Information fusion algorithm of GNSS / INS integrated navigation system

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Abstract. Inertial navigation system (INS) has high short-term accuracy, while satellite navigation positioning system (GNSS) has high long-term accuracy. The integrated navigation system integrates two or more different navigation systems with hardware and software, and uses their respective advantages to make up for the shortcomings of a single system. In this paper, a dual-antenna GNSS/MIMU integrated navigation system is designed, and experimental research is performed on different integrated navigation systems. Algorithms of GNSS satellite positioning and dual-antenna attitude measurement, strapdown inertial navigation attitude calculation and update, and integrated navigation filtering are studied. Static and dynamic experiments are performed to study the performance of the system under different GNSS/MIMU combinations. The experimental results show that the combined system has smaller errors in terms of horizontal position, heading angle, pitch angle, and roll angle.

1. Introduction
The US Global Positioning System (GPS), China’s Beidou Satellite Navigation System (BDS), EU’s Galileo Navigation System (GALILEO), and Russia’s GLONASS Navigation System (GLONASS) form the GNSS (Global Navigation Satellite System) [1,2]. Satellite navigation systems have the advantages of high accuracy, all-weather, low cost, and no signal error accumulation. However, there are also poor signal visibility, low data update frequency, and poor anti-interference ability. Its signal strength is seriously affected by the environment. In a multi-occlusion environment, short-term signal interruptions are very likely to occur, which can not meet real-time requirements.

Inertial navigation technology has good autonomy and shielding, and is widely used in military, civil, industrial, indoor, underwater and other fields. Gyroscopes and accelerometers are the main measurement devices for inertial navigation[3]. A gyroscope is a precision device that measures the angular velocity and angular acceleration of a carrier, while an accelerometer measures the acceleration of the carrier in various axial directions through various physical principles. However, due to the problems of large volume and high cost of inertial devices, their application is very limited. Micro-Electro-Mechanical System (MEMS, Micro-Electro-Mechanical System) solves the applicability of inertial devices well. Because MEMS sensors have the disadvantages of low accuracy, large drift, and error accumulation over time, they cannot provide attitude information within the accuracy range for a long time[4,5]. Therefore, MEMS inertial devices need to be used in conjunction with other navigation systems in order to effectively provide accurate and reliable navigation information.

Integrated navigation system integrates two or more different navigation systems through hardware level or software level, and uses their respective advantages to make up for the shortcomings of a single system that is difficult to improve[6,7], so that the accuracy of the integrated navigation system
is greatly improved and meets the requirements. Civil or military navigation performance is now required. The inertial navigation system has good short-term accuracy, and the long-term accuracy of satellite navigation and positioning systems such as GPS and BDS, coupled with the complementary navigation characteristics of the two, has prompted the INS/GNSS integrated navigation system to be widely used in various fields. The combination of different navigation systems has different effects. In this dissertation, the performance of the dual-antenna integrated navigation system composed of GNSS and MIMU is experimentally investigated, and the results of their respective outputs are analyzed to compare the performance differences of different integrated navigation systems. The research of information fusion algorithm has great significance to precise navigation system.

2. GNSS / INS integrated navigation system
The single-mode dual-antenna GPS/MIMU integrated navigation system consists of a GPS satellite board, MIMU, antenna, navigation computer, and rotary turntable. The GPS board is used to receive GPS satellite messages[8]. The contents of the messages include position messages (BESTPOS), speed messages (BESTVEL), and heading messages (HEADING), which provide the system with longitude, latitude, altitude, carrier speed, and heading. And other external auxiliary information[9]. MIMU contains three accelerometers and three micro-gyros to acquire inertial measurement information. The rotating mechanism is used to carry the GPS board, antenna and MIMU to compensate for system errors[10,11]. The navigation computer consists of FPGA and DSP. DSP is used to solve navigation information. FPGA is responsible for interacting with external hardware and DSP. The host PC is used to display and store navigation information.

The GPS board selected for the single-mode dual-antenna GPS/MIMU integrated navigation system is NovAtel's OEM617D GNSS board. The board can work with dual antennas, and can capture GPS, Beidou and other satellite signals[12]. The horizontal positioning accuracy of OEM617D board can reach single point L1 1.5m, single point L1/ L2 1.2m, positioning initialization time is less than 10s, and the update rate of original data and positioning data can reach 20Hz. In addition, OEM617D has the characteristics of small size, light weight, low power consumption and various interfaces, which is very suitable for this system.

Compared with traditional mechanical gyroscopes, fiber optic gyroscopes, and laser gyroscopes, although MIMU does not have such high accuracy, its small size, low power consumption, and low cost are very suitable for experimental research of integrated navigation systems. In addition, through some error compensation techniques, the output accuracy of MIMU can also be greatly improved. The MIMU used in this system is the STIM300 launched by the Norwegian company Sensonor. The STIM300 consists of three accelerometers, three gyroscopes and three inclinometers. The system sampling rate can reach 2000Hz and the power consumption does not exceed 1.5w.

The navigation computer is the central link of the entire integrated navigation system. It not only needs to collect the raw data output by each sensor, such as the angular velocity information and acceleration information output by MIMU, and the navigation messages output by the GNSS receiver. The navigation computer also needs to perform algorithmic processing on this information, including error compensation, attitude solution, and filtering. In addition, the navigation computer is responsible for storing and displaying this navigation information so that the entire system can be monitored in real time. Therefore, the navigation computer of the integrated navigation system needs to have a processor with high-speed computing capability and multiple interfaces. DSP is a microprocessor that processes a large amount of information through digital signals. Its internal structure is a Harvard structure, which allows the use of instruction fetching and executing instructions at the same time. In addition, it has a fast RAM and a hardware multiplier on the chip, which can execute multiple Operation, so with strong data processing capabilities and high-speed operation speed, it is very suitable as the main processor of the integrated navigation system. However, because the DSP does not have rich hardware interfaces and high-throughput data transmission interfaces, it also needs to be matched with FPGAs. Using the FPGA's good external scalability and data buffering functions, the navigation computer can effectively handle navigation algorithms and data transmission.
The dual-antenna GNSS/MIMU integrated navigation system requires three channels of data collection, which are the satellite navigation message data output by the GNSS board, the inertial parameter data output by the MIMU, and the angle data of the rotating mechanism. The GNSS board, the MIMU and the rotating mechanism are connected to the FPGA through a serial port to input three channels of data. The FPGA is also connected to the DSP and the MCU. It is used to transfer three channels of data into the DSP for combined navigation and solution, and to transfer the original data to the MCU. It is stored on the SD card through the MCU’s SDIO interface, so that subsequent adjustments can be made. Offline processing and storage of navigation data.

The GNSS board is connected to the dual antenna through the built-in SMA interface to receive satellite navigation data. The interactive form of the board data is based on the command and message mode, that is, the user can configure the board parameters through software commands, and the board sends the received data to the user in a response manner. The satellite navigation data is transmitted through the TTL protocol serial port. Its baud rate is 230400 and the data update rate is 5Hz. It records ephemeris, user coordinates, visible satellite information, RANGE of the primary and secondary antennas, and a data volume of 15KB per second.

3. Integrated navigation algorithm

The system uses the Kalman filter of the indirect filtering method, that is, the output error amount of each subsystem is used as the state vector of the filter. The dual-antenna GNSS/MIMU integrated navigation system uses a 16-dimensional Kalman filter. The state vector of the system is:

\[
X = [\varphi_E, \varphi_N, \varphi_U, \delta V_E, \delta V_N, \delta V_U, \delta L, \delta \lambda, \delta h, \delta \xi_x, \delta \xi_y, \delta \xi_z, \delta \epsilon_x, \delta \epsilon_y, \delta \epsilon_z, \delta D_{cp}]^T
\]  

(1)

Among them, \(\varphi_E\), \(\varphi_N\), \(\varphi_U\) are the error angles of strapdown inertial navigation platform, \(\delta V_E\), \(\delta V_N\), \(\delta V_U\) are the east, north, and altitude errors, \(\delta \xi_x\), \(\delta \xi_y\), \(\delta \xi_z\) and \(\delta \epsilon_x\), \(\delta \epsilon_y\), \(\delta \epsilon_z\) are the offset errors of the three-axis gyroscope and the offset errors of the three-axis accelerometer in MIMU, and \(\delta D_{cp}\) is the information error of the four satellites captured. Carrier phase information.

The state equation of the system is:

\[
\dot{X}(t) = F(t)X(t) + G(t)W(t)
\]  

(2)

Among them, \(X(t)\) is the state vector of the system, \(W(t)\) is the noise matrix of the system, \(F(t)\) is the state transition matrix of the system, and \(G(t)\) is the noise transition matrix of the system. The system noise matrix \(W(t)\) is composed of the white noise of the gyroscopes and accelerometers, and is specifically expressed as:

\[
W = [\omega_{gx} \omega_{gy} \omega_{gz} \omega_{ax} \omega_{ay} \omega_{az}]^T
\]  

(3)

The measurement equation of the integrated navigation system is:

\[
Z(t) = H(t)X(t) + V(t)
\]

\[
\begin{bmatrix}
Z_V(t)

\end{bmatrix} = \begin{bmatrix}
H_V(t)

\end{bmatrix} \begin{bmatrix}
X(t)

\end{bmatrix} + \begin{bmatrix}
V_V(t)

\end{bmatrix}
\]  

(4)

The observation vector \(Z(t)\) is composed of three-dimensional vectors, which are a velocity observation vector, a position observation vector, and a four-dimensional satellite observation vector.

Velocity observation vector \(Z_V(t)\):

\[
Z_V(t) = [V_{IE} - V_{GE} \quad V_{IN} - V_{GN} \quad V_{IU} - V_{GU} ]^T = \begin{bmatrix}
\delta V_E + \delta V_{GE} \\
\delta V_N + \delta V_{GN} \\
\delta V_U + \delta V_{GU}
\end{bmatrix} = H_V(t)X(t) + V_V(t)
\]  

(5)

\[
H_V(t) = \begin{bmatrix}
0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 & 0 & 0 & 0 & 0
\end{bmatrix}_{3 \times 19}
\]

\[
V_V(t) = [V_{VE} \quad V_{VN} \quad V_{VV}]^T
\]  

(6)

(7)
In the formula, $V_E$, $V_N$, $V_R$ are the speeds output by the inertial system, $V_{GE}$, $V_{GN}$, $V_{GU}$ are the speeds output by the GNSS system, $\delta V_E$, $\delta V_N$, $\delta V_R$ are the speed errors of the inertial system, and $\delta V_{GE}$, $\delta V_{GN}$, $\delta V_{GU}$ are the speed errors of the GNSS system. $H_p(t)$ and $V_p(t)$ are the speed measurement matrix and the speed measurement noise variance matrix, respectively.

Position observation vector $Z_p(t)$:

$$Z_p(t) = \begin{bmatrix} L_l - L_G \\ \lambda_l - \lambda_G \\ h_l - h_G \end{bmatrix} = \begin{bmatrix} \delta L + \delta P_{GE} \\ \delta \lambda + \delta P_{GN} \\ \delta h + \delta P_{GU} \end{bmatrix} = H_p(t)X(t) + V_p(t)$$  \hspace{1cm} (8)

$$H_p(t) = \begin{bmatrix} 0 & 1 & 0 & 0 & \cdots & 0 \\ 0 & 0 & 1 & 0 & \cdots & 0 \\ 0 & 0 & 0 & 1 & \cdots & 0 \end{bmatrix}_{3 \times 19}$$  \hspace{1cm} (9)

$$V_p(t) = [V_{PE} \ V_{PN} \ V_{PU}]^T$$  \hspace{1cm} (10)

In the formula, $L_l$, $\lambda_l$, $h_l$ are the latitude, longitude and altitude information output by the inertial system, $L_G$, $\lambda_G$, $h_G$ are the latitude and longitude and altitude information output by the GNSS system, and $\delta L$, $\delta \lambda$, $\delta h$ are the latitude, longitude and altitude errors of the inertial system. And $\delta P_{GE}$, $\delta P_{GN}$, $\delta P_{GU}$ are the position errors of the GNSS system in the east, north, and sky directions, and $H_p(t)$ and $V_p(t)$ are the position measurement matrix and the position measurement noise variance matrix, respectively.

Satellite observation vector $Z_s(t)$:

$$Z_s(t) = \begin{bmatrix} S^s_1 - \nabla \Delta \phi^{01} - \delta D^1_{cp} \\ S^s_2 - \nabla \Delta \phi^{02} - \delta D^2_{cp} \\ S^s_3 - \nabla \Delta \phi^{03} - \delta D^3_{cp} \\ S^s_4 - \nabla \Delta \phi^{04} - \delta D^4_{cp} \end{bmatrix} = H_s(t)X(t) + V_s(t)$$  \hspace{1cm} (11)

$$H_s = \begin{bmatrix} H^s_{4 \times 3} : 0_{4 \times 12} : \text{diag}[1 \ 1 \ 1] \end{bmatrix}_{4 \times 19}$$  \hspace{1cm} (12)

$$V_s = [V_{s1} \ V_{s2} \ V_{s3} \ V_{s4}]^T$$  \hspace{1cm} (13)

In the formula, $S^s_i$ ($i = 1, 2, 3, 4$) is the projection of the difference between the unit vector of the host star and the rest of the $i$th satellite on the rotation system $s$. Here, the host star is the satellite with the highest altitude angle. $\nabla \Delta \phi^{0i}$ is the carrier phase double difference between the main star and the $i$th satellite, and $\delta D^i_{cp}$ is the information error of the other four satellites represented by the $i$th satellite. $H_s$ and $V_s$ represent the satellite information measurement matrix and the measurement noise variance matrix, respectively, where $H^s_{4 \times 3}$ is the cross product of the baseline vector in the navigation system and $S^s_i$, and $S^s_i$ represents the main star and the $i$th satellite. The projection of the difference between the unit vectors on the navigation system.

4. Experiment

By separately analyzing the navigation performance of single-mode BDS/MIMU combined system, single-mode GPS/MIMU combined system and dual-mode BDS /GPS/MIMU combined system under static conditions, it can be concluded that each integrated navigation has better performance under static conditions Steady-state accuracy. Compared with the position, speed and attitude output of the satellite navigation system board, the standard deviations of the position error, speed error and attitude angle error of the three combined systems are calculated and compared. Tables 1 and 2 can be obtained. The position error, pitch angle error, roll angle error, and heading angle error of the combined system are all greatly suppressed.

| Table 1. Systematic errors of experiment 1. |
|------------------------------------------|
| Northward position error | Eastward position error | Northward speed error | Eastward speed error |
| 0.12                     | 0.1                    | 0.03                   | 0.04                  |
Table 2. Systematic errors of experiment 2.

| Pitch angle error | Roll angle error | Heading angle error |
|-------------------|------------------|---------------------|
| 0.10              | 0.08             | 0.13                |

5. Conclusion

The performance of different GNSS/INS combined systems is analysed, static and dynamic experiments are carried out to analyze the position, velocity and attitude accuracy of each combined system. In order to explore the advantages and disadvantages of dual-mode integrated navigation and single-mode integrated navigation, the performance of two integrated navigation systems in a complex environment was compared. Aiming at the impact of different baseline lengths on the performance of the dual-antenna integrated navigation system, a comparative test was conducted. The combined system's performance has been greatly improved in terms of horizontal position, heading angle, pitch angle and roll angle.

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