Research Article

Satellite/Inertial Navigation Integrated Navigation Method Based on Improved Kalman Filtering Algorithm

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With the continuous development of positioning technology in today's world, the accuracy requirements for navigation and positioning are also getting higher and higher. Global Positioning and Navigation System (GPS) can provide high-precision long-term navigation and positioning information. However, it has a strong dependence on the external environment, which means that it is easily disturbed by environmental changes and affects the accuracy of navigation and positioning and even leads to positioning failure. The inertial navigation system (INS) is an autonomous navigation system. It uses sensors to measure the specific force and angular velocity of the carrier for positioning and navigation, which means that it is less affected by the environment. However, the inertial navigation device will produce a certain initial error due to the restriction of the manufacturing level, and the error will increase with time, so the inertial navigation method is not suitable for long-term navigation. Therefore, it is of great practical significance to realize satellite/inertial navigation integrated navigation by combining the respective advantages of satellite navigation and inertial navigation methods and avoiding their respective disadvantages. This paper is aimed at studying the satellite/inertial navigation integrated navigation method based on the improved Kalman filter algorithm. The satellite inertial navigation integrated navigation experiment is carried out based on the improved Kalman filter algorithm. In the experiment, the noise reduction experiment of the designed satellite inertial navigation system was carried out by using the filtering noise reduction function of the improved Kalman filter algorithm, and the conclusion was drawn after the experiment. The navigation accuracy of the satellite inertial navigation system is improved by a total of 2 m after the improved Kalman filter algorithm is used to filter the noise reduction.

1. Introduction

With the development of science and technology, the requirements for the accuracy of navigation and positioning in all walks of life are getting higher and higher. There are many navigation systems currently on the market, with different functions and their own advantages and disadvantages, such as satellite navigation systems and inertial navigation systems. Satellite navigation systems and inertial navigation systems are currently commonly used navigation systems. Satellite navigation system is a navigation method formed by combining astronomical navigation and radio navigation. Since the birth of the satellite navigation system, after years of development, it can provide high-precision positioning, navigation, and timing functions for a long time. The inertial navigation system refers to the navigation

method in which the inertial component data is measured by sensors, and then, the inertial navigation solution is performed by using Newtonian mechanics. The elements of inertial navigation are mainly composed of gyroscopes and accelerometers. They are, respectively, used to measure the navigation information such as the angular velocity and acceleration of the moving carrier; calculate the speed, position, and attitude angle of the moving carrier through the mathematical model; and finally realize the purpose of navigation and positioning. Integrated navigation refers to the fusion of two or more navigation systems to enhance the strengths and avoid weaknesses, to improve the navigation accuracy of the navigation system. At the same time, the method of combined navigation can also improve the redundancy of a single navigation system, improve the stability of the navigation system, and has high application value.

Satellite navigation systems and inertial navigation systems have their own advantages and disadvantages, and there are good complementary characteristics between them. The fusion application of these two navigation systems can give full play to their respective advantages and can improve the positioning and navigation accuracy of the system to the greatest extent. In this paper, based on the improved Kalman filter algorithm, the research on the combined navigation method of satellite and inertial navigation is carried out.

The main innovations of this paper are as follows: (1) The fusion application research is carried out on the two navigation methods and systems of satellite navigation and inertial navigation, and a satellite inertial navigation integrated navigation system is designed. (2) The improved Kalman filter algorithm is introduced in detail. Combined with the algorithm, the satellite/inertial navigation integrated navigation experiment is carried out, and finally, an effective conclusion is drawn.

2. Related Work

There have been many researches related to improving the Kalman filter algorithm in academia. Among them, Ren et al. mainly studied the improved Kalman filter algorithm to solve the problems of real-time estimation difficulty and low accuracy of lithium-ion battery state of health estimation under various working conditions. He established an improved model based on the improved Kalman filter algorithm to improve these problems [1]. Hao et al. put forward a positioning method based on the improved Kalman filter algorithm through his research to eliminate the problem of clock synchronization in most positioning systems [2]. Through his research, Li et al. proposed a gradient boosting decision tree algorithm based on the improved Kalman filter algorithm to improve the performance of GBDT [3]. Wang et al. proposed a new highway traffic state estimation method based on the improved Kalman filter algorithm to improve the accuracy and time efficiency of highway traffic state estimation [4]. Zhu-Li et al.'s research found that the standard Kalman filter algorithm cannot accurately predict the prior statistical characteristics of system noise and observation noise. Therefore, he proposed an improved Kalman filter algorithm to improve the problem [5]. Zhang proposed a new control method based on the improved Kalman filter algorithm to improve the landing accuracy of the aircraft [6]. Although the above researches are closely related to improving the Kalman filter algorithm, the practicability of these researches is not strong enough. And the research process is also more complicated and difficult to operate.

3. Satellite/Inertial Navigation Integrated Navigation Method

3.1. Overview of Satellite Navigation and Inertial Navigation and Positioning System. First of all, the Beidou satellite navigation and positioning system are a satellite positioning and communication system completely developed by China. It consists of three parts: space base, ground monitoring, and user terminal. The ground monitoring part of satellite navigation consists of an injection station that sends navigation information to satellites, a main control station that processes data, and a detection station that provides real-time observation data to the main control station [7]. The satellite navigation user equipment part analyzes the Beidou satellite messages in real time according to the NEMA-0183 protocol and obtains the receiver's position, speed, and other navigation and positioning information, to provide users with positioning and navigation services [8]. The composition of the satellite navigation system is shown in Figure 1.

Inertial navigation systems, on the other hand, work according to the principle of inertia. It does not need to rely on external information when working, and the system itself may autonomously and covertly measure the carrier's specific force and angular velocity and other positioning information under all weather conditions. It can provide the complete motion state information of the carrier in time. It is an indispensable and important navigation equipment for the carrier [9, 10].

The core measurement devices in an inertial navigation system are gyroscopes and accelerometers. The accelerometer can measure and analyze the force on the three axes. It uses Newton's second law to measure the acceleration, and then, the magnitude and direction of the acceleration for the three axes of the accelerometer can be obtained. And it can get the velocity and displacement of the carrier by integrating and calculating in the time domain. Specifically, the calculation method of the instantaneous speed of the carrier is shown in the following formula [11]:

$$V = V_0 + \int_0^t a. \tag{1}$$

The displacement of the carrier is given by the following formula:

$$S = S_0 + V_0^t. \tag{2}$$

It can be obtained from the above formula that the inertial navigation system only needs to perform data acquisition and integral operation on the attitude sensor fixed on the carrier to obtain the current displacement data without external electromagnetic interference and without external radiation information [12]. When the three-axis accelerometer is placed horizontally, the accelerometer is only supported by gravity and vertically upwards in the vertical direction. Therefore, there is only the vertical acceleration, and the value is the gravitational acceleration value. Because this paper only discusses two-dimensional positioning, the carrier only moves on the horizontal plane, so the acceleration value component in the vertical direction is not considered, and the acceleration value of the carrier on the horizontal plane is obtained [13].

$$a = \sqrt{a_x^2 + a_y^2}. \tag{3}$$

The pitch and roll angles of the carrier can be calculated from the acceleration values. However, the yaw angle in the
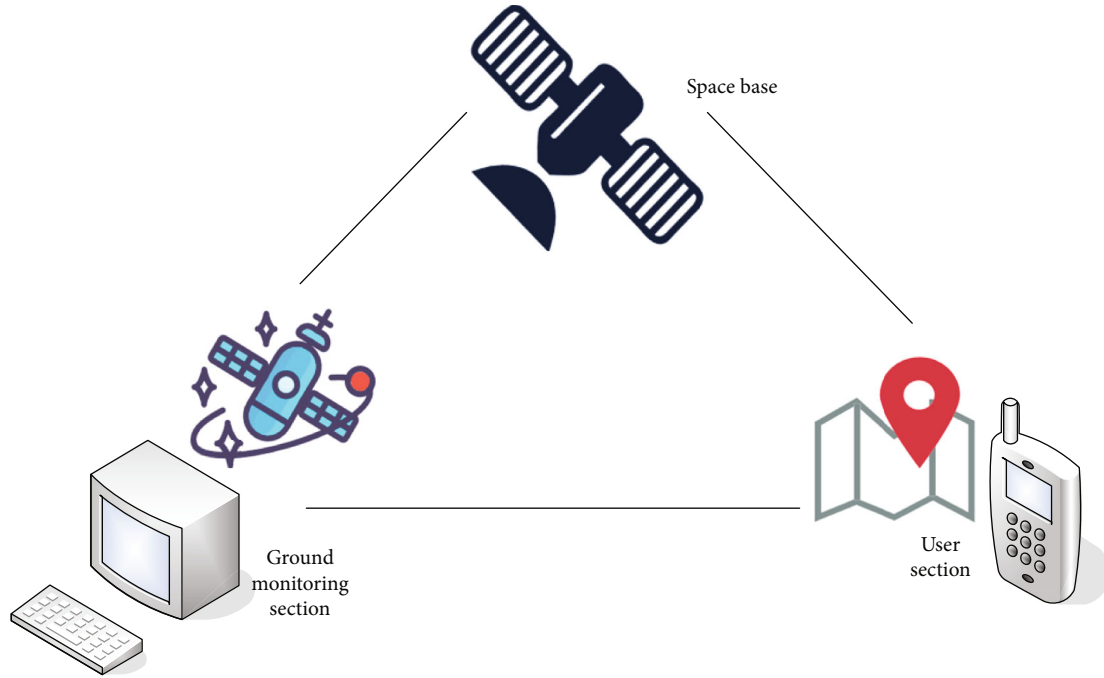
FIGURE 1: Satellite navigation system.

X-Y plane can only be obtained by integrating the angular velocity output by the gyroscope. The MEMS three-axis gyroscope first measures a voltage signal proportional to the angular velocity. The voltage signal is converted into a discrete signal after analog-to-digital conversion and input to the microcontroller, and the signal at this time is the instantaneous angular velocity data. Then, the X-axis, Y-axis, and Z-axis ADC module values of the three-axis gyroscope of the carrier are read separately. Finally, the time is integrated to obtain the yaw angle, and its calculation formula is as follows [14, 15]:

$$\theta = \theta_0 + \int_t^{t+1} (\text{Gyro} - \theta\text{bias})dt. \qquad (4)$$

Among them, θ_t represents the yaw angle at time t, and Cyro is the angular velocity value output by the gyroscope. θbias is the static drift error constant of the gyroscope [16]. However, when the carrier is moving, the external noise and jitter will make the measurement of the angular velocity value inaccurate, so it needs to be corrected by the static drift error constant of the gyroscope [17].

3.2. The Positioning Principle and Application of Satellite/ Inertial Navigation Integrated Navigation System. The basic principle of satellite inertial navigation integrated navigation (SINS/GNSS) is to establish the system state formula and system measurement formula. It uses Kalman filter technology for fusion and estimates the errors of SINS and GNSS. It can feedback and correct system errors in real time or eliminate them to achieve the purpose of high-precision integrated navigation. When using Kalman filter for SINS/ GNSS integrated navigation, the system state formula and measurement formula need to be established first. According

to the selection of state variables, it can be divided into direct filtering and indirect filtering. The direct method filtering directly takes the navigation parameters of the SINS/GNSS navigation system as the estimation object. For example, the acceleration value and the angular velocity value are directly used as the state variables of the system formula. The indirect method filtering takes the error between each navigation system as the estimation object [18].

In the direct method filtering, the magnitude of the state variable is large, and the change is fast. Information such as velocity, attitude angle, and position is all instantaneous values. In practice, its state formula is often nonlinear. The direct method filtering is shown in Figure 2.

In the indirect method filtering, the error value between SINS and GNSS navigation system is used as the state variable. Compared to the navigation parameters themselves, their magnitudes are much smaller and change relatively slowly. The transfer law of navigation error can be described more accurately by using the linear state formula. Therefore, the estimation accuracy of the state variables is relatively high [19]. Indirect filtering is a commonly used method in engineering applications. The indirect filter diagram is shown in Figure 3.

As can be seen from Figure 3, the indirect method of filtering and correcting navigation parameters can be divided into two types: output correction and feedback correction. The output correction is to directly use the state estimation value to correct the output value of the strapdown solution of the SINS or feed it back into the solution flow of the subsystem, to ensure that the navigation subsystem will no longer generate accumulated errors. If the output correction cannot track the navigation error inside the navigation subsystem and correct it, the filtering is easy to diverge after working for a long time. The feedback calibration can track
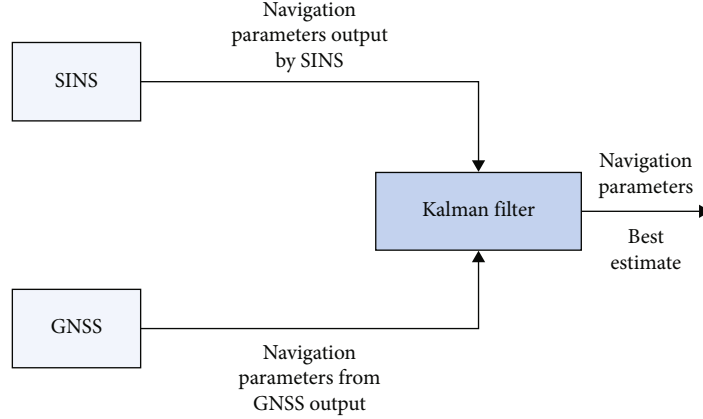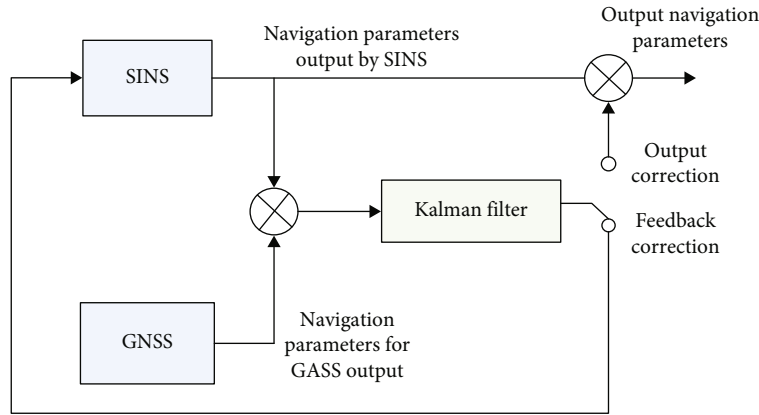
FIGURE 2: Direct method filtering.

FIGURE 3: Indirect method filtering.

and correct the navigation error inside the subsystem, so it can also ensure the stability and convergence of the filtering when working for a long time.

3.3. Improved Kalman Filter Algorithm

3.3.1. Kalman Filter Algorithm. Kalman filter algorithm (UKF) is an algorithm that uses the linear system state formula to optimally estimate the system state through the system input and output observation data. However, the traditional Kalman algorithm still needs to be improved in terms of convergence speed, calculation accuracy, and prediction accuracy. Therefore, the improved Kalman filter algorithm appeared. The improved Kalman filter algorithm is mainly aimed at improving the state noise adaptive Kalman filter algorithm and the observation disturbance adaptive Kalman filter algorithm [20].

3.3.2. Improvement of Kalman Filter Algorithm Adaptive to State Noise. To make the derivation under additive noise easier to understand, the observation formula is assumed to be linear and then the innovation covariance, that is, the sequence of prediction residuals in the UKF algorithm:

$$p_k = \frac{1}{m} \sum_{j=1}^{m} (x_{k1} - x_{k2}). \tag{5}$$

The predicted variance p_k obtained in the above formula is the calculated innovation covariance $\tilde{p}_k$. Considering the importance of variance prediction, the scaled state noise variance should be compared to the changes in state noise variance obtained from p_k and $\tilde{p}_k$. The innovation and prediction formulas are generated:

$$d_k = (H_k x_k + v_k) - H_k \tilde{x}_k. \tag{6}$$

Assuming that the filtering is optimal, the variable whose Gaussian white noise sequence is expected to be 0 is d_k, take the square root of both sides of the equal sign of the above formula, and take the variance:

$$\frac{1}{m} \sum_{j=1}^{m} d_{k-j} = H_k + R_k. \tag{7}$$

Although $\check{p}_k$ cannot be solved by the above formula, it is used as a criterion for estimating the variance of state noise, and a scaling factor β_k is added:

$$\beta_k = \frac{tr\left((1/m)\sum_{j=1}^{m} d_{k-j} - R_k\right)}{tr H_k p_k}. \tag{8}$$

To make the final effect of variance under state noise approximately smooth, it needs to be scaled by the following formula:

$$\tilde{\delta}_k = \delta_{k-1}\sqrt{\beta_k}. \tag{9}$$

3.3.3. Improvement of Kalman Filter Algorithm Adaptive to Observation Interference. Residuals emerge from the filtered values and observed differences as follows:

$$e(k) = y_k - \tilde{y}_k. \tag{10}$$

In the above formula, when the observation value y_k and the filter value $\tilde{y}_k$ are filtered without deviation, the variance $e(k)$ needs to satisfy the following formula to perform the mean square root:

$$\frac{1}{\mu}\sum_{k-\mu+1}^{k} e(j) = P_k + p_{yk}. \tag{11}$$

In the above formula, μ represents the size of the rolling window, P_{yk} represents the estimated variance of the observation, and R_k represents the variance matrix of the observation noise. When the observation disturbance occurs in the estimation system, the actual error will be higher than the theoretical value, and the equal conditions on the left and right sides of the equal sign in the above formula will also not exist. Therefore, the addition of adaptive $S(k)$ is necessary. The definition of the adaptive matrix $S(k)$ is as follows:

$$s(k) = \frac{1}{\mu}\sum_{k-\mu+1}^{k} e(j) - R_k. \tag{12}$$

Therefore, the definition of the adaptive matrix $S(k)$ is as follows:

$$s(k) = \frac{1}{\mu}e(j) - p_k. \tag{13}$$

The existence of abnormal values can be observed by detecting $S(k)$, and the adaptive matrix generated by each round of filtering is judged by self-adaptation, namely:

$$s^2 = \frac{1}{n-1}\sum_{i=1}^{k} z. \tag{14}$$

From the distribution properties of s^2, it can get:

$$s^2(n-1) = \frac{n-1}{\delta^2}. \tag{15}$$

Then, the final state estimate can be revised as follows:
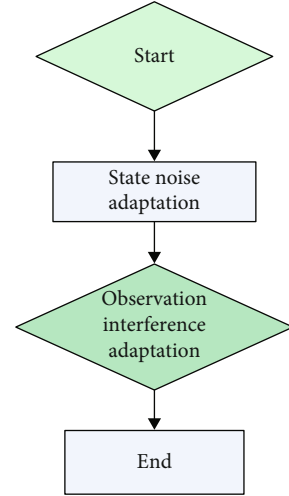
$$x(k+1) = g(k)e(k)\check{x}^2. \tag{16}$$

FIGURE 4: The overall process of the improved Kalman filter algorithm.

The overall process of the improved Kalman filter algorithm is shown in Figure 4.

As can be seen from Figure 4, the entire process of improving the Kalman filter algorithm is not complicated. The experimental section below will also apply to this algorithm.

4. Satellite/Inertial Navigation Integrated Navigation Experiment

4.1. Experimental Design and Main Steps. In this experiment, a satellite inertial navigation combined system is first designed, and then, the system is used to conduct a positioning and navigation experiment in a certain area of Nanchang. After the preliminary positioning and navigation experiment on the selected area based on the system are completed, the positioning and navigation accuracy of the system for the selected area is tested by combining the filtering and noise reduction function of the improved Kalman filter algorithm. The positioning and navigation accuracy of the system on the selected area is tested by combining with the improved Kalman filter algorithm. In the whole experiment, the positioning and navigation effect of the satellite inertial navigation integrated navigation system is judged mainly by the error calculation of the navigation position and speed. The satellite inertial navigation integrated navigation system designed in this experiment is shown in Figure 5.

It can be seen from Figure 5 that the satellite inertial navigation integrated navigation system designed in this experiment is mainly divided into hardware platform and software part. The hardware platform includes a core processor module (Tiny6410), an inertial measurement unit (BWT901CL nine-axis gyro attitude sensor), a satellite receiver (UM22-11I), a wireless communication module (ESP8266), and auxiliary equipment such as a power supply module and compiler. The software part mainly runs on the core processor Tiny6410, which realizes the functions of data acquisition and calculation, data preprocessing, evolution strategy selection, data transmission and debugging,
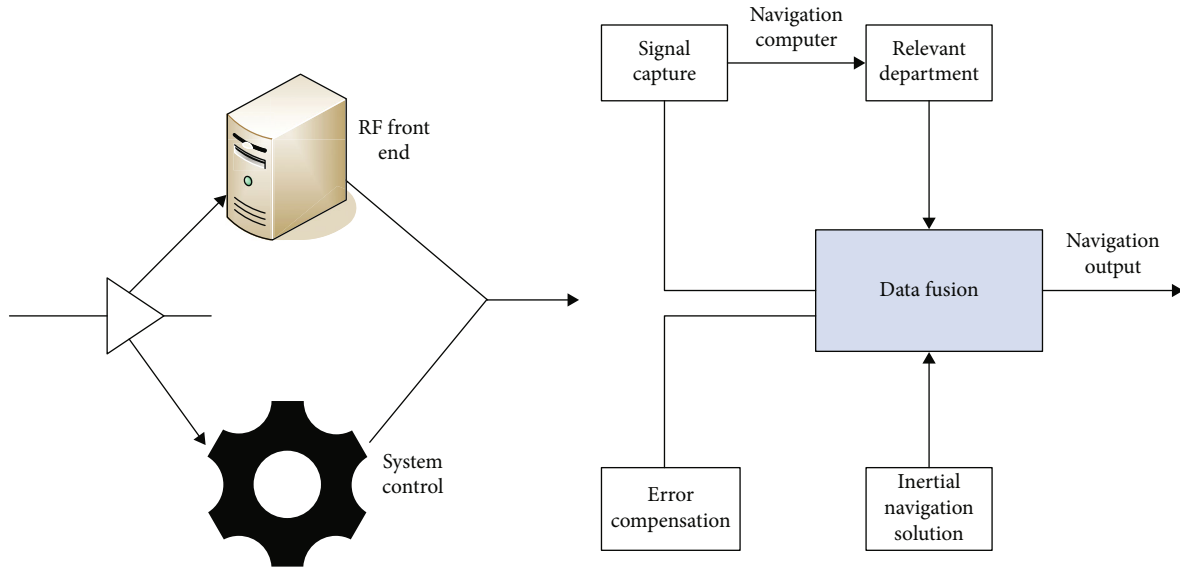
FIGURE 5: Satellite inertial navigation integrated navigation system.

TABLE 1: System performance parameters.

Parameter	Technical indicators	
Attitude	Output range, dynamic accuracy, resolution	$0 \sim 360$
GPS	Positioning accuracy, startup time	Position: 10 m circular error, speed: 0.1 m/s, time: 1 μs
Measuring range	Accelerometer	Gyroscope, magnetometer

TABLE 2: Experimental area positioning information.

Position	Longitude	Latitude
East	115°27′E	114°27′N
South	116°27′E	111°27′N
West	116°21′E	113°27′N
North	115°26′E	115°27′N

and user terminal display. At the same time, by improving the evolutionary game algorithm to build a combined navigation model, it can choose different combination strategies and different weights according to the specific environment to improve the quality of the navigation data and speed up the data convergence speed, which can achieve the best performance.

The performance parameters of the system are shown in Table 1.

4.2. Preliminary System Positioning and Navigation. First, the positioning data of the selected area based on the satellite inertial navigation integrated navigation system designed in this experiment are shown in Table 2.

After the positioning of the selected area is completed, the landmark buildings located in the four directions of the east, south, west, and north in the area are randomly selected; the designed satellite inertial navigation integrated navigation system is used to start the navigation experiment on these landmark buildings. After the navigation of the sys-

tem is completed, the navigation results of these landmark buildings by the system are compared with the actual situation, and the navigation errors of the system's position and speed for the selected area within 30 s are calculated, to judge the navigation accuracy of the system.

The position and velocity navigation error results of the system for the east, south, west, and north positions of the selected area within 30 s are shown in Figures 6 and 7.

It can be seen from Figures 6 and 7 that the system controls the position and velocity navigation errors of the selected area as well as a whole. The navigation error values of both position and speed are controlled within 0-5 m. And the maximum error value for position and speed navigation is only 2.2 m. The maximum navigation error value in the four directions of east, south, west, and north is 2.7. Therefore, after comprehensive calculation, it can be obtained that the comprehensive navigation error value of the satellite inertial navigation integrated navigation system designed in this experiment for the selected area is 2.4 m.

4.3. Navigation Accuracy Test Based on Improved Kalman Filter Algorithm. The last step of the experiment is to test the positioning and navigation accuracy of the satellite inertial navigation integrated navigation system designed in this experiment for the selected area combined with the improved Kalman filter algorithm. The principle of this step is to use the filtering and noise reduction function of the improved Kalman filter algorithm to reduce the navigation
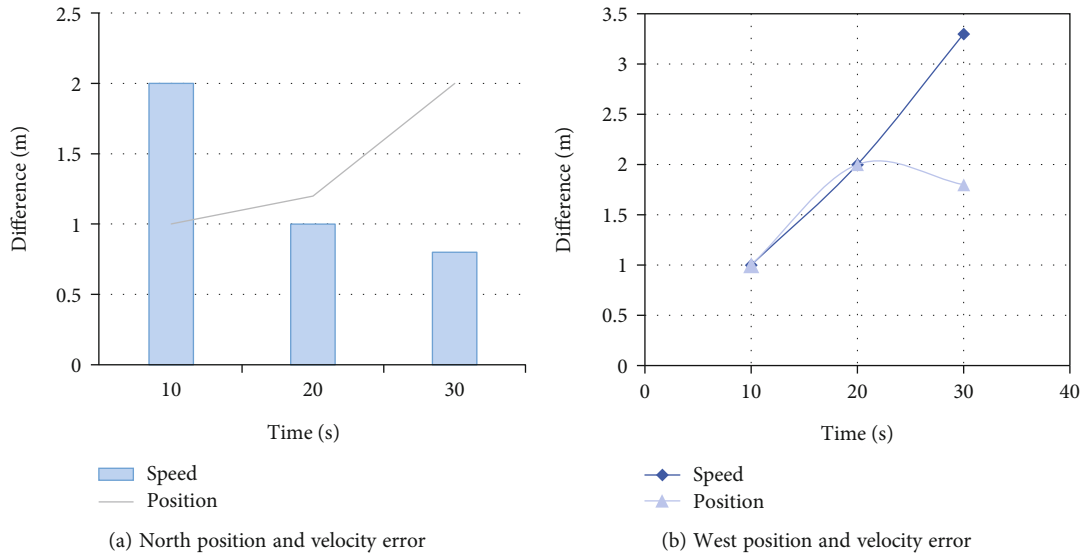
(a) North position and velocity error

(b) West position and velocity error

FIGURE 6: Velocity and position errors within 30 s of navigation for east and west systems.

(a) South position and velocity error
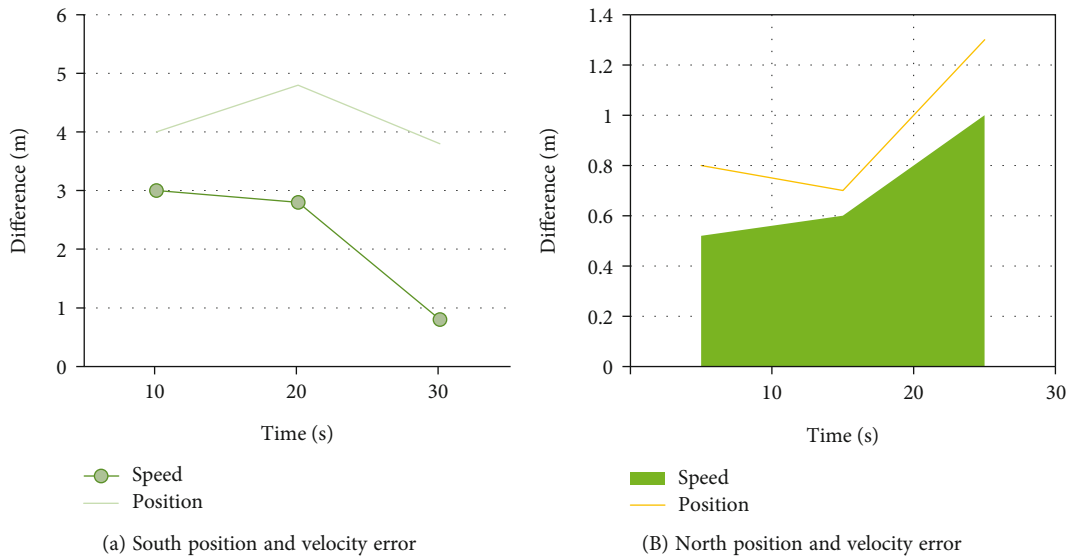

(B) North position and velocity error

FIGURE 7: Velocity and position errors within 30 s of south and north system navigation.

error of the system, thereby improving the navigation accuracy of the system. The test results are shown in Figure 8.

It can be seen from Figure 8 that after the improved Kalman algorithm filtering and noise reduction, the position error value of the system's overall navigation has decreased by 1 m, and the speed error value has also decreased by 1 m. From this calculation, it can be seen that after the improved Kalman filter algorithm filtering and noise reduction, the overall navigation accuracy of the system is improved by 2 m.

At this point, the whole experiment is over. The experimental conclusions drawn can be summarized as follows: Based on the filtering and noise reduction function of the improved Kalman filter algorithm, the overall navigation accuracy of the satellite inertial navigation system is improved by 2 m.

5. Discussion

With the growing demand for navigation services in various industries, many navigation systems with different functions and advantages and disadvantages have emerged in the market, such as satellite navigation systems and inertial navigation systems. However, no matter which single navigation system is used, there are certain navigational limitations. This is because individual navigation systems are always flawed in some way. If the complementary roles between different navigation methods can be brought into play, the formed integrated navigation system can be applied; it is possible to improve the problems of navigation with a single navigation system to a certain extent.

This paper mainly studies the satellite inertial navigation integrated navigation system composed of satellite navigation

(a) The overall error before filtering and noise reduction

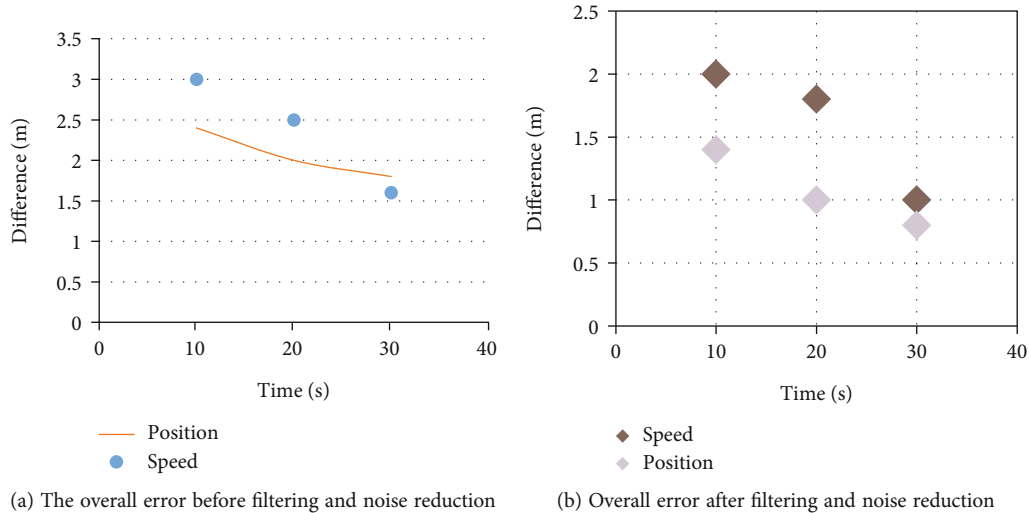(b) Overall error after filtering and noise reduction

FIGURE 8: Improved Kalman filtering algorithm navigation error noise reduction results.

system and inertial navigation system. Satellite navigation system is a navigation system composed of three parts: space base, ground monitoring, and user terminal. However, it falls a little short on the navigation speed. The inertial navigation system is a navigation system that works according to the principle of inertia. However, it has certain flaws in navigation accuracy. Therefore, combining the satellite navigation system and the inertial navigation system to form a satellite inertial navigation integrated navigation system can improve the problems existing in the single satellite navigation system and the inertial navigation system and improve the overall navigation accuracy.

In addition, this paper also combined the improved Kalman filter algorithm to carry out the navigation experiment of the satellite inertial navigation integrated navigation system. A satellite navigation integrated navigation system is experimentally designed, and the improved Kalman filter algorithm is mainly used to filter and reduce the navigation error of the designed satellite inertial navigation system. Finally, it is found that the overall navigation accuracy of the satellite inertial navigation integrated navigation system is improved by 2 m by combining the filtering and noise reduction function of the improved Kalman filter algorithm. This experimental conclusion can be said to be of great significance for improving the navigation accuracy of the satellite inertial navigation system.

6. Conclusions

To sum up, the research conclusions of this paper on the satellite inertial navigation integrated navigation method based on the improved Kalman filter algorithm are as follows: Based on the improved Kalman filter algorithm, the overall navigation accuracy of the satellite inertial navigation system is improved by 2 m. And the accuracy of navigation position and speed has been improved. The research conclusions drawn in this paper undoubtedly have a certain reference values for the application of the improved Kalman filter algorithm in improving the navigation accuracy of the satel-

lite inertial navigation integrated navigation system. It is also of great significance to promote the progress and development of satellite inertial navigation integrated navigation methods. However, it cannot be said that the research in this paper is perfect. In fact, due to the limited research level and conditions, the research in this paper also has certain deficiencies in some aspects. For example, the research methods and research angles are not comprehensive and innovative enough. It is hoped that continuous efforts will be made in the future to improve the existing problems in the research, to make more contributions to the research of satellite inertial navigation integrated navigation methods. It also contributed some modest efforts to promote the update and development of the satellite inertial navigation integrated navigation system.

Data Availability

Data sharing not applicable to this article as no datasets were generated or analyzed during the current study.

Conflicts of Interest

The author declares that there are no conflicts of interest.

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