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Research on High Precision Positioning of Beidou/Inertial Compact Unit for Automatic Driving

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Abstract In order to meet the needs of high precision, high availability and high safety positioning for automatic driving, aiming at the technical difficulties of automatic driving positioning in the complex urban environment, an inertial navigation model suitable for the dynamic characteristics of vehicles is established. A tight combination method of Beidou/Inertial high precision positioning is also proposed, which can solve the problem of rapid accumulation of positioning errors in the weak signal environment of Beidou. The results show that when the Beidou signal is completely interrupted and the inertial navigation is combined tightly, the positioning accuracy and continuity are improved significantly, and the maximum error is less than 0.5m. As a result, it can realize the high-precision continuous navigation and positioning of automatic driving in the complex urban environment.

Keywords: Automatic driving; Beidou/Inertial compact unit; High-precision positioning; Neural Networks; Adaptive fusion

1 Introduction

The real-time, high-precision, continuous and reliable positioning result is one of the core technologies to achieve automatic driving, and it is also the basis for subsequent perception and decision-making. Therefore, automatic driving needs continuous positioning at decimeter level in the whole domain. In the complex urban environment, Beidou/GNSS accuracy is affected by satellite signal occlusion, multi-path, etc. The observation quality is poor when the number of satellites is small, and it is difficult to output continuous and reliable high-precision positioning results. Inertial navigation is an independent navigation system, which can output high-precision position, speed and attitude information in a short time. However, due to the influence of inertial device error and algorithm error, positioning error accumulates rapidly with time, which is difficult to meet the positioning requirements of automatic driving [1]. Therefore, Baidu, Uber and other auto driving manufacturers have adopted GNSS and inertial integrated navigation as the main positioning mode. In the GNSS/Inertial Integrated Navigation and positioning scheme, the integrated hardware and software solution provided by novatel company of Canada is adopted by many automatic driving companies due to its superior performance. In addition, momenta, Xiaoma Zhixing, Jingchi, Tucson and other automatic driving solution providers have developed their own integrated navigation and positioning system based on GNSS/Inertial .

　　GNSS/Inertial tight integration can update the inertial navigation when there are more than 1 GNSS satellite and less than 4 GNSS satellites. It has better positioning accuracy and reliability in complex urban environment, so it is widely used in automatic driving. In the study of compact combination model, people have developed from non geometric model to geometric model's cycle slip

repair method, which greatly improves the success rate and reliability of cycle slip repair. In view of the frequent loss of signal lock in urban environment, the high-precision position output in a short time of inertial   navigation is used to assist the accurate estimation of GNSS parameters. It can reduce the search space of cycle ambiguity, and greatly improve the efficiency of cycle slip repair with the rapid development of Beidou system construction. The research trend of cycle slip detection combined with inertial   navigation and three frequency observation value of Beidou is to further improve the performance of tight combination technology in complex environment [16]. On the other hand, neural network-assisted compact combination technology and improving the positioning accuracy in complex environments by mining hidden information of vehicle carriers have also become research hotspots in recent years to improve the positioning performance of GNSS/Inertial   compact combination systems in urban complex environments.

2 Proposed Methods

The research content of this project includes building a Beidou/Inertial   high-precision positioning tight combination model, studying inertial -assisted Beidou cycle slip repair and ambiguity fixation methods, enhancing Beidou positioning capability under weak satellite signal environment, analyzing vehicle dynamic characteristics change laws and hidden vehicle restraint information to intelligently identify the vehicle's motion status, and proposing an inertial   autonomous navigation model that conforms to the vehicle's motion.

2.1 Key techniques

(1) Beidou/Inertial adaptive fusion in weak signal environment
The Beidou observation data under the weak signal environment shows a low signal-to-noise ratio, a significant increase in cycle slip gross error, and complex and variable data quality. However, the inertial sensor cannot be effectively corrected for a long time, showing a nonlinear error accumulation. The Kalman filter fusion strategy is difficult to identify and resist the anomalies in the observations, thereby polluting the positioning solution results. Therefore, the research team adopted the Beidou/Inertial adaptive fusion method to solve the problem.
(2) Identification and modeling of principal components in vehicle motion state
The new inertial model is built on the basis of the dynamic characteristics and constraints of the vehicle. The hidden information of the vehicle is excavated in line with the law of vehicle movement. Whether the new model can be effectively applied to the vehicle carrier, the key is to determine the main components of the vehicle motion state and accurately model it.
(3) Neural network structure design and training sample selection
The design of neural network structure will determine the learning ability and generalization ability of neural network, while the training samples will directly affect the performance of neural network, and the complexity and representativeness of the samples will determine the training results of neural network. In order to more effectively predict the pseudo location of Beidou Positioning, the structure design of neural network and the selection of training samples will be the key [2].

2.2 Technical methods

For the key technologies that need to be broken through, the solutions we adopt are as follows:
(1) Beidou/Inertial fusion positioning technology based on tight combination
The traditional Beidou/Inertial information fusion mainly adopts the loose combination method. The position and inertia obtained through Beidou's separate solution are fused. The information fusion of this method is relatively loose, and the complementary advantages between sensors are not fully utilized. The loose combination filter will not be able to carry out observation and update under the condition of the number of satellites less than 4. Beidou/Inertial tight combination positioning is the fusion at the original level of the observation value, which is not limited by the number of satellites. It can fuse the effective information of Beidou and inertia to the maximum extent through adaptive filtering. In addition, inertia can assist the cycle slip detection and repair the Beidou data and the fast fixation of the ambiguity. Thereby, the Beidou Positioning ability under the weak satellite signal environment is enhanced. The research of Beidou/Inertial tight combination fusion method is one of the key technologies to achieve high-precision positioning in complex urban environment. The implementation steps include in figure 1:
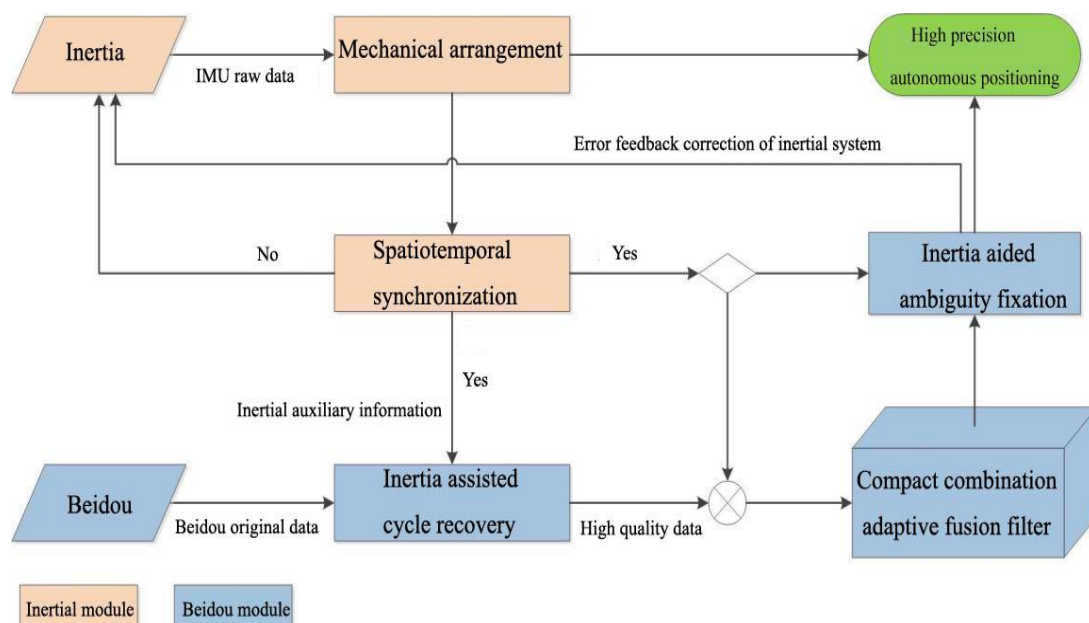
Figure 1   High precision autonomous positioning process of Beidou/Inertial compact unit

Step 1: The inertial   element outputs the original observation values of accelerometer and gyroscope with high frequency sampling rate, uses the quaternion mechanical arrangement algorithm to get the position, speed and attitude, and synchronizes with the original data of Beidou in time and space;

Step 2: Inertia assisted cycle recovery [3]. Owing to the phase observation value of Beidou signal before and after cycle slip is whole cycle. Therefore, it can be used as a parameter to establish a non-combined epoch difference observation model of pseudo range phase for cycle slip estimation:

$$\begin{cases} \Delta P = \Delta \rho + \Delta dt_s - \Delta dt_r + \Delta d_{trp} + \Delta d_{ion} + \Delta \varepsilon_p \\ \lambda\ \Delta\phi = \Delta\rho + \Delta dt_s - \Delta dt_r + \Delta d_{trp} - \Delta d_{ion} + \lambda\ \Delta N + \Delta \varepsilon_\phi \end{cases} \qquad (1)$$

In the formula (1), Δ represents the difference operator between the epoch. when there is cycle jump, ΔN is not zero, and it needs to be solved when the parameter is to be evaluated [4]. The broadcast ephemeris can provide Δdt_S, and Δd_{trp} represents the tropospheric variation. In fact, the troposphere is very stable in a very short time, which can be ignored, and Δd_{ion} represents the ionospheric variation, which can be obtained through ionospheric modeling and prediction. In the meantime, the satellite and receiver position information is included in $\Delta\rho$.

In order to improve the condition number of the cycle jump repair equation, the position change parameter in the cycle jump repair equation is constrained by the high precision displacement which is recursively deduced in a short time. In addition, when the number of satellites is less than 4, the cycle slip repair equation can still be solved due to the constraints of inertia recursive displacement, which is very useful for the case of serious satellite signal occlusion. After obtaining the floating-point value and its covariance matrix, the integer least square search method is used to fix it as an integer, and the final cycle jump value is obtained, and it is corrected to the original phase observation value for repair, so as to avoid the phase ambiguity reinitialization.

Step 3: The tight combination adaptive filtering is used to fuse Beidou/ Inertial positioning data [5]. The 15 dimensional state equation including position, velocity, attitude, accelerometer bias and gyro bias is established. According to the difference of Beidou enhanced information, the RTK / RTD observation equation is automatically switched. The noise and observation noise are reasonably constructed. Kalman filter is often applied to the fusion solution at the original observation value level. The residual distribution and standard deviation of the observation value after the test are integrated, and the robust theory is taken as the basis The optimal fusion is achieved by automatically judging
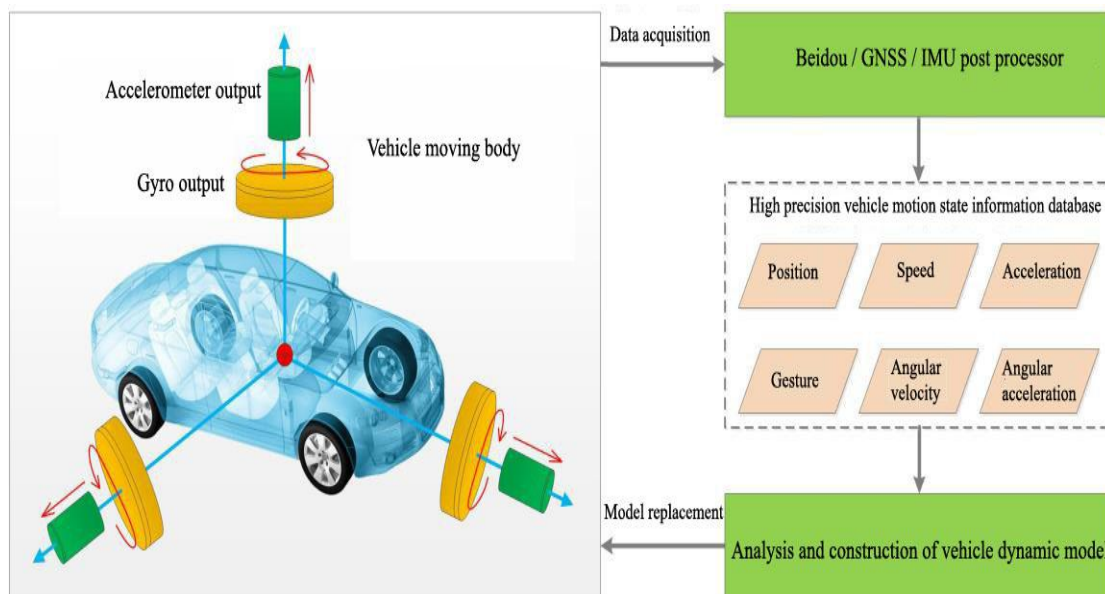
Figure 2   Method of building inertial autonomous navigation model in line with vehicle dynamic characteristics

gross error and adaptively adjusting the variance of each observation value.

Step 4: Fast convergence and fixation of Fuzziness with inertial assistance [6]. The high-precision position information provided by the inertia is used as the initial information to participate in the floating-point ambiguity resolution, which is used to improve the accuracy of floating-point ambiguity estimation, narrow the scope of integer least square search, consider the satellite height angle related to the ambiguity, tracking epoch number, filtering accuracy, etc., and use lambda method to carry out the ambiguity fast search. Then, through ration test, the correct ambiguity is finally confirmed and fixed [7].

Step 5:Parameter update and closed-loop correction[8] . Establish the coupling relationship between the fuzziness and other states, take the fixed part of the fuzziness as the virtual observation value, set the reasonable variance, and update the remaining states; then, implement the closed-loop correction of the inertial   sensor system error, and feedback the position, speed, attitude correction to the mechanical editing In the upper row, the zero bias is fed back to the original output data of the inertial sensor to ensure the error of the inertial sensor is minimized.
After the above steps, Beidou can carry out high-precision positioning when the number of satellites is less than 4, while the inertial sensor has been fully corrected due to various system errors, so it can achieve long-term high-precision autonomous positioning.

(2) Construction of inertial autonomous navigation model in line with vehicle dynamic characteristics
In order to conduct the long-term autonomous positioning of Beidou/Inertial   compact unit in urban environment, the accumulated error of inertial sensor is suppressed. The inertial navigation equation derived from the theory of translation and rotation in rigid body mechanics is universal and suitable for any motion of all carriers. As a vehicle moving on the ground, the autonomous driving vehicle has special dynamic properties. For example, vehicle motion is often limited to a plane. How to build an inertial navigation model suitable for vehicle carrier and make full use of the constraints of vehicle itself is one of the effective means to suppress the error accumulation of inertial sensors.
The method of building an inertial autonomous navigation model in line with the dynamic characteristics of the vehicle is shown in Figure 2. The main steps include:

Step 1: Analyze the general laws and constraints of vehicle motion [9]. If the road surface is regarded as a smooth surface, the vehicle can be abstracted as a box moving on the surface. The movement of the box on the surface can be divided into forward-backward straight line movement and left-right curve rotation. Its lateral movement and up-down movement are zero. At the same time, due to the constraints of traffic rules and ride comfort, the vehicle movement is relatively gentle, and there is little possibility of sudden changes. These vehicle constraints are abstracted into certain model equations.

Step 2: Sample data collection and processing [10]. In a good observation environment, artificial simulation of automatic driving, collection of GNSS/Inertial combination data under different roads and different vehicle motion states, use the combination of RTS smoothing and bi-directional combination smoothing for post-processing, high-precision solution of vehicle motion state information.

Step 3: Establish the vehicle motion state information database [11]. Through the spatial relationship between the inertial sensor and the vehicle body, the GNSS/Inertial combination results are transferred to the vehicle body coordinate system. The position, velocity and attitude can be obtained directly, the acceleration and angular velocity can be derived from the original inertial data after the system deviation correction, and the angular acceleration can be obtained by the epoch difference of angular velocity. All vehicle state information is related to the track after quality inspection, and the state of any point on the track is obtained by curve fitting and interpolation.

Step 4: The vehicle dynamic model is analyzed and built [12]. Analyze the vehicle behavior under different shapes of roads and moving speeds, find out the necessary and unnecessary state quantities in vehicle movement, such as heading angle, forward and backward speed, etc. are necessary States, while roll angle and lateral speed are unnecessary states. In the modeling, increase the contribution factors of necessary state quantities, and transform the vehicle constraint conditions into observation equations to include In the inertial model, the inertial model which accords with the dynamic characteristics of the vehicle is constructed.

Step 5: Model build replacement and iterative testing [13-15]. The new model is used for iterative testing, parameter setting is optimized continuously, the system error and its change rule of unmodeled inversion are analyzed, the unmodeled system error is absorbed by parameter augmentation, and the time-varying process of system error is modeled by Gaussian Markov process.
The new inertial model is built on the basis of the dynamic characteristics and constraints of the vehicle, which fully excavates the hidden information of the vehicle and conforms to the law of vehicle motion, so it has a better ability of autonomous positioning.

(3) Inertial autonomous positioning method based on neural network learning
In essence, neural network is to realize the non-linear mapping from input space to output space. Without knowing the model of the system accurately, the relationship between input and output can be established after learning. Therefore, it has been widely studied and applied in the analysis, modeling and prediction of non-linear system. This project introduces the method of neural network learning. When the Beidou signal is normal, the neural network is used to learn the mapping relationship between the inertial output and the Beidou Positioning. When the Beidou signal is completely interrupted, the neural network predicts the Beidou Positioning through the trained model, which is the inertial reference For filtering and fusion of pseudo position, the fast accumulation of positioning error in Beidou weak environment can be effectively suppressed. The scheme of inertial autonomous positioning based on neural network learning is shown in Figure 3.
The neural network training model provides a virtual Beidou Positioning result for the inertial navigation. If the positioning accuracy of the prediction is better than that of the inertial dead reckoning, the error accumulation of the inertial navigation can be effectively suppressed.

3 Results and Discussion

3.1 Construction of on-board test platform

In view of the requirements of safe, reliable and high-precision positioning for the application of automatic driving, the research group built a Beidou/Inertial integrated positioning vehicle software and hardware platform and tested it, designed a test scheme of automatic driving positioning in complex urban environment, carried out test verification in different scenarios, and established a corresponding positioning test verification field by measuring its decimeter level reference position, Test the software and hardware platform of vehicle positioning developed by this project, mainly test the positioning accuracy, reliability and stability under the application condition of automatic driving. The test method adopts the combination of black box test and white box test to test the overall architecture and functional modules of the vehicle positioning software and hardware platform in detail, analyze the working performance parameters of Beidou+Inertial navigation in different environments,
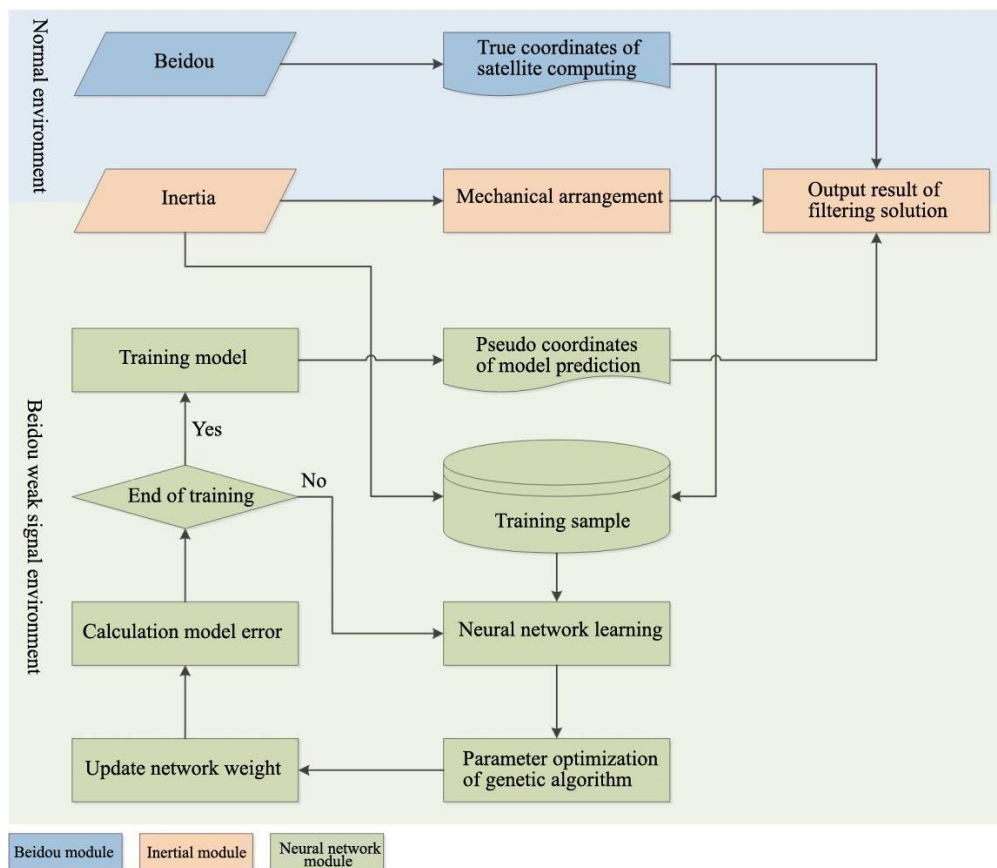
Figure 3　　Inertial autonomous positioning scheme based on neural network learning

and improve the positioning accuracy through continuous optimization of the depth fusion filtering method. The main contents include:

(1) Beidou/Inertial tight combination positioning software and hardware platform navigation and positioning test

Select typical vehicle positioning scenes that can basically cover urban complex environment, including open sky, urban canyon, tree lined Road, viaduct and tunnel. In these selected test scenarios, the vehicle positioning software and hardware platform developed in this project is road tested, and provides rich test data for subsequent navigation and positioning parameters optimization. The open sky test is mainly to verify the functions of the vehicle integrated navigation and positioning platform, focusing on the location and heading accuracy, and the accuracy and performance of wide area GNSS positioning; the urban canyon test is mainly to investigate the Beidou/Inertial tight combination navigation accuracy (such as gross error resistance ability) under the GNSS signal environment with obvious multi-path effect; the tree lined road test is mainly to investigate the weak signal GNSS signal environment Next, based on the accuracy of Beidou / INS tight integrated navigation; the viaduct test is mainly to investigate the integration and positioning effect of Beidou/Inertial tight integrated navigation when the short-term GNSS is missing on the viaduct; the tunnel test is mainly to investigate the position accuracy retention ability of INS data when the long-term GNSS is missing.

(2) Optimization of positioning parameters for Beidou/Inertial tight integrated navigation

Based on the calculation results of the previous tests, the optimization of integrated navigation and positioning parameters is carried out. Through the comparison between the actual scene test results and the reference positions provided on the high-precision map, we can get the navigation and positioning performance and the corresponding problem performance of Beidou / INS tight integrated navigation system in the more severe environment. Combined with the influence relationship and change trend of the relevant parameters on the navigation and positioning results, we can optimize the model parameters, quality control threshold parameters and auxiliary information Mining the accuracy limit of the integrated navigation and positioning system to ensure that the vehicle integrated navigation and

positioning results meet the requirements of all-weather, all road complex urban environment automatic driving.

3.2 Beidou RTK/Inertial tight combination positioning test

When the vehicle automatically runs in a typical complex environment, some satellite signals will be blocked under the influence of trees and shelters on the road. Simultaneously, jumping points or even interruptions will happen when only use the Beidou RTK Positioning solution. Therefore, we use the short-term high-precision position recurrence ability of the inertial navigation to help the Beidou RTK ambiguity fixed and continuous positioning.We analyze the vehicle data collected in practice, select all Beidou System satellites received, and compare the results of single Beidou RTK solution and Beidou RTK/Inertial   compact combination solution.

In the whole acquisition process, the number of satellites in most periods is maintained at about 8, and there is no more time satellite signal interruption. However, due to the influence of trees and high buildings on both sides of the road, the number of available satellites in some calendar elements is only four. At this time, the corresponding PDOP value is not stable.

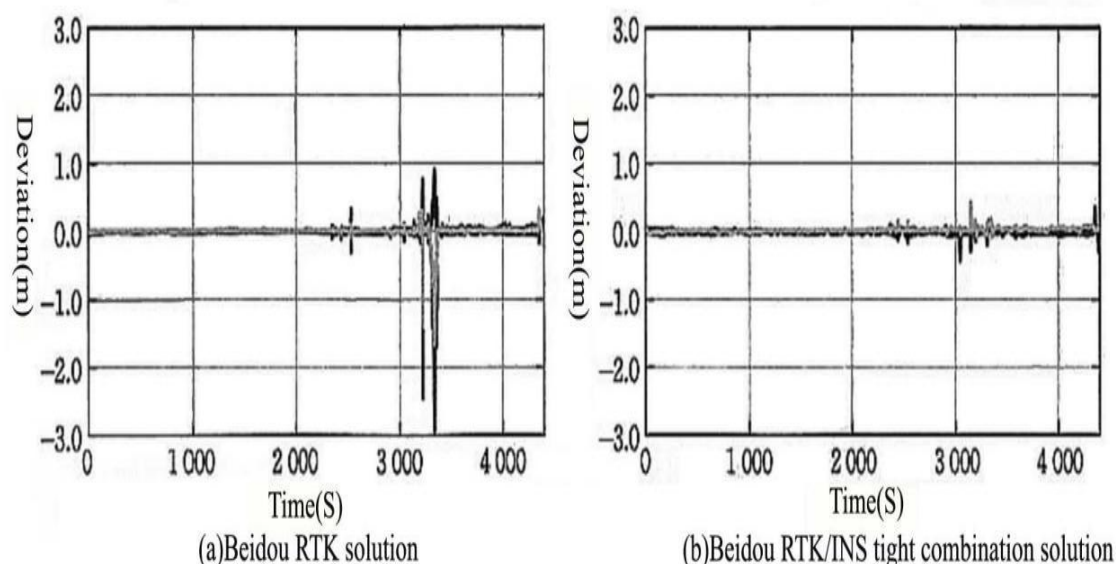(a)Beidou RTK solution   (b)Beidou RTK/INS tight combination solution

Figure 4   Position error

It can be seen from the position error diagram of RTK solution result in Figure 4 that when the number of Beidou available satellites jumps, the RTK solution result also shows obvious jumping points, especially in 3170-3370s, because the number of Beidou available satellites is only 4 in some epoch. The geometry of satellite positioning is affected, and the observation quality of 4 satellites is poor. As a result, it leads to the interruption of positioning results and the maximum positioning error of 3m. After the tight combination of Beidou/Inertial, the positioning accuracy and continuity are improved significantly, the positioning result is smoother, and the maximum error is less than 0.5m. Therefore, when the single Beidou RTK can not be solved successfully, the continuous positioning result of better than 0.25m can still be output with the aid of inertial navigation. It can be seen that the tight combination positioning of Beidou/Inertial is conducive to improving the positioning accuracy and reliability in complex environment.

The main innovations of this paper are as follows:

(1) The tight combination technology of inertial-assisted Beidou cycle jump repair and fuzzy degree fast fixed integration is proposed. The technology can achieve deep information fusion at the original observation level, and is not limited by the number of satellite observations. It can achieve long-term high-precision autonomous positioning in the urban weak signal environment.

(2) Compared with the general inertial navigation model, the new model can fully mine the implicit information and constraints of the vehicle, which is in line with the law of vehicle motion, and has better autonomous positioning ability.

(3) This paper proposes a method of learning the mapping relationship between inertial navigation output and Beidou Positioning Based on neural network. This method can output a Beidou pseudo position according to the training model when there is no Beidou signal, and realize high-precision

positioning by fusing inertial sensors.

4 Conclusion

In this paper, a Beidou/Inertial tight combination positioning method based on extended Kalman filter is studied, and the vehicle data is verified and analyzed. The results show that the Beidou/Inertial compact combination can significantly improve the stability and positioning accuracy of the positioning results, and can maintain the positioning level at decimeter level. The related technologies and systems developed in this project can greatly expand the application depth and efficiency of the existing automatic driving technology. Through the establishment of win-win market cooperation mechanism with domestic traditional automobile industry enterprises and new generation Internet automobile enterprises, it can be directly applied to the technology upgrading of domestic automobile enterprises. This will accelerate the application of automatic driving in the field of mass consumption, facilitate the rapid development of navigation positioning industry, promote the progress and maturity of automatic driving technology, and promote production. The integration and development of the industry will eventually promote the upgrading and leaping development of society.

Acknowledgments

References

[1] Ji S, Xu W, Yang M. 3D convolutional neural networks for human action recognition. *IEEE transactions on pattern analysis and machine intelligence*, 35(1) : 221-31,2013,.

[2] Urmson C, Anhalt J, Bagnell D. Autonomous driving in urban environments: Boss and the urban challenge. *Journal of Field Robotics*, 25(8) :425-66, 2008.

[3] Sotelo MA, Rodriguez FJ, Magdalena L. Acolor vision-based lane tracking system for autonomous driving on unmarked roads. *Autonomous Robots*,16(1) :95-116, 2004.

[4] Bhat A, Aoki S, Rajkumar R. Tools and methodologies for autonomous driving systems. *Proc IEEE*, 106: 1700–1716,2018.

[5] Basu C, Singhal M. Trust dynamics in human autonomous vehicle interaction: a review of trust models.*In: Proceedings of AAAI Spring Symposia, Palo Alto*,85–91,2016.

[6] C. Katrakazas, M. Quddus, W. H. Chen, and L. Deka, "Real-time motion planning methods for autonomous on-road driving: State-of-the-art and future research directions," *Transport. Res. C*, vol. 60, pp. 416-442,Nov. 2015.

[7] S. M. Zhang, W. W. Deng, Q. R. Zhao, H. Sun, and B. Litkouhi,"Dynamic trajectory planning for vehicle autonomous driving," *in Proc.IEEE Int. Conf. Systems, Man, and Cybernetics*, Manchester, UK, 2013,pp. 4161-4166.

[8] R. X. Cui, Y. Li, and W. S. Yan, "Mutual information-based Multi-AUV path planning for scalar field sampling using multidimensional RRT," *IEEE Trans. Syst., Man, Cybern.: Syst.*, vol. 6, no. 7, pp. 993-1004,Jul. 2016.

[9] X. M. Hu, L. Chen, B. Tang, D. P. Cao, and H. B. He, "Dynamic path planning for autonomous driving on various roads with avoidance of static and moving obstacles," *Mech. Syst. Signal Process.*, vol. 100, pp.482-500, Feb. 2018.

[10] W. Z. Hu, Q. Zhuo, C. S. Zhang, and J. K. Li, "Fast branch convolutional neural network for traffic sign recognition," *IEEE Intellig. Transport.Syst. Mag.*, vol. 9, no. 3, pp. 114-126, Jul. 2017.

[11] M. Kurdej, J. Moras, V. Cherfaoui, and P. Bonnifait, "Map-aided evidential grids for driving scene understanding," *IEEE Intellig. Transport.Syst. Mag.*, vol. 7, no. 1, pp. 30-41, Jan. 2015.

[12] T. Gindele, S. Brechtel, and R. Dillmann, "Learning driver behavior models from traffic observations for decision making and planning," *IEEE Intellig. Transport. Syst. Mag.*, vol. 7, no. 1, pp. 69-79, Jan.,2015.

[13] M. Pfeiffer, M. Schaeuble, J. Nieto, R. Siegwart, and C. Cadena, "From perception to decision: A data-driven approach to end-to-end motion planning for autonomous ground robots," *in Proc. IEEE Int. Conf. Robotics and Automation (ICRA)*, Singapore, 2017, pp. 1527-1533.

[14] F. Y. Wang, N. N. Zheng, D. P. Cao, C. M. Martinez, L. Li, and T. Liu,"Parallel driving in CPSS: A unified approach for transport automation and vehicle intelligence," *IEEE/CAA J. Autom. Sinica*, vol. 4, no. 4, pp.577-587, Sep. 2017.

[15] K. F. Wang, C. Gou, and F. Y. Wang, "Parallel vision: An ACP-based approach to intelligent vision computing," *Acta Autom. Sinica*, vol. 42,no. 10, pp. 1490-1500, Oct. 2016.
[16] S. Thomas, S. Ridhi, er al. "Efficacy of automatic emergency braking among risky drivers using counterfactual simulations from the SHRP 2 naturalistic driving study", *safety science*, vol.128, no.1,pp.112-123, 2020.