Improving Land Vehicle Gravimetry Using a New SINS/GNSS/VEL Method

Ruihang Yu¹, Xiaotian Qiu¹, Juliang Cao¹, Shaokun Cai¹, Shuhai Lu¹, Xiao Xu¹, and Lin Wang²,∗

¹College of Intelligence Science and Technology, National University of Defense Technology, Changsha, China
²College of Advanced Interdisciplinary Research, National University of Defense Technology, Changsha, China
∗Corresponding author: wanglinshanda@163.com

Abstract. GNSS plays a key role in land vehicle gravimetry. However, GNSS is unstable due to the influence of the observation environment, which adversely affects the gravimetry accuracy. The velocimeter can get rid of the restrictions on the use of GNSS by land vehicle gravimetry. In this paper, a SINS/GNSS/VEL method is proposed. This method uses both centralized filtering and federated filtering methods to process the gravity data. Based on the SGA-WZ02 strapdown gravimeter developed by the National University of Defense Technology (NUDT), the vehicle gravimetry test was carried out on a road of approximately 37 kilometers in east Changsha. The test consists of 4 lines in the south-north direction with an average speed of 40 km/h. Compared with traditional SINS/GNSS method, the accuracy of repeated lines using the centralized filtering method improves from 1.58 mGal to 1.37 mGal, and the external accuracy improves from 2.31 mGal to 2.19 mGal with a resolution of 2 km. Using federal filtering method, the internal accuracy is 1.36 mGal and the external accuracy is 2.22 mGal. It indicates that these two methods proposed could both improve the accuracy of gravimetry compared with the traditional SINS/GNSS method. Meanwhile, with adding the external sensor observation, these methods can improve the stability of gravimetry especially for practical survey operations that will save cost and improve efficiency. Finally, several discussions are proposed on the applicability and further improvement of the method.

1. Introduction

Kinematic gravimetry has caused much concern these years. It has been widely studied and rapidly applied in many geophysical applications during the last few decades[1-2]. Several different principles dynamic gravimeters have been developed and used for commercial geophysical surveys, such as LCR Gravimeter that is two-axis stable platform type[3], GT series gravimeters and AIRGrav gravimeters which are gimbaled inertial navigation systems[4-5], and SGA-WZ series strapdown gravimeter which are based on strapdown inertial navigation system (SINS) like[6].

Kinematic gravimetry can be implemented by multiple carriers such as aircraft, ships, satellites and cars. Different applications have different requirements because of different carriers. Especially in certain particular geophysics and geology applications, where the knowledge of a local gravity field with a level of 1-10 km spatial resolution is required. Therefore in the future, the land vehicle gravimetry, which has the properties of slower velocity and closer to the earth surface, is playing and will continue to serve as a critical role in future applications[7-8].
However, land vehicle gravimetry still faces large challenges. In traditional SINS/GNSS gravimetry method, GNSS provides high-precision position and velocity observation for SINS, but there is a problem that the GNSS is unstable due to the large influence of the observation environment, which adversely affects the gravity accuracy results\cite{8}. The SINS/VEL method, as a new vehicle gravimetry method, can perform vehicle gravity measurement tasks with the use of a velometer-assisted SINS without being restricted by GNSS usage\cite{9}. In the SINS/VEL vehicle gravimetry method, the velometer can provide stable and smooth speed observation information. However, there is an error accumulated over time inevitably, which leads to an increase in the integrated navigation positioning error and eventually affects the data quality of gravity measurement.

Based on the SINS/GNSS method and SINS/VEL method, a new SINS/GNSS/VEL method which comprehensively utilizing GNSS data and velometer data is proposed in this paper. This multi-source data fusion method helps improve the test efficiency, and meanwhile, ensuring the accuracy of gravity measurement. Section 2 shows the principle of centralized Kalman filtering SINS/GNSS/VEL method and Section 3 shows the principle of federal Kalman filtering SINS/GNSS/VEL method. Practical experiment results of land gravimetry test are shown in Section4 with corresponding discussions. Finally, conclusions and suggestions are made in Section 5.

2. Principle of Centralized Kalman Filtering SINS/GNSS/VEL Method

There are two main methods for integrated navigation estimation using Kalman Filtering (KF): one is centralized KF method, and the second is federated KF method. Collecting all the state information in the navigation system, centralized Kalman filtering calculates the estimation in one Kalman filter. In theory, the optimal estimation of the error state can be calculated by centralized Kalman filtering. In land vehicle gravimetry, both GNSS and velometer are able to provide the external observations for gravimeter systems.

Selecting $X(t) = \begin{bmatrix} \delta p & \delta \nu & \psi & b_s & b_v \end{bmatrix}^T$ as the state variable, the Kalman filter equation of state can be written as following:

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

(1)

details of Equation (1) are shown in the reference\cite{10}.

In land vehicle gravimetry, the gravimeter is equipped with different sensors such as GNSS and velometer for external observation. Although differential GNSS can provide high-precision position information, it can only provide low speed accuracy and high noise. The velometer, as a professional speed measuring device, can provide high-precision speed information in real time. Therefore, the position difference between GNSS position and SINS calculation position, the speed measured by the velometer and the speed calculated by SINS are selected as the state variables. These two differences are combined as the measuring information, so the measurement equation can be written as

$$Z(t) = \begin{bmatrix} \delta p \\ \delta \nu \end{bmatrix} = \begin{bmatrix} p^G_{\text{GNSS}} - p^G_{\text{SINS}} \\ v^v_{\text{GNSS}} - v^v_{\text{SINS}} \end{bmatrix} = H(t)X(t) + V(t)$$

(2)

Measurement matrix in Equation (2) can be expressed as

$$H(t) = \begin{bmatrix} I_{3 \times 3} & 0 & 0 & 0 & 0 \\ 0 & I_{3 \times 3} & 0 & 0 & 0 \end{bmatrix}$$

(3)

where, $p^G_{\text{GNSS}}$ is the position obtaining from GNSS in navigation frame, $p^G_{\text{SINS}}$ is the position calculated by SINS in navigation frame, $v^v_{\text{GNSS}}$ is the velocity measured by velometer and $v^v_{\text{SINS}}$ is the velocity calculated by SINS in n-frame. $I_{3 \times 3}$ is a $3 \times 3$ identity matrix.
3. Principle of Federated Kalman Filtering SINS/GNSS/VEL Method

Although centralized filtering can theoretically give an optimal estimate of the error state, it also has disadvantages such as high dimensionality state, poor fault tolerance, and heavy computational burden. The federated filtering method in decentralized filtering has been paid attention to and favored by N. A. Carlson [11-12]. Because of its flexible designing, good fault tolerance and small amount of calculation, it has been widely used and improved in the field of information fusion data processing for multi-sensor and multi-system.

The federated filtering uses two-step cascading and block filtering estimation data fusion technology. Its core idea is to distribute the system in parallel and work in parallel, and then combine the data of the subsystem to obtain the global optimal estimation. The calculation process of federated filtering can be summarized as: (1) initial value setting and information distribution, (2) time update, (3) measurement update, (4) data fusion.

Depending on various values of the information distribution coefficients, the federated filter has various structural forms. The federated filters of different structures have different fault tolerance, precision, and calculation amount. They are mainly divided into a fusion feedback structure and a zero-form structure, no reset structure and fusion reset structure [13,14]. In the process of selecting the federal filter for Kalman filter estimation, it is necessary to comprehensively consider the appropriate information distribution factor according to the actual requirements such as calculation accuracy, calculation performance and fault tolerance performance to obtain the ideal calculation effect.

Considering the actual situation of land vehicle gravimetry, selecting the SINS as the main navigation system, using SINS combined with GNSS and the velometer respectively, SINS/GNSS subfilter and SINS/VEL subfilter can be established. These two subsystems are then combined according to the federated filter structure. The SINS/GNSS/VEL federated filtering processing flow chart is shown in Figure 1.

![Fig. 1. SINS/GNSS/VEL federated filtering data processing chart](image)

In Figure 1, The vehicle gravimetry federated filter uses a two-stage processing structure with a main filter and two sub-filters. SINS is selected as the common reference system, and its output information $X_s$ is combined with GNSS and velometer to form a combined navigation sub-filter, in addition to directly entering the main filter. The SINS/GNSS sub-filter system calculates the local filter estimation value $\hat{X}_s$ and the covariance matrix $P_s$. The SINS/VEL calculates the filtered estimation value $\hat{X}_v$ and the covariance matrix $P_v$. The data enters the main filter for data fusion. The partial estimation state is comprehensively calculated to obtain a global estimate $\hat{X}_f$ and a global covariance matrix $P_f$. According to the allocation principle, the global covariance matrix is amplified to $\beta_i^+P_f$ (where $\sum_{i=1}^{2}\beta_i=1, i=1,2$ ) and be feedbacked to the sub-filter. Using the global estimate $\hat{X}_f$ to enter the main filter and sub-filter, it can be realized the resetting and correction of the sub-filter, which is
\[ \hat{X}_i = X_f, \quad \hat{P}_i = \beta_f^{-1} \hat{P}_f \]  

Selecting the error equation of SINS/GNSS subsystem, which is

\[ \dot{X}(t) = F(t)X(t) + G(t)W(t) \]  

Where, \( X(t) = [\delta \mathbf{p} \quad \delta \mathbf{v} \quad \psi \quad b_x \quad b_y]^T \) is selected as the state variables.

Selecting the difference between the position and velocity obtained by GNSS and SINS respectively as the measurement information, the SINS/GNSS subsystem measurement equation can be expressed as following.

\[ Z_i(t) = \begin{bmatrix} \delta \mathbf{p} \\ \delta \mathbf{v} \end{bmatrix} = \begin{bmatrix} -\mathbf{p}_{\text{GNSS}}^n + \mathbf{p}_{\text{INS}}^n \\ -\mathbf{v}_{\text{GNSS}}^n + \mathbf{v}_{\text{INS}}^n \end{bmatrix} = \mathbf{H}_i(t)X_i(t) + \mathbf{V}_i(t) \]  

The measurement information of the SINS/VEL subsystem is selected as the difference between the speed measured by the speedometer and the speed calculated by SINS. The measurement equation is

\[ Z_z(t) = \begin{bmatrix} \mathbf{v}_{\text{VEL}}^n - \mathbf{v}_{\text{INS}}^n \end{bmatrix} = \mathbf{H}_z(t)X_z(t) + \mathbf{V}_z(t) \]  

In the processing of federated Kalman filtering calculation, the main filter is used to fuse the sub-filter estimation values and the covariance matrix of the prediction error to obtain the global error state estimation value, which is

\[ \hat{X}_f = P_f^{-1}(P_f^{-1} \hat{X}_f + P_z^{-1} \hat{X}_z) \]

\[ P_f = (P_f^{-1} + P_z^{-1})^{-1} \]  

It can be seen that the information in the two subsystems is processed by fusion, and this information has an impact on the filtering of the last main function. Especially when one of the subsystems fails, other systems can still provide external observation, which will maintain the reliability of the filtering system.

4. Experimental Results & Discussions
The test route map is shown in Figure 2.

Fig. 2. Test route of land vehicle gravimetry

Based on the SGA-WZ02 developed by NUDT, the vehicle gravimetry test was implemented on a road of approximately 37 kilometers in eastern Changsha. The test consists of four measuring lines in the north-south direction with an average speed of 40 km/h.

4.1. Results of Centralized Kalman Filtering Method
Using the centralized Kalman filtering method, the gravity disturbances of four repeated measure lines are shown in Figure 3.
Generally, we use two methods to evaluate the accuracy of gravity results: internal and external accuracy. To evaluate the accuracy of repeated measuring lines, the internal accuracy represents the gravimeter’s repetitiveness property sensed on the similar trajectory for several times. In addition, the external accuracy represents the gravimeter’s objectiveness compared with true gravity data by accessing the difference between calculated data and reference data\(^{[15]}\). Statistics Details of the internal and external accuracy results are shown in Table 1.

### Table 1. Statistics of internal and external accuracy (mGal)

| Line  | Max  | Min  | Mean | RMS | Total RMS |
|-------|------|------|------|-----|-----------|
| Internal |      |      |      |     |           |
| Line 1 | 2.93 | -2.18| 2.56 | 1.16| 1.37      |
| Line 2 | 4.16 | -4.82| -0.83| 1.56|           |
| Line 3 | 3.08 | -2.45| -1.08| 1.21|           |
| Line 4 | 3.16 | -3.20| -1.65| 1.46|           |
| External |      |      |      |     |           |
| Line 1 | 4.93 | -6.59| 2.57 | 2.07| 2.19      |
| Line 2 | 6.81 | -6.64| -0.82| 2.63|           |
| Line 3 | 3.93 | -4.87| -1.05| 1.90|           |
| Line 4 | 6.01 | -4.74| -1.26| 2.11|           |

Compared with the traditional SINS/GNSS method, the accuracy of the four repeated lines in the centralized filtering method improves from 1.58mGal to 1.37mGal, and the external accuracy is improved from 2.31mGal to 2.19mGal with a resolution of 2 km.

### 4.2. Results of Federated Kalman Filtering Method

Gravity disturbances of four lines using federated Kalman filtering method are shown in Figure 4. Table 2 shows the statistics details of the internal accuracy and external accuracy results.
Table 2. Statistics of internal and external accuracy (mGal)

|       | Max   | Min   | Mean  | RMS  | Total RMS |
|-------|-------|-------|-------|------|-----------|
|       |       |       | ϵ_j   | ϵ   |           |
| Internal | Line 1 | 2.78  | -2.20 | 3.60 | 1.18      | 1.36      |
|         | Line 2 | 4.26  | -4.75 | -0.87| 1.56      |           |
|         | Line 3 | 3.09  | -2.47 | -1.07| 1.23      |           |
|         | Line 4 | 3.21  | 3.18  | -1.65| 1.47      |           |
|       |       |       |       | σ_j  | σ         |           |
| External| Line 1 | 4.86  | -6.53 | 3.59 | 2.04      | 2.22      |
|         | Line 2 | 6.91  | -6.59 | -0.88| 2.69      |           |
|         | Line 3 | 3.97  | -4.76 | -1.08| 1.88      |           |
|         | Line 4 | 6.01  | -4.70 | -1.66| 2.11      |           |

From Table II, the result shows that the internal accuracy of the federal filtering method is within 1.36mGal and the external accuracy is 2.22mGal. It indicates that the two methods proposed can both improve the accuracy of gravity measurement compared with the traditional SINS/GNSS method. Meanwhile, with adding the external sensor observation, these methods can improve the stability of gravity measurement especially for practical survey operations that will save cost and improve the efficiency.

5. Conclusion
An SINS/GNSS/VEL method which uses multi-sensor data is proposed. Both centralized filtering and federated filtering methods were proposed in this paper to obtain the gravity data. Based on the SGA-WZ02 developed by NUDT, the land vehicle gravimetry test was implemented in Changsha. Compared with the traditional SINS/GNSS method, the two methods proposed can both improve the accuracy of gravity measurement. Accuracy of the four repeated lines in the centralized filtering method improved from 1.58mGal to 1.37mGal, and the external accuracy improved from 2.31mGal to 2.19mGal at the resolution of about 2km. Using federated filtering method, the internal accuracy is 1.36mGal and the external accuracy is 2.22mGal. Moreover, these methods can help to save cost and improve the efficiency of practical survey operations by adding the external sensor observation.

Acknowledgement
The research is supported by the Key Laboratory Fund (Grant No. 6142003190201) and the National Key Research and Development Program to support the research (Grant No. 2017YFC0601703, 2017YFC0601701, 2016YFC0303002). Thanks are also given to the College’s Young Teacher Innovation Project (Grant No. ZN-13).

References
[1] K. Zhang, Research on the Methods of Airborne Gravimetry Based on SINS/DGPS. Ph.D. Thesis, National University of Defense Technology, Changsha, China(2007).
[2] K. P. Schwarz, M. Wei. Some Unsolved Problems in Airborne Gravimetry. In Gravity and Geoid, H. Sü nkel, I. Marson, Springer: Berlin, Germany, pp. 131–150(1995).
[3] J. H. Kwon. Airborne Vector Gravimetry Using GPS/INS. Ph.D. Thesis, The Ohio State University, Columbus, OH, USA, 2000.
[4] S. T. Ferguson, Y. Hammada. Experiences with AIRGrav: Results from a new airborne gravimeter. In Gravity, Geoid and Geodynamics 2000, Springer: Berlin, Germany, pp. 211–216(2002).
[5] M. Studinger, R. Bell, N. Frearson. Comparison of AIRGrav and GT-1A airborne gravimeters for research applications. Geophysics. I51–I61, 73 (2008).
[6] S. Cai, M. Wu, K. Zhang, et al. The First Airborne Scalar Gravimetry System Based on SINS/DGPS in China. Sci. Chin. Earth Sci. 56, 2198–2208 (2013).
[7] D. Titterton, J. L. Weston. *Strapdown Inertial Navigation Technology*. 2nd ed. American Institute of Aeronautics and Astronautics, Reston, USA, 2004.

[8] R. Yu, S. Cai, M. Wu, et al. An SINS/GNSS Ground Vehicle Gravimetry Test Based on SGA-WZ02. *Sensors* **15**, 23477–23495(2015).

[9] R. Yu, M. Wu, K. Zhang, et al. A New Method for Land Vehicle Gravimetry Using SINS/VEL. *Sensors*, **17**, 766(2017).

[10] R. Yu. Research on Key Technologies for Strapdown Ground Vehicle Gravimetry. *Ph.D. Thesis*, National University of Defense Technology, Changsha, China, 2017.

[11] Carlson N A. Federated filter for fault-tolerant integrated navigation systems[C]// *Proceedings of the Position Location and Navigation Symposium, 1988 Record Navigation Into the Century IEEE Plans '88*, IEEE, (1988).

[12] Carlson N A, Berarducci M P. Federated Kalman Filter Simulation Results. *Navigation*, **41** (3): 297-322(1994).

[13] Y. Qin, H. Zhang, S. Wang. *Kalman Filtering and Integrated Navigation Principle*. 2nd Edition. Xi’an, Northwestern Polytechnical University Press, 2012.

[14] L. Yu. Multi-sensor active fault-tolerant estimation method based on federated filtering. *China Sciencepaper*, **10**, 1124-1130(2014).

[15] R. Yu, M. Wu, J. Cao, et al. A new method of GNSS fault data detection for strapdown land vehicle gravimetry. *2018 IEEE International Conference on Applied System Invention (ICASI)*, Chiba, pp. 299-302(2018).