PSO-Based Refinement of Map Transformation in Multi-Robot SLAM

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***Abstract*— This paper addresses the problem of estimating map transformation in multi-robot simultaneous localization and mapping (SLAM) with unknown initial relative poses among multiple robots. While inter-robot observation measurements are not available, the map transformation among multiple robots can be estimated by map matching or loop closure algorithms. However, there may be inevitable errors in the estimated map transformation due to the errors in sensor measurements and the limited algorithm performance. To solve the problem, this paper proposes a particle swarm optimization (PSO)-based refinement method which can improve the accuracy of map transformation initially estimated by map matching or loop closure algorithms. The proposed method does not rely on specific algorithms and is applicable to any map matching or loop closure algorithms once they produce initial guesses of map transformation. The proposed method was tested by experiments with real-world datasets and validated by showing improved accuracy of map transformation.**

Keywords—Particle swarm optimization, Map transformation, Multi-robot SLAM

I. Introduction

Multi-robot systems have gained increasing attention in recent years due to their ability to perform multiple tasks simultaneously, thereby significantly reducing overall task completion time compared to single-robot systems. In order to operate such systems efficiently, accurate and up-to-date environmental information is essential. In particular, when prior maps of the environment are not available, each robot must perform simultaneous localization and mapping (SLAM) to estimate its own pose while concurrently building a map of its surroundings. In this context, multi-robot SLAM [1] offers several advantages. Each robot can explore different parts of the environment and share map information with others, enabling more efficient path planning and mission execution.

If the relative poses between robots are known in advance or can be reliably measured during operation, map merging can be straightforward. However, in most practical scenarios, it is difficult to use such information, especially in unknown environments. Even inter-robot observation measurements are available, they require strong assumptions—e.g., predefined meeting points or direct encounters. Besides, the measurements are inherently prone to sensor noise and estimation errors. As a result, map transformation among multiple robots is often estimated through map matching or loop closure algorithms, without relying on direct inter-robot observations. However, these methods can still suffer from limited accuracy due to sensor noises, non-overlapping areas, and imperfect initial guesses, which ultimately lead to errors in the merged map. To resolve the problem, this paper propose a particle swarm optimization (PSO)-based refinement method which improves the accuracy of inter-robot map transformations.

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II. Map Transformation Estimation

In multi-robot SLAM, the problem of map merging can vary depending on the system configuration. In this paper, we address the problem of two-dimensional grid map merging in multi-robot SLAM. If individual grid maps are three-dimensional, they can be projected into two-dimensional spaces by our previous work [2]. Consequently, map merging problem can be formulated as the estimation of a transformation matrix between local maps, as shown in the following equation [2].

$$\mathbf{T}(\Delta x, \Delta y, \Delta\theta) = \begin{bmatrix} \cos\Delta\theta & -\sin\Delta\theta & \Delta x \\ \sin\Delta\theta & \cos\Delta\theta & \Delta y \\ 0 & 0 & 1 \end{bmatrix} \quad (1)$$

where Δx, Δy and $\Delta\theta$ are respectively the translation amounts along x and y axes and the rotation angle between the maps.

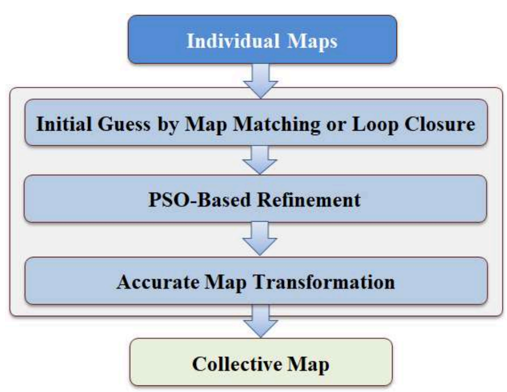

Fig. 1. The whole structure of the map transformation estimation with our PSO-based refinement method for multi-robot SLAM.

III. PSO-Based Refinement

The whole structure of the map transformation estimation with our PSO-based refinement method for multi-robot SLAM is shown in Fig. 1. Firstly, individual three-dimensional (3D) maps can be produced by the SLAM algorithm [3] with the 3D LiDAR-based system configuration as shown in Fig. 2. Their projected grid maps can be obtained by our previous work [2] as shown in Fig. 3. From these individual maps, an initial guess can be estimated by map matching algorithms or loop closure algorithms [4-6]. Then, the proposed method refines the map transformation using the PSO within reduced search spaces by the initial guess.

Particle Swarm Optimization (PSO) [7] is a sampling-based optimization algorithm inspired by swarm intelligence. It solves optimization problems by iteratively updating a population of candidate solutions—referred to as particles—to search for the optimal solution based on a predefined objective function. The behavior of PSO is governed by the following key principles. First, each particle is attracted toward a global target. Second, each particle retains memory of its personal best position. Third, particles share information through their velocities and positions within the swarm. Finally, the particles gradually converge toward the optimal region of the solution space over successive iterations. Based on these principles, the swarm collectively explores and exploits the search space, and eventually converges to a near-optimal or optimal solution. The objective function between two individual grid maps, M_1 and M_2, to measure the quality of each particle with the i-th candidate, q_i, is defined as follows:

$$\Psi(\mathrm{M}_1, \mathrm{M}_2, \mathrm{q}_i) = \sum_{x=a_1}^{a_2} \sum_{y=b_1}^{b_2} \mathrm{M}_1(x,y) \cdot [\mathrm{T}(\mathrm{q}_i)\mathrm{M}_2(x,y)] \quad (2)$$

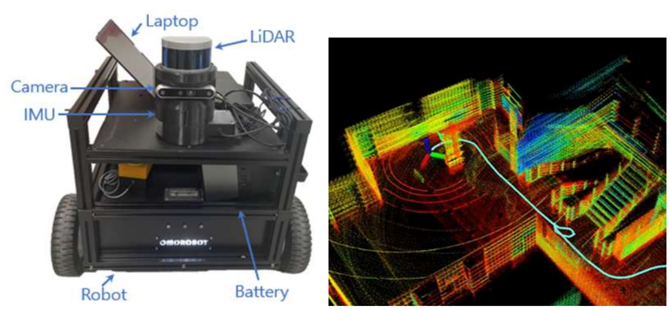

Fig. 2. System configuration (left) and an example of three-dimensioanl map (right) built by the robot and sensor system.

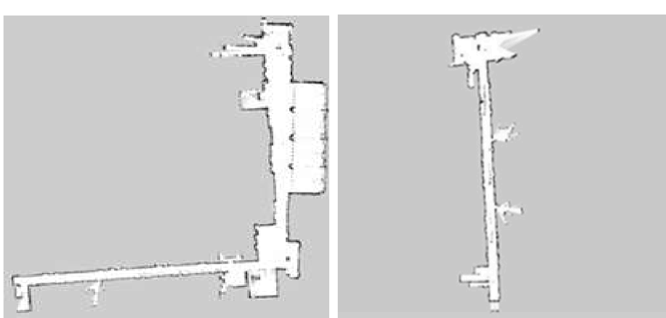

Fig. 3. Indivisual grid maps. They can be obtained by not only projecting the 3D point cloud maps into the 2D space but also applying 2D map matching algorithms directly.

Fig. 4. Collective map obtained using the proposed method (left) and the accuracy evaluation with the real floor plan (right).

where a_1 and a_2 are respectively the minimum and maximum of the x-coordinate of M_1 and M_2. b_1 and b_2 are respectively the minimum and maximum of the y-coordinate of M_1 and M_2. The collective map obtained using the proposed method and the accuracy evaluation with the real floor plan are shown in Fig. 4. One of the two individual maps was merged into the other's map built with respect to its local coordinate system. The results show that the collective map was overlapped well with the real floor plan, which indicates that the proposed method was successfully conducted by estimating the map transformation accurately.

IV. Conclusions

This paper proposed the PSO-based refinement method that improves the accuracy of inter-robot map transformations. The proposed method does not rely on specific existing algorithms once they can produce an initial transformation. The proposed method was validated through experiments using real-world datasets collected from mobile robots equipped with a LiDAR-based sensor system. The results show the proposed method significantly improves the accuracy of map transformation and enhances the quality of the collective map. In future work, the performance will be evaluated more precisely to analyze the possibility of applying the proposed method to practical real-time systems.

References

[1] H.-C. Lee, S.-H. Lee, M. H. Choi and B.-H. Lee, “Probabilistic Map Merging for Multi-Robot RBPF-SLAM with Unknown Initial Poses,” Robotica, vol. 30, 2012, pp. 205-220.

[2] D. Kim and H. Lee, "Efficient 3D Map Merging with Feature Matching of Projected Maps in Multi-Robot SLAM," Journal of Korean Institute of Information Technology, vol. 22, no. 5, 2024, pp. 71-81.

[3] T. Shan and B. Englot, "LeGO-LOAM: Lightweight and Ground-Optimized Lidar Odometry and Mapping on Variable Terrain," in Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), Madrid, Spain, 2018, pp. 4758-4765.

[4] S. Carpin, "Fast and Accurate Map Merging for Multi-Robot Systems," Autonomous Robots, vol. 25, Jul. 2008, pp. 305-316.

[5] H.-C. Lee and B.-H. Lee, "Enhanced-Spectrum-based Map Merging for Multi-Robot Systems," Advanced Robotics, vol. 27, no. 16, Jul. 2013, pp. 1285-1300.

[6] H. Lee and S. Lee, "Extended Spectra-based Grid Map Merging with Unilateral Observations for Multi-Robot SLAM," IEEE Access, vol. 9, May 2021, pp. 79651-79662.

[7] J. Kennedy and R. Eberhart, “Particle Swarm Optimization,” in Proceedings of the IEEE International Conference on Neural Networks, 1995, pp. 1942-1948.