Application of SINS/DGPS integrated navigation technology in unmanned mining vehicles

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Abstract. The continuous development of driverless technology has provided more possibilities for the expansion of unmanned operation. In this paper, the SINS/DGPS integrated navigation system is used in the unmanned mining vehicle, and its combination mode and working mechanism are expounded. The equations and observation equations of the combined navigation filter system are derived. The measurement residual error checking algorithm is designed to eliminate DGPS Gross error. At the end of the paper, the correctness of the combined system is verified on the simulation platform, and the robustness is better.

1. INTRODUCTION
With the gradual maturity of unmanned technology, the application of SINS/DGPS integrated navigation technology to mining vehicles in large open-pit mining areas has become a research hotspot. At present, in the mining of large-scale open pit mines, as the mining depth increases year by year, the phenomenon of large slopes and many curved roads gradually increases, making it increasingly difficult for mine production. As the unmanned operation of the mining area is an effective way to speed up the construction of digital smart mines, it will help to achieve safe production, reduce the cost of labor and vehicle use, and improve operational efficiency. Navigation is a core technology for driverless driving, which plays a vital role in production. Because the mining area is an open environment, satellite information is generally not easily blocked. Therefore, the SINS/DGPS integrated navigation technology is particularly suitable for use in unmanned driving areas of the mine, providing almost all motion information for the driverless decision system[1].

SINS is an autonomous navigation system that does not rely on external information and radiate energy to the outside. Its most prominent advantages include: it is free from external interference, high sampling frequency, and can obtain nearly all motion information such as carrier attitude, speed, angular rate, acceleration and position. The above characteristics make SINS an indispensable navigation method in both military and civilian fields. However, the accumulation of SINS positioning error over time makes it difficult to work independently for a long time, and the requirement for higher positioning accuracy will require high-precision inertial devices, which affects the promotion and application of inertial navigation systems.

The GPS satellite navigation system uses artificial earth satellites for navigation. The use of artificial satellites can not only achieve global or regional high-precision navigation, where navigation errors do not accumulate over time, but also can integrate communication, timing, search and rescue, traffic control, unmanned and other fields. With the rapid development of GPS technology, the demand for fast and high-precision position information in the civilian field is growing, especially the unmanned
technology. Differential GPS technology (DGPS) has emerged due to this demand. The most widely used DGPS technology is RTK (Real-Time Kinematic). The keys to RTK technology are the use of GPS carrier phase observation, and the spatial correlation of the observation error between the reference station and the mobile station. In addition, most of the errors in the observation data of the mobile station are removed by differential means, thereby achieving high precise positioning (in decimeters or even centimeters). However, the disadvantage of GPS technology is that when the carrier encounters terrain obscuration, the GPS navigation information may be interrupted or the error would be large, and the update frequency of the navigation information is relatively low, which is difficult to meet the requirements of real-time control.

The inertial system-based SINS/DGPS integrated navigation system can combine the advantages of the above two navigation systems to achieve complementary advantages and complement each other. The high-precision positioning information of the GPS receiver compensates the cumulative error of the strapdown inertial navigation system by combining the navigation Kalman filter, and improves the accuracy and robustness of the navigation system[2-3].

2. SINS/DGPS COMBINATION MODE and WORKING PRINCIPLE

In the SINS/DGPS combination system, both DGPS and SINS work independently. As shown in Figure 1, when DGPS is working normally, the measurement data would be inputted to the combined navigation Kalman filter through a dedicated interface. The effect of the combination is represented by using DGPS navigation information (position or position + speed) to compare and construct the observations with the navigation information corresponding to the SINS. Then, based on the relationship between the observation and the navigation error of the SINS system, the Kalman filter is used to estimate and correct the navigation error of the SINS, so that the SINS can always maintain a high navigation accuracy. When the DGPS information is not available and the SINS selects a higher precision inertial device, relying on the SINS system to work independently can maintain high navigation accuracy in a short time[4-5].

This combination mode is simple, easy to implement and has a certain margin, so it has been widely used in engineering. When DGPS works well or does not work for a short time, the navigation accuracy of the combined system is high, would not lower than DGPS accuracy generally.

![Fig.1 SINS/DGPS combination system and its working principle](image-url)
3. SINS/DGPS COMBINED NAVIGATION FILTERING ALGORITHM

The SINS/DGPS combined navigation state space model with velocity and position error as observations is as follows (shown in Formula 1):

\[
\begin{align*}
X = F X + G W^b \\
Z = \begin{bmatrix}
    v^\text{INS} - v^\text{GNSS} \\
    P^\text{INS} - P^\text{GNSS}
\end{bmatrix} = H X + V
\end{align*}
\]  

(1)

The system state variables are as follows:

\[
X = \begin{bmatrix}
    \phi \\
    (\delta v)^T \\
    (\delta p)^T \\
    (e^b)^T \\
    (\nabla^b)^T
\end{bmatrix}
\]

Variables interpretation:

- \( \phi \) represents the Misalignment angle of SINS system;
- \( \delta v \) represents the speed error of the SINS system under the navigation system;
- \( \delta p \) represents Position error for the SINS system;
- \( e^b \) represents Gyro constant drift of SINS system;
- \( \nabla^b \) represents SINS system's constant value;
- \( F \), System noise matrix \( G \), Observation matrix \( H \), as follows:

\[
F = \begin{bmatrix}
    -\omega^b_x \times & M_2 & M_{ap} & -C_b^v & 0_{3 \times 3} \\
    f^v & M_v & M_{vp} & C_b^v & 0_{3 \times 3} \\
    0_{3 \times 3} & M_{pp} & 0_{3 \times 3} & 0_{3 \times 3} & 0_{6 \times 3}
\end{bmatrix},
G = \begin{bmatrix}
    -C_b^v & 0_{3 \times 3} \\
    0_{3 \times 3} & C_b^v \\
    0_{6 \times 3}
\end{bmatrix},
W^b = \begin{bmatrix}
    W^v \\
    W^p
\end{bmatrix}
\]

Variables interpretation:

\[
M_1 = \begin{bmatrix}
    0 & 0 & 0 \\
    -\omega^s_\theta \sin L & 0 & 0 \\
    \omega^s_\theta \cos L & 0 & 0
\end{bmatrix},
M_2 = \begin{bmatrix}
    0 & -1/R_{Nh} & 0 \\
    1/R_{Nh} & 0 & 0 \\
    \tan L/R_{Nh} & 0 & 0
\end{bmatrix},
M_3 = \begin{bmatrix}
    0 & 0 & v_e/R_{Nh}^2 \\
    0 & 0 & -v_e/R_{Nh}^2 \\
    v_e \sec^2 L/R_{Nh} & 0 & -v_e \tan L/R_{Nh}^2
\end{bmatrix}
\]

\[
M_{ap} = M_1 + M_3;
\]

\[
M_v = (v^s \times) M_2 - (2\omega^s_\theta + \omega^v \alpha) \times ;
\]

\[
M_{vp} = (v^s \times)(2M_1 + M_3)
\]

\[
W^v \text{ and } W^p \text{ represent Gyro angular velocity measurement white noise and accelerometer specific force measurement white noise respectively. } V^v \text{ and } V^p \text{ represent Satellite receiver speed measurement white noise and position measurement white noise respectively.}
\]

The SINS/DGPS integrated navigation standard Kalman filter is constructed by the above equations, and the measurement is updated when the DGPS signal is valid. When the DGPS signal is invalid, a one-step prediction update is performed, and the system can maintain the accuracy in a short time.

The standard Kalman filter equation is as follows:
State one-step prediction
\[ \hat{X}_{k|k-1} = \Phi_{k|k-1} \hat{X}_{k-1} \]  
State one-step prediction mean square error
\[ P_{k|k-1} = \Phi_{k|k-1} P_{k-1} \Phi_{k|k-1}^T + \Gamma_{k-1} \Omega_{k-1} \Gamma_{k-1}^T \]  
Filter increment
\[ K_k = P_{k|k-1} H_k^T (H_k P_{k|k-1} H_k^T + R_k)^{-1} \]  
State estimation
\[ \hat{X}_k = \hat{X}_{k|k-1} + K_k (Z_k - H_k \hat{X}_{k|k-1}) \]  
State estimation mean square error
\[ P_k = (I - K_k H_k) P_{k|k-1} \]

4. MEASUREMENT RESIDUAL TEST
When the DGPS signal has a large error, it will cause the oscillation of the integrated navigation system. At the same time, the estimation error of SINS navigation error will become larger. The filter may be diverged in the case of serious. In order to solve the problems that may be encountered in the above engineering, the robustness of the integrated navigation system is increased, and the measurement residual check link is added in the system to eliminate the gross error of the DGPS signal. Measurement residuals check shown in formula (10):
\[ r = Z_k - H_k \hat{X}_{k|k-1} \]
\[ A = H_k P_{k|k-1} H_k^T + R_k \]
\[ |r| \leq 3 \sqrt{\text{diag}(A)} \]

Compare the 3 times the figure for the A-line diagonal elements' square roots with the corresponding element of the r-array. If any element does not satisfy \[ |r| \leq 3 \sqrt{\text{diag}(A)} \], it will not be updated.

5. SIMULATION TEST
The trajectory generator is used to generate the vehicle trajectory, the idiom data and the DGPS data, as shown in Table 1-3, and then the combined navigation algorithm is verified by using the data. Adding the wild value to the DGPS data, the robustness of the integrated navigation algorithm is evaluated, and the DGPS data is deleted at some moments to simulate the influence of the DGPS signal on the algorithm in the case of short-term occlusion.

| Device | Gyro precision (°/h) | Accuracy (μg) |
|---------|---------------------|--------------|
| Magnitude | 0.01 | 100 |

| DGPS Accuracy | Horizontal positioning accuracy (cm) | High precision (cm) |
|---------------|-------------------------------------|---------------------|
| Magnitude | 2 | 4 |

| Carrier track | Type | duration (s) |
|----------------|------|--------------|
| First Distance | Starting acceleration section, acceleration 1.5m/s² | 10 |
| Second Distance | Uniform linear motion section | 30 |
| Third Distance | Turn left | 5 |
| Fourth Distance | Uniform linear motion section | 30 |
The actual track information of the vehicle is shown in Figure 2-5:

Insert the wild value (the error of 100 meters is added in each of the three directions of latitude, longitude and altitude) in the DGPS position information at the 40th. In addition, the DGPS position information in the 5 seconds from the 60th to 65th is deleted, and the DGPS signal is temporarily lost. In the above two extreme cases, the accuracy and robustness of the integrated navigation algorithm are evaluated. The specific simulation results are shown in Figure 6-11:
According to the above simulation results, the wild value inserted in the DGPS position information at the 40s is successfully eliminated, and the combined navigation result is not affected. In the 60th-65s, there is no DGPS information for this period, and the integrated navigation still obtains a higher positioning result by pure inertia extrapolation. In addition, the integrated navigation has reached the centimeter-level positioning accuracy, providing a high position reference and speed reference for the unmanned mining vehicle, and has strong environmental adaptability.
6. CONCLUSION
This article discusses the SINS/DGPS integrated navigation system used on unmanned mining vehicles. The combination mode and working principals are expounded, and the equations and observation equations of the combined navigation filter system are derived. Then the measurement residual check algorithm is designed to eliminate the coarse error of DGPS. Finally, the correctness and robustness of the combined system are verified by simulation.

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