National University of Sciences and Technology

School of Mechanical and Manufacturing Engineering

MS Robotics and Intelligent Machine Engineering

SUBMITTED TO	Dr. Yasar Ayyaz
SUBMITTED BY	Hafiz Muhamad Shahid Tariq
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iRotate: Active Visual SLAM for Omnidirectional Robots

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Introduction

Simultaneous Localization and Mapping (SLAM) plays a crucial role in enabling robots to navigate and operate within unknown environments. Visual SLAM (V-SLAM), which utilizes visual data from onboard cameras, has emerged as a popular approach due to its rich information content and versatility. However, traditional V-SLAM systems often operate passively, relying on predefined paths or external control inputs. This can lead to inefficient exploration strategies and suboptimal map quality.

Active V-SLAM addresses these limitations by integrating perception and action. In active V-SLAM, robots make intelligent decisions about their movement based on the current map estimate and sensor data. This allows for a more directed and efficient exploration of the environment, leading to faster mapping and reduced uncertainty.

Omnidirectional robots, with their ability to independently control translation and rotation, offer unique advantages for active V-SLAM. Their ability to freely adjust their heading without changing position allows for the observation of a wider area and the capture of more informative views. This paper focuses on developing a novel active V-SLAM approach specifically tailored for omnidirectional robots.

The proposed method introduces a hierarchical framework with three levels of active control:

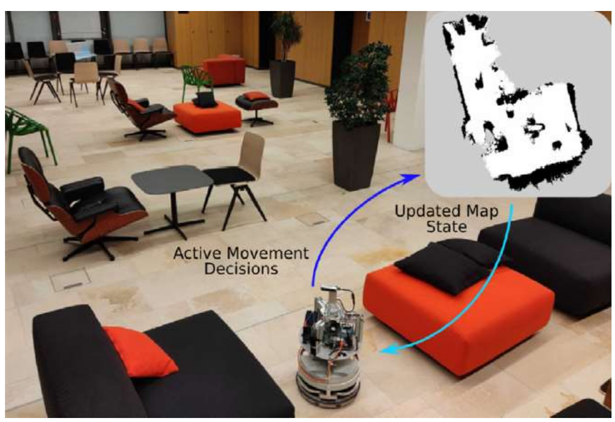

Figure 1 Scenario

Global Path Planning:

This layer focuses on selecting informative goal locations, typically frontier points representing boundaries between explored and unexplored areas. The system then generates paths to these goals, optimizing each waypoint along the path for maximum information gain.

Local Waypoint Refinement:

Upon reaching each waypoint, the system re-evaluates the optimal heading for the next waypoint, considering the updated map information and potential changes in map entropy. This ensures the robot adapts its path based on the latest knowledge of the environment.

Real-time Heading Refinement

Between waypoints, the robot continuously adjusts its heading based on real-time 3D feature information extracted by the V-SLAM system. This keeps a maximum number of features within the field of view, improving map consistency and facilitating loop closure detection.

The paper also explores novel utility functions that guide the robot's exploration. These functions consider factors such as Shannon entropy, obstacle presence, and the robot's location relative to the goal, allowing for a dynamic balance between exploration and exploitation.

Through rigorous simulations and real-world experiments using an omnidirectional robot platform, the paper demonstrates the effectiveness of the proposed active V-SLAM approach. The results show significant reductions in travel distance and map entropy compared to traditional methods, highlighting the potential of this approach for efficient and accurate mapping of unknown environments.

Working Principles

The proposed active V-SLAM system operates through a coordinated interplay of three distinct layers, each contributing to efficient exploration and high-quality map generation:

Global Path Planning (First-Level Activeness):

Goal Selection:

The system begins by identifying potential goals for exploration, focusing on reachable frontier cells. These frontiers represent the boundaries between explored and unexplored regions of the map.

A modified frontier extraction algorithm is used to identify clusters of frontier cells and select candidate goal locations at their centroids.

If a centroid is unreachable, a greedy search is performed within the cluster to find the nearest reachable frontier cell as a candidate goal.

Path Generation:

For each candidate goal, an A* planner is employed to generate a collision-free path through the current map.

The path is discretized into a series of waypoints with a fixed distance between them, facilitating smoother robot movement and reducing computational complexity.

Heading Optimization:

Each waypoint is then optimized by computing the ideal heading direction that maximizes the information gain for the robot. This optimization considers the sensor's field of view and the expected distribution of information in the environment.

To avoid redundant observations, the system accounts for the frustum overlap between consecutive waypoints, ensuring that the robot focuses on observing new areas.

Utility Calculation:

A novel utility function is employed to evaluate the overall informativeness of each path to the candidate goals. This function goes beyond simply considering the final goal location and instead assesses the potential information gain at each waypoint along the path.

The paper introduces and compares several variations of the utility function, including:

Shannon Entropy: Directly measures the uncertainty associated with each map cell.

Obstacle-aware: Incorporates the presence of obstacles in the environment, prioritizing observations of areas likely to contain features and requiring further refinement.

Distance-weighted: Dynamically balances the importance of observing new areas versus refining previously explored regions based on the robot's distance to the goal.

Path Selection:

The path with the highest overall utility is selected as the current target for the robot's exploration.

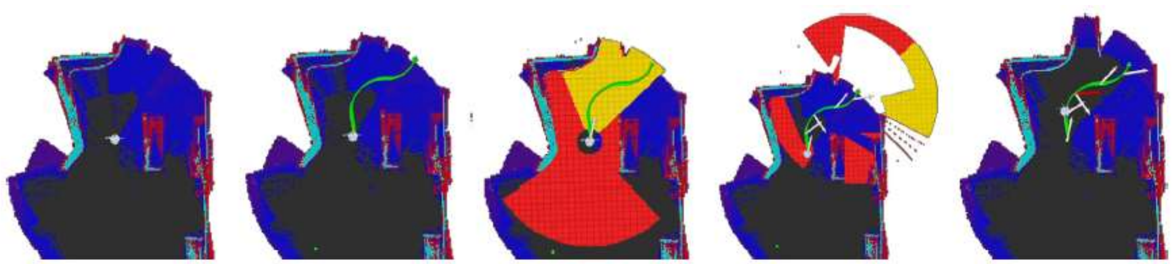

Figure 2 Representation

Local Waypoint Refinement (Second-Level Activeness):

Upon reaching a waypoint, the system re-evaluates the optimal heading for the subsequent waypoint. This accounts for any changes in the map information that occurred since the initial path planning, such as newly discovered obstacles, loop closures, or map updates. This ensures the robot's path remains optimized based on the latest available information.

Real-time Heading Refinement (Third-Level Activeness):

As the robot travels between waypoints, it continuously adjusts its heading to maximize the visibility of 3D features detected by the V-SLAM system.

This is achieved by analyzing the real-time distribution of features and computing the optimal heading that keeps the maximum number of features within the sensor's field of view.

The system dynamically balances the importance of maintaining feature visibility with the pre-computed optimal heading from the second level, ensuring smooth transitions between waypoints.

Strengths

- Increased Efficiency: The multi-layered approach significantly reduces the distance traveled by the robot while maintaining high map quality and low entropy. This translates to lower energy consumption and improved autonomy.
- Continuous Adaptation: The system continuously adapts to new information by re-planning and re-optimizing headings at both global and local levels. This allows for robust performance in dynamic environments and improves the overall mapping accuracy.
- Enhanced Loop Closure Detection: The focus on keeping features within the field of view increases the likelihood of loop closures, leading to more accurate map estimates and reduced trajectory errors.
- Modular Design: The proposed approach is modular, allowing for the use of different utility functions and variations in the active layers to suit specific application requirements.

Weaknesses

- Computational Complexity: The continuous optimization and re-planning processes can be computationally expensive, requiring a powerful computational unit for real-time performance.
- Start-Stop Behavior: The frequent adjustments in heading can lead to a start-stop behavior, which may not be desirable in some applications. This can be mitigated by fine-tuning parameters and employing more advanced planning strategies.
- Limited Applicability: The current implementation is specifically designed for omnidirectional robots and may require modifications to be applied to other platforms.