Land Vehicle Navigation Using Odometry/INS/Vision Integrated System

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Abstract—**Dead reckoning using odometry/INS can enhance the positioning accuracy compared with INS alone because odometry measurement errors won't grow over time. The scaling error of odometry, however, turns to be the main factor influencing on the system performance. So an improved odometry/INS integration approach is proposed that calibrate the scaling error real time at the beginning stage of integration based on the high accurate solution of INS, hence improve the positioning accuracy remarkably. But position errors are still increasing with the traveled distance since the heading error exists. Therefore, a new orientation method is proposed to re-initialize the odometry/INS system that utilizes the angle information to three known landmarks measured by the electro-optical detection system mounted on the roof of the vehicle. Simulation results show that the position and heading of land vehicles can be accurately determined only based on once measurement information of each landmark by the electro-optical detection system. The odometry/INS/vision land navigation system presented in this article is able to provide the relatively high precision navigation information over long distances at a relatively low cost, hence of great value in practice.**

Keywords—**land navigation, odometry, INS, the electro-optical detection system, integrated navigation**

I. INTRODUCTION

For today's military land vehicles, guidance and navigation information remains critical to mission success and survivability. Thus the demands for high precision land navigation are increasingly urgent.

Inertial Navigation Systems (INS), which is totally self-contained and can provide continuous position, velocity, and also orientation estimates, is one of the most widely used navigation methods and always chosen as main navigation system for all kinds of vehicles. Its vital drawback is that errors, especial position errors, are growing over time due to sensor drifts and will cause an unbounded error characteristic. Therefore, INS can be used alone for land navigation only when the ZUPT (Zero Velocity Update) is employed. However, this requires periodic stopping car about 5~10min hence is so inconvenient that cannot meet the demand of mobility for modern military land vehicles.

Odometry is capable of providing the vehicle with an accurate estimate of its velocity, hence is the indispensable part of the dead-reckoning systems for land vehicles[1-5]. The scaling error will introduce position error proportional to the traveled distance. Therefore, the challenge faced when using odometry is that the scaling error should be precisely calibrated. In addition, odometry cannot be used alone for navigation without orientation information.

Thus odometry and INS to some degree have the complementary characteristics. INS can provide the heading/attitude information, while odometry can remarkably limit the position error accumulation of INS with respect to time.

The solution accuracy of traditional odometry/SIN system is dependent partly on the scaling error of odometers. Generally, the scaling error magnitude of odometers is about the order of one per cent to five in a thousand, which means that the position error is about 10~20m after the vehicle travels 10km, and it cannot meet the higher and higher requirements of land vehicle applications today. Thus some calibration methods should be taken to enhance the estimation accuracy of odometer scaling error. Tape measures are the commonly used methods, but it is time-consuming and inconvenient. In this article, an improved odometry/INS integrated approach is proposed that can calibrate the scaling error real time to the order of five to two in a ten thousand at the beginning stage of integration on the basis of the so high accurate solution of INS, and hence improve remarkably the positioning accuracy of odometry/INS integrated system.

On the other hand, the solution accuracy is also dependent on the orientation errors, which odometry/INS systems cannot resolve. So other measures should be employed. When error grows over a fixed threshold, other sensors are used to determine the current location and orientation of the vehicle and therefore re-initialize the odometer/INS system (self-location).

Both satellite navigation system and electro-optical detection system are the good choice, but the satellite systems are vulnerable to the jamming and shading, especially for land vehicles. With of the ability of anti-jamming and self-contained, electro-optical systems are playing more and more important part in the field of navigation [6-11]. In our research, the electro-optical detection system is used and a novel approach of positioning and orientating for land vehicles is proposed that utilizes the angle information related to three landmarks obtained by the electro-optical detection system.

Therefore, the land navigation system proposed in this article consists of three subsystems, namely odometer, INS and electro-optical detection system.

The remainder of this article is organized as follows. In the next section, an improved odometry/INS integration approach is presented and computer simulations are carried out. And a novel approach of positioning and orientating using the electro-optical detection system for land vehicles is proposed in section III and the simulation results illustrate its effectiveness. Finally, in Section IV the concluding remarks are offered.

II. IMPROVED ODOMETRY/INS INTEGRATION

Odometers are the instruments that measure the velocity of land vehicles, which are capable of positioning solutions on the basis of the heading/attitude information from INS. The velocity of odometers can be expressed as following equation

$$\hat{\mathbf{v}}_D^b = \mathbf{v}_D^b + \delta K_d \mathbf{v}_D^b \tag{1}$$

Where δK_D is the scaling error, which will results in the position errors increased proportionally of the distance that the vehicle travels.

Traditional odometry/INS integration approach does nothing about the scaling error, so it becomes the main factor influencing on the system performance other than heading error. However, INS actually can do something about the scaling error.

It is well known that the solutions of INS are so much accurate in a short time when the INS just operates in navigation mode after initial alignment, so the odometer scaling error can be estimated accurately by Kalman filter when integrating the velocity solutions of the odometer and INS. Through feedback correction, the odometer employs the estimated scaling error to solve the velocity and distance of the vehicle and improves the positioning precision of the integrated system.

Therefore, the improved odometry/INS integration is divided into two stages: the first is the scaling error calibration stage, which is the focus of this article, and the second is dead-reckoning, which is so well-known that is skipped over hereafter.

In the first stage, the dynamic model of Kalman filter consists of two parts, one is the INS error model, and the other is the odometer scaling error. The INS error model and its linear approximation are well known and well developed [12]. The following error state equation of the INS is applied in this article:

$$\dot{\mathbf{X}}_I(t) = \mathbf{F}_I(t)\mathbf{X}_I(t) + \mathbf{G}_I(t)\mathbf{W}_I(t) \tag{2}$$

where $\mathbf{X}_I(t)$ is 12×1 system state vector, $\mathbf{W}_I(t)$ is 9×1 system noise vector, $\mathbf{F}_I(t)$ is 12×12 system dynamic matrix and $\mathbf{G}_I(t)$ is 12×9 system noise matrix. $\mathbf{X}_I(t)$ is defined as follows

$$\mathbf{X}_I(t) = [\delta v_E \; \delta v_N \; \phi_E \; \phi_N \; \phi_U \; \delta L \; \delta\lambda \; \varepsilon_{xb} \; \varepsilon_{yb} \; \varepsilon_{zb} \; \nabla_{xb} \; \nabla_{yb}]^T$$

Where $\delta v, \phi$ are the velocity and attitude error respectively; δL , $\delta\lambda$ and δh are latitude, longitude and altitude error respectively; ε is the gyro drift; ∇ is the accelerometer error, subscripts *x*, *y* and *z* denote the respective east north and up axes of navigation frame, subscripts *xb*, *yb* and *zb* denote the respective right transverse, longitudinal and vertical axis of body frame (b-frame). And the further information can be referred to [8-10].

For odometers, the scaling error can be modeled as follows:

$$\delta K_D = \delta K_c + \delta K_r + w_D \tag{3}$$

Where δK_c is the random constant; δK_r is the one-order Markov process; w_D is the white noise.

So, the error model can be written by:

$$\left.\begin{aligned} \delta \dot{K}_c &= 0 \\ \delta \dot{K}_r &= -\beta_D \delta K_r + w_r \end{aligned}\right\} \tag{4}$$

Here β_D is the correlation time.

On the ground of equation (3) and (4), the dynamic model of the scaling error can be written by:

$$\dot{\mathbf{X}}_K(t) = \mathbf{F}_K(t)\mathbf{X}_K(t) + \mathbf{G}_K(t)\mathbf{W}_K(t) \tag{5}$$

Where $\mathbf{F}_K(t) = \begin{bmatrix} 0 & 0 \\ 0 & -\beta_D \end{bmatrix}$, $\mathbf{G}_K(t) = \begin{bmatrix} 0 & 0 \\ 0 & 1 \end{bmatrix}$, $\mathbf{W}_K(t) = [0\ w_r]^T$.

Consequently, the dynamic model of the Kalman filter can be obtained by augmenting (5) into (2) and read as follows:

$$\dot{\mathbf{X}}(t) = \mathbf{F}(t)\mathbf{X}(t) + \mathbf{G}(t)\mathbf{W}(t) \tag{6}$$

When integration, the velocity measurements are employed since they are the direct measurements of odometers. Thus, the measurement model of the Kalman filter can be written as follows:

$$\mathbf{Z} = \mathbf{C}_b^n(\hat{\mathbf{v}}_I^b - \hat{\mathbf{v}}_D^b) = [\delta v_E^{'}\ \delta v_N^{'}]^T \tag{7}$$

Where $\delta v_E^{'}$, $\delta v_N^{'}$ are respectively the components of the difference between velocities measured by INS and odometer along east- and north-axis in the geographical frame.

Equation (7) can be expressed in terms of matrix form as

$$\mathbf{Z} = \mathbf{H}\mathbf{X} + \mathbf{V} \tag{8}$$

Where $\mathbf{H} = \begin{bmatrix} 1 & 0 & \mathbf{0}_{1\times10} & -v_{DE}^n & 0 \\ 0 & 1 & \mathbf{0}_{1\times10} & -v_{DN}^n & 0 \end{bmatrix}$, $\mathbf{V} = [N_E \quad N_N]^T$.

When estimate the scaling error of odometer by the accurate measurement information of INS within several or tens seconds, the velocity accuracy of the odometer can be greatly enhanced. And then the dead-reckoning algorithm is performed using the velocity from odometer and the attitude information given by INS.

For validating the effectiveness of this improved method, the computer simulations are performed. An vehicle trajectory is designed including starting, speeding, turning and so on for a total time 3 600 seconds in which the vehicle travels about 65 kilometers. The vehicle's initial position is at latitude of 40 deg north, longitude of 116 deg east and height of 0 m, and the initial attitude error (0.5 0.5 3) arc min. The gyro drift and the accelerometer bias are both modeled as first-order Markov process. The gyro random drifts along three axes of the body frame are 0.1deg/hr, correlation time 1800 second, and white noise 0.03deg/hr. The accelerometer biases along two axes of the body frame are 10^{-4}g, correlation time 800 second, and white noise 10^{-4}g. And the scaling error of the odometer is 0.005, correlation time 3600 second, and white noise 0.0003.

To compare the performances of the proposed improved approach and the traditional odometry/INS integration method, simulations are performed under the same conditions. Their simulation results are shown in Figures.1 and 2. From the simulation results, it can be seen that the proposed approach results is more accurate estimates than the traditional method. The magnitude of scaling error is dropped about one order in about ten second; as a result, the position errors are remarkably reduced compared with those using traditional integration. On the ground of simulation results, it is demonstrated that the improved approach proposed in this article is effective.

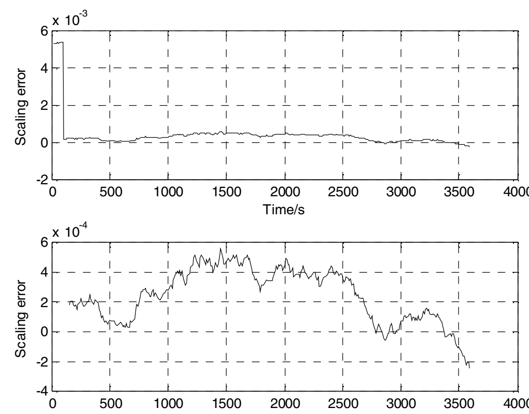

Figure.1 The scaling error estimation accuracy by the improved approach

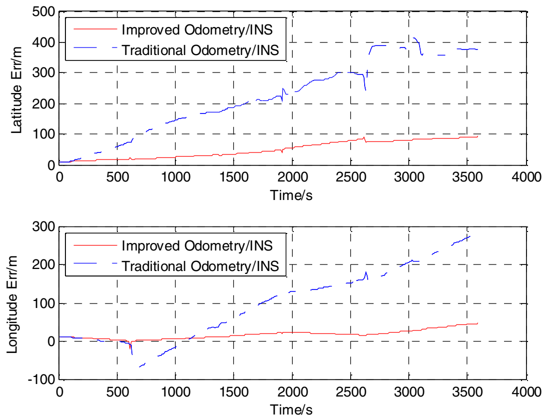

Figure.2 The position accuracy by traditional and improved approach

III. HEADING CORRECTION BY VISION METHOD

Odometry/INS integration system mentioned above can reduce the magnitude of scaling error about one order, hence improves the positioning precision of the integrated system. However, actually the positioning precision is still affected by the orientation error, which cannot be estimated accurately only by odometry/INS system, thus other measures should be employed to further enhance the performance of land navigation systems.

Here a novel orientation determination approach using electro-optical detection system is proposed, and the basic idea is as follows. The electro-optical detection system is assumed to mount on the roof of the vehicle and oriented with the viewing axis along the vehicle's longitudinal body-axis. When heading determination, according to the round position and attitude/heading information provided by INS, the electro-optical detection system turns to the three landmarks in turn, which positions are precisely pre-determined, and read out the angles between each landmark and the vehicle's longitudinal body-axis. Considering the heading angle provided by INS, the azimuth angles of three landmarks can be calculated, and the three lines can be determined on the basis of the position and azimuth angle of each landmark. In case that the heading of vehicles is accurate, these three lines will intersect to the one point, viz. the true position of the vehicle, shown as in figure.3a. However, the heading given by INS is always inaccurate, thus these three lines will intersect to three points A, B and C and form a triangle, which is called the "error triangle", see figure.3b. Obviously, this error triangle is in the token of heading error, so we can estimate the heading error from it.

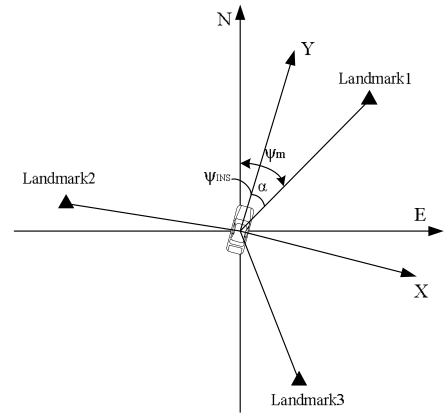

Figure. 3a. Estimate the vehicle's position and heading by 3 landmarks' position and azimuth angles (INS heading without error）

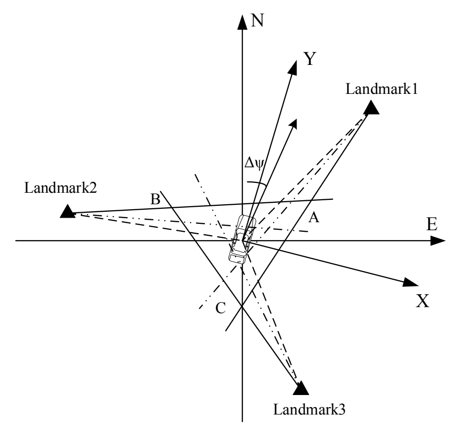

Figure. 3b. Estimate the vehicle's position and heading by 3 landmarks' position and azimuth angles (INS heading with error)

Without loss of generalization, the 2-dimentional scenario is discussed in this article. Assume that the land vehicle is located on the origin of the frame, namely the true position of the vehicle is $(x,y)=(0,0)$, and the true heading of the vehicle points the north, viz. $\psi_T = 0°$. Let (x_{Li}, y_{Li}) $(i=1,2,3)$ be 3 landmarks in plane frame. And the heading and position provided by INS are respectively as follows:

$$\psi_{INS} = \psi_T + \Delta\psi = \Delta\psi \quad (9)$$

$$x_{INS} = x + \Delta x = \Delta x \quad (10)$$

$$y_{INS} = y + \Delta y = \Delta y \quad (11)$$

Where $\Delta\psi, \Delta x$ and Δy are the heading and position error of INS respectively.

The azimuth angles of landmarks can be written as

$$\psi_m = \psi_{INS} + \alpha \qquad (12)$$

Where α is the angle between vehicle's longitudinal body-axis and the landmark measured by the electro-optical detection system.

Or the equation (12) can be written in another way

$$\psi_{mi} = \psi_i + \Delta\psi + n_i \quad (i = 1,2,3) \qquad (13)$$

Where $\psi_i = \arctan(\frac{x_{Li} - x}{y_{Li} - y})$ is the true azimuth angle of the landmark, and n_i is the measurement noise of the electro-optical detection system.

Thus three lines can be drawn using the positions and azimuth angles of the landmarks

$$l_i : (y - y_{Li}) = \tan\psi_{mi}(x - x_{Li}) \qquad (i = 1,2,3)$$

And the intersection of these three lines consists three points: $A(x_A, y_A)$, $B(x_B, y_B)$ and $C(x_C, y_C)$. If ignoring the measurement noise, the inclination angles of these three lines change the same angle with respect to the change of the INS' heading error, and the formed error triangles are similar triangles, as a result, the sides of error triangles are proportionate to the heading error (Figure.4). Therefore, the side of error triangles can be used as cost function and estimate the heading error by searching or iterative algorithms, and then correct the azimuth angles of the landmarks using estimation and calculate the vehicle's more accurate position.

The computer simulations are fulfilled for the validation of this approach. Assuming that INS' position error $(\Delta x, \Delta y) = (500m, -500m)$ and heading error $\Delta\psi = -30'$, the revolution of electro-optical detection system is 14″ and its measurement noise can be modeled as the white noise with covariance of 30″. The land vehicle locates the centre of the equilateral triangle formed by three artificial landmarks and 1000m apart. 100 Monte Carlo simulations are performed and the results are shown in Figure.5. It can be drawn that both estimation errors of vehicle position along east- and north-axis are mostly less than 0.1 meters, and the heading error can reach 20 arcsec (2σ). Besides high accuracy, the approach proposed is simple and quick, and it could serve several land vehicles at the same time.

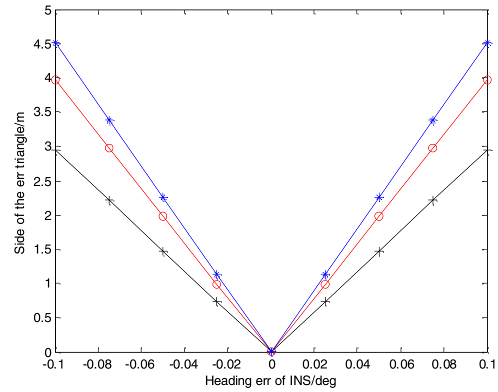

Figure 4. Relation between INS heading error and side of the error triangle

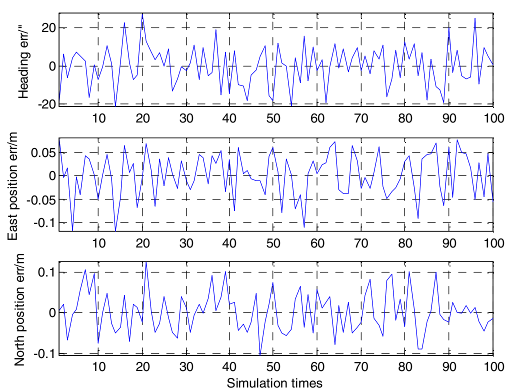

Figure.5 Orientation and position accuracy

IV. CONCLUSIONS

In odometry/INS integration, the scaling error limits the performance of system, so improving its estimation accuracy is the key to land navigation system. In this article, an improved odometry/INS integration approach is proposed which can estimate the scaling error real-time by the accurate information of INS at the beginning stage and then use it to limit the error accumulation of INS and remarkably enhance the performance of odometry/INS integration.

For orientation determination which cannot be solved well by odometry/INS integration, a new approach is presented that utilizes the angle information to three known landmarks measured by the electro-optical detection system. Computer simulation results indicate that the position and azimuth of land vehicles can be accurately determined only based on once measurement information of each landmark by the electro-optical detection system. Besides high accuracy, the approach proposed in this article is simple and quick, and it is capable of serving several land vehicles at the same time. Employing it, the land navigation system can be reinitialized after traveling a relatively long distance about several tens or one hundred kilometers, hence further enhance the system performance.

In summary, the land navigation system proposed in this article can achieve relatively high precision with low cost, hence is of great value in practice.

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