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Abstract

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Introduction

Robots are emerging from controlled factories and laboratories into our homes, workplaces, roads, and public airspaces. Alongside their transition into these unstructured and transient environments comes their need to be able to explore, characterize, and catalog their surroundings. Mobile robot autonomy is generally accomplished by referring to a map - a 2D or 3D probabilistic representation of the locations of obstacles in the workspace. With access to a map, robots can localize to determine their position, plan collision-free trajectories to goals, locate objects for interaction, and make decisions by reasoning about the geometry and dynamics of the world. Given that a robot's map is of critical importance for most autonomy tasks, robots that find themselves initialized without a priori access to a map should be capable of autonomously, efficiently, and intelligently creating one.

The exercise of choosing and executing actions that lead a robot to learn more about its own map is known as *active perception* or *exploration*, and is the central topic of this thesis. Active perception has previously been studied with a multitude of sensor models, environment representations, and robot dynamics models. The active perception task itself can be split into two components [3]:

1. Identifying regions in the environment that, when visited, will spatially extend or reduce uncertainty in the current map

2. Autonomously navigating to the aforementioned regions, while simultaneously localizing to the map and updating it with acquired sensor measurements

A motivating example is depicted in Fig. 1.1, where a household service robot is initialized in an unknown environment. Prior to accomplishing tasks that a human might ask it to perform, the robot must learn its surroundings and build a map of the house. Ideally this phase of initialization would be fast, as it is a prerequisite to the main functionality of the robot, and also might be required when furniture is moved or household objects are displaced. Where should the robot travel to observe the most of the environment in the shortest amount of time? Virtually any autonomous robot operating in an uncontrolled environment will require a map-building initialization phase, motivating algorithms for high-speed and intelligent exploration.

This thesis introduces an assortment of information-theoretic optimizations that increase the efficiency of active perception when using a beam-based sensor model (e.g. LIDAR, time-of-flight cameras, structured light sensors) and an occupancy grid map [1]. Applying these optimizations during exploration allows a robot to consider a significantly larger number of future locations to move towards in its partially observed environment, regardless of the planning strategy used. Additionally, this thesis presents a method for analyzing the complexity of the local environment and adapting the robot's map resolution, planning frequency, movement speed, and exploration behaviors accordingly. By adapting these parameters online, an exploring robot is able to

Figure 1.1: A household service robot awakes in an unknown environment. Prior to accomplishing its main functionalities, it will require a map of its surroundings. What sequence of actions should it take to minimize the amount of time spent exploring?

(a) A geometric approach is used to identify frontiers, or the intersections between free and occupied cells in the robot's map.

(b) Information-theoretic exploration

Figure 1.2: A robot is faced with a decision-making problem. Will the red or green path lead to a higher future reward?

1.1 Previous Work

Prior approaches to mobile robot active perception fall into two broad categories: *geometric* approaches that reason about the locations and presence of obstacles and free space in the robot's map [], and more recently, *information-theoretic* approaches that treat the map as a multivariate random variable and choose actions that will maximally reduce its uncertainty []. Both categories of approaches solve the first enumerated item in the above list, and assume that a planner and Simultaneous Localization and Mapping (SLAM) framework are available to accomplish the second item.

Many successful geometric exploration approaches build upon the seminal work of Yamauchi [4], guiding the robot to *frontiers* - regions on the boundary between free and unexplored space in the map (Fig. 1.2a). As multiple frontiers often exist simultaneously in a partially explored map, a variety of heuristics and spatial metrics can be used to decide which frontier to travel towards [2]. For example, an agent may decide to visit the frontier whose path through the configuration space from the robot's current position has minimum length, or requires minimal time or energy input to traverse. Similarly, an agent may decide to only plan paths to locations from which frontiers can be observed by its onboard sensors.

Other geometric exploration algorithms include

While effective in 2D environments, geometric exploration algorithms have several restrictive qualities. First, the naïve extension of frontier exploration from 2D to 3D poses a non-trivial challenge [3]; as the dimensionality of the workspace increases, frontiers are more frequently identified in locations that do not truly represent boundaries between free and occupied space.

1.2 Thesis Problem

Thesis Problem: Solutions to the mobile robot active perception task that involve optimization of information-theoretic cost functions are too computationally expensive for high-speed exploration in complex environments.

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