Analysis of Key Technology Enhancements for Lane-Level Navigation

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Abstract. With the acceleration of urban construction and the paving of structured roads, lane-level navigation has emerged to provide drivers with detailed road scene information and accurate guidance. This paper discusses the principles and current research status of the key technologies of the two components, Global Navigation Satellite System/ Inertial Navigation System(GNSS/INS) combined system and odometer, which constitute lane-level navigation, and analyses the challenges they face. The paper concludes that the problems faced by GNSS/INS systems can be classified into two parts, namely, partial obscuration of satellite signals and complete obscuration; for partial obscuration, an augmented positioning system using Kalman filter is developed, and for complete obscuration, an error constraint model is established. In addition, the deficiencies of existing mechanical and electronic odometers in terms of stability and accuracy are analysed, and the method of constructing binocular visual odometers is adopted to assist positioning. Finally, the comprehensive application of lane-level navigation is emphasised and the development direction of integrating more hardware and software is pointed out, which provides ideas and references for the subsequent research and application work carried out.

Keywords: Lane-Level Navigation; Combined Gnss/Ins Navigation; Visual Odometry; Positioning System

1 Introduction

With the acceleration of urbanisation and the continuous updating and construction of infrastructure, the transport network around the world is constantly expanding and developing, and the modern transport environment has become more complex. To solve the traffic congestion, urban two-dimensional space is limited and other problems, an efficient organisation of each element of traffic travel, three-dimensional traffic came into being. With the promotion of three-dimensional traffic, overpasses, tunnels and other roads more and more, and often accompanied by multi-lane, complex intersections and other characteristics. At this time, the traditional navigation system can only provide overall line guidance, in multi-lane, multi-intersection road conditions such as positioning accuracy is insufficient to meet the driver's need for lane

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information. Therefore, lane-level navigation came into being, in complex road conditions, through high-precision technology to restore the real road scene, to provide drivers with more detailed and accurate navigation services, to achieve accurate vehicle positioning and provide the best route selection [1]. Lane-level navigation as an integral part of intelligent traffic, connected with signal lights, traffic management systems, etc., to aggregate the data of each user, play an important role in the macro deployment of traffic conditions, and feedback real-time information to the user to improve the level of urban traffic intelligence and traffic efficiency. Lane-level navigation improves driving safety and efficiency, provides real-time traffic information alerts and lane decision support while achieving accurate positioning, and optimises the use of road resources.

One of the key technologies for lane-level navigation is combined Global Navigation Satellite System/ Inertial Navigation System(GNSS/INS) navigation. At present, global research in the field of combined GNSS/INS navigation is quite active. The United States has successfully launched a new generation of Global Positioning System (GPS) satellites, which have been optimised in terms of navigation payload, anti-jamming capability, accuracy and hardware facilities. As for China's BeiDou group network, it has been developed in terms of high-precision and miniaturised combined navigation and positioning attitude fixing system, which has achieved high positioning accuracy. Researchers have conducted in-depth analyses of the performance of GNSS/INS combined navigation systems in different environments and classified their combination methods into shallow coupling, tight coupling and deep coupling. Research progress has also been made in low-cost GNSS/MIMU deep-combined navigation systems, providing more possibilities for the application of deep-combined technology.

Another key technology for lane-level navigation is the odometer. Modern purely mechanical odometers usually consist of a worm gear mechanism, a wire flexible shaft, etc., and display the mileage through mechanical transmission. In contrast, mechanical-electronic odometers use processed pulse signals to obtain speed and mileage information. With the further development of electronic technology, purely electronic odometers began to appear. Its electronic sensor does not direct contact with any mechanical parts, and outputs pulse signals by sensing the rotation of the target wheel, thus calculating the speed information and mileage information. As a low-cost sensing source, the odometer mainly provides longitudinal positioning data, and it is an indispensable on-board sensor.

This paper is based on the separate enhancement of some of the key systems of lane-level navigation, aiming to improve the overall stability of navigation. In Chapter 2, the applications and some technical components of lane-level navigation are briefly introduced. In Chapter 3, the challenges faced by combined navigation satellite system signals when subjected to environmental interference and some of the methods for their accuracy enhancement are discussed, and some of the methods for auxiliary enhancement to address the shortcomings of wheeled odometers are explored. Recommendations and perspectives are presented in chapter 4.

2 Lane-level navigation applications and key technology features

2.1 Integrated lane-level navigation applications

Lane-level navigation has a wide range of applications and can be useful in a variety of fields. Lane-level navigation has become a platform for the development of technologies in many different fields, which make use of the high-precision coordinate information provided by lane-level navigation in order to monitor the vehicle's driving status in real time.

For example, under the high precision conditions of lane-level navigation, it is possible to design dangerous driving behaviour detection algorithms that not only provide timely warnings of dangerous driving behaviour to reduce accidents but also provide statistical analysis of drivers' driving habits to better regulate driving.

And driverless cars are developing rapidly, with a growing audience at home and abroad and in various fields. In China, travel service platforms such as Radish Express and Wenyuan Zhixing are developing rapidly, using driverless cars to provide intelligent and convenient travel services for the public. Robovan, released by Tesla in the US in November 2024, has also received extensive attention from the market. The practical application of these driverless vehicles cannot be separated from the development of high-precision lane-level navigation, and the integration of driverless procedures and lane-level navigation procedures will make traveling more efficient.

2.2 Introduction to combined GNSS/INS navigation

GNSS refers to the global satellite navigation system, including GPS, BeiDou satellite navigation system, Galileo, etc., which can provide high-precision three-dimensional position, speed and timing information, etc. GNSS consists of space satellites transmitting navigation signals, and the user's receiver receives the satellite signals and then decodes the user's position and speed information, etc. The average minimum accuracy of GNSS is in the form of single-digit in meters, but the signal propagation path is long and susceptible to multipath effects and signal attenuation. The signal propagation path is long, easy to be affected by multipath effect and signal attenuation, etc., and there is uncertainty in inter-star chain transmission, in this regard, there are hybrid star chain planning algorithms and other methods to improve its stability[2-5].

The inertial navigation system (INS) mainly measures acceleration and angular velocity by inertial measurement units, and obtains information of velocity, yaw angle, and position in the navigation coordinate system after calculation. During its operation, computational errors and hardware errors occur, which are amplified and accumulated in the continuous integration [6].

The combined navigation system is a combination of the two, GNSS provides high-precision absolute position information, which is used to calibrate and compensate for the accumulated errors of INS. INS is able to provide more accurate position data for a short period of time when the GNSS signal is briefly interrupted. Combined navigation relies more on the accuracy and data of GNSS, and when it is interfered or even fails, the overall system accuracy is more affected [7].

GNSS signals are easily blocked by complex environments, due to navigation satellites far from the ground (usually between 20,000~30,000km), the satellite signal propagation to the ground (receiver) has been very weak, the user side of the surrounding environment due to obstacles blocking, reflecting the satellite signals, resulting in poor signal reception, especially man-made buildings are more and more diversified in the environment of the city high-rise subject to the The multipath effect [8] is more obvious, and structured roads are more and more complex, such as tunnels and other scenarios, the diversity of interferences, so that the satellite navigation is facing a greater challenge. In this paper, signal masking is divided into two cases, partial signal masking and total masking, and countermeasures are proposed respectively.

2.3 Introduction to vehicle wheeled odometers

A wheel odometer is a sensor used to obtain the speed and displacement of a vehicle. It is based on the rotational motion of the wheels, and by recording the angle of rotation of each wheel and the distance traveled, it deduces the change in the vehicle's position during the movement [9]. It is low-cost and more mature technology, with sufficient accuracy for short-distance movements, and is widely used in mobile systems.

The existing mechanical and electronic wheeled odometers for vehicles are not stable enough. Due to the influence of many factors, such as wheel wear, ground friction, uneven road surface, tyre side-slip, etc., often because the wheel rotation distance does not match with the actual forward distance of the vehicle, resulting in cumulative errors in the measurement results of wheeled odometers, and the error is unavoidable (longitudinal positioning accuracy), which affects the accuracy of the measurement. In this paper, a visual odometer will be established to make up for its lack of accuracy.

3 Key technology enhancements

3.1 Solving the problem of partial occlusion of GNSS navigation signals

Provided that GNSS is effective, an augmented positioning system will be established to improve lane-level navigation and positioning accuracy.

3.1.1 Enhanced positioning system framework.

Based on combined GNSS/INS navigation, the combined navigation algorithm is designed using a Kalman filter and loose coupling. Kalman filter is an algorithm for optimal estimation of the system state using linear system state equations. Loose coupling, on the other hand, is a data and system integration method, featuring weak dependencies between subsystems. The combined navigation algorithm fuses cameras to identify the regulated lane lines and vehicle lateral distances on structured roads. Next, a lane change recognition algorithm is designed to calculate the vehicle lane change status. Lane information and left and right boundary information are subsequently fed into the boundary lateral positioning method and a continuous algorithm is used to smoothly control the navigation route trajectory, thus enhancing the lateral positioning accuracy and error convergence of the GNSS/INS system [10].

The augmented positioning system has good positioning accuracy in structured road scenarios, and its design trajectory is continuously smooth, which significantly reduces the error of combined GNSS/INS navigation.

The input of this design is based on the camera, and the camera itself has some instability, such as when it is subjected to bright light, electromagnetic interference, physical blocking, etc., the input image, if distorted, will break the stability of the system.

3.1.2 Combined GNSS/INS navigation algorithms.

Firstly, the vehicle speed and attitude information measured by GNSS is converted into a coordinate system to transform its elevation, latitude and longitude into the navigation coordinate system, and under the effective premise of GNSS, the linear error is measured by Kalman filtering after making a difference with the speed, position and attitude information measured by the inertial measurement unit IMU, and then the error feedback is carried out after the error is corrected for the result of inertial navigation, and then it is output. The inertial navigation results are corrected and then output.

3.1.3 Camera and lane line based enhancement algorithm.

The lane change recognition algorithm uses the camera to identify the lane information, in the case of a clear lane line, only based on the measured distance from the side of the line can determine whether the vehicle is changing lanes. In the case where the lane line is not clear or cannot be detected, the vehicle can be judged to have changed lanes based on several factors, such as swing angle speed, heading angle, and length of lane change. After that, based on map matching, the initial left and right boundary points are updated by comparing the driving distance and the spacing of the discrete points on the lane line, and then the final position coordinates are determined by weighted average of the lateral positioning of the bilateral boundaries. Finally, the fluctuating and disconnected vehicle trajectories are corrected and smoothed by combining the vehicle motion parameters.

3.2 Solving the problem of complete occlusion of GNSS navigation signals

An error constraint model will be developed to improve lane-level navigation and positioning accuracy in the presence of GNSS failures.

3.2.1 Error modeling framework and sources of error.

In the downgrading of the combined navigation to INS inertial guidance, the established vehicle dynamic model is converted based on the measurement input method of the combined navigation Kalman filter. The state of the moving object is estimated using kinematics theory and the operating environment, and its velocity and position values are measured virtually, respectively. Both can be used individually or in combination to improve navigation accuracy during signal interruptions [11].

Bias introduced by inertial navigation is divided into two types of uncompensated bias: accelerometer uncompensated bias and horizontally aligned gyroscope uncompensated bias. The loss of GNSS signals does not allow for an accurate compensation correction of the bias.

3.2.2 Velocity and position models.

Firstly, the X-axis velocity and Z-axis velocity of the velocity error constraint model are zero, and the direction cosine matrix and the velocity of the measured object in the navigation coordinate system are taken as the parameters to construct the state and measurement equations of the Kalman filter, and the system state model and system measurement model are thus established. Afterwards, in the position error constraint model, the value of elevation is fixed, and the Kalman filter model is constructed with the latitude, longitude and elevation of the calendar element before the disappearance of the GNSS signal, and then the measurement vectors and measurement matrices are constructed, which can constrain the accumulation of the error to a certain extent[12], and the higher the match between the actual operating environment and the preset environment, the more obvious the error constraint is, and the lower the match, the more obvious it is, and it also has the effect of suppression of error, and the measurement noise is also used as an element in the formula. noise is also used as an element in the formula to compensate for the motion deviation in a short period of time. Both velocity and position constraints can be modeled independently or in combination with other constraints.

3.3 Addressing the lack of accuracy of wheeled odometers

In addition to the common wheeled odometers, binocular vision odometers are constructed to improve positioning accuracy.

Points in different captured images, thus providing a positional estimation of the target [13-14]. Firstly the imaging principle of the camera can be analogised with small hole imaging, only the inverted imaging is processed for inversion, and then the image is corrected for the camera aberrations produced by the lens. With a binocular camera, the image data acquired by the two cameras can be compared and processed in order to build a more accurate 3D model to restore the real scene. Secondly, the image acquisition is based on feature points, and the image is first pre-processed such as grey scale processing, distortion processing, etc. for subsequent recognition, and then the image is processed using Scale-Invariant Feature Transform (with scale and rotation invariance), Binary Robust Invariant Scalable Keypoints (with Robust to Noise), Speeded Up Robust Features (faster computation) and other feature point detection algorithms are used to track and identify the feature points of continuously changing images and feature matching is performed to determine a space.

The distortion-processed camera ingested image is input into the YOLACT instance segmentation model, the left eye image is detected, the vehicle MASK is obtained, the MASK is expanded morphologically in order to expand its range, and after that, the extracted ORB feature points are screened with the MASK, and dynamic feature points (such as those on surrounding vehicles and pedestrians) are eliminated. The binocular image parallax map is obtained using the SGBM algorithm, and then this is used to obtain the parallax of the static feature points, and the spatial coordinates of the spatial points corresponding to the static feature points are calculated in the camera coordinate system. The Lucas-Kanade sparse optical flow is used to track the feature points to obtain their positions in the next frame of the image, and the key points are screened according to the range thresholds of the error and coordinates, and their spatial coordinates are obtained by combining the parallax information. Finally, the camera itself is used for position estimation using the RANSAC algorithm and minimising the reprojection error. The overall system is robust and accurate. A more accurate positioning system is obtained by combining the position results with the GNSS positioning information.

4 Recommendations and perspectives

In this paper, the improvement of the combined GNSS/INS navigation and the design of the visual odometer is based on the camera. And there are many sensors other than cameras available. For example, the LiDAR sensor (SLAM), which measures the distance and estimates the position and direction by emitting laser pulses, has the advantage of being independent of light conditions over the camera, and can briefly replace the camera in unexpected situations such as strong light or severe lack of light. Ultrasonic radar, on the other hand, has the advantages of low cost and simple information processing.

As a result, the advantages of different sensors can be fully utilised to further improve the robustness and accuracy of lane-level navigation in multivariate situations. In addition, the loosely coupled approach taken by the algorithms involved in this paper is scalable and also provides interfaces for incorporating more sensors, which can further improve the overall performance of different algorithms if they are integrated. The environmental challenges faced by lane-level navigation are still many, the scene of urban roads is changing all the time, the speed of three-dimensionalization is getting faster and faster, and the adaptability of lane-level navigation in the face of unexpected environments still needs to be improved. The improvement of each key technology of lane-level navigation will support its qualitative change.

5 Conclusion

This paper gives a brief introduction to the functions and development of the combined GNSS/INS system and vehicle odometer, analyses the urban three-dimensional traffic scenarios to be faced nowadays, and determines the direction of improvement by analysing the shortcomings of the existing technology in facing complex traffic conditions and conducting error analysis on its components, to improve the combined GNSS/INS navigation system and vehicle odometer respectively. Firstly, the GNSS signals are classified into two kinds of situations: partial and complete occlusion, which are targeted to be solved by establishing an enhanced positioning system and an error harvesting model, and secondly, a binocular visual odometer is designed to make up for the shortcomings of wheeled odometers. In this paper, a camera is introduced for environment sensing, and auxiliary algorithms are developed to constrain the error and assist positioning so that the robustness and accuracy of lane-level navigation can be effectively improved. If multi-sensor-assisted positioning can be fused, the working performance of navigation will be further improved.

References

1. Skog, I., Handel, P.: 'In-car positioning and navigation technologies—A survey', IEEE Transactions on Intelligent Transportation Systems, 2009, 10, (1), pp. 4-21
2. Nasser, G., J, H. V., Hubert, R., et al.: 'A review of GNSS-independent UAV navigation techniques', Robotics and Autonomous Systems, 2022, 152, pp. 104069
3. Montenbruck, O., Steigenberger, P.: 'The 2024 GPS accuracy improvement initiative', GPS Solutions, 2024, 29, (1), pp. 33-33
4. Tan, H., Huang, J.: 'DGPS-based vehicle-to-vehicle cooperative collision warning: Engineering feasibility viewpoints', IEEE Transactions on Intelligent Transportation Systems, 2006, 7, (4), pp. 415-428
5. Ding, R.: 'Hybrid interstellar link planning method for navigation satellite networks', Central South University, 2023. DOI:10.27661/d.cnki.gzhnu.2023.003342
6. Zhu, J.: 'Research on BeiDou-3/Inertial Navigation Combined Positioning Technology', Shenyang University of Aeronautics and Astronautics, 2023. DOI:10.27324/d.cnki.gshkc.2023.000091
7. Chen, M.: 'Research on combined GNSS/SINS navigation technology in complex urban environment', Nanjing University of Information Engineering, 2024. DOI:10.27248/d.cnki.gnjqc.2024.000279
8. Park, D. K., Yoon, J. W., Lee, S. J.: 'Reduction of multipath effect in GNSS positioning by applying pseudorange acceleration as weight', Sensors, 2024, 24, (21), pp. 6880-6880
9. Ma, L.: 'Research on AGV positioning and autonomous navigation based on multi-sensor fusion', South China University of Technology, 2022. DOI:10.27151/d.cnki.ghnlu.2022.004993
10. He, K.: 'Research on key technology of lane-level positioning and navigation system for driverless cars', Jilin University, 2023. DOI:10.27162/d.cnki.gjlin.2023.007119
11. He, T.: 'Research on key technology of GNSS/MEMS IMU/CSAC vehicle-mounted combined navigation', University of Chinese Academy of Sciences (National Timing Centre of Chinese Academy of Sciences), 2023. DOI:10.27547/d.cnki.gkgsc.2023.000014
12. Klein, I., Sagi, et al.: 'Pseudo-measurements as aiding to INS during GPS outages', Navigation, 2010. DOI:10.1002/j.2161-4296.2010.tb01765.x
13. Lowe, D. G.: 'Distinctive image features from scale-invariant keypoints', International Journal of Computer Vision, 2004, 60, (2), pp. 91-110
14. Bay, H., Tuytelaars, T., Van Gool, L.: 'SURF: Speeded up robust features', European Conference on Computer Vision, Springer, Berlin, Heidelberg, 2006, pp. 404-417.