Fast Closed-Loop SLAM based on the fusion of IMU and Lidar

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Abstract. In the large-scale mapping of Lidar SLAM, there are problems of slow closed-loop detection speed and false detection. To solve this problem, this paper proposed a method based on the fusion of IMU and Lidar. Use IMU geomagnetic data for geomagnetic matching and filter the pose nodes in the map to reduce the search space during closed-loop detection. At the same time, due to the reduction of the search space, it can effectively reduce the high local similarity in Lidar SLAM false detection caused. This experiment verified the method by collecting Lidar point cloud data and IMU three-axis geomagnetic data in a real environment, the closed-loop detection speed and map average absolute error of frame-by-frame method, branch-and-bound method, DTW fusion algorithm and Fast-DTW fusion algorithm were verified and compared. Experimental results shown that, compared with DTW fusion algorithm, the proposed algorithm improved the closed-loop detection speed by 17%, reduced the average absolute error of translation by 16%, and reduced the average absolute error of rotation by 10%.

Keywords: Lidar SLAM; closed-loop detection; geomagnetic matching

1. Introduction

SLAM (simultaneous localization and mapping) is a key technology used to solve the environmental map and positioning information of wheeled robots. SLAM technology considers the real topological structure of the environment, can directly and effectively obtain the environment map, and can update the map as the environment changes. SLAM based on Lidar can accurately measure the angle and distance of obstacle points and is not affected by light when working. It is widely used in fields such as unmanned vehicles, indoor and outdoor robot navigation and 3D reconstruction. When the structure of the mapping scene has a certain similarity, the Lidar point cloud will not be enough to clearly describe the real environment, and it is easy to produce false alarms during SLAM closed-loop detection, thereby reducing the performance of SLAM and causing the map to be inconsistent with the real environment. The fusion of auxiliary information can effectively reduce the misdetection caused by high local similarity in SLAM, improve the efficiency of closed-loop detection, and reduce the accumulated map error.

The intensity and direction of the magnetic field will change with the change of the observation position. This shows that the results of magnetic field measurement contain position information. [1] first used geomagnetism to solve the SLAM problem and proved the feasibility of the experiment. [2] proved that the anomalies of the magnetic field inside the building are almost static and they have enough local variability to provide the only magnetic fingerprint for positioning. [3] proposed a smart phone indoor
positioning system to locate the location of indoor target pedestrians. [4] believed that low-cost magnetometers in mobile phones could not meet the positioning accuracy requirements and proposed the use of geomagnetic positioning in combination with other positioning methods. [5] combined geomagnetism with motion mode and proposed an attitude map SLAM Based on key frame. To enhance the adaptability and accuracy of geomagnetic positioning, [6]-[8] applied Dynamic Time Warping (DTW) to geomagnetic positioning to improve geomagnetic matching speed and positioning accuracy. [9] combined the ant colony algorithm with DTW algorithm, although it can obtain high geomagnetic positioning accuracy, but the method has high complexity and poor real-time performance. [10] proposed a geomagnetic location algorithm based on fast dynamic time warping (Fast-DTW) to solve the problem of poor real-time performance of DWT algorithm in geomagnetic matching location. While maintaining high positioning accuracy, the real-time performance of positioning was improved by reducing search strategy. Aiming at the problems of slow closed-loop detection matching speed and false detection during large-scale mapping, this paper combines Fast-DTW geomagnetic matching and proposes a SLAM based on the fusion of IMU and Lidar.

2. The fusion strategy of geomagnetic matching and Lidar SLAM

DTW can compare the similarity of two sequences very well. Its core idea is to calculate the sum of the Euclidean distances of the points \( X \) and \( Y \) of the two-time series of \( X_i \) and \( Y_j \) corresponding to the coordinates \((i, j)\) of all points passed by this path. The smaller the distance, the more similar the two sequences. According to the ideas of dynamic programming:

\[
D(i, j) = \text{Dist}(i, j) + \min\{D(i - 1, j), D(i, j - 1), D(i - 1, j - 1)\}
\]

The DTW algorithm will continuously search for the cost matrix element \( D(i, j) \) according to formula (1) and will search all elements each time it is executed, which is inefficient. When the two sequences are long sequences, the real-time performance of the algorithm will be very low. Reducing the search space of the algorithm can effectively reduce the complexity of the algorithm. Fast-DTW improves the DTW algorithm mainly in two points:

- Constraints-limit the number of cells evaluated in the cost matrix, such as the Sakoe-Chuba Band constraint and Itakura Parallelogram constraint, as shown in Figure 1.
- Abstraction-Firstly, the large matrix composed of two long-time sequences is coarse-grained, and then the shortest path is calculated using the DTW algorithm, and then fine-grained under the condition of controlling the search range of the path.

![Figure 1. A graph is sakoe chuba band constraint, b graph is Itakura parallelogram constraint.](image-url)
The process of Fast-DTW is shown in Figure 2. When using Fast-DTW for geomagnetic matching, the goal is to find the minimum similarity distance of the geomagnetic data sequence. The modulus of the geomagnetic field is selected as the geomagnetic characteristic quantity. For example, the geomagnetic component in the x-axis direction is \( d_x \), the geomagnetic component in the y-axis direction is \( d_y \), and the geomagnetic component in the z-axis direction is \( d_z \), then the modulus of the geomagnetism is:

\[
DC = \sqrt{(d_x)^2 + (d_y)^2 + (d_z)^2}
\]  

(2)

Suppose the length of the geomagnetic data sequence to be matched is \( m \), \( DC_M = (DC_1, DC_2, \ldots, DC_m) \), and the length of the geomagnetic database sequence is \( n(n > m) \), \( DC_N = (DC_1, DC_2, \ldots, DC_n) \). When performing geomagnetic matching, intercept data with the same length as \( DC_M \) from \( DC_N \) for matching, until all data of the \( DC_N \) matches the \( DC_M \). According to Fast-DTW, the similar distance \( L \) of each pair of data is obtained. After all the data are matched, a similar distance set \( L=(l_1, l_2, \ldots, l_s) \) is obtained. The data corresponding to the minimum value in the set is the optimal matching data. In the fusion of geomagnetic matching and Lidar SLAM, the unmanned vehicle obtains the corresponding three-axis geomagnetic data while scanning the environment map, calculates the geomagnetic modulus value and adds it to the geomagnetic database. When the environmental map scan is completed, the geomagnetic database data \( DC_N \) is established. When the Lidar SLAM performs a closed-loop search, the submap-to-submap matching is used. When the new submap \( submap_{new} \) is constructed, a corresponding geomagnetic data sequence \( DC_{new} \) is generated, and the Fast-DTW algorithm is used to search for the smallest similar distance to \( DC_{new} \) in the \( DC_N \) Geomagnetic sequence \( DC_{match} \), and then add the pose node in the \( submap_{match} \) to the closed-loop detection candidate pose set \( P \), and then use formula (9) to calculate the best closed-loop pose \( \xi \).

3. Experiment and result analysis

The experimental platform used in this article is the Beijing Union University United Rainbow series of unmanned vehicles. The sensors used are Leishen Intelligent 16-line Lidar and Sparkfun 9-axis IMU. The experimental scene selected for this experiment is the 1st floor of the experimental building of Beijing Union University. The geomagnetic matching and Lidar SLAM experimental platform is shown in Figure 3.
Figure 3. Experimental platform of geomagnetic matching and Lidar SLAM

Through many linear velocity and angular velocity tests, the linear velocity of 1.5m/s and angular velocity of 30deg/s were selected to test and compare the four algorithms of frame-by-frame method, branch-and-bound method, DTW fusion method and Fast-DTW fusion method. Each algorithm was tested 100 times, and the average value was taken to compare and analyse the closed-loop detection speed and absolute error. The closed-loop detection speed comparison of the four algorithms is shown in Table 1, the translation error comparison is shown in Figure 4, the rotation error comparison is shown in Figure 5, and the mean absolute error pairs are shown in Table 2.

Table 1. The closed-loop detection speed comparison of the four algorithms

| Algorithms             | Candidate set | Time consuming |
|------------------------|---------------|----------------|
| Frame-by-frame         | 157           | 12968ms        |
| Branch-and-bound       | 58            | 6638ms         |
| DTW                    | 23            | 943ms          |
| Fast-DTW               | 14            | 806ms          |

According to Table 1, the search and matching efficiency of the frame-by-frame method is the lowest. There are 157 candidate sets satisfying the closed-loop detection score threshold, and the single search and matching time is 12968ms. The branch-and-bound method is optimized in the search step size, the number of candidate sets is reduced to 58, and the single search and matching time is 6638ms. DTW fusion method according to the result of geomagnetic matching greatly narrowed the search scope, the decrease in the number of candidates for 23, a single search matching time for 943ms, this article uses Fast-DTW fusion method, not only reduces the search range, and accelerated the speed of geomagnetic matching, the decrease in the number of candidates to 14, a single search matching takes only 806ms. From the experimental results, it can be seen that compared with the frame-by-frame method and the branch-and-bound method, the Fast-DTW fusion method greatly improves the speed of closed-loop detection. Moreover, compared with the DTW fusion method, the Fast-DTW fusion method used in this paper increases the speed of closed-loop detection by 17%, which can effectively improve the real-time performance of closed-loop detection.

Figure 4. The translation error comparison of 100 experiments.
Figure 5. The rotation error comparison of 100 experiments.

Table 2. The average absolute error comparison of the four algorithms

| Algorithms       | Average translation absolute error | Average rotation absolute error |
|------------------|------------------------------------|---------------------------------|
| Frame-by-frame   | 0.09504m                           | 0.27096deg                      |
| Branch-and-bound | 0.05050m                           | 0.25101deg                      |
| DTW              | 0.04276m                           | 0.19535deg                      |
| Fast-DTW         | 0.03575m                           | 0.17571deg                      |

According to Figure 4 and 5, the Fast-DTW fusion method is the best among the four algorithms, and the absolute errors of translation and rotation are the lowest. According to Table 2, Compared with the frame-by-frame method and the branch-and-bound algorithm, the Fast-DTW fusion method greatly reduce the average absolute error of translation and rotation. Compared with the DTW fusion algorithm, the translation average absolute error of the Fast-DTW fusion method is reduced by 16%, and the rotation average absolute error is reduced by 10%. Therefore, this algorithm can effectively improve the accuracy of SLAM.

4. Conclusion
In this paper, a fast closed-loop detection method combining Fast-DTW geomagnetic matching and lidar point cloud matching was proposed to solve the problems of slow matching speed and false detection in large-scale unmanned mapping. This paper collected the experimental data in the real environment and made a comparative analysis of four methods: frame by frame method, branch-and-bound method, DTW fusion method and Fast-DTW fusion method. The experimental results shown that the closed-loop detection speed and average absolute error of Fast-DTW fusion algorithm are the best among the four algorithms, which can effectively improve the real-time performance of closed-loop detection and reduce the mapping error. But there is still room for improvement, such as fusion with vision sensor.

5. Reference
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Acknowledgments
This work was supported, the National Natural Science Foundation of China (Grant No. 61932012), the Beijing Municipal Commission of Education Project (No.KM202111417001), the Academic Research Projects of Beijing Union University(No. ZB10202003, ZK80202001, XP202015), the Postgraduate research and innovation funding project of Beijing Union University (yz2020k001).