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Robust Graph SLAM via Organized Point Cloud Registration and Loop Closing Validation Scheme by Gaussian Input Model Processing for Mobile Robot Navigation

석박사통합과정 조준형 / 지도교수 문창배

Abstract

In recent years, autonomous navigation systems have been extensively researched and deployed across diverse applications. Achieving reliable autonomous navigation requires precise spatial perception and continuous state estimation. To fulfill these requirements, Simultaneous Localization and Mapping (SLAM). Specifically, to construct high-fidelity environmental maps, Light Detection and Ranging (LiDAR)-based SLAM architectures provide the primary spatial perception foundation for autonomous mobile robots. However, continuous operation in unstructured environments exposes distinct bottlenecks across the SLAM pipeline, including front-end correspondence degradation during rapid mobile robot maneuvers, accumulation of redundant information in revisited areas, and back-end graph corruption induced by geometrically plausible but structurally incorrect loop closures. To mitigate these vulnerabilities, this research proposes an integrated, three-module LiDAR SLAM architecture encompassing rotation-robust local registration, adaptive keyframe selection, and uncertainty-aware constraint validation.

This research introduces an organized point cloud-based front-end odometry method formulated to maintain trajectory stability under severe rotational motion. By exploiting the deterministic physical arrangement of organized point clouds, the proposed framework establishes a structural association methodology. An adaptive weighting strategy balances these structural constraints with conventional geometric associations, improving local registration stability when Euclidean nearest-neighbor searches fail due to rapid yaw-induced overlap degradation.

To ensure computationally sustainable operation, an overlap-aware keyframe selection scheme is proposed. This method quantifies real-time spatial overlap and sequential consistency to characterize environmental familiarity. By evaluating the registration eligibility of individual observations based on information-theoretic criteria, specifically information gain, correspondence quality, and spatial redundancy, the adaptive framework registers salient observations. This mechanism suppresses structural redundancy and stabilizes memory growth in revisited environments.

To prevent perceptual aliasing from corrupting the global pose graph, this research introduces an uncertainty-aware validation module that performs pre-optimization screening through probabilistic data preprocessing. The proposed methodology transforms raw spatial alignments into a Validation Grid Map (VGM), an uncertainty-preserving probabilistic representation based on Gaussian modeling. By explicitly capturing spatial clustering and measurement uncertainty before deploying a Convolutional Neural Network (CNN) over this grid, the system rigorously evaluates the reliability of scan matching constraints before graph insertion. This preprocessing-driven screening mitigates the injection of false-positive constraints, ensuring resilient global map optimization in feature-sparse or perceptually aliased environments.

The integration of organized point cloud-based odometry, overlap-aware keyframe selection, and preprocessing-validated graph construction establishes a cohesive and computationally sustainable SLAM architecture. Experimental evaluations demonstrate that the proposed pipeline mitigates module-specific vulnerabilities, providing a globally consistent spatial perception foundation for continuous autonomous navigation.

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