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A Comparative Study of Path-Planning Algorithms for Autonomous Mobile Robot Navigation

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ABSTRACT

An autonomous mobile robot must find its way from where it is to where it must go without colliding with the obstacles around it, and the algorithm that computes this route, the path planner, largely determines how good the route is and how quickly it is found. This study compares several widely used path-planning algorithms for mobile robot navigation, by the quality of the paths they produce and the effort they require. Three representative algorithms were considered: an uninformed graph search that explores outward from the start, an informed graph search that uses a heuristic to guide its exploration toward the goal, and a sampling-based planner that builds a tree of random feasible motions through the space, and each was used to plan a path from a start to a goal in an environment containing obstacles. The two graph-search algorithms found the shortest, or very nearly the shortest, path, but the uninformed search explored far more of the environment to do so, while the informed search, guided by its heuristic toward the goal, reached the same path having explored much less, and so was faster. The sampling-based planner found a feasible path quickly even though the path was not the shortest and was less smooth, and it scaled better to larger and higher-dimensional spaces where the graph searches become expensive. No single algorithm was best in every respect; the graph searches offered optimality at greater cost in confined spaces, and the sampling-based planner offered speed and scalability at the cost of optimality. The study shows that the choice of path-planning algorithm should be guided by whether optimality, speed, or scalability matters most for the robot and its environment.

KEYWORDS: *Path planning, Mobile robots, A* algorithm, Dijkstra's algorithm, Rapidly-exploring random tree, Autonomous navigation, Motion planning, Obstacle avoidance, Sampling-based planning*

INTRODUCTION

Autonomous mobile robots must move through their environment to accomplish their tasks, and to do so they must plan how to get from their current position to a desired destination without colliding with the obstacles in their way. This problem, of computing a collision-free route from a start to a goal, is called path planning, and it is one of the most fundamental problems in mobile robotics (9). The path planner takes a description of the environment and the start and goal, and produces a path the robot can follow, and the quality of that path, its length, its smoothness, and its safety, together with the time taken to compute it, are central to how well the robot performs.

The difficulty of path planning lies in finding a route that is both feasible, avoiding all obstacles, and good, ideally short and smooth, while computing it quickly enough to be useful, all in an environment that may be cluttered, large, or of high dimension. Different algorithms strike different balances among these aims. Some search a grid or graph representing the environment exhaustively or with guidance, and can guarantee the shortest path but may explore a great deal to find it; others build a path from random samples of feasible motions, finding a route quickly but without guaranteeing it is the shortest (10). Which is preferable depends on what the robot most needs.

This paper compares several widely used path-planning algorithms for mobile robot navigation, by the quality of the paths they produce and the effort they require. Three representative algorithms are considered, an uninformed graph search, an informed graph search guided by a heuristic, and a sampling-based planner, and each is used to plan a path from a start to a goal among obstacles. The aim is to bring out the trade-offs among optimality, speed, and scalability that distinguish the algorithms, and to draw guidance for choosing among them according to the robot and its environment.

LITERATURE REVIEW

Path planning has been studied for decades, and the literature offers a rich variety of algorithms, broadly divided into graph-search methods and sampling-based methods. The graph-search methods represent the environment as a graph of positions connected by feasible moves and search it for a path. The classic uninformed search expands outward from the start in order of distance, guaranteeing the shortest path but exploring widely (1); the informed search adds a heuristic estimate of the remaining distance to the goal, which guides the expansion toward the goal and so finds the shortest path while exploring far less (2).

GRAPH-SEARCH AND SAMPLING-BASED METHODS

The literature characterises the two families of methods:

- Uninformed graph search explores in order of cost from the start and finds the optimal path but explores widely (1).
- Informed graph search uses a heuristic to guide exploration toward the goal, finding the optimal path with far less exploration (2).
- Sampling-based planners, building a roadmap or tree from random feasible configurations, find feasible paths quickly and scale to high dimensions (3, 4).
- Variants extend these: optimal sampling-based planning (5), faster bidirectional trees (6), and replanning in changing environments (7, 8).

A recurring theme is that graph searches offer optimality but become costly in large or high-dimensional spaces, while sampling-based methods offer speed and scalability at the cost of optimality and smoothness.

The sampling-based planners arose to address the difficulty graph searches face in large and high-dimensional spaces; where building and searching a fine graph becomes prohibitively expensive (3). They build a path from randomly sampled feasible configurations, connecting them into a roadmap (4) or growing a tree from the start (3), and find a feasible path quickly with high probability, though not necessarily the shortest. Later work made them asymptotically optimal, approaching the best path as more samples are taken (5), sped them

up with bidirectional growth (6), and addressed replanning when the environment changes during
execution (7, 8). Comprehensive treatments of these methods are given in standard references (9, 10).

RESEARCH GAP

Although the individual algorithms are well studied, a concise comparison that plans a path from the same start to the same goal in the same environment with a representative algorithm of each kind, and contrasts the resulting path quality and computational effort, remains useful for guiding the choice. There is therefore value in a study that places an uninformed search, an informed search, and a sampling-based planner side by side and relates their behaviour to their principles.

OBJECTIVES

The objectives of this study are:

- To plan a path from a start to a goal among obstacles using an uninformed graph search, an informed graph search, and a sampling-based planner.
- To compare the quality of the paths produced, in length and smoothness.
- To compare the computational effort, in the exploration and time required.
- To relate the differences to the principles of the algorithms and to draw guidance for choosing among them.

METHODOLOGY

1. Algorithms and Environment

Three representative path-planning algorithms were considered: an uninformed graph search that expands outward from the start in order of distance (1); an informed graph search that uses a heuristic estimate of the distance to the goal to guide its expansion (2); and a sampling-based planner that grows a tree of random feasible motions from the start until it reaches the goal (3). Each was used to plan a path from the same start to the same goal in an environment containing obstacles. The algorithms are summarised in Table 1.

Table 1: Path-planning algorithms compared

Algorithm	Approach
Uninformed graph search	Expands from the start in order of distance
Informed graph search	Heuristic guides expansion toward the goal
Sampling-based planner	Grows a tree of random feasible motions
Environment	Two-dimensional space with obstacles

2. Evaluation

The paths produced by the three algorithms were compared by their length, relative to the shortest possible, and their smoothness, and the computational effort was compared by how much of the environment each explored and the time each took to find its path. These were assessed for the same planning problem so that the algorithms could be compared directly, and the comparison was related to how each algorithm searches for a path.

RESULTS AND FINDINGS

The algorithms found their paths in characteristically different ways, as shown in Figure 1, which displays the paths from the start to the goal through the obstacles. The two graph-search algorithms found the shortest, or very nearly the shortest, path, a clean route through the gaps between the obstacles, whereas the sampling-based planner found a feasible but longer and less smooth path, wandering more on its way to the goal because it was built from random motions rather than by systematic search.

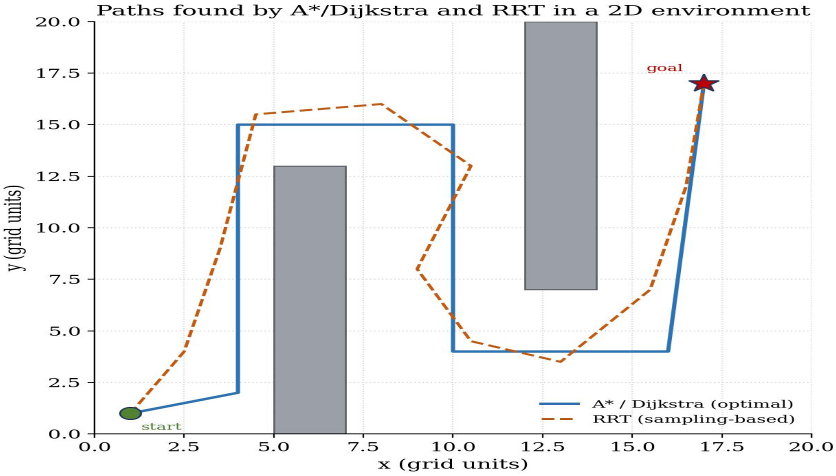

Figure 1: Paths found by the graph-search and sampling-based algorithms in a 2D environment

The difference between the two graph searches lay not in the path but in the effort: the uninformed search explored much more of the environment to find the shortest path, expanding in all directions from the start, while the informed search, guided by its heuristic toward the goal, found the same path having explored far less, and so was faster (2). The sampling-based planner found its feasible path quickly even in this environment, and its advantage grows in larger and higher-dimensional spaces, where the graph searches must explore a vast graph (3). The comparison is summarized in Table 2.

Table 2: Path quality and computational effort of the algorithms

Measure	Uninformed	Informed	Sampling-based
Path length	Optimal	Optimal	Longer
Path smoothness	Good	Good	Less smooth
Exploration	Extensive	Limited	Moderate
Scalability	Poor	Moderate	Good

DISCUSSION

The results bring out the trade-offs among optimality, speed, and scalability that distinguish the algorithms. The graph searches guarantee the shortest path because they systematically consider the possibilities, but this thoroughness is costly: the uninformed search, lacking any sense of where the goal lies, explores in all directions and so does much unnecessary work (1), whereas the informed search uses its heuristic to concentrate its exploration toward the goal, achieving the same optimal path with far less effort (2). This is why the informed search is generally preferred over the uninformed one for the same problem: it loses nothing in path quality and gains greatly in speed.

The sampling-based planner embodies a different trade-off. By building a path from random feasible motions rather than searching systematically, it gives up the guarantee of the shortest path, and indeed its paths are typically longer and less smooth, but it finds a feasible path quickly and, crucially, scales to large and high-dimensional spaces where the graph searches become impractical, since it need not represent the whole space as a fine graph (3). Its paths can be improved toward the optimum by taking more samples, with optimal variants approaching the best path in the limit (5), and shortened or smoothed by post-processing, and its speed can be increased by growing trees from both start and goal (6). It is therefore the method of choice where the space is large or high-dimensional, as for robots with many degrees of freedom.

The practical conclusion is that the choice of path-planning algorithm should be guided by whether optimality, speed, or scalability matters most. Where the environment is small and a shortest path is wanted, an informed graph search is well suited, giving optimality efficiently (2); where the space is large or high-dimensional, a sampling-based planner is preferable for its speed and scalability, accepting a longer path (3); and where the environment changes as the robot moves, replanning methods that update the path efficiently are needed (7, 8). The robot and its environment thus determine the best planner. The main caveats are that the comparison was made in a single representative environment and that the precise behaviour of each algorithm depends on the environment, the resolution of the graph, and the implementation.

LIMITATIONS

The following limitations apply to this study:

- The comparison was made in a single representative two-dimensional environment and would vary with the environment.

- The behaviour of each algorithm depends on the resolution of the graph and on implementation choices.

- Three representative algorithms were compared, among the many path-planning methods that exist.

- The study considered planning a path; the execution of the path by a real robot, with its dynamics and sensing, was not addressed.

FUTURE SCOPE

Future work could extend the present study as follows:

- Comparison across a range of environments, including large and high-dimensional spaces.

- Inclusion of optimal and bidirectional sampling-based planners and of replanning methods for changing environments.

- Assessment of path execution by a real robot, accounting for its dynamics and sensing.

- Combination of methods, such as smoothing sampling-based paths or seeding graph search with samples.

- Evaluation of planning in dynamic environments with moving obstacles.

CONCLUSION

Several path-planning algorithms for mobile robot navigation were compared by the quality of the paths they produce and the effort they require. The two graph-search algorithms found the shortest, or nearly the shortest, path, but the uninformed search explored far more of the environment than the informed search, which used a heuristic to reach the same path with much less effort, while the sampling-based planner found a feasible but longer and less smooth path quickly and scaled better to larger and higher-dimensional spaces. The study shows that no single algorithm is best in every respect, that graph searches offer optimality at greater cost in confined spaces while sampling-based planners offer speed and scalability at the cost of optimality, and that the choice should be guided by whether optimality, speed, or scalability matters most for the robot and its environment, with the comparison depending on the environment and implementation.

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