Journal of Computer and Communications, 2023, 11, 96-106
https://www.scirp.org/journal/jcc
ISSN Online: 2327-5227
ISSN Print: 2327-5219

Personnel Localization Method in Transformer Substation Based on Factor Graph

Haifei Yang[1], Yuntao Zhou[1], Huaijun Li[1], Baojun Wu[1], Fuchao Liu[2]

[1]Status Grid Shanxi Yangquan Power Supply Company, Yangquan, China
[2]School of Automation, Beijing Information Science & Technology University, Beijing, China
Email: 690585554@qq.com, y740720@163.com, 755606134@qq.com, hq050176@163.com, lfcbisu@163.com

How to cite this paper: Yang, H.F., Zhou, Y.T., Li, H.J., Wu, B.J. and Liu, F.C. (2023) Personnel Localization Method in Transformer Substation Based on Factor Graph. *Journal of Computer and Communications*, **11**, 96-106.
https://doi.org/10.4236/jcc.2023.118007

Received: May 12, 2023
Accepted: August 22, 2023
Published: August 25, 2023

Abstract

A SINS/GNSS location method based on factor diagram is proposed to meet the requirement of accurate location of substation construction personnel. In this paper, the inertial autonomous positioning, carrier motion information acquisition and satellite positioning technologies are integrated. The factor graph method is adopted to abstract the measurement information received by inertial navigation and satellite into factor nodes, and the state information into variable nodes, so as to construct the SINS/GNSS construction personnel positioning fusion factor graph model. The Gauss-Newton iterative method is used to implement the recursive updating of variable nodes, and the optimal estimate of the location information of the construction personnel is calculated, which realized the high precision location of the construction personnel. The factor graph method is verified by pedestrian navigation data. The results show that the factor graph method can continuously and stably output high-precision positioning results, and realize non-equidistant fusion of SINS and GNSS. The positioning accuracy is better than Kalman filter algorithm, and the horizontal positioning accuracy is less than 1 m. Therefore, the factor graph method proposed can provide accurate location information for substation construction personnel.

Keywords

Personnel Positioning, Factor Graph, SINS/GNSS, Gauss-Newton Iteration, Information Fusion

1. Introduction

With the development of electric power technology and the improvement of electricity quality requirements of power consumption units, the automation, safety and intelligent construction of substation needs urgent. Near power operation is an important means to ensure stable and sustainable power supply. Maintenance personnel and large engineering vehicles need to work near live high-voltage equipment. However, the complex electromagnetic environment in the substation is a typical high-risk work area. Once the site maintenance personnel and the operator of the engineering vehicle cross the safety distance in the case of negligence or misoperation, or even the engineering vehicle directly into contact with the live high-voltage equipment, it will lead to casualties and seriously affect the safe production of electricity.

In order to ensure the operation safety of substation construction personnel, it is very necessary to equip high-precision positioning devices and realize danger warning in the construction process. Multi-source information fusion based on SINS/GNSS combination is an important means to replace a single positioning method and improve the positioning accuracy of personnel. The current fusion methods include Kalman estimation method and improved Kalman method, which are not effective in the process of nonlinear combination positioning information. Factor graph, as an undirected probability graph model, has a remarkable effect in solving the edge distribution and has been widely used [1].

Wen [2] [3] [4] proposed the GNSS/INS combination positioning method based on factor graph and realized the precise positioning of vehicle with the assistance of camera. Yang [5] and Zhang [6] used factor graph method to verify and test the algorithm of indoor unmanned vehicle positioning. Xu [7] proposed a multi-source integrated navigation factor graph fusion algorithm based on sliding window iterative maximum posterior estimation. Gao [8] used factor graph to build the vehicle INS/GNSS/OD positioning system model, analyzed the asynchronous and delay problems of multiple sensors, and verified the robustness of factor graph model. Dai [9] proposed a robust incremental smoothing algorithm based on factor graphs, which improves the filtering estimation accuracy and convergence speed of the combined positioning system. Ma [10] proposed SINS/DVL/TAN/MCP combination localization method based on factor graph, which verified the flexibility and expansibility of the algorithm. Marco Cox [11] approached Bayesian inference from a message-passing perspective, based on a Forney-style factor graph (FFG) description of probabilistic generative models. Chiu [12] described a framework that expands factor graph formulation to encode sensor measurements with different rates, latencies, and noise distributions. Lin [13] proposed a single satellite positioning method based on factor co-location assistance. The method can complete location calculation by using the high-precision ranging information between the positioning targets and the positioning hyperbola which is constructed with the pseudo-range difference of the satellites. Han [14] proposed a sensor selection and optimization approach based on factor graph that meets the demand of environment adapting in multi-sensor fusion. To improve the navigation performance and robustness of integrated navigation algorithm based on factor graph under the condition that the performance of each sensor changes and the output is abnormal in the actual complex navigation environment, an improved factor graph method based on enhanced robustness is proposed [15]. The navigation and positioning methods via factor graph are considered and classified. Focuses in the current research on factor graph-based navigation and positioning is also discussed with emphasis on its practical application [16].

Aiming at the problems of satellite navigation in pedestrian integrated navigation systems, such as easy interference, long hours of inertial navigation system and accumulated errors caused by navigation position calculation, this paper adopted the theory of factor graph, abstracted measurement information received by inertial navigation system and satellite into factor nodes and status information into variable nodes, and constructed the SINS/GNSS construction personnel positioning fusion factor graph model. The Gauss-Newton iterative method was used to implement the recursive and updating of variable nodes, and the optimal estimated value of the positioning information of the construction personnel was calculated, thus realizing the high-precision positioning of SINS/GNSS integrated navigation system.

2. Factor Graph Model of Combined Positioning System

The combined positioning System of substation construction personnel is provided by the Global Navigation Satellite System (GNSS) with personnel location and speed information. Strapdown Inertial Navigation System (SINS) provides information about human acceleration and angular velocity. It mainly uses the SINS factor model during its work. When the GNSS measurement information is valid, it connects the corresponding factor nodes to the SINS factor model. Then the factor graph model of the combined positioning system is constructed.

Due to the different sampling frequencies of different sensors in the process of multi-source information fusion, sensor data is not synchronized. The factor graph model technology is used to solve the problem of multi-sensor information fusion is not synchronized, overcome the shortcomings of existing algorithms, and meet the plug-and-play characteristics of positioning system. Obtain relevant positioning information according to the positioning target, set the system noise and various initial information, and select the positioning state quantity. Because the parameters of each sensor will change with time and environment, resulting in poor positioning accuracy. Therefore, the positioning accuracy of the combined system can be effectively improved by expanding the key parameter model of the sensor and making estimation and feedback correction of the key parameters.

2.1. Factor Graph Model of SINS

Considering the error characteristics among gyroscope, accelerometer and satellite, the state quantity of the fusion system is established as follows [17]:

$$X(t)=\begin{bmatrix}\phi_E & \phi_N & \phi_U & \delta v_E & \delta v_N & \delta v_U & \delta L & \delta\lambda & \delta h & \varepsilon_{gx} & \varepsilon_{gy} & \varepsilon_{gz} & \nabla_{ax} & \nabla_{ay} & \nabla_{az}\end{bmatrix} \tag{1}$$

where ϕ_E represents the angular rate component of misalignment in the east direction, ϕ_N represents the northward misalignment angular rate component, ϕ_U represents the angular rate component of celestial misalignment, δv_E represents the angular rate component of celestial misalignment, δv_N Represents the northbound velocity error component, δv_U represents the component of celestial velocity error, δL represents the latitude error component, $\delta\lambda$ represents the longitude error component, δh represents the height error component, ε_{gx} and ε_{gy} and ε_{gz} represents the triaxial constant drift error of gyroscope respectively, ∇_{ax} and ∇_{ay} and ∇_{az} represent the zero deviation error of the accelerometer in three axial directions respectively.

The function factors are initialized, and the corresponding cost functions are established according to each sensor factor model. First, the time update equation of the inertial positioning system state is established as follows [17]:

$$\hat{x} = h_c\left(x, \alpha, f, \omega\right) \tag{2}$$

where x is the positioning state quantity, including speed information, position information and attitude information, α is the amount of error generated by the inertial device, f is the specific force, ω is the angular rate.

The measurement equation of inertial positioning system can be expressed as:

$$z_k = \left\{f, \omega\right\} \tag{3}$$

Associated with adjacent positioning states x_{k+1} and x_k, the time update equation is discretized to obtain:

$$x_{k+1} = h\left(x_k, \alpha_k, z_k\right) \tag{4}$$

According to the time update equation after discretization, the nodes of the inertia factor graph can be defined as:

$$f^{SINS}\left(x_{k+1}, x_k, \alpha_k\right) \triangleq d\left(x_{k+1} - h\left(x_k, \alpha_k, z_k\right)\right) \tag{5}$$

The two positioning state quantities x_{k+1} and x_k and the error α_k generated by the inertial device are connected through this factor diagram node $f^{SINS}\left(x_{k+1}, x_k, \alpha_k\right)$, the current positioning state x_k predicts the positioning state x_{k+1} at the next moment through measurement information z_k, the error function between the prediction quantity and the positioning state at the next moment is obtained. With the update of time, the error of the inertial device also changes. The error function is defined as:

$$\alpha_{k+1} = g\left(\alpha_k\right) \tag{6}$$

Similarly, the graph node of deviation factor related to error variables generated by inertial devices can be written as:

$$f^b\left(\alpha_{k+1}, \alpha_k\right) \triangleq d\left(\alpha_{k-1} - g\left(\alpha_k\right)\right) \tag{7}$$

In the above equation, an inertial positioning system deviation factor graph node is defined, and the two error variables α_k and α_{k+1} are connected through the factor graph node $f^b\left(\alpha_{k+1}, \alpha_k\right)$.

2.2. Factor Graph Model of GNSS

The satellite factor graph node is constructed according to the satellite measurement equation, which is as follows [16]:

$$z_k^{GNSS} = h^{GNSS}(x_k) + n^{GNSS} \tag{8}$$

where $h^{GNSS}(x_k)$ represents the measurement function of satellite information, n^{GNSS} represents the measurement noise of satellite information. According to the measurement equation, the node of the satellite factor graph is defined as:

$$f^{GNSS}(x_k) \triangleq d\left(z_k^{GNSS} - h^{GNSS}(x_k)\right) \tag{9}$$

According to the cost function $d\left(z_k^{GNSS} - h^{GNSS}(x_k)\right)$, node $f^{GNSS}(x_k)$ of the satellite factor graph is only related to the positioning state variable at the current moment, and has nothing to do with the state variable before and after the moment.

Input measurement information, determine the input factor according to the sensor of measurement information for processing, according to the above measurement equation and cost function of the relevant variable node selection, determine the inertia factor and satellite factor. The SINS/GNSS factor diagram model is shown in Figure 1.

3. Information Fusion Algorithm Based on Factor Graph

According to the inertia factor and satellite factor determined in the steps of Section 2, the SINS/GNSS combination factor graph was constructed to process the incremental information update, including the speed increment of the inertial positioning system, the position increment information and the position increment information of the satellite positioning system. The above positioning information is further updated and fused to obtain the optimal positioning estimate. The optimal estimate value $\hat{X}_k$ can be determined by Gauss-Newton iterative calculation, and the estimated correction value ΔX meets the following requirements [15]:

$$\Delta X' = \arg\min_{\Delta X} \left\| J\left(\hat{X}_k\right)\Delta X - b\left(\hat{X}_k\right)\right\|^2 \tag{10}$$

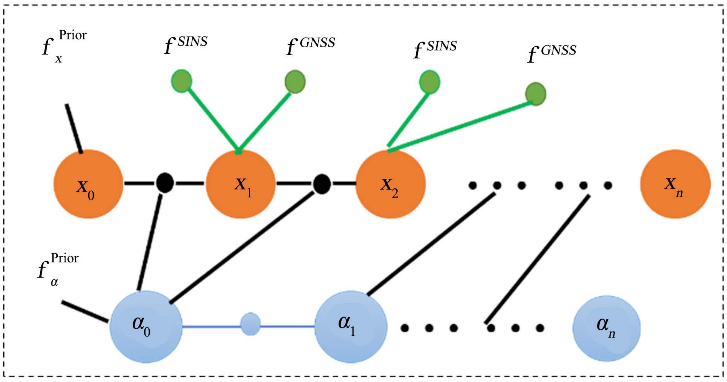

Figure 1. Factor graph model of SINS/GNSS.

where $J(\hat{X}_k)$ is the sparse Jacoby matrix of the current position estimate $\hat{X}_k$, $b(\hat{X}_k)$ is the measured residual of the current position estimate $\hat{X}_k$, in order to solve and update ΔX, we need to decompose the Jacoby matrix into the upper triangular matrix form using QR decomposition. In order to obtain the extreme value of ΔX, partial differentiation of the formula $\arg\min_{\Delta X} \left\| J(\hat{X}_k)\Delta X - b(\hat{X}_k) \right\|^2$ and make it equal to zero can be obtained:

$$J\Delta X = b \tag{11}$$

After calculating ΔX, a new position estimate $\hat{X}_k + \Delta X$ is obtained, which is iteratively calculated until the optimal position estimate is obtained.

4. Experiment and Result Analysis

4.1. Experimental Equipment and Conditions

In order to verify the GNSS/SINS information fusion algorithm proposed in this paper based on factor graph and collect personnel positioning data, a self-developed GNSS/SINS integrated navigation device was adopted in the experiment, and the test device was installed at the waist through the belt. The positioning test device mainly includes positioning reference station and positioning mobile station, including positioning GNSS RTK, inertial measurement module, GNSS antenna, digital communication module and mobile power module, etc. The experimental prototype is shown in Figure 2, and the installation diagram of the testing device is shown in Figure 3.

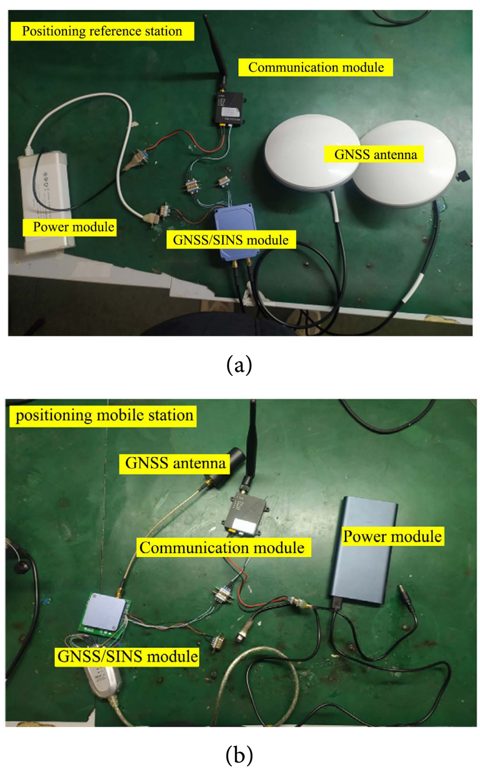

Figure 2. Experimental prototype. (a) Positioning reference station; (b) Positioning mobile station.

Figure 3. Installation diagram.

The positioning reference station is placed in a fixed position outdoors to ensure that the GNSS of the reference station can work stably. The GNSS RTK and inertial measurement module of the mobile station are fixed on the waist of the human body through the belt, and the data of the position reference station, human movement information and positioning information are transmitted to the upper computer software through the wireless data transmission module. Real-time observation and storage of human movement trajectory and movement data, and later analysis and processing of experimental data.

4.2. Experimental Analysis

In order to verify the outdoor positioning accuracy of the construction personnel, the experiment scene was selected around the office building, and the personnel positioning experiment was conducted around the office building. The strap-down inertial navigation system (SINS) composed of gyroscope and accelerometer developed by Core Motion Union and GNSS positioning module developed by Big Dipper Star Com was used for multi-source information fusion, so as to obtain the pedestrian movement attitude, speed and position information. The data output frequency was 200 Hz, and the sampling interval was 0.1 s. The speed and position in the carrier coordinate system were obtained by using the positioning device, and then converted to the navigation system through the coordinate system to obtain the real positioning information of personnel. The personnel positioning trajectory is shown in **Figure 4**, the northbound position error is shown in **Figure 5**, and the eastbound position error is shown in **Figure 6**.

It can be seen from **Figure 4** that the factor graph method and the traditional Kalman filter method can always maintain relatively stable navigation results during the whole moving period, but the traditional Kalman filter method has a large deviation from the reference positioning trajectory, indicating that the factor graph algorithm proposed in this paper has higher positioning accuracy. **Figure 5** and **Figure 6** show the northbound position error and eastbound position error respectively. The maximum northbound and eastbound errors calculated

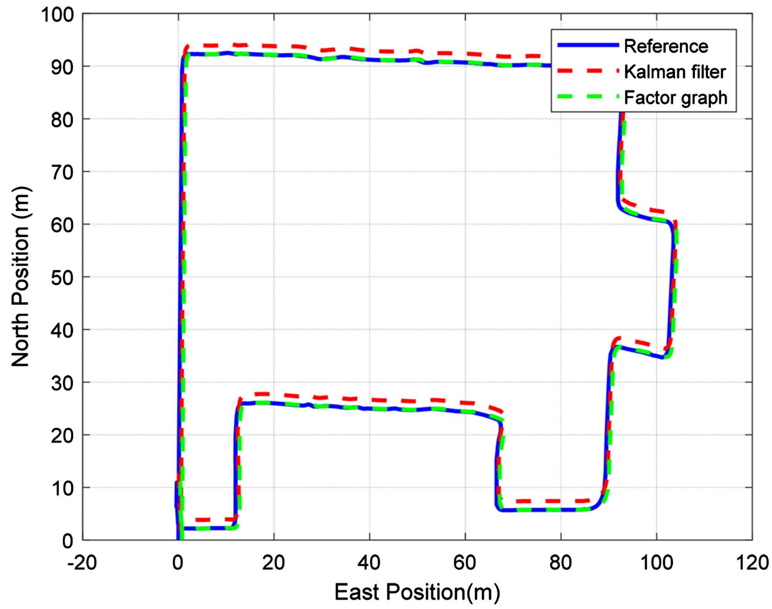

Figure 4. Personnel location track.

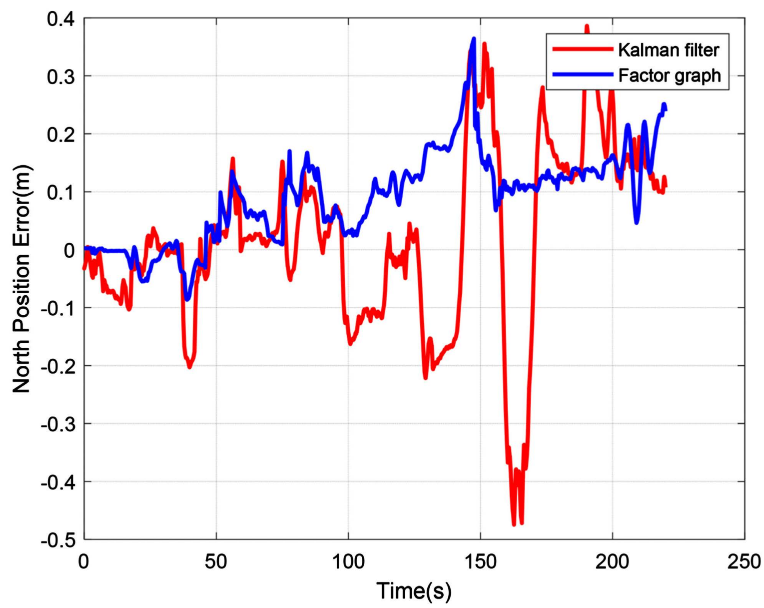

Figure 5. North position error.

by the traditional Kalman filtering method is 0.47 m and 0.71 m respectively. The maximum northbound and eastbound error calculated by the factor graph method is 0.36 m and 0.66 m respectively.

In order to quantitatively analyze the errors of each positioning parameter, the mean values and standard deviations of errors of the north and east positions of the factor graph method and the traditional Kalman filtering method were calculated respectively. The calculation results are shown in **Table 1**.

As can be seen from **Table 1**, the positioning accuracy of factor graph method is better than that of traditional Kalman filtering method, and it is consistent

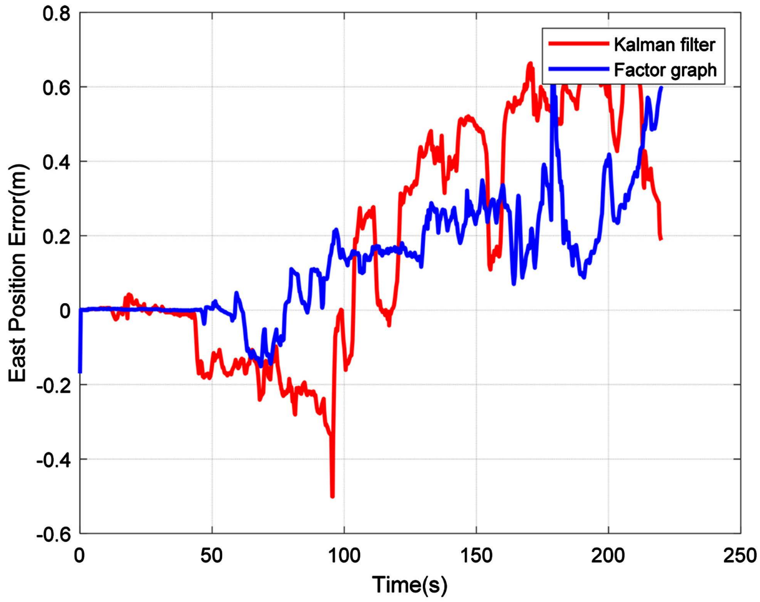

Figure 6. East position error.

Table 1. North and east position error.

algorithm	statistic	North position Error (m)	East position error (m)
Kalman filter	Standard Deviation	0.254	0.305
	Mean value	0.237	0.288
Factor Graph	Standard Deviation	0.181	0.153
	Mean value	0.155	0.136

with the conclusion drawn from the curve. Since latitude and longitude are direct measurements, factor graph method can overcome the influence of asynchronous information fusion and introduce the measurements into the calculation network in time. Therefore, the positioning accuracy of factor graph method is relatively high.

5. Conclusion

In this paper, SINS/GNSS combination positioning method based on factor graph is proposed to solve the problems of poor positioning accuracy of substation construction personnel and large error of multi-source heterogeneous information fusion. In this method, the measurement information received by inertial navigation system and satellite was abstracted as factor nodes, and the status information is abstracted as variable nodes. The integrated factor graph model of SINS/GNSS construction personnel location is constructed. The recursive and updated variable nodes are realized by Gauss-Newton iterative method, and the optimal value of construction personnel location was calculated. The results of personnel positioning experiment show that the SINS/GNSS combination positioning method based on factor graph can continuously and stably output high-precision navigation results, and effectively solve the problem of SINS/GNSS non-equispaced fusion. Compared with the Kalman filter algorithm, it has higher positioning accuracy, and can provide accurate location information for the construction personnel in the substation. At present, most researchers study the theory of navigation optimization based on factor graphs, and few scholars design the hardware platforms. In engineering practice, the development of hardware platforms based on factor graph navigation should be increased.

Acknowledgements

This work is supported by the Science and Technology Projects of State Grid Corporation of China (Grant No. 5205C0220001).

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

References

[1] Zhou, X.Y., Wei, H.E. and Guo, H. (2013) Research on the Improved Personnel Localization Method in Transformer Substation Based on ZigBee Wireless Sensor Network. *Power System Protection and Control*, **41**, 56-62. (In Chinese)

[2] Wen, W., Pfeifer, T., Bai, X. and Hsu, L.-T. (2021) Factor Graph Optimization for GNSS/INS Integration: A Comparison with the Extended Kalman Filter. *Navigation*, **68**, 315-331. https://doi.org/10.1002/navi.421

[3] Wen, W., Bai, X., Kan, Y. and Hsu, L.-T. (2019) Tightly Coupled GNSS/INS Integration via Factor Graph and Aided by Fish-Eye Camera. *IEEE Transactions on Vehicular Technology*, **68**, 10651-10662. https://doi.org/10.1109/TVT.2019.2944680

[4] Wen, W., Pfeifer, T., Bai, X. and Hsu, L.-T. (2020) Performance Comparison of GNSS/INS Integrations Based on EKF and Factor Graph Optimization. *Proceedings of the* 32*nd International Technical Meeting of the Satellite Division of The Institute of Navigation* (*ION GNSS*+ 2019), Miami, 16-20 September 2019, 3019-3032. https://doi.org/10.33012/2019.17129

[5] Yang, S. and Hsu, L.-T. (2020) Tightly Coupled Integrated Navigation System via Factor Graph for UAV Indoor Localization. *Aerospace Science and Technology*, **108**, Article ID: 106370. https://doi.org/10.1016/j.ast.2020.106370

[6] Zhang, L., Du, T. and Jiang, C. (2019) Indoor 3-D Localization Based on Received Signal Strength Difference and Factor Graph for Unknown Radio Transmitter. *Sensors*, **19**, Article No. 338. https://doi.org/10.3390/s19020338

[7] Xu, H.W., Lian, B.W. and Liu, S.B. (2019) Multi-Source Integrated Navigation Algorithm for Iterated Maximum Posteriori Estimation Based on Sliding-Window Factor Graph. *Acta Armamentarii*, **40**, 807-819. (In Chinese)

[8] Gao, J.Q., Tang, X.Q., Zhang, H. and Wu, M. (2018) Vehicle INS/GNSS/OD Integrated Navigation Algorithm Based on Factor Graph. *Systems Engineering and Electronics*, **40**, 2547-2553. (In Chinese)

[9] Dai, H.F., Bian, H.W., Ma, H. and Wang, R.Y. (2018) Application of Robust Incre-

mental Smoothing Algorithm Based on Factor Graph in Integrated Navigation of Unmanned Surface Vehicle. *Journal of Chinese Inertial Technology*, **26**, 778-786. (In Chinese)

[10] Ma, X.S., Liu, X.X., Zhang, T.W., Liu, X.J. and Xu, G.X. (2019) AUV Multi-Sensor Integrated Navigation Algorithm Based on Factor Graph. *Journal of Chinese Inertial Technology*, **27**, 454-459. (In Chinese)

[11] Cox, M., van de Laar, T. and de Vries, B. (2019) A Factor Graph Approach to Automated Design of Bayesian Signal Processing Algorithms. *International Journal of Approximate Reasoning*, **104**, 185-204. https://doi.org/10.1016/j.ijar.2018.11.002

[12] Chiu, H.P., Zhou, X.S., Carlone, L., *et al*. (2014) Constrained Optimal Selection for Multi-Sensor Robot Navigation Using Plug-and-Play Factor Graphs. 2014 *IEEE International Conference on Robotics and Automation* (*ICRA*), Hong Kong, 31 May-7 June 2014, 663-670. https://doi.org/10.1109/ICRA.2014.6906925

[13] Lin, H., Lian, B. and Yi, H. (2017) Synergy Factor Graph Aided Single-Satellite Positioning Algorithm. 2017 *IEEE International Conference on Signal Processing, Communications and Computing* (*ICSPCC*), Xiamen, 22-25 October 2017, 1-6. https://doi.org/10.1109/ICSPCC.2017.8242591

[14] Han, C., Pei, L., Zou, D.P., *et al*. (2018) An Optimal Selection of Sensors in Multi-sensor Fusion Navigation with Factor Graph. 2018 *Ubiquitous Positioning, Indoor Navigation and Location-Based Services* (*UPINLBS*), Wuhan, 22-23 March 2018, 1-88. https://doi.org/10.1109/UPINLBS.2018.8559802

[15] Wei, X.K, Li, J., Zhang, D.B. and Feng, K.Q. (2021) An Improved Integrated Navigation Method with Enhanced Robustness Based on Factor Graph. *Mechanical Systems and Signal Processing*, **155**, Article ID: 107565. https://doi.org/10.1016/j.ymssp.2020.107565

[16] Wu, X.W., Xiao, B., Wu, C.H., Guo, Y.M. and Li, L.W. (2022) Factor Graph Based Navigation and Positioning for Control System Design: A Review. *Chinese Journal of Aeronautics*, **35**, 25-39. https://doi.org/10.1016/j.cja.2021.09.001

[17] Zeng, Q.H., Chen, W.N., Liu, J.Y. and Wang, H.Z. (2017) An Improved Multi-Sensor Fusion Navigation Algorithm Based on the Factor Graph. *Sensors*, **17**, Article No. 641. https://doi.org/10.3390/s17030641