator to evaluate the UAV performance is good or bad. There are so many ways to recycle the UAV, the traditional recycling can be generally summarized as the parachute recycling, airbag landing recycling, net recycling, air recycling, rotor vertical landing recycling and landing gear pulley landing recycling, etc. There is a new type of landing method, such as rope hook recycling, line recycling, block landing recycling, "bird" landing recycling, rolling wing machine and flying butterfly UAV vertical landing recycling. These recovery methods are time-consuming and labor-intensive requiring a high man-made operation and are not suitable for recycling on a mobile platform such as a shipborne platform, for example, and it is not suitable for multi-stage UAV simultaneous take-off and landing situation. With the rapid development of BDS, UAV using BDS precise navigation technology has opened a new direction for automatic approach. Using the BDS navigation technology to realize automatic UAV with landing, precise UAV navigation system is one of the necessary conditions to complete the task, that is to say, the UAV navigation system according to the requirements of the flight,

provide the corresponding high precision, high reliability of the navigation parameters (position, speed, heading, gesture, etc.), correctly guide UAVs fly in flight and landing. The dynamic to dynamic relative positioning technology in BDS is a hot and difficult problem in the field of positioning measurement. To achieve the high precision of the BDS move position requirements, actually positioning is usually based on carrier phase positioning, and the core of carrier-based phase positioning technology is the on-line solution of dynamic integer ambiguity [1] (Ambiguity Resolution on - the - fly, AROF or OTF), Integer ambiguity symbolized as N. Traditional dynamic to dynamic positioning is easily affected by signal quality. If the receiver signal is blocked by the building the location information cannot be obtained in real time which leads to the failure to locate accurately in real time. In view of inertial navigation system can independently navigate positioning so when the navigation receiver into the tunnel indoor or tall streets and other places in a short time the receiver cannot obtain satellite signals you can continue to support the inertial navigation positioning system output more accurate positioning information.

II. THE UAV AUTOMATICALLY LANDING PROGRAMME

UAV landing platform equipped with three sets of BeiDou receiver (a main antenna, the rest are auxiliary antennas), the main antenna receives the BeiDou satellite signal and figure out the platform's position and speed information then sent the information to the computer, the computer receives the data and after calculating the data, sends the information about the position, posture and speed of the landing platform to the UAV in real time. The UAV solves the position and velocity information of the UAV through the on-board antenna and the calculation module, and measured the posture information of the UAV. The UAV airborne solution module obtains the relative position information and the relative posture information by calculating the UAV's position information, the posture information and the speed information, and adjust the aircraft posture and flight parameters through the aircraft flight control system so that the aircraft smooth and secure landing. Among them, the MEMS inertial information assists BDS design mainly to measure posture information of UAV. However, it can also be used to calculate relative positioning data results when the number of visible satellites is less than 4. The use of MEMS auxiliary information to calculate the relative positioning data results while ensuring the satellite signal is short-term interference or obstruction continue to provide navigation for the UAV role to enhance the UAV immunity safety and reliability. During the UAV landing the

key is to ensure high accuracy and real-time performance of satellite navigation.

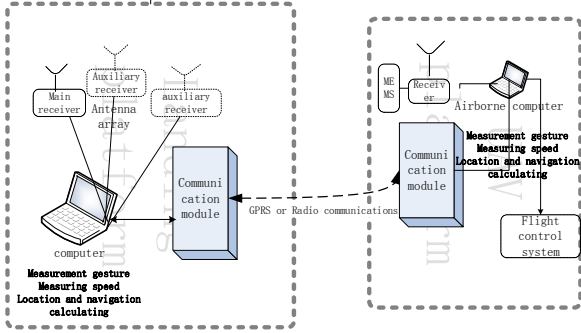


FIGURE 1. A SCHEMATIC DIAGRAM OF THE AUTOMATIC LANDING FUNCTION MODULE OF UAV.

III. KEY TECHNOLOGIES

A. Basic Model of the Dynamic to Dynamic Relative Positioning

UAV automatic landing key technology is relative motion positioning technology, in order to ensure the reliable navigation and safe landing of the UAV, this paper presents a dynamic to dynamic relative positioning method based on MEMS inertial information to aid the BDS.

The mobile station (landing platform) and the mobile station (UAV) receiver can simultaneously observe the n satellites ($n > 4$), for two of these satellites i and j , at a time epoch can get two stations 1 and 2 on the BeiDou B_1 carrier wave alley combination observation equation:

$$\lambda_w \varphi_{12,w}^{ij} = \rho_{12,w}^{ij} + \lambda_w N_{12,w}^{ij} + \varepsilon_{12,w}^{ij} \quad (1)$$

Where, λ is the carrier wave length, φ is the carrier phase observation value, ρ is the distance between the station star, N is the whole week fuzzy degree, ε is the carrier phase observation noise, W represents the wide lane combination.

For a wide lane carrier, the least square equation for the full week ambiguity [2] is as follows:

$$\begin{bmatrix} A^T C^{-1} A & A^T C^{-1} B \\ B^T C^{-1} A & B^T C^{-1} B \end{bmatrix} \begin{bmatrix} X \\ N \end{bmatrix} = \begin{bmatrix} A^T C^{-1} L \\ B^T C^{-1} L \end{bmatrix} \quad (2)$$

In the above equation, X is baseline vector, $N_{\alpha\beta}$ is two-difference fuzzy vector of the combination, A and B is coefficient matrix and the weight matrix. It is assumed that the BeiDou frequency points of the composition model are B_1

and B_2 , the coefficients of their respective frequency points are α, β . The combination ambiguity is $N_{\alpha\beta}$, that is:

$$\varphi_{\alpha\beta} = \alpha \varphi_{B_1} + \beta \varphi_{B_2} \quad (3)$$

$$N_{\alpha\beta} = \alpha N_{B_1} + \beta N_{B_2} \quad (4)$$

The phase ambiguity $N_{\alpha\beta}$ after the combination can be obtained by the least squares method, Because only α and β , the mathematical relationship is unable to correctly solve their ambiguity, so if any search for a new set of coefficients η and γ as on the type of combination, it may, in accordance with the following combination equation of solving ambiguity N_{B_1} and N_{B_2} , after solving the ambiguity [3], also can according to (2) the solution of the baseline vector.

$$\begin{bmatrix} N_{\alpha\beta} \\ N_{\eta\gamma} \end{bmatrix} = \begin{bmatrix} \alpha & \beta \\ \eta & \gamma \end{bmatrix} \begin{bmatrix} N_{B_1} \\ N_{B_2} \end{bmatrix} \quad (5)$$

To be sure, under the condition of visible satellite ($n \geq 2$), the observation model based on carrier phase difference equation containing ($n-1$) an unknown ambiguity and three for three-dimensional coordinate, so visible satellite number must be greater than or equal to four conditions to solve effectively.

B. Ambiguity Resolution of Observing Satellites with Fewer Conditions

In view of this problem, using the output three-dimensional information [4] of MEMS system and BDS double difference information based on Kalman for filtering fusion solution [5], the specific method is:

It is assumed that the three-dimensional space position of the MEMS navigation output is R_{ins} , when the number of visible satellites is less than four, the following equation can also be obtained:

$$\begin{bmatrix} L_\rho \\ L_\varphi \\ 0_{3 \times 1} \end{bmatrix} = \begin{bmatrix} B & 0_{(n-1) \times (n-1)} \\ B & -\lambda E_{n-1} \\ E_3 & 0_{3 \times (n-1)} \end{bmatrix} \cdot \begin{bmatrix} N^{21} \\ N^{31} \\ \dots \\ N^{n1} \end{bmatrix} + \begin{bmatrix} e_\rho \\ e_\varphi \\ e_{ins} \end{bmatrix} \quad (6)$$

It is important to note that because of lack of visible satellite number four, cause the ambiguity of variable number is less than 4, in some cases even only one, the above combination equation using the least squares method [6], can get ambiguity float solution, remember to: $N^{21}, N^{21}, \dots, N^{n1}$ ($N^{21}, N^{21}, \dots, N^{n1}$).

Now suppose inertial gesture matrix of the output is C_b , R_{lb} is the baseline vector obtained by using the inertial navigation output information. The vector R_b in the coordinate system is the baseline of the guard receiver antenna mounted on two dynamic stations. ϕ is the error angle vector of the inertial navigation platform. The baseline vector obtained from the inertial output information obtained by this algorithm is:

$$R_{lb} = C_b R_b - C_b \phi \times R_b = C_b R_b + C_b R_b \times \phi \quad (7)$$

According to the variance matrix of the combined filter output, the baseline vector variance matrix calculated using the inertial navigation position is:

$$P_l = \text{cov } R_{lb} = C_b R_b \times \text{cov}(\phi \phi^T) R_b^T C_b \quad (8)$$

Therefore, the ambiguity vector is obtained by the two - difference carrier phase observation equation and the baseline vector and variance matrix of inertial output.

$$N = (\nabla \Delta \varphi - A_k R_{lb}) / \lambda \quad (9)$$

$$\text{cov } N = (\text{cov}(\nabla \Delta \varphi) + A_k P_l A_k^T) / \lambda^2 \quad (10)$$

IV. TEST VERIFICATION

In order to verify the feasibility of this scheme and the validity and reliability of key technologies, the dynamic to dynamic positioning test base on MEMS-assisted BDS is carried out by using vehicle platform equivalent the landing platform and UAV platform. The experiment was conducted on May 10, 2017 together with relevant test personnel from Wuhan University on a long enough 15 ° slope of Gutian Road, Liberation Avenue, Wuhan. Prior to the test, a vehicle equipped with a MEMS inertial device and a satellite navigation system (antenna, receiver etc.) was selected as a mobile station and a vehicle equipped with a satellite navigation system was used as a moving reference station for relative positioning test. The receivers were all dual-band Novatel company BDS / GPS type, test vehicle equipped with the situation shown in Figure II:



FIGURE II. TWO MOBILE STATION VEHICLES AND EQUIPMENT EQUIPPED SCHEMATIC.

During the test, Mobile station vehicles drive down from a slope of about 15 degrees to the base station vehicles, mobile base station vehicles do low-speed movement down the slope. The receiver's positioning mode is set to BDS / GPS dual-frequency combination positioning, set the satellite cut-off height angle to 15 °, the data update frequency is 1Hz, BDS and GPS data are collected and saved respectively and the MEMS data are also saved in real time in the data collector. The duration of the whole experiment was 1h.



FIGURE III. TWO STATIONS MOVE TRACK (RED: MOBILE STATION, GREEN: MOBILE STATION).

At the end of the experiment, first of all, the original data collected in the experiment were calculated and processed by traditional Dual-band differential respectively for GPS and BDS. Among them BDS adopted B1 and B2 frequency points while GPS adopted L1 and L2 frequency points. In the process of traditional dual-frequency calculated and processed of BDS B1 frequency points are used for fixing and some of the index results are shown in FIG. 4, including the Ratio value for finding the best ambiguity and the position-error (Hereinafter referred to as PE) recorded as σ , calculation publicity is as follows:

$$\sigma = \hat{\sigma}_0 \cdot PDOP \quad (11)$$

In the formula, $\hat{\sigma}_0$ said posterior unit weighted error, PDOP said geometric accuracy attenuation factor. Usually, we test the correctness of the results by using the size of σ . In the short baseline (less than 10km) case, σ generally less than 0.05 meters, if it is more than 0.10m the result of the calculation is incorrect.

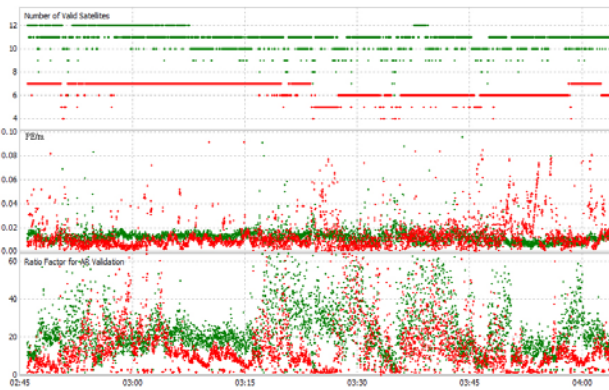


FIGURE IV. SOME INDEX RESULTS DURING THE EXPERIMENT THE BDS AND GPS DUAL-FREQUENCY SINGLE EPOCHS CALCULATED .

As can be seen from Figure IV, the number of BDS satellites is greater than or equal to 4 at the beginning and end of the observation epoch, but its number changes frequently, which affects the quality of receiver data, in actual calculation, the number of epochs is less than the number of epochs saved simultaneously. Table 1 below gives some of the indicators of GPS and BDS data processing during the test.

TABLE I. PART OF THE INDICATORS RESULTS OF THE BDS AND GPS PROCESSING DURING THE TEST

System	Total epoch / Calculation epoch	Number of Satellites	Ratio Average Value	Ratio Interval Distribution			PE Value Distribution	
				>3	[2,3]	<2	<=5cm	>10cm
BDS	1120/1080	8.0	35.2	98.10	1.58	0.32	99.24	0.37
GPS	1120/995	5.8	18.2	87.40	4.72	7.88	97.46	1.62

As can be seen from Table I, during the post-processing of the experimental data, the number of GPS actual calculation epochs is only 995 which is smaller than the number of data saved in the same time and segment of the synchronization, compared with the BDS data, only 40 can't be solved. It can be seen that the number of BDS can still be kept more when the observation conditions are poor. For calculation epoch, BDS dual-frequency ambiguity fixed success rate (and considered Ratio value greater than 3 is successful) is about 20% higher than the GPS dual-frequency, and the BDS positioning error is less than the GPS positioning error. A 95% confidence probability statistical accuracy analysis was performed on the resolved BDS results for the entire process, we can the horizontal, vertical and three-dimensional positioning accuracy shown in Table II.

TABLE II. BDS DUAL-FREQUENCY SINGLE EPOCH POSITIONING ACCURACY RESULTS TABLE

System	N	E	U	Horizontal	Three-dimensional
Accuracy	0.196	0.325	0.015	0.236	0.372

It can be seen from Table II, the system has a horizontal positioning accuracy of 0.236m and a vertical positioning accuracy of 0.015m (2σ , 95%).

At this moment, in order to verify the auxiliary effect of adding MEMS system, the MEMS-aided BDS filtering method proposed in this paper is used to filter the experimentally stored MEMS data and BDS data. The obtained epoch baseline results are compared with the post-dynamic software (Grafnav) processed GPS. The results of the comparison in the deviation shown in Figure V.

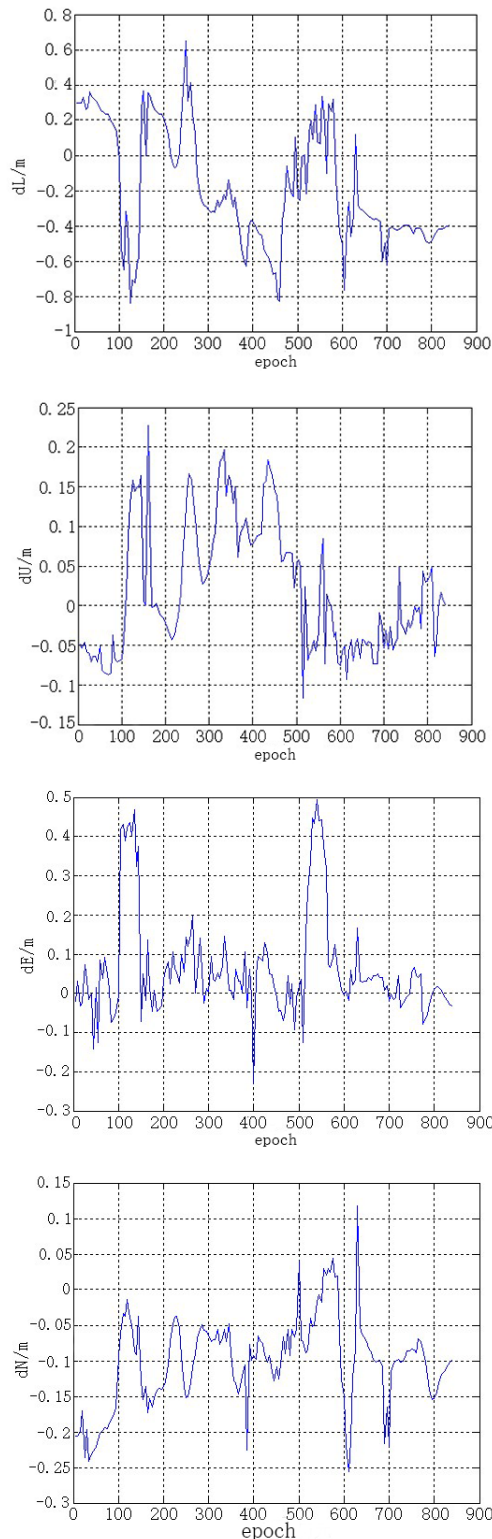


FIGURE V. BASELINE VECTOR COMPONENTS AND LENGTH ERROR OF MEMS ASSISTED BDS CALCULATION.

It can be seen from Figure V, the relative baseline obtained by MEMS-assisted BDS filtering has a smaller deviation in N

and U directions and a larger error in E with a maximum value of about 0.5 m.

Similarly, the results of the above-mentioned filtering solution 95% confidence probability of statistics, get the N, E, U to the accuracy of the following Table III.

TABLE III. MEMS AUXILIARY BDS DYNAMIC TO DYNAMIC POSITIONING ACCURACY RESULT TABLE

MEMS/BDS	N	E	U	Horizontal	Three-dimensional
Accuracy	0.168	0.283	0.014	0.224	0.325

Combining Table II and Table III, it can be seen that the accuracy of BDS motion estimation after MEMS system assisted is improved to a certain extent mainly in N and E upward. In addition, the auxiliary function of MEMS is reflected in the data interruption of the epoch Compensation and recursive calculations to ensure the real-time positioning of BDS. Table III shows that the horizontal accuracy of BDS dynamic to dynamic positioning with the aid of MEMS system is 0.224m (2σ , 95%) and the vertical positioning accuracy is 0.014m (2σ , 95%).

V. CONCLUSION

In this paper we design a scheme of using BeiDou satellite navigation system to realize automatic landing of UAVs, and analyze the key technologies therein. A method of using MEMS inertial information to assist the relative positioning of BDS is proposed. By analyzing the localization problems under different satellite observation conditions, the inertial information is used to help solve the ambiguity when the number of satellites is insufficient and a method to solve the ambiguity by tight combination filtering is given. Based on this, an equivalent test system is set up and the kinematic positioning test of the combined system is carried out. According to the above test results, it is proved that the relative positioning accuracy of the motion using the BDS is high real-time and strong usability, UAV can meet the accuracy requirements of automatic landing. And, the MEMS-assisted BDS dynamic to dynamic positioning horizontal positioning accuracy of 0.224m vertical positioning accuracy of 0.014m compared with the simple BDS positioning accuracy is higher, and more to improve the accuracy of UAV automatic landing and the reliability and security of the UAV's automatic landing system.

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