Scan Matching and SLAM for Mobile Robot in Indoor Environment

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Introduction

Autonomous indoor mobile robots are very promising application of robotics. In order to realize autonomous navigation, a robot that enters an unknown environment needs to reconstruct a consistent map of the environment and estimate its pose with respect to the map, simultaneously. This problem is well known as the Simultaneous Localization And Mapping (SLAM) problem, which has attracted a lot of interest from researchers in past few decades. The most popular approaches towards SLAM problem are usually developed based on the probabilistic methods, such as Extended Kalman Filter (EKF) SLAM, particle filter SLAM, and maximum likelihood SLAM. In recent years, a robust technology named “Scan Matching” plays a very important role in solving the SLAM problem. By matching sensor scans that are taken from different poses, the scan matching method can efficiently estimate the rigid transformation of the robot between two poses. Due to the fact that the exploring sensors are usually very accurate and fast, scan matching is very efficient for mobile robot to localize itself with respect to the given reference scans or maps.

Although vision based approaches are getting more and more popular in SLAM research field, vision sensors are sensitive to the unpredictable variations of environment, such as the change of the lighting condition. Besides, most vision based solutions construct sparse feature points based maps which are not sufficient for robot autonomous navigation. Therefore Laser Range Finder (LRF) based scan matching method and fast indoor SLAM framework are still widely desired in consideration of the robustness of LRF towards environment changes. Another widely adopted sensor is Inertial Measurement Unit (IMU) which provides measurements of accelerations and rotating rates at the same time. In consideration of cost efficiency, Micro Electrical Mechanical Systems (MEMS) technology based IMU is preferable in consuming grade applications as well as robotic researches. However, the measurements of low-cost MEMS-IMUs are usually corrupted by various types of noises. Thus, a calibration work to compress noises is necessary before the usage of MEMS-IMU.

The contributions of this study are consisted of following three main parts:

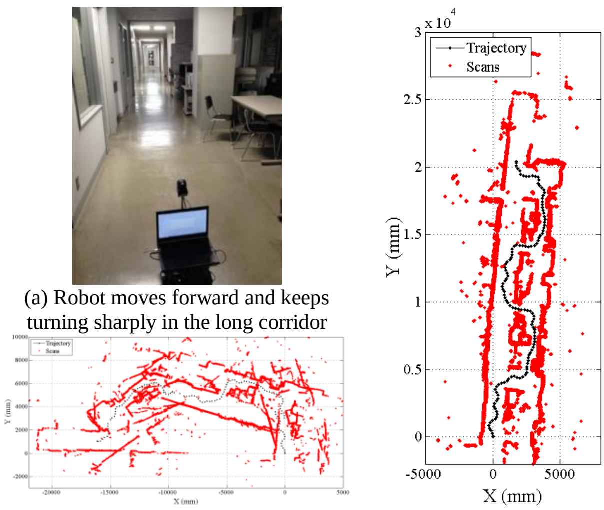
1) Various scan matching methods have been introduced. And the most widely used methods, Iterative Closest Point (ICP) and its variants, have been investigated and modified to obtain even better scan matching performance. Furthermore, an incremental scan matching frame that can be utilized in large scale environment has been proposed.

2) A line-segment based EKF-SLAM approach is proposed for the application in structured indoor environment. In addition to fulfilling planar SLAM task with line-segment based maps, this method can efficiently detect the slope and edge that exist in structured indoor environment.

3) Taking advantage of the proposed robust scan matching solution, a straightforward and efficient calibration method toward MEMS-IMU has been developed.

Fast and Robust Scan Matching

ICP is the most widely applied scan matching method in robotics for its superior simplicity and efficiency. In this study, two ICP variants, Point-to-Point ICP and Point-to-Line ICP (PLICP) have been deeply investigated. To overcome the weakness of ICP variants when they match scans with large rotation, an algorithm named Iterative Closest Normal (ICN) that can efficiently correct the unexpected large rotation between two scans has been proposed. ICN estimates the rotation by iteratively associating the points in two scans that have similar radial distance and similar normal vector with the smallest compensating angular distance. After rotation between scans has been compensated by using ICN, ICP and PLICP are applied to estimate the residual transformation, respectively. The experimental results show that ICP variants become more robust against large rotation and be more accurate after introducing the ICN algorithm, as shown in Figure 1. In most experiments, PLICP performs relatively better than ICP in the convergence speed and matching accuracy. Therefore the combination of ICN and PLICP is a better solution of LRF scan matching for indoor robot SLAM.



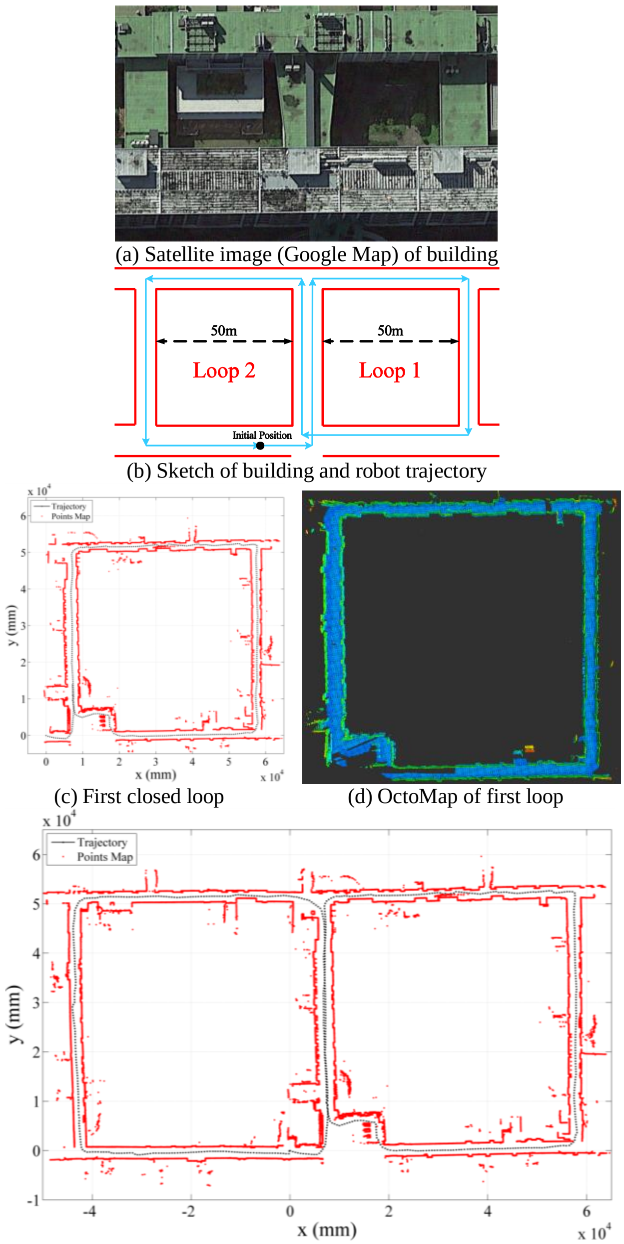
(a) Robot moves forward and keeps turning sharply in the long corridor

(b) Scan matched by using PLICP only

(c) Scans matched by using ICN and PLICP

Figure 1. The experiment of ICN verification

To speed up the process of ICP variants, several nearest neighbor search methods have been introduced. Then, the superior property of incident angle in point to point association has been detailed and a scan matching preprocessor Radial distance and Incident angle based Alignment (RIA) has been proposed. To further improve the data association of ICP variants in under-constraint environment, an Incident Angle Fused Metric (IAFM) has been proposed. In consideration of large scale indoors, Split Sparse Point Map (SSPM) ICP has been presented to fulfill scan matching tasks in large loops with the manner of incremental scan matching. The proposed SSPM-ICP framework does not require probabilistic processing. Based on the maps joining framework and a straightforward, efficient trajectory bending method, loop closure task has been fulfilled. Experiments have been conducted in various real indoor environments. The satisfactory results and corresponding analyses have verified the validities of the proposed methods, as shown in Figure 2.



(a) Satellite image (Google Map) of building

(b) Sketch of building and robot trajectory

(c) First closed loop

(d) OctoMap of first loop

(e) Final SSPM-ICP result with two closed loops

Figure 2. Scan matching in large scale indoor loops

EKF-SLAM with Slope and Edge Detection

In indoor environment, slope and edge detection is an important problem in SLAM which is one of the basic requirements for mobile robot autonomous navigation. The slope detection allows robot to find more traversable areas while the edge detection can prevent robot from falling. Three-dimensional (3D) solutions usually require large memory and high computational cost.

This study proposes an efficient two-dimensional (2D) solution to combine slope and edge detection with a line segment based extended Kalman filter SLAM (EKF-SLAM) in structured indoor. The robot is designed to use two fixed 2D laser range finders (LRFs) to perform horizontal and vertical scans, as shown in Figure 3. After being modeled into line segments swiftly from each vertical scan with local area orthogonal assumption, the slope and edge are merged into the EKF-SLAM framework, as shown in Figure 4. The EKF-SLAM framework features an optional prediction model that can automatically decide whether the application of ICP is necessary to be conducted on successive scans to compensate the dead reckoning error. Figure 5 demonstrates the architecture of whole system.

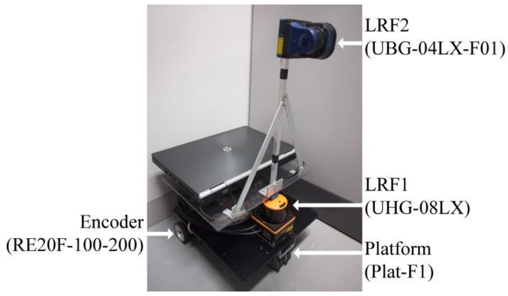


Figure 3. The mobile robot and sensors.

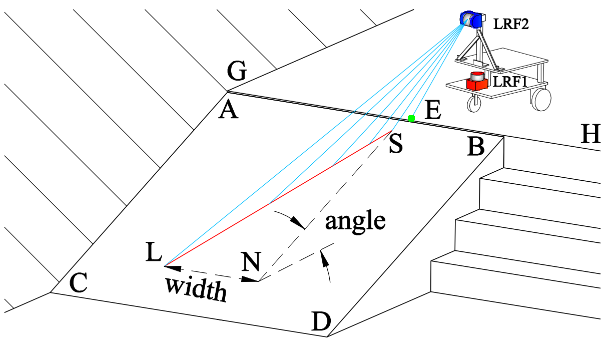


Figure 4. Slope and edge detection by the vertical scan

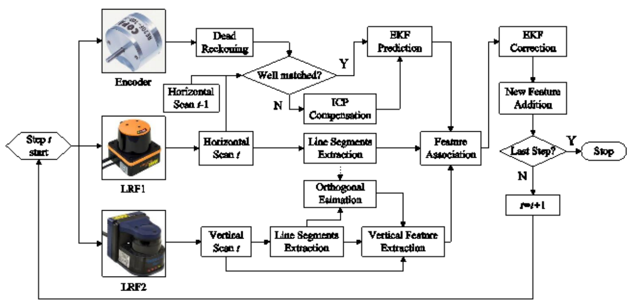
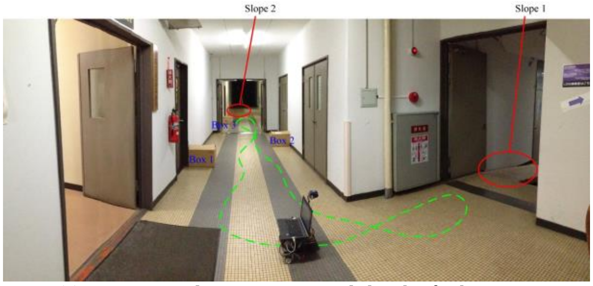
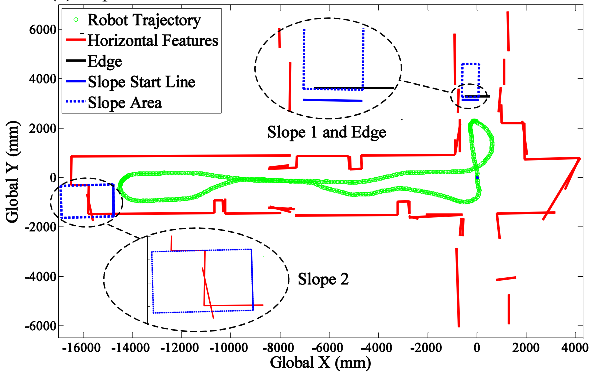


Figure 5. Overview of the system architecture



(a) Experimental Environment and sketch of robot motion



(b) Line-segment based EKF-SLAM result

Figure 6. Experimental environment and result

The experiment has been conducted in real indoor where there are two slopes and one edge. The SLAM result demonstrates that the proposed algorithm is capable of building accurate 2D map which contains sufficient vital information of edge and slope, as shown in Figure 6.

MEMS-IMU Calibration

Although some high grade MEMS-IMUs have been precisely calibrated and have no requirements for further calibration, most of the consumer grade MEMS-IMUs have been poorly calibrated for saving the cost on calibration. Calibration is defined as the process of comparing instrument outputs with known reference information, and determining coefficients that force the outputs to agree with the reference over a range of output values. Local gravity is a good reference for accelerometer calibration since it is constant, stable and obviously over the resolution of sensor. In the case of gyroscope, the naturally existing Earth's rate is inapplicable for MEMS-IMU because Earth rotation rate is under the resolution of this kind low cost sensor. Classical method for MEMS-IMU calibration is performed using precise biaxial or tri-axial turntable that rotates the MEMS-IMU to different orientations. The readings of accelerometer when MEMS-IMU is static are compared with local gravity, while measurements of gyroscope during the rotation are compared with known rotation rate of the turntable. This method needs costly and high-precision equipment that may not be available to all researchers.

In this study, a low-cost consumer grade MEMS-IMU that captures tri-axial gyroscope and tri-axial accelerometer has been investigated. Various types of sensor errors that affect the accuracy of measurements of low-cost MEMS-IMU have been firstly introduced. And a uniform sensor error model of accelerometers and gyroscopes has been adopted. To align two sensors into a uniform reference frame, a plastic cube that is made by 3D printer is introduced to be the body frame. Then, the static performance of MEMS-IMU is examined and a straightforward calibration process has been proposed to compress the error of the MEMS-IMU, as shown in Figure 8 and Figure 9. Local gravity is utilized as the reference of accelerometers' measurements while proposed scan matching method offers accurate angular reference for gyroscopes' calibration.

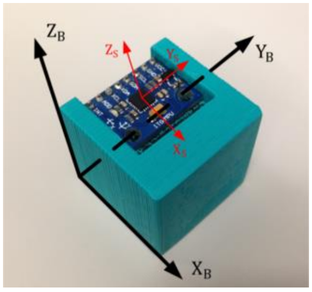


Figure 7. Body frame and sensor frame

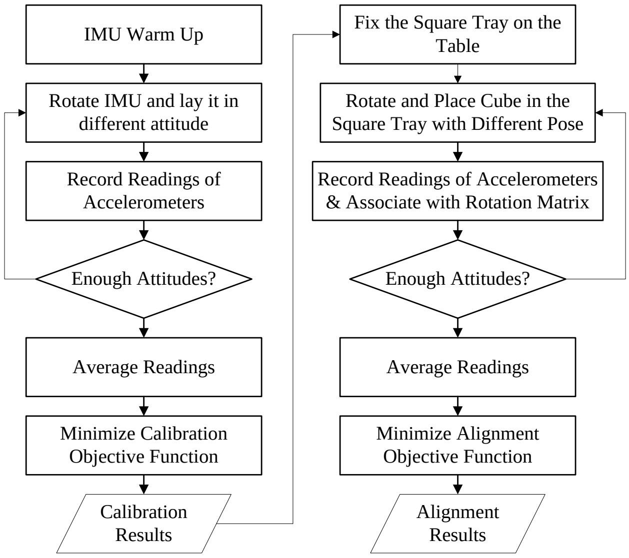


Figure 8. Accelerometer calibration and alignment

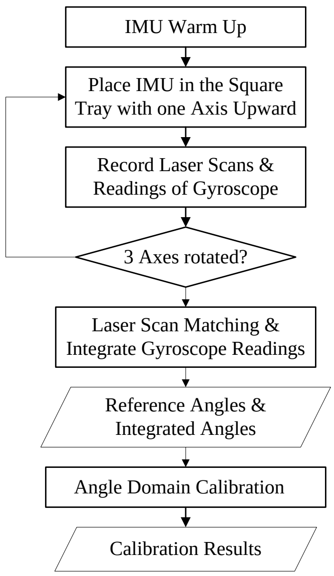
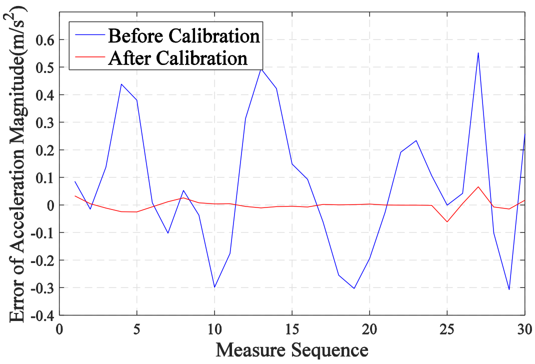
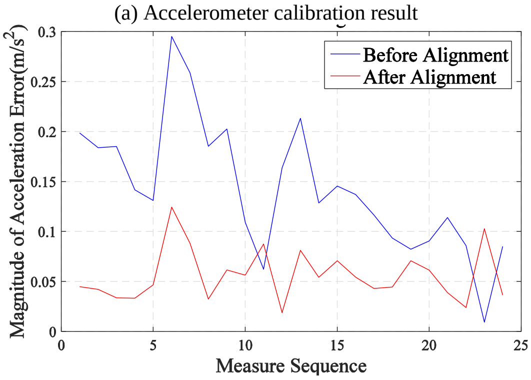


Figure 9. Gyroscope calibration

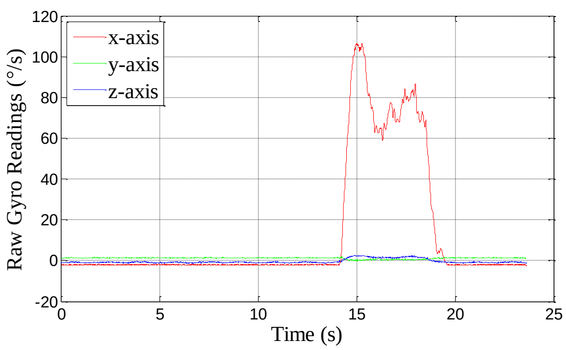


(a) Accelerometer calibration result

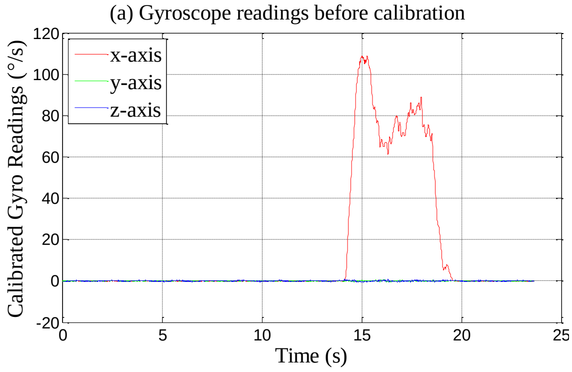


(b) Accelerometer alignment result

Figure 10. Errors comparison of accelerometer



(a) Gyroscope readings before calibration



(b) Gyroscope readings after calibration

Figure 11. Gyroscope readings comparison when IMU is rotated around x-axis

The uncalibrated/calibrated measurements of MEMS-IMU are compared with the references to verify the efficiency of the proposed calibration method, as shown in Figure 10 and Figure 11. The results clearly show the improvement brought by the proposed calibration work.

Conclusion

This study is focusing on the study of indoor mobile robots navigation. SLAM is one of the primary techniques to enable mobile robot to realize autonomous navigation. A key methodology in SLAM, scan matching has been intensively investigated in this study.

The contributions of this study can be summarized as follows:

1) Orientation Estimator for Scan Matching: A new orientation estimator ICN has been proposed and compared with another straightforward orientation estimator POE. ICN turns out to be more accurate and more robust against the effect of translation.

2) Pre-processor for Scan Matching: Based on the analysis on the incident angle, a pre-processor for scan matching named RIA has been proposed. RIA can efficiently eliminate dominant component of the transformation between scans.

3) New association metric for Scan Matching: Another application of incident angle is a new association metric named IAFM. Based on this new metric, closest point rule based association process becomes more efficient and robust on excluding outliers.

4) New framework for incremental scan matching: To overcome the limitation of SPM-ICP, a sub-maps joining version of it, Split SPM-ICP has been presented in this study. This new framework can handle loop closure problem as well as reducing computational cost of scan matching.

5) Optional prediction model for EKF-SLAM: Utilizing robust and efficient scan matching algorithm, a hybrid prediction model for EKF-SLAM has been proposed. This new prediction method can eliminate the effect brought by outlier readings from wheel odometer. And it is able to automatically switch prediction method between odometer and scan matching, which saves the computational cost and makes the prediction result reliable.

6) Slope and edge detection by using line-segment based EKF-SLAM: Based on the sound Orthogonal Assumption, the structured indoor slope and edge have been modelled into line-segment and merged into EKF-SLAM framework. This method is straightforward and does not need to extract features from 3D point clouds, which dramatically simplifies the calculation work.

7) Straightforward calibration method for MEMS-IMU: By using scan matching method, accurate angular displacement estimation has been provided for gyroscope calibration. The accelerometer has been calibrated by utilizing local gravity as the reference vector. A plastic cube that is made by 3D printer has been introduced to eliminate the residual misalignment error.