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SINS and Dual Odometers Based on Integrated Navigation System

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Abstract—The strapdown inertial navigation system is being broadly applied for land vehicle positioning and navigation because of its complete autonomy. To restrain the positioning error accumulation along with time of SINS more effectively and achieve higher precision of navigation, a method of the dual odometers assisting SINS to obtain more accurate velocity and direction angle information is presented in this paper. Based on the establishment of the error state and observation model of SINS and dual odometers based integrated navigation system, the general and feasible Kalman filtering algorithm is listed correspondingly. The SINS/dual odometers integrated navigation method was validated by a comparison experiment among the single SINS system, SINS/OD integrated navigation system and SINS/dual OD based integrated navigation system, the results of which examines the high performance and indicates the superiority of the proposed method.

Keywords-SINS; Dual Odometers; Integrated Navigation System; Kalman Filter

I. INTRODUCTION

Inertial navigation system calculates the navigation attitude, coordinates and velocity information through rotating angular velocity and linear acceleration, which are output by inertial measurement units (IMU). IMU are mainly gyroscope and accelerometer: the gyroscope measures rotating angular velocity of a vehicle and the accelerometer measures line acceleration of a vehicle in the inertial navigation system. This paper will be involved in vehicle navigation system based on the strapdown inertial navigation system (SINS), which has become widely used for its providing comprehensive and completely autonomy navigation information. The navigation errors of SINS are accumulated over time, however, seriously impact on the navigation precision of the system [1], therefore how to control the errors of SINS is a critical problem of a SINS.

Although the problem of error accumulation can be effectively solved by SINS/GPS integrated navigation system, but in the system, the GPS dynamic response ability may be poor, vulnerable to electronic interference and easily obscured so that the SINS/GPS integrated navigation system can't work normally when failures happen on GPS signal [2][3]. In order to solve the problems above, in purpose of improving the autonomy, the stability and reliability of vehicle navigation, a structure that integrates the odometer (OD), as a complementary sensor, and SINS, fuses the collected data, and obtains a highly precise navigation data is presented. Odometer is used to measure vehicle speed and distance, but it can't be used for vehicle positioning alone, instead decoding location through acquiring attitude and heading information from SINS and cumulative errors are smaller.

At present, the SINS/OD integrated navigation system [4-8]usually adopt single odometer, the velocity information of which corrects the navigation error of SINS, thus the navigation accuracy is more effectively improved. However, for example, systems in [7][8] adopt velocity combination method, decomposing the velocity measurement value of the odometer into the navigation coordinate system, then comparing the velocity calculation value of SINS, namely the OD only provides the velocity measurement information while ignoring the errors of direction angle, this method results positioning errors of SINS/OD integrated navigation system slowly accumulate with vehicle travels miles and positioning accuracy has a tendency to diverge slowly. So in this paper, the dual odometers are used to obtain more accurate velocity and direction angle information, thus errors accumulation of SINS is restrained more effectively. That is to say, utilizing the fusion of dual odometers and SINS and applying Kalman filter technology achieve higher precision of navigation.

II. ERROR MODELS

If the output of the navigation system is adopted as a state, the navigation parameters being directly estimated, there will be a problem that mathematical model describes system dynamic process with nonlinear equations and through the nonlinear Kalman filter, resulting in many difficulties in practical application. On the contrary, if the error in each subsystem can be a state, that is to say error parameters are considered as estimated object, indirect method for integrated navigation filter processing will make filtering equations linear. Consequently, the states of model include errors of navigation parameters of each subsystem: SINS and odometers are regarded the estimation object in the Kalman filtering process. According to the error equations of SINS and odometer,

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continuous model of integrated navigation system should be established, and first of all, the coordinate systems involved are configured as follows: North-East-Universe geographic coordinate system is taken as navigation coordinate system that denoted by n system; When the SINS is installed in a certain position of the vehicle, vehicle body coordinate system and SINS coordinate system can be regarded as consistent and denoted by b system; Assuming that OD coordinate system and b system are parallel, it is denoted by m system. The axis direction of b and m system is defined as: x axis is along the vehicle horizontal axis, pointing to the right side, y axis is along the vehicle vertical axis, pointing to the forward side, z axis is perpendicular to the x and y axis, and x, y and z axis are in a right-handed coordinate system.

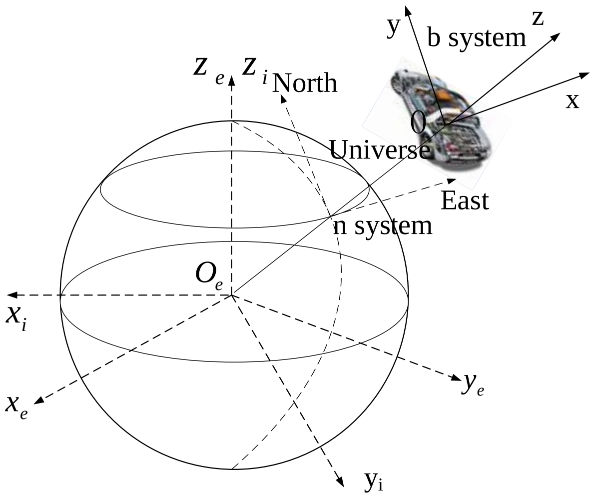

Figure 1. Configuration of n and b coordinate systems

A. Error Model for SINS

Error models for SINS are stated in detail [9][10], and can be summarized as in this paper. The attitude error equation is:

$$\dot{\varphi} = -\left(\omega_{ie}^n + \omega_{en}^n\right)\times\varphi + \left(\delta\omega_{ie}^n + \delta\omega_{en}^n\right) - C_b^n\varepsilon^b \tag{1}$$

The velocity error equation is:

$$\delta\dot{v}^n = f^n \times\varphi - \left(2\omega_{ie}^n + \omega_{en}^n\right)\times\delta v^n - \left(2\delta\omega_{ie}^n + \delta\omega_{en}^n\right)\times v^n + C_b^n\nabla^b \tag{2}$$

The position error equations is:

$$\begin{cases} \delta\dot{L} = \dfrac{\delta v_E^n}{R_M + h} - \dfrac{v_N^n\delta h}{\left(R_M + h\right)^2} \\ \delta\dot{\lambda} = \dfrac{\left(\delta v_N^n secL + v_E^n secLtanL\right)}{R_N + h} - \dfrac{v_E^n secL\delta h}{\left(R_N + h\right)^2} \\ \delta\dot{h} = \delta v_U^n \end{cases} \tag{3}$$

where $\varphi=[\varphi_E \;\; \varphi_N \;\; \varphi_U]^T$ is the vector of the east, north, and universe attitude error angles calculated by SINS; δL, $\delta\lambda$ and δh are the position errors, respectively, latitude, longitude and altitude errors; ω_{ie}^n is the projection of the earth's rotation angular rate in the navigation coordinate system and ω_{en}^n is projection of the navigation coordinate system's angular rate related to the earth coordinate system in the navigation coordinate system; fn is the specific force in navigation coordinate system; $\varepsilon_b=[\varepsilon_x \;\; \varepsilon_y \;\; \varepsilon_z]$ is the gyro drift in vehicle body coordinate system and $\nabla^b=[\nabla_x \;\; \nabla_y \;\; \nabla_z]$ is the accelerometer zero drift in vehicle body coordinate system; C_b^n is the attitude matrix, R_M and R_N are respectively meridian and the prime vertical radius of the earth.

B. Error Model for Odometer

Different from the traditional single odometer, odometer error model of this paper deduce the velocity from the vehicle's position and attitude information, which will improve the precision successfully. Assuming at the moment of t, the wheels' angle velocities are respectively ω_{od1} and ω_{od2} measured through the left and right odometers in SINS/OD integrated navigation system. The coordinate system shown in figure 2 is parallel to the xoy plane in b system, θ is defined as the direction angle of the vehicle, the centroid of the vehicle is point C(x, y), and a three dimensional vector (x, y, θ) is used to describe the vehicle's position and attitude information[11]. Then

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \end{bmatrix} = \frac{r}{2}\begin{bmatrix} \dfrac{\cos(\theta-\gamma)}{cos\gamma} & \dfrac{\cos(\theta+\gamma)}{cos\gamma} \\ \dfrac{\sin(\theta-\gamma)}{cos\gamma} & \dfrac{\sin(\theta+\gamma)}{cos\gamma} \\ -\dfrac{1}{lcos\gamma} & \dfrac{1}{lcos\gamma} \end{bmatrix}\begin{bmatrix} \omega_{od1} \\ \omega_{od2} \end{bmatrix} \tag{4}$$

where r is radius of the wheel; γ is the included angle between BC and horizontal axis of two wheels, and point B is center of the wheel; l is the length of BC.

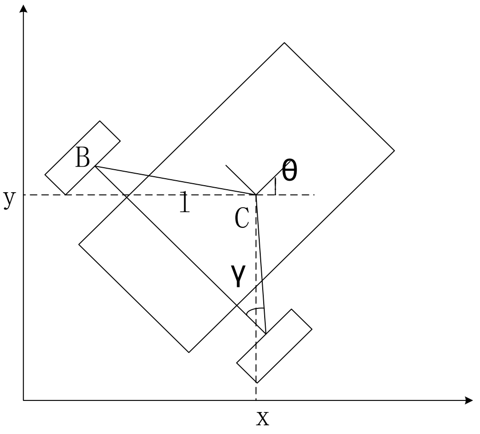

Figure 2. Vehicle's position and attitude.

According to this, the vehicle velocity obtained from odometers is

$$v_{od} = \sqrt{\left(\dot{x}cos\theta + \dot{y}sin\theta\right)^2 + \left(-\dot{x}sin\theta + \dot{y}cos\theta\right)^2} \tag{5}$$

which points to right forward of the vehicle, and the projection vector of v_{od} in b system is

$$v_{od}^{b} = \begin{bmatrix}0 & v_{od} & 0\end{bmatrix}^{T} \tag{6}$$

the projection of which in n system is

$$v_{od}^{n} = C_{b}^{n} v_{od}^{b} \tag{7}$$

The velocity error of dual odometers is mainly caused by the odometer scale coefficient error δk and the attitude angle error φ, and δk is determined by the factors such as the wheel pressure and road conditions. Then the actual calculation equation of the odometer velocity can be expressed as

$$v_{od}^{n\,'} = C_{b}^{n'} v_{od}^{b\,'} = \left[I_{3\times3} - \left(\varphi\times\right)\right] C_{b}^{n}\left(1+\delta k\right) v_{od}^{b} \tag{8}$$

where φ× is the antisymmetric matrix of vector φ. Ignoring the high order small amount of δk and φ, then from the equation above

$$v_{od}^{n\,'} = v_{od}^{n} - \varphi\times v_{od}^{n} + v_{od}^{n}\delta k \tag{9}$$

so the velocity error equation of odometer is

$$\delta v_{od}^{n} = v_{od}^{n\,'} - v_{od}^{n} = v_{od}^{n}\times\varphi + v_{od}^{n}\delta k \tag{10}$$

Similarly, the projection vector of direction angle of odometers in b system is

$$\theta_{od}^{b} = \begin{bmatrix}\theta & 0 & 0\end{bmatrix}^{T} \tag{11}$$

the error equation of which also need to introduce direction angle coefficient error, similar to δk, because of SINS's high measurement accuracy in a short time , so both of the coefficient errors of can be calibrated by SINS. So the direction angle error equation are obtained as

$$\delta\theta_{od}^{n} = \theta_{od}^{n}\times\varphi + \theta_{od}^{n}\delta\theta \tag{12}$$

III. THE KALMAN FILTER MODEL OF INTEGRATED NAVIGATION SYSTEM

When the vehicle's GPS cannot work properly, the system will be in SINS/dual OD integrated navigation mode. In vehicle start period, as long as there is a displacement of the vehicle, Kalman filter will be used by SINS to estimate the odometer errors, and then the odometer will correct the error accumulation of SINS. To design the Kalman filter of integrated navigation system, firstly the system state equation that based on the SINS error equation should be established, and secondly the system observation equation based on the integrated navigation system error equation should be established.

A. State Equation of the Integrated Navigation System

On the basis of the analysis of performance and errors of the SINS and OD, attitude errors, east, north and universe velocity error, latitude, longitude and altitude error, three gyro constant drift, three horizontal accelerometer constant zero offset are selected as state quantities of the SINS, and scale coefficient error and direction angle coefficient error are selected as state quantities of odometers, then state quantities of SINS/dual OD integrated navigation model

$$\mathrm{X}(\mathrm{t}) = \begin{bmatrix}\varphi_E & \varphi_N & \varphi_U & \delta v_E \delta v_N \delta v_U & \delta L & \delta\lambda & \delta h & \varepsilon_x & \varepsilon_y & \varepsilon_z & \nabla_x & \nabla_y & \nabla_z & \delta k & \delta\theta\end{bmatrix}^{T} \tag{13}$$

The state equation of integrated navigation system can be described

$$\dot{\mathrm{X}}(\mathrm{t}) = \mathrm{F}(\mathrm{t})\mathrm{X}(\mathrm{t}) + G(t)W(t) \tag{14}$$

where F(t) is the system matrix, which can be described as $\begin{bmatrix}F_{sins} & 0_{15\times2} \\ 0_{2\times15} & 0_{2\times2}\end{bmatrix}$, F_{sins} is a matrix of 15×15 [12], G(t) is the system noise transfer matrix, W(t) is the system noise, they can be solved by the error equations for SINS.

B. Observation Equation of the Integrated navigation System

When in the mode of SINS/OD integrated navigation, the differences between the data of the SINS and the odometer are selected as observation quantities of the Kalman filter, and then the observation equations are

$$Z_1(\mathrm{t}) = v_{sins}^{n} - v_{od}^{n} = H_1(t)X(t) + v_1(t) \tag{15}$$

$$Z_2(\mathrm{t}) = \theta_{sins}^{n} - \theta_{od}^{n} = H_2(t)X(t) + v_2(t) \tag{16}$$

where $v_1(t)$、$v_2(t)$ are observation noise vectors, and from the equations (10) and (12)

$$v_{sins}^{n} - v_{od}^{n} = \delta v_{sins}^{n} - \delta v_{od}^{n} = \delta v_{sins}^{n} - v_{od}^{n}\times\varphi - v_{od}^{n}\delta k \tag{17}$$

$$\theta_{sins}^{n} - \theta_{od}^{n} = \varphi - \delta\theta_{od}^{n} = \varphi - \theta_{od}^{n}\times\varphi - \theta_{od}^{n}\delta\theta \tag{18}$$

where v_{sins}^{n} and δv_{sins}^{n} are respectively the velocity and error output of SINS, θ_{sins}^{n} is the direction angle output of SINS，also the attitude angle. The observation matrix of the system

$$H_1(t)=\begin{bmatrix} 0 & v_{odU}^n & -v_{odN}^n & 1 & 0 & 0 & 0_{1\times 9} & -v_{odE}^n & 0 \\ -v_{odU}^n & 0 & v_{odE}^n & 0 & 1 & 0 & 0_{1\times 9} & -v_{odN}^n & 0 \\ v_{odN}^n & -v_{odE}^n & 0 & 0 & 0 & 1 & 0_{1\times 9} & -v_{odU}^n & 0 \end{bmatrix} \qquad (19)$$

$$H_2(t)=\begin{bmatrix} 1 & \theta_{odU}^n & -\theta_{odN}^n & 0_{1\times 13} & -\theta_{odE}^n \\ -\theta_{odU}^n & 1 & \theta_{odE}^n & 0_{1\times 13} & -\theta_{odN}^n \\ \theta_{odN}^n & -\theta_{odE}^n & 1 & 0_{1\times 13} & -\theta_{odU}^n \end{bmatrix} \qquad (20)$$

where v_{odE}^n , v_{odN}^n and v_{odU}^n are respectively the east, north and universe velocity of the vehicle measured by odometers joined SINS information, θ_{odE}^n , θ_{odN}^n and θ_{odU}^n are respectively the east, north and universe attitude angle of the vehicle measured by odometers joined SINS information.

The continuous model should be discretized, and then through the discrete Kalman filter the SINS error is estimated and compensated.

The above are the classical Kalman filtering algorithm for SINS and dual OD integrated navigation system, estimating and amending the error state in order to effectively reduce the navigation error accumulation.

IV. EXPERIMENT AND ANALYSIS

The vehicle SINS and OD error parameters are set as follows: gyro random constant drift is 0.02/h and noise is 0.01/h; Accelerometer random constant zero drift is 0.15 mg and noise is 0.05 mg; Odometer scale coefficient error is 0.2% and the direction angle coefficient error is 0.3%; The SINS's initial alignment horizontal attitude angle error is1', heading angle error is 10'.

The experiment is designed to be a vehicle trajectory comparison test in a particular circle path, as shown in figure 3(a)(b)(c), by comparing the tracks of vehicle calculated by the single SINS system, SINS/OD integrated navigation system and SINS/dual OD integrated navigation system, it is found that pure SINS navigation position errors diverge quickly as time goes on. The system in this paper functions more stable among the vehicle's motion processes and achieves higher trajectory coincidence with the real one, especially compared with the integrated system of SINS and single odometer, improving the precision of positioning, thus illustrates effectiveness and superiority of the SINS and dual odometers integrated navigation system.

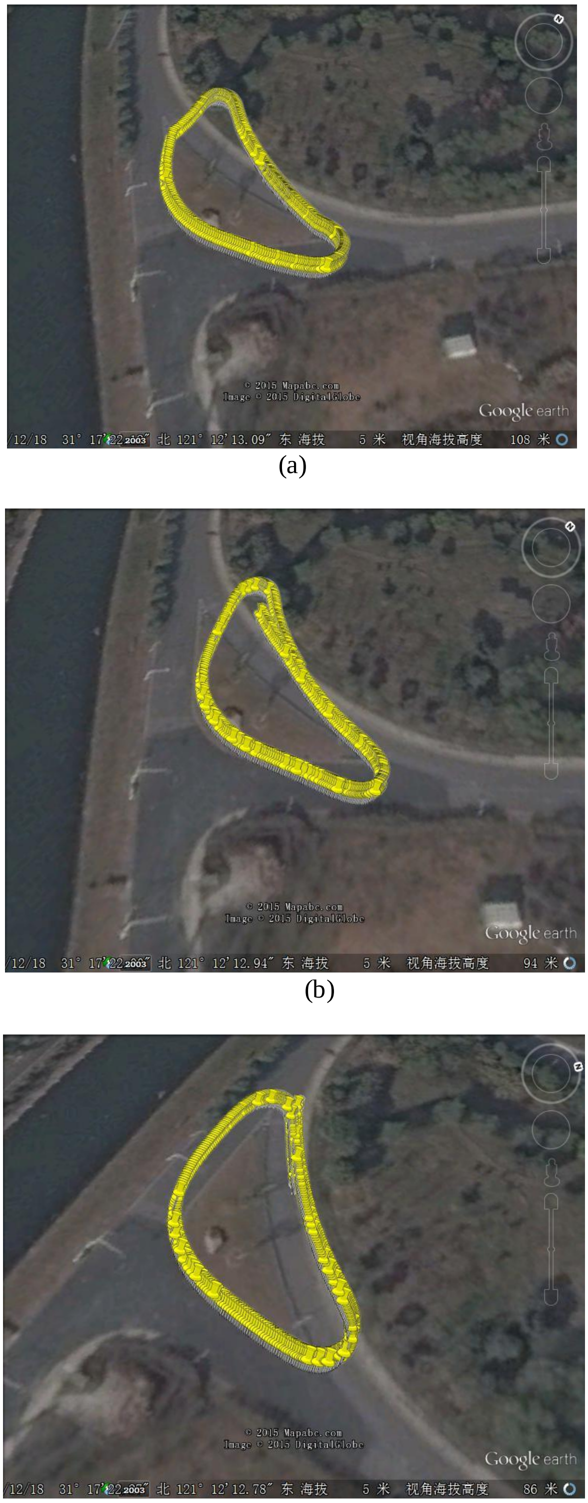

Figure 3. Comparison of tracks of navigation systems:

(a) Track of vehicle calculated by the single SINS system;
(b) Track of vehicle calculated by the SINS/OD integrated navigation system;
(c) Track of vehicle calculated by the SINS/dual OD integrated navigation system.

V. CONCLUSIONS

This paper proposes and discusses the SINS and dual odometers integrated navigation method, lists the SINS error model and the odometer error model is deduced, and based on these, the error state model and the observation model of integrated navigation system are established, which obtain the accurate and feasible Kalman filtering algorithm. Furthermore, the simulation illustrates that velocity and direction angle information of dual odometers can effectively correct the output of SINS, and reduce the errors of navigation parameters. The success of experiment shows that this kind of navigation system has good application value and also improves the performance of existing systems.

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