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An AUV Integrated Navigation Method Based on Multi-sensor Data Fusion

Jie Shen[1, 2], Zhen Zhang [1], Hongyang Bai [3], Shengchun Liu [4], Hui Gu[1] and Huibin Wang[1,*]

[1]College of Computer and Information Engineering, Hohai University, Nanjing, China
[2]PLA University of Science and Technology, Nanjing, China
[3]School of energy and power engineering, Nanjing University of Science and Technology, Nanjing, China
[4]School of physical science and technology, Heilongjiang University, Haerbin, China

Abstract

Autonomous Navigation Vehicle (AUV) navigates to the specified longitude and latitude on water surface by means of Global Positioning System (GPS), Inertial Navigation System (INS) and Electronic Compass (EC), then dives to the specified depth according to the measurements of Depth Gauge (DG). To overcome the low location accuracy of existing navigation technologies in AUV, an integrated navigation method based on multi-sensor data fusion of GPS/INS/EC/DG has been proposed. Since the systematic stability and high precision in short-term measurement of INS, it takes the INS as common reference system. The problem which measurement error accumulates with time is solved by the combination of four sub-filters and a main filter. The sub-filters output the measured velocity, position, orientation and depth error to the main filter, which fuse the data to obtain the global optimal estimation and feedback to the INS system. Realistic environment parameters are simulated in MATLAB to verify the rationality of the navigation algorithm. The feasibility of method is proved by the comparison of position errors with and without combined navigation.

Keywords: *AUV; autonomous navigation; integrated navigation; Kalman filtering; error correction*

1. Introduction

Autonomous Navigation vehicles (AUV) undertake important tasks such as autonomously navigate to the specified area and detect water quality parameters. Where, autonomous navigation of AUV is one of the difficulties in system design. Generally, the starting point and end point of AUV navigation are set as a same point to make sure the routes of AUV to be a closed curve [1]. Since GPS signal is suitable for accurate propagation in the air, the navigation of AUV is mainly constitute by the navigation on water surface. When AUV navigates to a specified latitude and longitude, it will dive into the water depth according to the command of depth meter. After the task at certain depth is complete, it will emerge from the water and navigate to the next point. Obviously, the selection of navigation device is the primary factor to be considered. Navigation devices have been increasingly used for civil, military and scientific purpose for its high speed and accurate positioning. The deeper exploration of navigation technology is still a very important research topic in the field of modern technology [2, 3].

The common navigation devices include Global Positioning System (GPS), Inertial Navigation System (INS), electronic compass and depth gauge, etc. GPS has advantages of short measuring time, all-weather global positioning and long-term high-precision [4, 5].

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[*] Corresponding Author

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However GPS outputs data in a lower frequency [6], needs good electromagnetic environment [7, 8] and mainly managed by the U.S. government, the military code of which is not open and the civil code is less accuracy [9]. INS is a subsequently developed navigation device that does not rely on external information. It provides full range of navigation parameter information, fast data updating speed, small short-term errors and high short-term accuracy [10, 11]. However the measurement errors of INS will gradually accumulate over time, a long-time initial calibration is needed before initial use [12]. EC is widely used in navigation systems owe to its small size, light weight and relatively high accuracy. However it is easily influenced by the variation of temperature and earth magnetic field, as well as the deviation of the sensor itself. Depth gauge is a water-proof depth measurement device which operating in the underwater environment.

For the deficiency of single navigation method, various integrated navigation methods have been proposed, including: the integration of GPS and INS; the integration of GPS and EC; the integration of GPS, INS and EC [13]. The above methods generally improve the precision of navigation system and enhance the anti-interference ability of system. However, these methods are designed for navigation applications above water surface that cannot fulfill the requirements of AUV underwater navigation.

To overcome the low location accuracy of existing navigation technologies in AUV, this paper presents an integrated navigation method based on multi-sensor data fusion of GPS/INS/EC/DG. It takes the INS as common reference system and designs a combination of four sub-filters and a main filter to solve the problem of measurement error accumulates with time. The sub-filters output the measured velocity, position, orientation and depth error to the main filter, which fuse the data to obtain the global optimal estimation and feedback to the INS system [14].

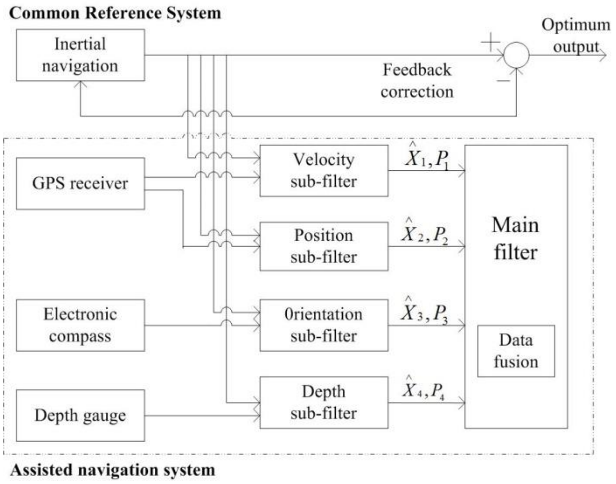

Figure 1. Overall Design Scheme of Proposed Method

2. Overall Design

The overall design scheme of proposed integrated navigation method is shown in Figure 1. Since the systematic stability and high precision in short-term measurement of INS, it takes the INS as common reference system, which can simultaneously acquire the velocity and position information of AUV. Considering the characteristics of INS which measurement error accumulated over time, an assistant navigation system composed of four sub-filters and a main filter is designed to continuously correct measurement error until obtain the best system output [15]. The four sub-filters are velocity sub-filter of INS and GPS; position sub-filter of INS and GPS; orientation sub-filter of INS and EC; depth sub-filter of INS and DG. The sub-filters send the measurements of velocity, position, orientation and depth to the main filter to analyze and calculate error information of velocity, position, orientation, accelerometer and gyroscope etc., then them feedback to the INS. After a period of analysis, the system can ensure the output optimal data of navigation [16]. The flow chart of the navigation algorithm to complete a measurement task is shown in Figure 2.

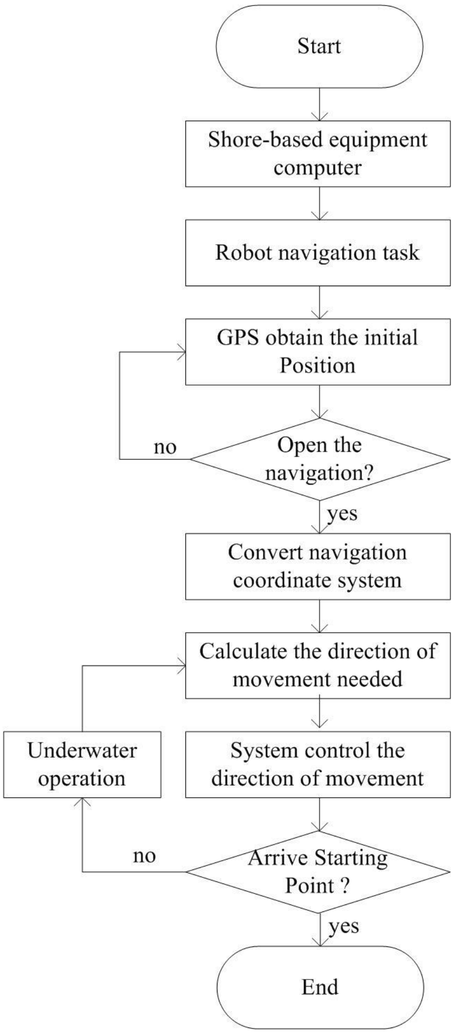

Figure 2. Flow Chart of Navigation Algorithm

3. Integrated Navigation Algorithm

3.1. Coordinate System Conversion

When AUV received the test task that transfer from the computer of shore-based equipment, immediately open the GPS navigation system, since the coordinate system of GPS navigation system and INS is not uniform, so need to convert the WGS-84 coordinates of GPS into geocentric coordinates firstly:

$$\begin{cases} X = (N + H)\cos B \cos L \\ Y = (N + H)\cos B \sin L \\ Z = [N(1 - e^2) + H]\sin B \end{cases} \tag{1}$$

In formula (1), X , Y , Z are the three parameters in the geocentric coordinate system, L , B , H are longitude, latitude and altitude in WGS-84 coordinate system. $N = a / \sqrt{1 - e^2 \sin^2 B}$ is the prime vertical earth radius, $e = \sqrt{a^2 - b^2} / a$ is earth first eccentricity, a is earth long axis length, b is earth short axle length. Then let geocentric coordinate system converted into geographic coordinate system. Geographic coordinate system is also called the northeast sky coordinates, which is also used by INS coordinates [17], the conversion relationship is as follows

$$\begin{pmatrix} X_n \\ Y_n \\ Z_n \end{pmatrix} = \begin{bmatrix} -\sin L & \cos L & 0 \\ -\sin B \cos L & -\sin B \sin L & \cos B \\ \cos B \cos L & \cos B \sin L & \sin B \end{bmatrix} \begin{pmatrix} X \\ Y \\ Z \end{pmatrix} \tag{2}$$

3.2. Position Sub-filters of INS and GPS

When the coordinate system unified, integrated navigation start to control the motor navigates to the specified latitude and longitude and depth. INS serve as a common reference system, Set the vectors: $\delta\phi_e$, $\delta\phi_n$, $\delta\phi_u$ are misalignment angles of northeast sky in three directions; δV_e , δV_n , δV_u are velocity errors, δL , $\delta\lambda$, δh are position errors: ε_{bx} , ε_{by} , ε_{bz} are gyro drift values in three directions, three values are constant; ε_{rx} , ε_{ry} , ε_{rz} are the first-order Markov process of gyro error; ∇_x , ∇_y , ∇_z are drift values of accelerometer in three directions, be treated as constants. State equation of INS the formula (3):

$$\hat{X}_I(t) = F_I(t) X_I(t) + G_I(t) W_I(t) \tag{3}$$

Wherein, $F_I(t)$ is the state transition matrix, $G_I(t)$ is the noise-driven matrix, $W_I(t)$ is the system noise.

For the position sub-filter composed of INS and GPS, the position information of both as the filter input, the difference between as the filter output. The position information of INS and GPS are formula (4), the formula (5): φ_1 , λ_1 , h_1 are INS; φ (Longitude), λ (Latitude), h (Height) are actual values. $\delta\varphi_1$, $\delta\lambda_1$, δh_1 are the errors between the actual values and the calculated value. Similarly, φ_g , λ_g , h_g of GPS are obtained by the same mathematical method.

$$\begin{cases} \varphi_1 = \varphi + \delta\varphi_1 \\ \lambda_1 = \lambda + \delta\lambda_1 \\ h_1 = h + \delta h_1 \end{cases} \tag{4}$$

$$\begin{cases} \varphi_g = \varphi - \dfrac{N_n}{R} \\ \lambda_g = \lambda - \dfrac{N_e}{R\cos\varphi} \\ h_g = h + N_h \end{cases} \tag{5}$$

Assume the sub-filter measurement equation is:

$$Z_1 = H_1 X_1 + V_1 = \begin{bmatrix} \varphi_1 - \varphi_g \\ \lambda_1 - \lambda_g \\ h_1 - h_g \end{bmatrix} = \begin{bmatrix} \delta\varphi_1 + \dfrac{N_n}{R} \\ \delta\lambda_1 + \dfrac{N_e}{R\cos\varphi} \\ \delta h_1 - N_h \end{bmatrix} \tag{6}$$

Accordingly, $H_1 = [0_{3\times5} \quad diag(R_N \cos(\varphi) \quad R_M \quad 1) \quad 0_{3\times10}]$, $V_1(t) = [N_e \quad N_n \quad N_u]^T$ is stationary random white noise.

3.3. Velocity Sub-filter of INS and GPS

Similar to the method of position sub-filter of INS and GPS. Output velocity of INS and GPS are respectively formula (7) and (8):

$$\begin{cases} V_{Ie} = V_e + \delta V_{Ie} \\ V_{In} = V_n + \delta V_{In} \\ V_{Iu} = V_u + \delta V_{Iu} \end{cases} \tag{7}$$

$$\begin{cases} V_{ge} = V_e + M_e \\ V_{gn} = V_n + M_n \\ V_{gu} = V_u + M_u \end{cases} \tag{8}$$

In formula (7), V_e , V_n , V_u are actual three-dimensional velocity of INS, V_{Ie} , V_{In} , V_{Iu} are velocity that INS measured, δV_{Ie} , δV_{In} , δV_{Iu} are velocity errors of INS, V_{ge} , V_{gn} , V_{gu} are velocity that GPS measured, M_e , M_n , M_u are velocity errors of GPS measured [18].

Assume the sub-filter measurement equation is:

$$Z_2(t) = H_2(t)X_2(t) + V_2(t) = \begin{bmatrix} V_{Ie} - V_{ge} \\ V_{In} - V_{gn} \\ V_{Iu} - V_{gu} \end{bmatrix} = \begin{bmatrix} \delta V_e - M_e \\ \delta V_n - M_n \\ \delta V_u - M_u \end{bmatrix} \tag{9}$$

In formula (9), $H_2 = [0_{3\times3} \quad I_{3\times3} \quad 0_{3\times4}]$; $V_2(t) = [M_e \quad M_n \quad M_u]^T$ is GPS stationary random white noise.

3.4. Orientation Sub-filter of INS and EC

INS and EC output orientation angle information respectively, and as input of the filter, the difference of both as the filter outputs [19]. INS and electronic compass orientation information output respectively of formula (10) and (11)

$$\begin{cases} \phi_{Ie} = \phi_e + \delta\phi_{Ie} \\ \phi_{In} = \phi_n + \delta\phi_{In} \\ \phi_{Iu} = \phi_u + \delta\phi_{Iu} \end{cases} \tag{10}$$

$$\begin{cases} \phi_{ee} = \phi_e + P_e \\ \phi_{en} = \phi_n + P_n \\ \phi_{eu} = \phi_u + P_u \end{cases} \tag{11}$$

In formula, ϕ_{Ie} , ϕ_{In} , ϕ_{Iu} are the three-dimensional information of orientation angle that INS estimated, ϕ_e , ϕ_n , ϕ_u are actual three-dimensional orientation angle information of INS, $\delta\phi_{Ie}$, $\delta\phi_{In}$, $\delta\phi_{Iu}$ are three-dimensional orientation error information, ϕ_{ee} , ϕ_{en} , ϕ_{eu} are three-dimensional orientation information of electronic compass, P_e , P_n , P_u are the three-dimensional orientation error information of electronic compass.

Assume the sub-filter measurement equation is:

$$Z_3(t) = H_3(t)X_3(t) + V_3(t) = \begin{bmatrix} \phi_{Ie} - \phi_{ee} \\ \phi_{In} - \phi_{en} \\ \phi_{Iu} - \phi_{eu} \end{bmatrix} = \begin{bmatrix} \delta\phi_{Ie} - P_e \\ \delta\phi_{In} - P_n \\ \delta\phi_{Iu} - P_u \end{bmatrix} \tag{12}$$

By the formula (12), calculate that $H_3 = [0_{3\times3} \quad I_{3\times3} \quad 0_{3\times4}]$, $V_3(t) = [P_e \quad P_n \quad P_u]^T$ is the electronic compass stationary random noise.

3.5. Depth Sub-filter of INS and DG

As the 3 seed filter principle mentioned above, the measurement values of INS and depth gauge as the filter input, the difference between them as the filter output, the sub-filter measurement equation is:

$$Z_4(t) = H_4(t)X_4(t) + V_4(t) \tag{13}$$

In formula, $H_4 = [0_{1\times 2} \quad I_{1\times 1} \quad 0_{1\times 15} \quad -I_{1\times 1}]$, $V_4(t)$ is stationary random white noise.

3.6. Data Fusion Algorithm of the Main Filter

The main function of the main filter is a fusion of the four sub-level filter output information of velocity, position, orientation, depth. Because between the various sub-filters are independent of each other, even if a sub - filter fails, the filter does not affect others data fusing, that means the algorithm that is relatively strong fault tolerance. The main filter integrate all the information of sub-filters in front and make error feedback to the input of INS, correct measured values constantly until the optimum output [20]. The data fusion algorithm of main filter for formula (14): P_f^{-1} is the inverse of overall error estimate ance matrix; P_1^{-1}, P_2^{-1}, P_3^{-1}, P_4^{-1} is the inverse of various sub-filter error estimation matrix equation, $\hat{X}_f$ is the state estimation value of the filter, $\hat{X}_1$ is the location state estimation value of the sub-filter, $\hat{X}_2$ is the velocity state estimation value of the sub-filter, $\hat{X}_3$ is the orientation angle state estimation value, $\hat{X}_4$ is the depth state estimation value.

$$\begin{cases} P_f^{-1} = P_1^{-1} + P_2^{-1} + P_3^{-1} + P_4^{-1} \\ \hat{X}_f = P_f(P_1^{-1}\hat{X}_1 + P_2^{-1}\hat{X}_2 + P_3^{-1}\hat{X}_3 + P_4^{-1}\hat{X}_4) \end{cases} \tag{14}$$

When knows the initial values of sub-filter and main filter, respectively update time and update measurement for each sub-filter. After the update is completed, fuse data using formula (14), then get global optimal estimate. After this round of optimal estimation resulted, go to the next cycle, that is, update time and update measurement again, and then estimate the global optimum [21].

4. Simulation Experiment of Integrated Navigation Algorithm

In order to verify the correctness and validity of navigation algorithm, in this paper, we doing simulation and analysis in MATLAB environment. Assuming AUV at speed of 60km / h sailing in the water environment, the initial position: longitude 118 ° 46 ', latitude 32 ° 03', the height is 600m. Initial speed: 15m / s to east, speed to north and sky is 0 m / s. The initial orientation angle: course angle is 45 °, pitch angle and roll angle are 0 °. Initial position errors of longitude, latitude and altitude are 1m. Initial velocity errors in three directions of north ,east and sky are 0.05 m / s. The initial position and orientation angle error: course angle is 0.1 °, pitch angle and roll angle are 0.25 °.The constant drift mean square deviation of accelerometers in the three directions is 5mg, correlation time is 1800 s. The constant drift mean square deviation of gyro in the three directions is 10 ° / h, correlation time is 3600 s. The mean square deviation of position error of GPS receiver is 25 m. The correlation time of longitude-latitude and high degree is 1200s. The mean square deviation of velocity error of GPS receiver is 0.05 m/s, correlation time is 0s. Correlation time of Electronic compass is 300s, correlation time of depth gauge is1800s. In Simulating the iteration cycle is 1s, simulation time is 900 s (15 minutes), sampling frequency of INS is 1000 Hz. The sampling frequencies of GPS, EC and DG are 10 Hz. The simulation results are as follows:

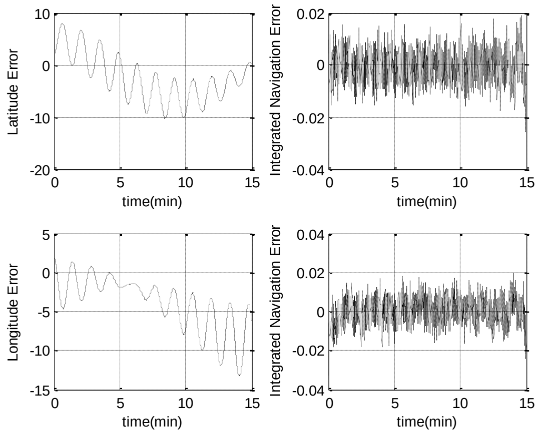

Figure 3. Comparison Chart of Latitude and Longitude Errors before and after Integrated Navigation

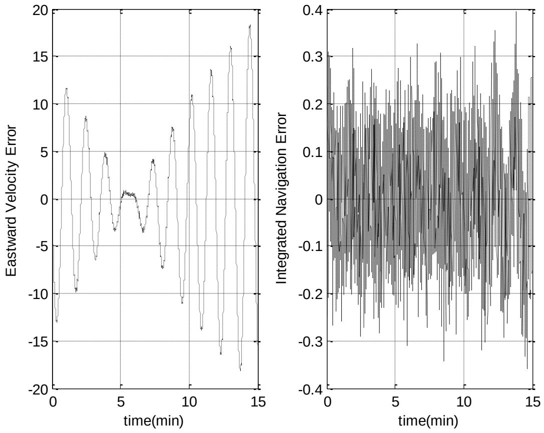

Figure 4. Comparison Chart of Velocity Error in East before and after Integrated Navigation

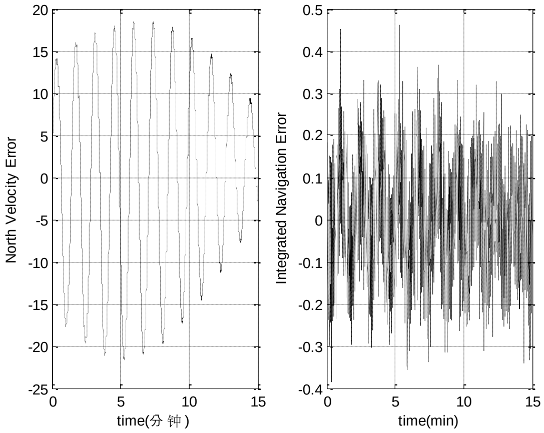

Figure 5. Comparison Chart of Velocity Error in North Before and After Integrated Navigation

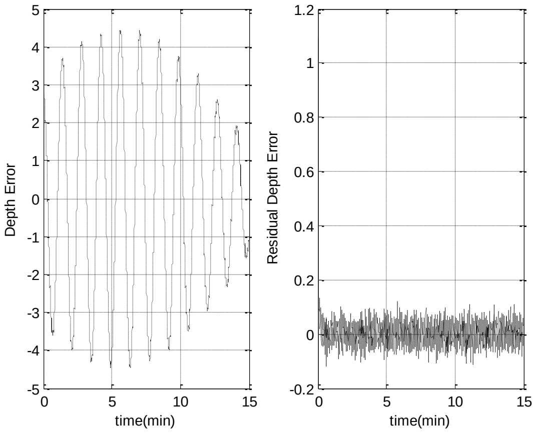

Figure 6. Comparison Chart of Depth Measurement Error before and after Integrated Navigation

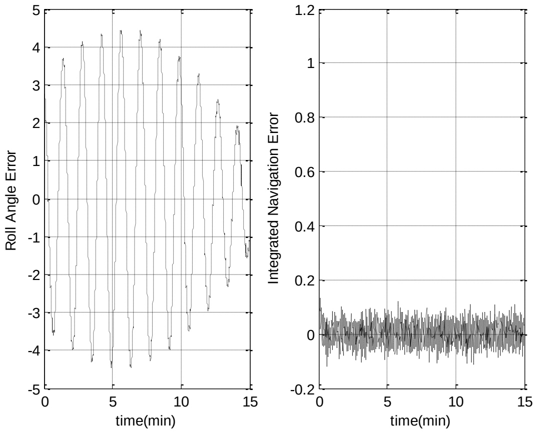

Figure 7. Comparison Chart of Roll Angle Error before and after Integrated Navigation

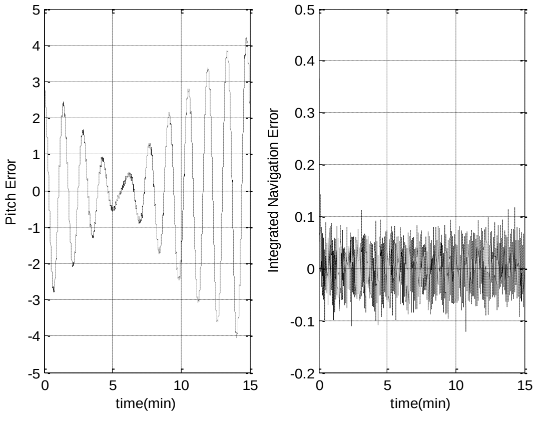

Figure 8. Comparison Chart of Pitch Error before and after Integrated Navigation

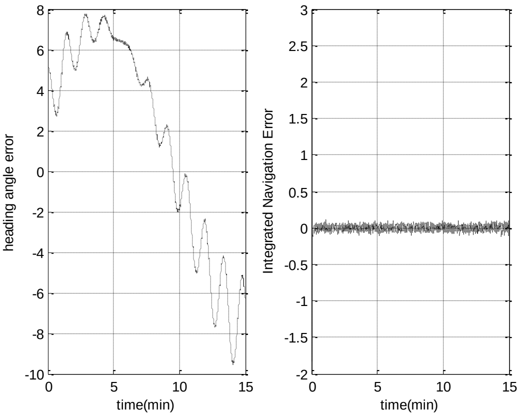

Figure 9. Comparison Chart of Heading Angle Error before and after Integrated Navigation

Figures 3 to 9 show the error correction renderings of integrated navigation algorithm based on federal Kalman filtering. In the figure, on the left side there are all error results that not used the integrated navigation algorithm , on the right side there are error statistical results that used integrated navigation algorithm. Simulation time is 900s, namely 15 min. Figure 3 shows that compressed longitude error estimates from fluctuation of ± 10 ° to fluctuation of ± 0.02 °, compressed fluctuation range of latitude error from 2° ~ -14° to ± 0.02°. Figure 4 and Figure 5 shows that compressed velocity error in east from fluctuation of ±20 m/s to fluctuation of ±0.4 m/s, compressed fluctuation range of velocity error in north from ±20 m/s to ±0.5 m/s. Figure 6 shows compressed the depth error estimation from ±5 m to ±0.2 m, the proportion of error is reduced very much. Figure 7 to Figure 9 shows roll angle, pitch angle and course angle error, after the function of the integrated navigation algorithm, error fluctuation is very limited, only slightly float in zero value up and down. Experiment shows that, both the theory and design of integrated navigation algorithm based on federal Kalman filtering algorithm are correct and feasible, and make a good foundation for future study.

5. Conclusions

This paper presents the overall design of integrated navigation method based on GPS / INS / EC / DG that uses the Kalman filtering method to do error correction analysis. In the MATLAB environment, simulate realistic environmental parameters, simulation rationality navigation algorithm. In the future research, we will continue the study around the following points: First, the system is only preliminary finished design in the level of theory and simulation platform, in practical applications the factors like errors of navigation device itself and interference of environment to be considered. Second, the Federal Kalman filtering algorithm needs to be further improved, the use of non-resettable Kalman filtering algorithm improves the fault tolerance performance and robustness of the system, but the filtering accuracy is affected. Third, a more accurate, comprehensive integrated navigation model should be established, increases the random noise that may exist within the system and other factors , simulate the scene as really as possible, improve accuracy of system navigation. The above work will continue in the future research.

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References

[1] P. Li, S. Qian and H. Cai, “Research on MIMU/GPS integrated Navigation technology”, Journal of System Simulation, **(2009)**.

[2] M. Liu, Z. Y. Zhou and Tao Zhao, “Research on SINS / GNS / DVS underwater integrated navigation based on Federal filters. Fire Control & Command Control”, vol. 12, 34, no. 12, **(2009)**, pp. 41-44.

[3] Y. Ma, B. L. Zhou and G. Zhen, “Data synchronization and fusion method in MIMU / GPS integrated navigation system”, Journal of Chinese Inertial Technology, vol. 12, no. 28-31, **(2004)**, p. 3.

[4] Y. Qin and S. M. Zhang, “Research on optimal four sample rotation vector algorithm for SINS attitude updating”, Journal of Chinese Inertial Technology, vol. 10, no. 2, **(2002)**, pp. 1-7.

[5] L. Z. Xu, X. F. Li and S. X. Yang, “Intelligent Information Processing and System Optimization”, Intelligent Automation and Soft Computing, vol. 17, no. 7, **(2011)**, pp. 829-833.

[6] A. J. Healey, D. P. Horner, S. P. Kragelund, B. Wring and A. Monarrez, “Collaborative Unmanned Systems for Maritime and Port Security Operations”, Proceedings of 7th IFAC Conference on Control Applications in Marine Systems, **(2007)**; Elaphusa, Croatia.

[7] X. Wang, X. J. Yan, G. F. Lv and T. H. Fan, “Balloon-borne spectrum–polarization imaging for river surface velocimetry under extreme conditions”, Infrared Physics & Technology, vol. 58, **(2013)**, pp. 5-11.

[8] N. Michael, J. Fink and V. Kumar, “Controlling a Team of Ground Robots via an Aerial Robot”, Proceedings of IEEE/RSJ International Conference on Intelligent Robots and Systems, **(2007)**; San Diego.

[9] P. B. Sujit, J. Sousa and F. L. Pereira, “UAV and AUVs Coordination [sic] for Ocean Exploration”, Proceedings of Oceans, Europe, **(2009)**; Europe.

[10] H. Ferreira, “SWORDFISH: An Autonomous Surface Vehicle for Network Centric Operations”, Proceedings of Oceans, **(2007)**; Europe.

[11] X. Wang, G. F. Lv and L. Z. Xu, “Infrared dim target detection based on visual attention”, Infrared Physics & Technology, vol. 55, no. 6, **(2012)**, pp. 513-521.

[12] B. Guan, “Research of MIMU / GPS / magnetometer integrated navigation technology”, Hunan: National University of Defense Technology, **(2010)**.

[13] H. Y. Liu, Z. Y. Yu and L. X. Wang, “Missile inertial guidance technology”, Xi'an: Northwestern Polytechnical University Press, **(2010)**.

[14] M. Perrier, L. Brignone and M. Drogou, “Communication Constraints and Requirements for Operating Multiple Unmanned Marine Vehicles”, Proceedings of the Seventeenth International Offshore and Polar Engineering Conference, **(2007)**, pp. 1053-1058.

[15] L. Z. Xu, H. Gu, C. M. Li, A. Y. Shi and J. Shen, “System design of water quality monitoring robot with automatic navigation and self-test capability”, International Journal of Control and Automation, vol. 6, no. 5, **(2013)**, pp. 67-82.

[16] A. Y. Shi, L. Z. Xu and F. Xu, “Multispectral and panchromatic image fusion based on improved bilateral filter”, Journal of Applied Remote Sensing, **(2011)**.

[17] G. B. Hu, L. Z. Xu and M. Jing, “Reliability testing for blind processing results of LFM signals based on NP criterion”, ACTA Electronic sinica, vol. 41, no. 4, **(2013)**, pp. 739-743.

[18] L. Z. Xu, A. Y. Shi and F. C. Huang, “A perceptual and computational mechanism for bionic compound eye systems with multi-source information fusion”, CAAI Transactions on Intelligent Systems, vol. 3, no. 4, **(2008)**, pp. 328-335.

[19] A. G. Rajala, D. B. Edwards and M. O'Rourke, “Collaborative Behavior for Vehicle Replacement in AUV Formations”, Proceedings of the IMECE, ASME International Mechanical Engineering Congress and Exhibition, **(2005)**; Orlando.

[20] M. X. Xu, F. Xu, C. R. Huang and M. Li, “Image restoration using majorization-minimization algorithm based on generalized total variation”, Journal of Image and Graphics, vol. 16, no. 7, **(2011)**, pp. 1317-1325.

[21] L. Z. Xu, X. L. Feng and C. L. Wen, “Sequential fusion filtering of networked multi-sensor system based on noise estimation method”, ACTA Electronic sinica, vol. 42, no. 1, **(2014)**, pp. 160-168.