# A GM/DR Integrated Navigation Scheme for Road Network Application

Xinchun Ji<sup>1</sup>, Dongyan Wei<sup>1</sup>, Wen Li<sup>1</sup>, Yi Lu<sup>1</sup>, Hong Yuan<sup>1</sup>

<sup>1</sup>Academy of Opto-electronics, Chinese Academy of Sciences, Beijing, China jixinchun@aoe.ac.cn

**Abstract.** Focused on the independence and precision requirements for vehicle navigation, an integrated navigation scheme with geomagnetic matching (GM) and dead reckoning (DR) was proposed. The magnetic reference map was constructed which included magnetic intensities, coordinates of the reference points (RPs) and road sections information. Then, a zero-mean correlation coefficient method was utilized to match the measured magnetic intensities with the magnetic map, and thereby to estimate the vehicle position. The positioning results from GM and DR were fused by a designed EKF to correct the heading and mileage errors of DR. Furthermore, the corrected DR results could effectively reduce the matching search range and solve the discontinuity of GM results at road intersections. Vehicle experiments showed that the proposed scheme could provide accurate and continuous positioning results and meet the demands of vehicle navigation well.

Keywords: Geomagnetic Matching, Integrated Navigation.

## 1 Introduction

For the vehicle independent navigation applications, the equipped navigation system requires the capability to maintain high performance during the long-term and long-distance travel. Due to the error accumulation of inertial measurement unit (IMU) and odometer, traditional inertial navigation system (INS) and dead reckoning system (DR) could not meet the performance requirements. In addition, the global satellite navigation system (GNSS), which is vulnerable to the unintentional or intentional interference and obstruction, is not usually used as a main method for the vehicle independent navigation system.

In the vehicle navigation field, getting high-performance position information through novel navigation technologies [1], [2], [3], [4], such as map matching, RFID maker, vision location, land-based radio network and geomagnetic matching (GM), has become an important research content. Compared with other methods, the GM positioning need not lay lots of signal source equipment and has the advantages of low cost, simple maintain and strong independence. Literatures [5], [6] use the standard deviation algorithm and the product correlation algorithm to match the measured magnetic data and the model data of main geomagnetic field, and then obtain the posi-

tion estimations in real time. Due to the low spatial resolution of main geomagnetic field model, the positioning accuracy grade is about 500m, which could not meet the requirement of vehicle navigation.

As the odometer assisted magnetic matching algorithm we have proposed in [4], the basic idea of this paper is to determine the position by matching the measured magnetic data with the magnetic map stored previously. To perform a continuous positioning in urban road network, the magnetic map with netted structure was constructed. By a designed EKF, the data fusing operation was implemented between the GM results and the DR results, and then achieves complementary advantages.

# 2 Characteristic analysis of geomagnetic anomaly data

As derived from the magnetized crustal permanent magnet, the characteristics of geomagnetic anomaly are closely related to the location [7]. As shown in Fig.1, the magnetic intensity measured at different mileages along the route appears an obvious fluctuation. That means the magnetic characteristics have high spatial resolution and it can provide the precise navigation information to land vehicle localization.

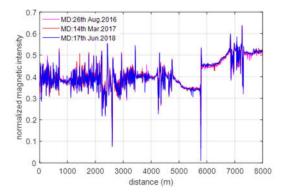


Fig. 1. The normalized magnetic intensity measured along the same route on different dates

## **3** GM positioning scheme in road network

#### 3.1 Magnetic reference map construction in road network

The magnetic intensity, the traveling distance and the coordinates of the road network are measured by magnetometer and reference localization system with high-precision, respectively. After the spatial alignment operation [4], the single-dimensional magnetic map can be constructed as,

$$\begin{array}{c} X, \theta, T \\ M, T \\ \end{array} \right|_{d}^{D,T} \left( \begin{array}{c} D, T \\ \Rightarrow \\ M, X, \theta \end{array} \right)_{map} \end{array}$$

$$(1)$$

where (M,T) is the magnetic intensity sequence,  $(X, \theta, T)$  is the coordinate and heading sequence, (D,T) is the mileage data sequence, d is the distance-interval sampling step and  $(M_k, X_k, \theta_k)_{max}$  is the k-th RP in magnetic map.

In the road network condition, the vehicle could travel along any route. Therefore, the magnetic reference map of road network should contain all road sections, joint-nodes and the connection relations among them. Fig. 2 shows the construction process of road-network magnetic map.

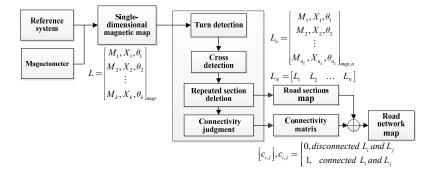


Fig. 2. The construction process of the magnetic reference map in road network

**Step 1: Turn detection.** The vehicle turning actions at the intersection can be used to divide the road sections directly. The turn detection algorithm is defined as,

$$Trs = \begin{cases} 1, & \left| \theta_k - \theta_{k+n_w} \right| \ge Th_{\Delta\theta} \\ 0, & else \end{cases}$$
(2)

where Trs is the turn detection result,  $Th_{\Delta\theta}$  is the threshold of heading variation range and  $n_w$  is the detection window length. The intermediate point  $X_{map,k+n_w/2}$  in the turning course is adopted as the division point of the road.

Step 2: Cross detection and repeated section deletion. The cross relation detection is implemented according to the space distance between different road sections. That is,

$$Crs = \begin{cases} 1, & \min_{n_{\mathcal{L}}} (|\Delta pos_{k}|) \le Th_{\Delta p}, \min_{n_{\mathcal{L}}} (|\Delta h_{k}|) \le Th_{\Delta h} \\ 0, & else \end{cases}$$
(3)

where  $\Delta pos_k$  is the horizontal distance between two road sections, and  $Th_{\Delta p}$  is the threshold.  $\Delta h_k$  is the altitude difference and its threshold is  $Th_{\Delta h}$ .  $n_L$  is the amount of RPs in current road section and  $k = 0, 1, 2..., n_L$ . There will be another division operation on the two road sections at the cross point if they meet the cross detection.

The repeated road sections will result in the non-unique RPs in the magnetic reference map. It is necessary to identify and remove the repeated sections in the whole map. The identification algorithm is,

$$rep = \begin{cases} 1, & \sum_{k=1}^{n_{i}} \left( X_{map,k}^{L_{i}} - X_{map,k}^{L_{j}} \right) \sin(\theta_{k}^{L_{i}} - \theta_{k}^{L_{j}}) \le n_{L} \cdot Th_{\Delta trj} \\ 0, & else \end{cases}$$
(4)

where  $L_i$  and  $L_j$  mean two different road sections.  $Th_{\Delta nj}$  is the average track difference threshold.

**Step 3: Connectivity judgment.** The basic criterion to judge the connectivity is that the space distance between the end point of current road section and the starting point of another road section is less than the pre-set threshold. Then, the connectivity matrix  $[c_{i,j}]_N$  can be expressed as,

$$[c_{i,j}]_{N} = \begin{cases} 0, disconnected \ L_{i} \ and \ L_{j} \\ 1, \ connected \ L_{i} \ and \ L_{j} \end{cases}$$
(5)

where  $c_{i,j}$  means the connection relation between section  $L_i$  and section  $L_j$ . N is the total number of the sections in road network and i, j = 1, 2, ..., N.

## 3.2 GM positioning online

**Step 1: Initial road section search.** To reduce the computation complexity of GM positioning in road network, a track matching method is utilized to determine the initial road section. The algorithm is expressed as,

$$path = \arg\min_{[map,N]} \sum_{k=1}^{w_{aj}} \left| \Delta pos_k \sin \Delta \theta_k \right|$$
(6)

where [map, N] means the search range of road sections, and  $w_{nj}$  is the window length of the DR-derived traveling track.  $\Delta pos_k \cdot \sin \Delta \theta_k$  is the difference between the DR traveling track and the road section in magnetic map, and  $k = 1, 2, ..., w_{nj}$ .

**Step 2: Optimum position matching.** An improved NPROD algorithm [4] is utilized for the matching solution and can be expressed as,

$$\begin{cases} \hat{X}_{opt} = \arg \max_{k \in (w, n_{L})} r_{k} \\ r_{k} = \frac{\sum_{i=1}^{w} (M_{map,k-i} - \overline{M}_{map})(M_{onl,w-i} - \overline{M}_{onl})}{\sqrt{\sum_{i=1}^{w} |M_{map,k-i} - \overline{M}_{map}|^{2} |M_{onl,w-i} - \overline{M}_{onl}|^{2}}} \end{cases}$$
(7)

where  $\overline{M}_{onl}$  and  $\overline{M}_{map}$  are the mean value of online magnetic intensity data and map magnetic intensity data in the sliding matching window, respectively. The mileage distance for the sliding window is  $(w-1) \cdot d$  and the mileage step is d.

One advantage of the sliding window matching is that the magnetic interference from building changes and other vehicles along the travel route can be suppressed. A self-evaluation is proposed to further reduce the mismatching errors. The GM result is valid only if it passes the evaluation. The self-evaluation can be represented as,

$$\begin{cases} r_{n,\max} \ge Th_{R} \\ \Delta p_{D} = \sum_{n=1}^{w_{n}} \left| \hat{X}_{opt,n} - \hat{X}_{opt,n-1} \right| - \Delta D_{w_{n}} \le Th_{D} \end{cases}$$

$$\tag{8}$$

where  $r_{n,\max}$  is the maximum correlation value and  $Th_R$  is the threshold.  $\hat{X}_{opt,n}$  is the nth position matching result,  $w_{ev}$  is the evaluation sliding-window length, and  $\Delta D_{w_n}$  is the total mileage increment.  $\Delta p_D$  is the distance difference and  $Th_D$  is the threshold. **Step 3: Road section splice.** When the vehicle travels at the joint-node, all the possible connected road sections are introduced in the matching process, according to the connectivity matrix  $[c_{i,j}]_N$ . If the GM results are constant in the same road section after the joint-node, this road section will be updated as the new current section. With this

the joint-node, this road section will be updated as the new current section. With this method, a continuous GM positioning is then achieved.

## 4 GM/DR positioning results fusion

A designed EKF is used to fuse the GM results with the DR results. The state vector  $X^{kf}$  is expressed as,

$$X^{kf} = [\delta pe, \delta pn, \delta D, \delta \theta]^{T}$$
<sup>(9)</sup>

where  $\delta pe$  is the east position error,  $\delta pn$  is the north position error,  $\delta D$  is the traveling distance error and  $\delta \theta$  is the heading error of DR.

The difference between GM derived position and DR derived position is adopted as the measurement vector Z,

$$Z = [pe_{g} - pe_{r}, pn_{g} - pn_{r}]$$

$$(10)$$

where  $(pe_g, pn_g)$  is the GM derived position, and  $(pe_r, pn_r)$  is the DR derived position at the same solution period.

The state equation can then be derived from the dynamic model of DR,

$$X_{n}^{k'} = \Phi_{n|n-1}X_{n}^{k'} + W_{n}$$

$$X_{n}^{k'} = \begin{bmatrix} \delta pe \\ \delta pn \\ \delta D \\ 0 \end{bmatrix}_{n} = \begin{bmatrix} 1 & 0 & \sin\theta_{n} & D_{n}\cos\theta_{n} \\ 0 & 1 & \cos\theta_{n} & -D_{n}\sin\theta_{n} \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \cdot \begin{bmatrix} \delta pe \\ \delta pn \\ \delta D \\ \delta D \\ \delta D \\ \delta \theta \\ n-1 \end{bmatrix} + \begin{bmatrix} W_{pe} \\ W_{pn} \\ W_{D} \\ W_{p} \\ W_{p}$$

where  $\Phi_{n|n-1}$  is the state transition matrix.  $[w_{pe}, w_{pn}, w_D, w_{\theta}]$  is the process noise vector.

 $\theta_n$  is the vehicle heading at  $t_n$ .  $D_n$  is the traveling distance between  $t_n$  and  $t_{n-1}$ .

The measurement equation is modeled as,

$$Z_{n} = H_{n} X_{n}^{k} + V_{n}$$

$$Z_{n} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix} \cdot \begin{bmatrix} \delta p e \\ \delta p n \\ \delta D \\ \delta \theta \\ \delta \theta \end{bmatrix}_{e} + \begin{bmatrix} v_{pe} \\ v_{pn} \end{bmatrix}_{n}$$
(12)

where  $H_{n}$  is the measurement matrix.  $[v_{pe}, v_{pn}]$  is measurement noise vector.

## 5 Experiment And Analysis

A road test was carried out in a simple urban road network. The test route includes some typical road conditions such as urban canyon, expressway and tunnel. The self-designed magnetometer (precision: 50 nT) and odometer (error ratio: 0.8%) are used to measure magnetic and mileage data respectively. The DR heading is provided by a navigation-grade IMU which the bias stability of azimuth gyroscope is 0.02°/h.

## 5.1 Reference map construction analysis

Fig.3 shows the magnetic map database of the test road network. It can be seen that the proposed method could accomplish the road section division, the joint-node identification and the connectivity judgment among divided-sections effectively.

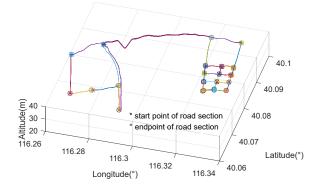


Fig. 3. Magnetic map database of the test road network

Additionally, the map database of a single road section is a single-dimensional spatial series. The serious position errors will occur if the test route deviates appreciably

from the RPs trajectory (multi-lane road, big crossroad, etc.). For a superior matching performance, the map construction considering multi lanes should be implemented.

## 5.2 Positioning performance analysis

During online positioning phase, the vehicle route was randomly selected and consisted of some separate road sections in the test road network. Fig.4 shows the position errors of original GM results. The maximum value of GM position errors is greater than 67m which could not be applied directly to correct DR errors.

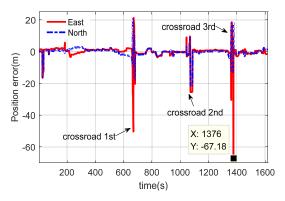


Fig. 4. Position errors of the original GM results

In Fig. 5, after the self-evaluation operation, the GM position error is  $3.34m (2\sigma)$  and the maximal value is reduced to 12.11m. Therefore utilizing the maximum correlation value and mileage difference to evaluate the original GM results is effective. It should be noted that the self-evaluation operation will degrade the continuity of GM results. The maximal positioning interval after evaluation is 293 meters in this experiment.

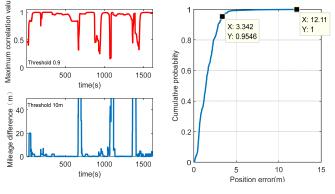


Fig. 5. Self-evaluation of GM results

Fig.6 compares the position errors between the DR results and the GM/DR results. With the proposed GM/DR scheme, the errors of heading angle, mileage and DR re-

sults could be estimated and corrected by the GM results after self-evaluation in real time. This approach prevents the position errors from growing over time and the maximum error in either direction is less than 5 meters. Subsequently high performances of the vehicle independent navigation system are achieved.

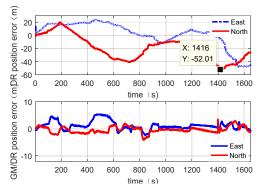


Fig. 6. DR and GM/DR position error

#### Acknowledgment

This work was supported by National Key Research Program of China "Collaborative Precision Positioning Project" (No.2016YFB0501900) and Entrepreneurship and Innovation Leadership Project of Qingdao (16-8-3-5-zhc).

#### References

- Byun, Yeun Sub, Young Chol Kim: Localization based on magnetic markers for an allwheel steering vehicle. Sensors 16.12 (2016).
- Li, Y., Zhuang, Y., Lan, H., et al: WiFi-aided magnetic matching for indoor navigation with consumer portable devices. Micromachines 6, 747–764 (2015).
- Li, W., Wei, D., Yuan, H., et al: A novel method of WiFi fingerprint positioning using spatial multi-points matching. In: 2016 International Conference on Indoor Positioning and Indoor Navigation, pp. 1–8. IEEEXplore, Spain (2016).
- Wei, D., Ji, X., Li, W., et al: Vehicle localization based on odometry assisted magnetic matching. In: 2017 International Conference on Indoor Positioning and Indoor Navigation, pp. 1–6. IEEEXplore, Japan (2017).
- Liu, F., Zhou, X., Yang, Y., et al: Geomagnetic matching location using correlative method. Journal of Chinese Inertial Technology 15(1), 59–62(2007).
- Chen, J., Xiong, Z., Xu, J., et al: Study of Geomagnetic Matching Aided Seamless INS/GPS Integrated Navigation. Aeronautical Computing Technique 44(6), 30–34(2014).
- Yamazaki K., Muramatsu K., Kato K., et al: A practical method for evaluating magnetic disturbance due to buildings for the design of a magnetic testing site. IEEE Transactions on Magnetics 41(5), 1856–1859(2005).