Summarization of Vehicle Position and Azimuth Fast Determining Technology

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Abstract. To improve the rapidity, accuracy and autonomy of vehicle position and azimuth determining is an important theme in the development of land launch equipment. Based on this topic, a comprehensive summary is made of the theories and methods related to vehicle position and azimuth determining technology, including autonomous integrated navigation, initial alignment technology, error estimation and compensation technology, observability analysis method, and nonlinear filtering method. By summarizing and analyzing the related progress in recent years, this paper points out the existing problems in the research, and probes into the development direction of vehicle position and azimuth fast determining technology.

1. Introduction

Repairing damaged satellite, providing information support to the ground, and other tasks need to have the ability to respond quickly to space [1], rapid space launch is an important technical support to achieve a rapid response space. Rapid space launch can be based on offshore platforms, space-based platforms, vehicle platforms, underground silos and other forms [2-4].

For rapid space launch, positioning and orientation technology is one of the key links. Positioning and orientation technology refers to the information such as the geographic coordinates, azimuth, and attitude of the carrier to accurately determine its location during the movement [5], the positioning and orientation accuracy directly affects the spacecraft's orbital accuracy, and the time and autonomy of positioning and orientation are directly related to the survivability and reliability of the vehicle platform in wartime. For the vehicle platform, it is required to reach any launch point you can immediately know your own attitude, azimuth, position and other information, and realize "launch while stopping" and "launch while walking" while ensuring accuracy [6]. At present, vehicle positioning and orientation are mainly based on the strapdown inertial navigation system (SINS) with the assistance of other equipment, including the global navigation satellite system[7-10], star sensor [11], radio frequency identification (RFID) [12], visual sensor [13,14] and map matching, these integrated navigation systems have their own characteristics, the advantages and disadvantages are shown in table 1.

Generally speaking, the existing system cannot well meet the requirements of rapidity, accuracy and autonomy of positioning and orientation for rapid launch in wartime environment only by its own performance. Odometer (OD) is autonomous, reliable, and cost-effective which is suitable for vehicle navigation to suppress the error drift of SINS [15-17]. Therefore, the integration of SINS and OD is a highly autonomous navigation orientation method with high precision. Laser Doppler Velocimeter
(LDV) has good long endurance stability and high measurement accuracy, so the integration of SINS and LDV is also an important choice [18].

At home and abroad, extensive research has also been carried out in the field of Rotational Modulation (RM), that is, the periodic rotation of the inertial device is used to achieve self-compensation for the constant error of the inertial device to improve navigation accuracy. Therefore, the RM technology is applied to the integrated navigation system can further improve navigation accuracy. At the same time, the system navigation accuracy can be improved through high-precision error estimation and compensation methods.

This paper focuses on improving the autonomy, accuracy and rapidity of vehicle-borne navigation positioning orientation, and on the basis of extensive reading and analysis, summarizes the key technologies and their research status, in order to provide useful references for researchers in this field.

| Method          | Advantage                        | Disadvantage                        |
|-----------------|----------------------------------|-------------------------------------|
| SINS            | Accurate in short time, autonomous | Errors accumulated                  |
| SINS/Satellite  | Accurate                         | Susceptible to interference         |
| SINS/Astronomy  | Accurate, autonomous             | Discontinuous output, climate affected |
| SINS/RFID       | Accurate                         | Requires deployment and limits mobility |
| SINS/Vision     | Low cost, accurate               | High sensitivity to light           |

2. Autonomous integrated navigation

2.1. Sins/od integrated navigation

For a launch vehicle, it must be able to adapt to complex conditions, especially in wartime. Therefore, its integrated navigation system must have high reliability and autonomy, and be able to meet the needs of high precision.

Based on the kalman filter (KF), SINS and OD integrated navigation is realized in [19], and the simulation comparison with the traditional dead reckoning is performed, which can effectively improves the autonomy and navigation accuracy. In [20] and [21], the navigation methods of installing MEMS-IMU on wheels are studied separately, no new transposition mechanism is needed, and the dead reckoning is based entirely on inertial sensor data. Using the gyroscope and the radius of the wheel to get the velocity, it acts as "OD" without having to integrate the accelerometer data twice. The results of both experiments show that the navigation accuracy of this method is better than that of the traditional OD dead reckoning method under the condition of steady or slight shaking, however, in a highly dynamic environment, accelerometer data are vulnerable to damage. In [22] and [23], the single-axis RM technology is introduced in the SINS/OD integrated navigation, and the rotation angular velocity is taken as 6 °/s. The effectiveness of the single-axis RM technology is verified by simulations respectively. The former simulation results show that compared with SINS/OD, the attitude accuracy is improved significantly, and the positioning error is not much different, the latter simulation results show that the heading accuracy and positioning accuracy are significantly improved. In short, the heading errors of both are effectively suppressed while the improvement effect of positioning error is different, the reason may be that the former chooses the up-facing z-axis of the carrier as the rotation axis, while the latter takes the forward-facing Y-axis of the vehicle as the rotation axis, and the error quantity considered in the process of establishing the error model is also different.
2.2. **SINS/LDV Integrated Navigation**

OD can be better used to suppress SINS errors and improve navigation accuracy, but there are also defects, such as its scale factor is susceptible to tire pressure, tread wear and other factors. Therefore, in recent years, many researchers have studied SINS/LDV integrated navigation.

In [24], the integrated navigation of one-dimensional LDV and SINS is studied, and an LDV based on the split reuse technology is designed to improve the energy utilization rate, the experimental results show that the SINS/LDV integration can effectively reduce the velocity error and improve the positioning accuracy compared with the SINS, however, the one-dimensional LDV cannot accurately measure the speed of the bumpy road. To solve this problem, a two-dimensional LDV is designed in [25], which is formed by two one-dimensional LDV, the experimental results show that the two dimensional LDV and SINS integration can effectively suppress the disturbance of vehicle turbulence, improve the horizontal positioning accuracy, and obtain more accurate height information.

### 3. The key technology

Many scholars continue to study the initial alignment technology, error estimation and compensation technology, because the initial alignment directly affects the accuracy of subsequent navigation positioning and orientation, error estimation and compensation technology can effectively complete the system error estimation and compensation.

#### 3.1. Initial Alignment Technology

Initial alignment is to establish the initial conditions necessary for the navigation system to enter the navigation state. For SINS, it is to find the transition matrix from the initial body system to the navigation system [26]. The initial alignment of the rotary SINS system is to determine the transformation matrix between the inertial element coordinate system and the navigation system at the initial time of navigation [27].

According to different accuracy requirements, the initial alignment is divided into two processes: coarse alignment and fine alignment, according to the state of movement of the carrier during alignment, it can also be divided into static base alignment and dynamic base alignment. The dynamic base mainly has slight shaking, large shaking, and moving base. The research under the static base has been mature, in recent years, the focus is more on the alignment under the dynamic base [28].

#### 3.1.1. Initial alignment under shaking base

In [29], it considers that the alignment algorithm should track the actual changes of the shaking base attitude during the alignment process. The solidification coordinate system method is adopted for rough alignment, and the alignment accuracy is less than 2°, which satisfies the linearization condition of KF. The KF is used for fine alignment to improve the algorithm's ability to track vehicle attitude. The alignment accuracy is about 0.04° and the alignment time is 180s.

In [30], the transformation matrix of solidified coordinate system from body system to body inertial system is converted into quaternion, and the equivalent rotation vector method is adopted to make the matrix solution more convenient. The simulation results show that the coarse alignment of solidified coordinate system is more effective than the analytic alignment.

Therefore, by means of the idea of inertial solidification of the coordinate system, the gravity vector at different moments in the inertial space is not collinear, and it can be solved by the algorithm of two-vector fixed attitude or multi-vector fixed attitude, which can better isolate the angular slopping interference. In addition to the angular rocking part, there is line vibration interference.

Aiming at the linear interference in the actual process of self-alignment of the shaking base in [31], a low-pass filter is designed to filter the projection of the force in the inertial system to eliminate the influence of line vibration interference. In order to achieve self-alignment of the rotary SINS under the condition of angular sloshing and line vibration interference, a self-alignment algorithm based on the inertial system and an improved multi-fading factor adaptive KF algorithm are proposed in [32]. By changing the embedding mode of the fading factor matrix in the prediction error covariance matrix,
suppressing the influence of uncertain noise on the prediction error covariance, and adjusting the optimal filter gain in real time, the stability and accuracy of the filter are improved. The influence of line vibration interference is eliminated by introducing wavelet threshold in [33].

An alignment algorithm based on matrix KF is proposed in [34], which transformed the nonlinear alignment problem of SINS under large misalignment angle slopping base into the linear matrix KF estimation problem of K matrix corresponding to the initial attitude, avoiding the assumption of large and small misalignment angle by traditional methods. In [35], the strong tracking filter (STF) is used to further improve alignment accuracy, the standard deviations of pitch, roll and heading angle are 0.0140°, 0.0097° and 0.91° respectively, which verified the effectiveness of the method under shaking base.

3.1.2. Initial alignment under moving base. It takes several minutes for the vehicle to complete the initial alignment under static conditions, which limits the vehicle's ability to move and respond quickly. Therefore, the study of alignment under the moving base is of great significance to improve the mobility and responsiveness of the vehicle.

In [36], the solution process of attitude matrix is transformed into Wahba attitude determination problem, and the optimal estimation of rough alignment in progress is realized by QUEST algorithm, the experimental results show that the algorithm can improve the accuracy of course alignment effectively. In [37], the rough alignment algorithm based on attitude estimation and the fine alignment algorithm based on KF are studied. The velocity update equation in integral form is established and the initial value of the attitude matrix is obtained by the least square method. In [38], SINS and OD are integrated to design a fast positioning and orientation system, the KF is firstly performed under the static base to complete the alignment of pitch angle and roll angle, and then the vehicle starts to travel and the trajectory similarity principle is adopted to complete the heading alignment. The RM technology is introduced into the alignment of the on-board SINS in [39], the simulation results show that the accuracy and speed of the continuous azimuth rotary alignment are better than the traditional multi-position alignment. The nonlinear alignment method based on Fast Orthogonal Search (FOS) and KF in the process of artillery maneuver is studied in [40], using the non-linear error model trained in advance for alignment, the linear attitude error is eliminated while the nonlinear attitude error is suppressed. The simulation results show that the alignment accuracy and real-time performance of the FOS/KF method are far superior to the extended KF (EKF).

In recent years, in order to improve the navigation accuracy under fixed-length navigation data by SINS/OD during moving, and with the development of computer technology, many researchers have studied the backtracking algorithm.

The backtracking algorithm is used in the process of SINS/OD alignment in [41]. The experimental results show that the alignment accuracy of the algorithm is better than 1mil, and the positioning accuracy is better than 0.3%D (D: 206km), which can achieve precise alignment without stopping and improve the maneuvering performance of the vehicle. The backtracking integration process of observation vector for initial alignment based on attitude determination is mainly focus on in [42]. After the rough alignment results are obtained by using the improved optimization based alignment method in [43], the initial alignment is completed by using the fine alignment method based on backtracking scheme. The experimental results show that the alignment scheme can achieve faster and higher accuracy than the optimization algorithm without backtracking scheme and the traditional algorithm.

The backtracking scheme is equivalent to increasing the amount of data used for alignment and improving the accuracy and speed of alignment. However, this kind of scheme also has some defects. If the sensor accuracy is not enough, the inherent error will lead to the poor performance of the existing estimation methods based on attitude determination. Even if the observation results meet the linearization requirements of subsequent fine alignment, the sensor observation noise will cause the SINS/OD model nonlinear and the ideal attitude and positioning accuracy cannot be obtained.
3.2. Error Compensation Technology

It is necessary to compensate for the error because of the increasing demand for navigation accuracy. In the vehicle-mounted navigation system, there are many error factors. Here, the compensation of gyroscope constant drift, accelerometer zero deviation, scale factor error, SINS installation error and lever arm error is analyzed.

3.2.1. Compensation of constant error. For the constant drift of the gyroscope and the zero deviation of the accelerometer, the RM technology can be used to achieve self-compensation.

In [44], the modulation effect of single-axial continuous rotation, positive and negative rotation, four-position rotation and stop was analyzed. In the improved four-position scheme with rotating angle less than 360°, considering the acceleration and deceleration of rotation, the relationship between angular acceleration and modulation angular velocity of the rotating mechanism and stop time is deduced, which can effectively eliminate the influence of constant value drift of the horizontal fiber optic gyroscope within one cycle and achieve the best self-compensation effect of error.

In view of the problem that the accuracy of the single axis rotary SINS is limited by the rotating axis, more researchers pay attention to the compensation of the double axis rotating modulation. In [45], a two-axis continuous positive and negative RM method is proposed, when the rotation rate between internal axis and external axis is 1:2, it can not only modulate the constant error of the inertial device, but also suppress the new error caused by rotation. Compared with the method of biaxial inversion modulation in [46], the simulation results are better. In [47], two error modulation schemes of synchronous positive and negative rotation around x and z axis and alternating four-position rotation around x and z axis are proposed based on fiber optic gyroscope. The simulation results show that the positive and negative rotation of synchronous axis is better than that of alternate rotation, and the faster the rotation speed, the better the compensation effect.

3.2.2. Compensation of the time-varying error. For the compensation of scale factor error and installation error, some biaxial rotation modulation schemes can modulate the error to some extent [48]. But it's more about designing error estimation algorithms.

In [49], OD scale factor error and SINS installation error are listed as state variables, and the difference of position between SINS and dead reckoning is taken as measurement and estimated by KF, the on-board test shows that the scheme can estimate the scale factor error and installation error quickly. In [50], the installation error, scale factor error and error angle are estimated and compensated effectively by EKF, and the error divergence of the system is solved well. In [51], SINS/OD integrated navigation adaptive strong tracking filter algorithm is proposed to realize real-time adaptive estimation and compensation of OD scale factor error. For SINS/LDV integrated navigation, considering the LDV scale factor error, installation error between SINS and LDV, the error of the lever arm in [52], then stable estimation results are obtained by KF, and the validity of scale factor error, installation error estimation and lever arm error estimation is verified by combining trajectory similarity principle and manual measurement.

4. Analysis method of observability of state

When the observability of the system state variable is observable, the filter estimation will converge. Therefore, it is necessary to analyze observability. For linear time-invariant systems, the theory of discriminating observability is more mature. The on-board SINS in motion is a time-varying system, PWCS method can be used to solve this problem.

4.1. PWCS Method

PWCS is used in [53] to analyze the observability of different uniaxial rotation schemes, analyzed the total observation matrix and extracted observation matrix of different periods, and the analysis results showed that a reasonable rotation scheme could improve the observability of the system state. Aiming at
the problem that the inertial system is not completely observable without maneuvering, the method of using IMU rotation to improve the observability of inertial navigation system is proposed in [54].

The limitation of the PWCS method is that it can only make qualitative analysis on the observability, and can't reflect the convergence speed and accuracy of the filter state estimation. Therefore, there also needs to be a "degree" to quantitative analysis.

4.2. Analysis Method of Observable Degree

In [55], an observable degree analysis method based on singular value decomposition (SVD) is proposed to quantitatively analyze observable measures through the singular values and singular vectors of the observable matrix, and the observability can be analyzed at the same time. It is widely used by researchers because it does not need to be filtered in advance. However, this method has its own defects, a detailed analysis through examples is performed in [56].

An improved method based on SVD is proposed in [57], which requires certain processing of the matrix $A_i$ corresponding to each singular value after singular value decomposition, so as to identify the size of the observable measure of each state.

Some researchers have also proposed a new method for analysis of observable measures. In [58], the diagonal elements of the estimated error transfer matrix were proposed as observable measures, and the observable measures were analyzed from the perspective of estimated error attenuation.

4.3. Global Observability Analysis Method

The global observability analysis method is simple, direct and effective to analyze the observability of SINS [59]. According to the global observability analysis of the system, an initial alignment scheme of moving base is proposed in [60]. In [61], the problem of system observability is transformed into the problem of judging whether there is a unique solution to the system state quantity, and the global observability analysis method is used to analyze the observability of system state, and a sufficient condition of system observability is given.

PWCS method, observability measure analysis method based on SVD theory, and global observability analysis method are mainly used to solve the observability analysis of linear systems, while for the observability analysis of nonlinear systems, only Lie derivative observability matrix determination method is used [62], and this method is more complicated to calculate. In practice, the analysis of the observability of nonlinear systems mostly transforms the nonlinear problems into linear problems, and then the corresponding method of linear systems is used for the analysis. Therefore, the observability analysis method of nonlinear systems needs to be further studied.

5. Nonlinear system filtering method

In the real environment, the system is often nonlinear, especially in the integrated navigation system, the system precision considering only linear filtering is very limited. Therefore, particle filter, cubature KF (CKF), predictive filter, neural network and other methods have attracted much attention in recent years.

An unbiased compact combination method for SINS/WSN based on EKF has been proposed in [63]. The main reason is that this method reduces the error introduced by the first order linearization of the nonlinear system by the Taylor series. In order to improve the underwater integrated navigation accuracy of SINS/Doppler log, a spherical simplex square root untracked particle filter algorithm is proposed based on the standard particle filter algorithm in [64]. In [65], the dimensional-reducing CKF algorithm was used to solve the problem that the number of sampling points was proportional to the number of state vectors in the initial alignment of SINS. The simulation results showed that the dimensional-reducing algorithm had the same alignment accuracy as the conventional CKF algorithm, but the time was only 1/3. A fifth order CKF algorithm is proposed in [66]. The experimental results show that the proposed algorithm has higher alignment accuracy than the traditional algorithm, but its robustness needs to be further verified.

In [67], the problem of vehicle-borne SINS initial alignment in the case of large misalignment Angle of motion is studied, and the adaptive CKF method combining the advantages of CKF and Sage-Husa
adaptive filtering is proposed. The simulation results show that the accuracy and robustness of ACKF/KF method are better than EKF, CKF and adaptive EKF. In [68], the untracked KF (UKF) and EKF were simulated and compared to solve the nonlinear problem of the combined navigation state error model and measurement model. The results show that UKF is more robust and can effectively improve the positioning accuracy. In [69], the radial basis neural network was improved to solve the problem of pure inertial navigation mode navigation during the unlocking of satellite signal, and was combined with the adaptive KF to improve the positioning accuracy. In [70], prediction filtering is used to provide one-step prediction for KF, which effectively improves the accuracy of error estimation for gyroscope and accelerometer.

The above nonlinear filtering methods have been well applied and developed. It can be found that most of them are used together because of the inherent disadvantages of using them alone [71]. The EKF needs to linearize the system, introduce errors and require accurate system noise statistics. Particle filtering requires a large number of sample data to complete effective filtering, which requires a large amount of computation. The convergence speed of neural network is slow and it is easy to fall into local optimization. Predictive filtering cannot estimate the accelerometer error. Reasonable combination of filtering can make up for their respective shortcomings and improve the filtering accuracy. Therefore, the combination between nonlinear filtering and KF, nonlinear filtering and adaptive filtering is worthy of further study.

6. Conclusion
In case of emergency, the positioning and orientation system must be autonomous and reliable, otherwise, once interfered or broken, the direction and position will be unknown or the accuracy will be severely damaged, which will make it impossible to effectively complete the launch mission. Therefore, it is of great significance to study the rapid, high-precision and autonomous positioning and orientation technology. This paper summarizes some theories and methods of vehicle navigation orientation, including autonomous integrated navigation, initial alignment technology, error compensation technology, state observability analysis method, nonlinear filtering algorithm, etc.

From the current research status, the development trend of vehicle-mounted fast, accurate and autonomous positioning and orientation technology mainly includes:

Highly integrated development of multi-sensor to realize complementary advantages between SINS, OD and LDV.

The RM technology is introduced to self-compensate the errors of the integrated navigation system, and the RM strategy should adapt to the high dynamic environment.

To low cost, small size, low power consumption based on MEMS inertial navigation system.

To a variety of new and robust alignment algorithm, new integrated filtering algorithm.

It can be seen that there are still algorithms and applications in the field of vehicle positioning and orientation that are worth studying.

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