Journal of Global Positioning Systems (*2022*)

Vol. 18, No.12: 88-89

Research on LiDAR/INS/ODO/GNSS vehicle integrated navigation algorithm based on graph optimization

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Graduation Date: Dec 2021

Abstract

With the rapid development of digital earth and smart city, the demand for localization-based services is becoming urgent. However, continuous, accurate, and reliable positioning navigation in complex environments is a common key technical issue that need to be solved. While GNSS positioning deteriorates or even fails in urban canyons; the positioning error of low-cost INS quickly diverges over time; LiDAR has poor positioning availability when environmental features are insufficient. In order to improve the positioning and navigation service capabilities, China plan to build a more ubiquitous, more integrated, and smarter national comprehensive PNT (Positioning, Navigation, and Timing) system in 2035. And the multi-sensor information fusion is one of the key components of the comprehensive PNT.

Since the insufficient vertical resolution of the low-beam LiDAR causes the degradation of LiDAR odometry in some environments, we propose a feature point-based probability map matching method, which combines the advantages of matching by feature point with a probability map. The process extracts the ground feature points and the non-ground feature points by segmentation. A probability map with different resolutions will be constructed to deal with those features, respectively, with a higher vertical resolution for the ground feature and a higher horizontal resolution for the non-ground part. Scan matching by a probability map constructed by feature points minimizes the dependence on the line and surface features in the environment. It has been compared with the well-known open-source LiDAR odometry, i.e. Cartographer and LeGO-LOAM. Evaluations were carried out in different feature scenes. In the areas with rich line and surface features, the positioning accuracy of the proposed method is better than Cartographer, primarily the positioning result on the elevation and horizontal attitude. In areas lacking line and surface features or with the ramped ground, the positioning error of LeGO-LOAM is larger than the proposed method, and it even crashed in some challenging scenarios.

Since incorrect exterior parameters of sensors cause inaccurate navigation results, a method for IMU/ODO and LiDAR/IMU calibration by utilizing ODO and IMU pre-integration are proposed:

(1) A method of IMU/ODO calibration by utilizing ODO pre-integration is proposed. It is based on the graph optimization theory and not sensitive to the

initial value of the exterior parameters. There is no need to estimate the state of the vehicle. It has the capability of lever arm estimation. The simulation and field tests show that the error of the lever arm is less than 5 cm, and the error of mounting angles is less than 0.1°. Since the ODO measurement value by the calibration result is equivalent to centimeter-level mileage increment, the calibration method can meet the requirements of centimeter-level positioning.

(2) A method of IMU pre-integration is proposed to eliminate the motion distortion of LiDAR, which not relies on GNSS information, and avoid the double alignment process in common calibration methods. In addition, the integral of IMU mitigates the impact of IMU noise. Simulation and real tests show that the lever-arm estimation error is about 1 cm, and the mounting angle estimation error is about 0.1°.

In order to improve the accuracy and usability of vehicle positioning in complex environments, a multi-source fusion algorithm based on graph optimization is designed and implemented. Based on the LiDAR odometry, this algorithm adopts IMU/ODO pre-integration constraints to enhance the positioning stability in environments with insufficient features. And the global pose assistance by a pre-built probability map matching ensures positioning accuracy when GNSS fails. The marginalization and the sliding window are employed to remove the historical parameters while keeping the efficiency of the optimizer. A fully functional LiDAR/INS/ODO/GNSS vehicle navigation software - *LIOGNS*, has been developed for algorithm validation. The performance of three navigation modes were tested and analyzed through multiple datasets, including positioning by a pre-built map, GNSS/INS/LiDAR fusion, and GNSS/INS/ODO/LiDAR fusion.

The mode of pre-built map matching of *LIOGNS* is tested in the international competition (JD Digital Technology Global Explorer Competition, ‘Autonomous Driving Map Optimization and Sensor Fusion’ track, 2018). The multi-source data fusion algorithm was utilized to optimize the point cloud mapping and the positioning mode with a pre-built map. **It achieved 5cm position accuracy and 0.1° attitude accuracy, and won the championship of the global finals**. The GNSS/INS/LiDAR-SLAM integrated positioning performance of *LIOGNS* was tested and compared with Cartographer and LIO-SAM, through simulated GNSS interruption and real frequent GNSS occlusion in campus environment. Since the Cartographer was designed suitable for low dynamic vehicles, its roll, pitch, and elevation errors are relatively large. Limited by the IMU noise modeling, the horizontal attitude and elevation error of LIO-SAM are equivalent to Cartographer, and the horizontal position accuracy is better than Cartographer. **The position and attitude accuracy of the proposed *LIOGNS* is superior than LIO-SAM and Cartographer, especially in the environment where the GNSS signal is weak or blocked.** The accuracy and usability of the odometer assistance were tested based on simulated GNSS interruptions and in a tunnel that lack of environmental features. Insufficient features in the tunnel lead to significant positioning drift along the longitudinal direction. However, **the odometer limits such drift effectively and significantly enhancing the reliability when both GNSS and LiDAR fail**.

In summary, this thesis proposed a LiDAR/INS/ODO/GNSS vehicle integrated navigation algorithm based on graph optimization, and completed the core algorithm design and software implementation. Through the datasets of open-sky area with simulated GNSS interruption, GNSS frequent failure environment and tunnel scenes, the proposed algorithms were thoroughly tested and analyzed. The scheme can meet the requirements of continuous, accurate and reliable positioning and navigation in complex environments for autonomous driving and mobile robot applications.

Key words: LiDAR SLAM, GNSS/INS, Wheel Odometer, Integrated Navigation, Preintegration, Graph Optimization, Exterior Parameter Calibration