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# Online calibration and compensation of total odometer error in an integrated system

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ABSTRACT

Odometer is a good information source for land vehicle navigation because it can detect the velocity or mileage of a vehicle. Odometer scale factor, misalignment, and level arm with inertial measurement unit are the three sources of integration inaccuracy. However, they are difficult to be calibrated using a single procedure as they vary with many factors, such as the environment temperature, loading, and mounting factors. The online calibration method of the total odometer error and the odometer-aided inertial navigation system algorithm based on Coriolis Law were derived in this study. Vehicle test results indicated that the proposed calibration method can perform a good estimation of total odometer error. Navigation accuracy can be improved significantly with the calibrated odometer when the Global Positioning System declares loss-of-lock, which is approximately 1‰ of the mileage.

## 1. Introduction

Integrated inertial navigation system (INS) and global navigation satellite system (GNSS) can continuously provide the position, velocity, and attitude information of a vehicle with the intended accuracy [1,2]. However, GNSS is easily interrupted for a short or even long time in a challenged environment, such as urban canyon, tunnel, and wooded area, which leads to the rapid degradation of navigation accuracy because INS errors accumulate with quadratic time complexity. Aided sensors should be utilized to guarantee navigation accuracy when GNSS is not available. Odometer produces impulses at equal angle intervals, which can be transformed to velocity or mileage increment in the time interval by multiplying the wheel diameter. Odometer errors accumulate with the linear mileage and thus slower than INS. Therefore, the navigation system can benefit from the odometer in maintaining the accuracy when GNSS declares loss-of-lock. The odometer can be a reliable and economical navigation source in land vehicle applications [3–6].

The practical performance of the odometer is susceptible to several parameters. First, the odometer scale factor differs at each travel and slowly changes according to temperature, weight, and tire pressure. Second, the inertial measurement unit (IMU) is not well-aligned with the vehicle body to which the odometer is usually attached. This misalignment should be calibrated to apply transformation between the IMU and the odometer measurements [7,8]. Moreover, the IMU is usually mounted inside the vehicle, whereas the odometer is mounted on the wheel. Considerable displacement exists and causes the level arm effect between two measurements [9]. The three odometer-related error sources are collectively called total odometer error. The total error must be calibrated and compensated before or during integration. Yan et al. and Wang et al. studied the scale factor and misalignment errors in INS/odometer integration. Yan et al. use geometric method to calibrate the errors [6], and Wang et al. developed Kalman Filter calibration method [8]. However, the level arm effect error was not considered in both researches. Hemerly and Schad performed level arm correction and odometer bias estimation with a Kalman Filter, but the misalignment was not included [9]. Seo et al. neutralized the total odometer error in the GPS/INS/odometer system, nevertheless, the error was assumed to be known in advance and the calibration method was not provided [10]. For the integration algorithm, besides the commonly used Kalman

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Filter [8,10], Li et al. and Georgy et al. applied fuzzy neural network and particle filter to process the GPS/INS/odometer integration, respectively [11,12].

This study, starting with the spatial relationship between the IMU and odometer, derived the constraint between the inertial and odometer measurements based on Coriolis Law. The online calibration of the total odometer error and the INS/odometer integration method were examined according to this constraint. In continuous GNSS, the INS can be used to calibrate the total odometer error after the GNSS/INS reaches convergence. When a GNSS outage is encountered, the well-calibrated odometer can restrain INS error. The field experiments showed that the online calibration and integration method for odometer has an excellent performance. The integration system could reach 1‰ mileage accuracy in a GNSS-denied environment.

## 2. Relationship between INS and odometer measurements

The integration algorithm is processed in an earth-centered, earth-fixed coordinates frame, which is denoted as the e frame. The vehicle body frame is denoted as the b frame, and its three axes follow the sequence right, forward, and up directions. The IMU and odometer positions in the e frame are represented by $x^e_{IMU}$ and $x^e_{ODO}$, respectively, and the level arm of the odometer relative to the IMU coordinated in the e frame is represented by $L^e$. The relationship (as demonstrated in Fig. 1) between the three vectors is

$$x^e_{IMU} = x^e_{ODO} - L^e \tag{1}$$

Applying the derivation to Eq. (1) leads to:

$$\dot{x}^e_{IMU} = \dot{x}^e_{ODO} - \dot{L}^e \tag{2}$$

Then, the level arm vector is transformed from the e frame to the b frame because it is usually measured and represented by the latter:

$$\dot{x}^e_{IMU} = \dot{x}^e_{ODO} - R^e_b(\dot{L}^b + \omega^b_{eb} \times L^b) \tag{3}$$

where $R^e_b$ is the transform matrix from b frame to e frame; $L^b$ and $\dot{L}^b$ are the level arm coordinated in b frame and its derivative, respectively; $\omega^b_{eb}$ is the angular rate of b frame relative to e frame coordinated in b frame; and Coriolis Law $\dot{x}^s = R^s_t(\dot{x}^t + \omega^t_{st} \times x^t)$ is applied in the transformation. Given that level arm is a constant value, that is, $\dot{L}^b = 0$, Equation (3) can be simplified as

$$\dot{x}^e_{IMU} = \dot{x}^e_{ODO} - R^e_b \Omega^b_{eb} L^b = \dot{x}^e_{ODO} - R^e_s R^s_b(\Omega^b_{sb} + \Omega^b_{is} - \Omega^b_{ie})L^b \tag{4}$$

where the subscript and superscript "s" represents the IMU frame; $\Omega^b_{eb}$, $\Omega^b_{sb}$, $\Omega^b_{is}$ and $\Omega^b_{ie}$ are skew symmetric matrix of angular rate $\omega^b_{eb}$, $\omega^b_{sb}$, $\omega^b_{is}$ and $\omega^b_{ie}$, respectively; $R^e_s$ is the transform matrix from s frame to e frame and $R^s_b$ is the transform matrix from b frame to s frame. The IMU is fixed on the vehicle. Thus, the b and s frames have no relative angular movement, that is, $\Omega^b_{sb} = [0_{3\times3}]$. Therefore, Equation (4) can be simplified as

$$\begin{aligned}\dot{x}^e_{IMU} &= \dot{x}^e_{ODO} - R^e_s R^s_b(\Omega^b_{is} - \Omega^b_{ie})L^b = \dot{x}^e_{ODO} - R^e_s R^s_b(R^b_s \Omega^s_{is} R^s_b - R^b_e \Omega^e_{ie} R^e_b)L^b \\ &= \dot{x}^e_{ODO} - (R^e_s \Omega^s_{is} R^s_b - \Omega^e_{ie} R^e_s R^s_b)L^b\end{aligned} \tag{5}$$

where $\Omega^s_{is}$ and $\Omega^e_{ie}$ are skew symmetric matrix of gyro output $\omega^s_{is}$, and earth rate $\omega^e_{ie}$, respectively. Eq. (5) represents the relationship between the IMU and the odometer in the e frame in which the level arm effect is also considered. Under a small integration time, the velocity equation can be transformed into a mileage increment equation:

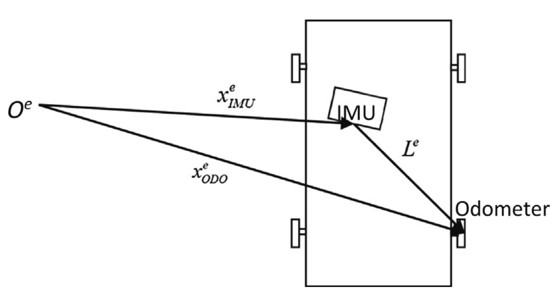


**Fig. 1.** Relative position between the IMU and the odometer.

$$\Delta x^e_{IMU} = \Delta x^e_{ODO} - (R^e_s \Omega^s_{is} R^s_b - \Omega^e_{ie} R^e_s R^s_b)L^b \Delta t \tag{6}$$

where $\Delta t$ is the integration time.

An odometer can only recognize the forward movement of a vehicle due to its mounting and measuring principle. The zero lateral and up velocities are introduced as the virtual measurements to create holonomic measurements in three directions. Then, the observation of odometer in the b frame is

$$N^b_{odo} = [0 \quad n \quad 0]^T \tag{7}$$

where $n$ is the impulse number of the odometer in the interval time. The mileage increment of the odometer in the e frame is

$$\Delta x^e_{ODO} = R^e_s R^s_b k N^b_{odo} \tag{8}$$

where $k$ is the odometer scale factor. By substituting Equation (8) into Equation (6), we can obtain the restrain relationship between the INS and odometer measurements:

$$\Delta x^e_{IMU} = R^e_s R^s_b k N^b_{odo} - R^e_s \Omega^s_{is} R^s_b L^b \Delta t + \Omega^e_{ie} R^e_s R^s_b L^b \Delta t \tag{9}$$

## 3. Principle of odometer calibration

In the GNSS well-observed condition, the INS is continuously updated by the GNSS to maintain high accuracy. Given that the INS mileage increment $\Delta x^e_{IMU}$, transformation matrix $R^e_s$, and angular rate $\Omega^s_{is}$ are well-estimated and compensated, the total odometer error can be calibrated by Eq. (9). The total odometer error is written in the form of error and estimation:

$$\begin{aligned}\Delta x^e_{IMU} &= R^e_s(1 + \alpha\times)\widetilde{R}^s_b(\widetilde{k} - \delta k)N^b_{odo} - R^e_s \Omega^s_{is}(1 + \alpha\times)\widetilde{R}^s_b(\widetilde{L}^b - \delta L^b)\Delta t \\ &\quad + \Omega^e_{ie} R^e_s(1 + \alpha\times)\widetilde{R}^s_b(\widetilde{L}^b - \delta L^b)\Delta t\end{aligned} \tag{10}$$

where $\widetilde{R}^s_b \widetilde{k}$, and $\widetilde{L}^b$ are the misalignment matrix, scale factor, and level arm of the odometer, respectively; $\alpha$ is the misalignment angle; $\delta k$ is the scale factor error; and $\delta L^b$ is the level arm error. By expanding Equation (10) and omitting the second and high-order items, we obtain

$$\begin{aligned}\Delta x^e_{IMU} &= R^e_s \widetilde{R}^s_b \widetilde{k} N^b_{odo} - R^e_s \Omega^s_{is} \widetilde{R}^s_b \widetilde{L}^b \Delta t + \Omega^e_{ie} R^e_s \widetilde{R}^s_b \widetilde{L}^b \Delta t - R^e_s \widetilde{R}^s_b N^b_{odo} \delta k \\ &\quad + (-R^e_s[\widetilde{R}^s_b \widetilde{k} N^b_{odo} \times] + R^e_s \Omega^s_{is}[\widetilde{R}^s_b \widetilde{L}^b \Delta t \times] - \Omega^e_{ie} R^e_s[\widetilde{R}^s_b \widetilde{L}^b \Delta t \times])\alpha \\ &\quad + (R^e_s \Omega^s_{is} \widetilde{R}^s_b \Delta t - \Omega^e_{ie} R^e_s \widetilde{R}^s_b \Delta t)\delta L^b\end{aligned} \tag{11}$$

Eq. (11) is simplified to obtain the following odometer calibration equation:

$$\Delta x^e_{IMU} - \Delta\widetilde{x}^e_{odo} = B_k \delta k + B_\alpha \alpha + B_L \delta L^b \tag{12}$$

where $\Delta\widetilde{x}^e_{odo} = R^e_s \widetilde{R}^s_b \widetilde{k} N^b_{odo} - R^e_s \Omega^s_{is} \widetilde{R}^s_b \widetilde{L}^b \Delta t + \Omega^e_{ie} R^e_s \widetilde{R}^s_b \widetilde{L}^b \Delta t$ is the mileage increment estimation of the odometer, $B_k = -R^e_s \widetilde{R}^s_b N^b_{odo}$, $B_\alpha = -R^e_s[\widetilde{R}^s_b \widetilde{k} N^b_{odo} \times] + R^e_s \Omega^s_{is}[\widetilde{R}^s_b \widetilde{L}^b \Delta t \times] - \Omega^e_{ie} R^e_s[\widetilde{R}^s_b \widetilde{L}^b \Delta t \times]$and $B_L = (R^e_s \Omega^s_{is} - \Omega^e_{ie} R^e_s)\widetilde{R}^s_b \Delta t$ are coefficient matrices of scale factor, misalignment angle and level arm.

If IMU misalignment does not exist, the transformation matrix $R^s_b$ is an identity matrix. Generally it is non-identical and composed by the heading misalignment angle $\alpha_y$, pitch misalignment angle $\alpha_p$, and roll misalignment angle $\alpha_r$ .