Chapter 1
Introduction to Mobile Robot Path Planning

Abstract Robotic is now gaining a lot of space in our daily life and in several areas in modern industry automation and cyber-physical applications. This requires embedding intelligence into these robots for ensuring (near)-optimal solutions to task execution. Thus, a lot of research problems that pertain to robotic applications have arisen such as planning (path, motion, and mission), task allocation problems, navigation, tracking. In this chapter, we focused on the path planning research problem.

1.1 Introduction

Moving from one place to another is a trivial task, for humans. One decides how to move in a split second. For a robot, such an elementary and basic task is a major challenge. In autonomous robotics, path planning is a central problem in robotics. The typical problem is to find a path for a robot, whether it is a vacuum cleaning robot, a robotic arm, or a magically flying object, from a starting position to a goal position safely. The problem consists in finding a path from a start position to a target position. This problem was addressed in multiple ways in the literature depending on the environment model, the type of robots, the nature of the application, etc.

Safe and effective mobile robot navigation needs an efficient path planning algorithm since the quality of the generated path affects enormously the robotic application. Typically, the minimization of the traveled distance is the principal objective of the navigation process as it influences the other metrics such as the processing time and the energy consumption.

This chapter presents a comprehensive overview on mobile robot global path planning and provides the necessary background on this topic. It describes the different global path planning categories and presents a taxonomy of global path planning problem.

A. Koubaa et al., *Robot Path Planning and Cooperation*, Studies in Computational Intelligence 772, https://doi.org/10.1007/978-3-319-77042-0_1

1.2 Overview of the Robot Path Planning Problem

Nowadays, we are at the cusp of a revolution in robotics. A variety of robotic systems have been developed, and they have shown their effectiveness in performing different kinds of tasks including smart home environments [1], airports [2], shopping malls [3], manufacturing laboratories [4]. An intelligence must be embedded into robot to ensure (near)-optimal execution of the task under consideration and efficiently fulfill the mission. However, embedding intelligence into robotic system imposes the resolution of a huge number of research problems such as navigation which is one of the fundamental problems of mobile robotics systems. To finish successfully the navigation task, a robot must know its position relatively to the position of its goal. Moreover, he has to take into consideration the dangers of the surrounding environment and adjust its actions to maximize the chance to reach the destination.

Putting it simply, to solve the robot navigation problem, we need to find answers to the three following questions: Where am I? Where am I going? How do I get there? These three questions are answered by the three fundamental navigation functions localization, mapping, and motion planning, respectively.

- Localization: It helps the robot to determine its location in the environment. Numerous methods are used for localization such as cameras [5], GPS in outdoor environments [6], ultrasound sensors [7], laser rangefinder [8]. The location can be specified as symbolic reference relative to a local environment (e.g., center of a room), expressed as topological coordinate (e.g., in Room 23) or expressed in absolute coordinate (e.g., latitude, longitude, altitude).
- Mapping: The robot requires a map of its environment in order to identify where he has been moving around so far. The map helps the robot to know the directions and locations. The map can be placed manually into the robot memory (i.e., graph representation, matrix representation) or can be gradually built while the robot discovers the new environment. Mapping is an overlooked topic in robotic navigation.
- Motion planning or path planning: To find a path for the mobile robot, the goal position must be known in advance by the robot, which requires an appropriate addressing scheme that the robot can follow. The addressing scheme serves to indicate to the robot where it will go starting from its starting position. For example, a robot may be requested to go to a certain room in an office environment with simply giving the room number as address. In other scenarios, addresses can be given in absolute or relative coordinates.

Planning is one obvious aspect of navigation that answers the question: ***What is the best way to go there?*** Indeed, for mobile robotic applications, a robot must be able to reach the goal position while avoiding the scattered obstacles in the environment and reducing the path length. There are various issues need to be considered in the path planning of mobile robots due to various purposes and functions of the virtual robot itself as shown in Fig. 1.1. Most of the proposed approaches are focusing on finding the shortest path from the initial position to goal position. Recently, researches are

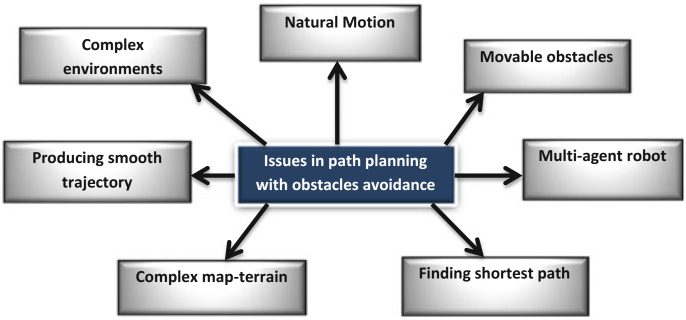


Fig. 1.1 Different issues of path planning

focusing on reducing the computational time and enhancing smooth trajectory of the virtual robot [9]. Other ongoing issues include navigating the autonomous robots in complex environments [10]. Some researchers consider movable obstacles and navigation of the multi-agent robot [11].

Whatever the issue considered in the path planning problem, three major concerns should be considered: efficiency, accuracy, and safety [12]. Any robot should find its path in a short amount of time and while consuming the minimum amount of energy. Besides that, a robot should avoid safely the obstacles that exist in the environment. It must also follow its optimal and obstacle-free route accurately.

Planning a path in large-scale environments is more challenging as the problem becomes more complex and time-consuming which is not convenient for robotic applications in which real-time aspect is needed. In our research work, we concentrate on finding the best approach to solve the path planning for finding shortest path in a minimum amount of time. We also considered that the robot operates in a complex large environment containing several obstacles having arbitrary shape and positions.

1.2.1 Problem Formulation

In [13], Latombe describes the path planning problem as follows:

- $A \subset W$: The robot, it is a single moving rigid object in world W represented in the Euclidean space as $\mathbb{R}^2$ or $\mathbb{R}^3$.
- $O \subset W$: The obstacles are stationary rigid objects in W.
- The geometry, the position, and the orientation of A and O are known a priori.
- The localization of the O in W is accurately known.

Given a start and goal positions of $A \subset W$, plan a path $P \subset W$ denoting the set of position so that $A(p) \bigcap O = \emptyset$ for any position $p \in P$ along the path from start to goal, and terminate and report P or $\emptyset$ if a path has been found or no such path exists. The quality of the path (optimal or not) is measured using a set of optimization

criteria such as shortest length, runtime, or energy.
Four different concepts in this problem need to be well described:

- The moving robot's geometry.
- The workspace (environment) in which the robot moves or acts.
- The degrees of freedom of the robot's motion.
- The initial and the target configuration in the environment, between which a trajectory has to be determined for the robot.

Using this information, we construct the workspace of the mobile robot. Path planning problems can be directly formalized and solved in a 3D workspace. However, these workspace solutions cannot easily handle robots with different geometries and mechanical constraints. To overcome these difficulties, path planning may be formalized and solved in a new space called **the configuration space**. In the configuration space, a robot with a complex geometric shape in a 3D workspace is mapped to a point robot. The robot's trajectory corresponds to a continuous curve in the high-dimensional configuration space, and the environment in which it travels is defined in a two-dimensional plane as depicted in Fig. 1.2. The advantage of the configuration space representation is that it reduces the problem from a rigid body to a point and thus eases the search. The notion of configuration space was first presented by Lozano-Pérez [14]. It contains all the robot configurations. It is denoted by C. In realistic robot applications, the environment in which the robot acts contains obstacles. These obstacles cause some configurations to be forbidden. For example, a configuration c is forbidden if the robot configured at c hits with any of the obstacles in the workspace. More generally, the configuration space C is partitioned into a set of forbidden configurations $C\ forb$, and a set of free configurations $C\ free$.

The robot's path is a continuous function $p : [0, L] \to C$, where L is the length of the path. The path planning problem consists to find an obstacle-free path between a given start configuration $s \in C$ and goal configuration $g \in C$. Formulated in terms of the configuration space C, that is finding a path p such that $p(0) = s$ and $p(L) = g$,

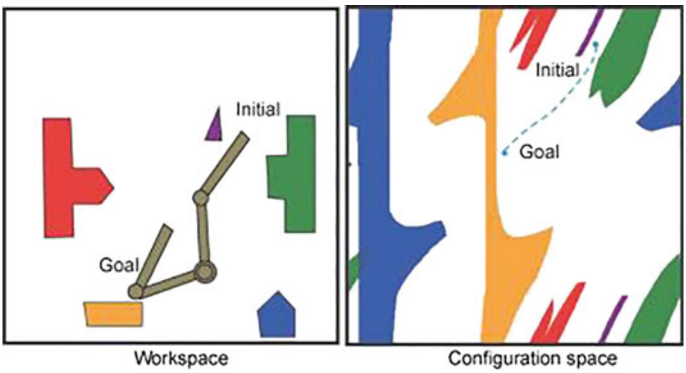


Fig. 1.2 Workspace and configuration space

and $\forall(pos \in [0, L]::p(pos) \in Cfree)$. If such a path does not exist, failure should be reported. In addition to this definition, one may define a quality of measure on all possible paths and require that the path that optimizes this measure is found.

1.3 Path Planning Categories

In this section, we give a classification of the different problems related to mobile robots path planning. It can be divided into three categories according to the robot's knowledge that it has about the environment, the environment nature, and the approach used to solve the problem as depicted in Fig. 1.3.

Environment Nature: The path planning problem can be done in both static and dynamic environments: A static environment is unvarying, the source and destination positions are fixed, and obstacles do not vary locations over time. However, in a dynamic environment, the location of obstacles and goal position may vary during the search process. Typically, path planning in dynamic environments encompasses is more complex than that in static environments due to uncertainty of the environment. As such, the algorithms must adapt to any unexpected change such as the advent of new moving obstacles in the preplanned path or when the target is continuously moving. When both obstacles and targets are moving, the path planning problem becomes even more critical as it must effectively react in real time to both goal and obstacle movements. The path planning approaches applied in static environments are not appropriate for the dynamic problem.

Map knowledge: Mobile robots path planning basically relies on an existing map as a reference to identify initial and goal location and the link between them. The amount of knowledge to the map plays an important role for the design of the path planning algorithm. According to the robot's knowledge about the environment, path planning can be divided into two classes: In the first class, the robot has an a priori knowledge about the environment modeled as a map. This category of path planning

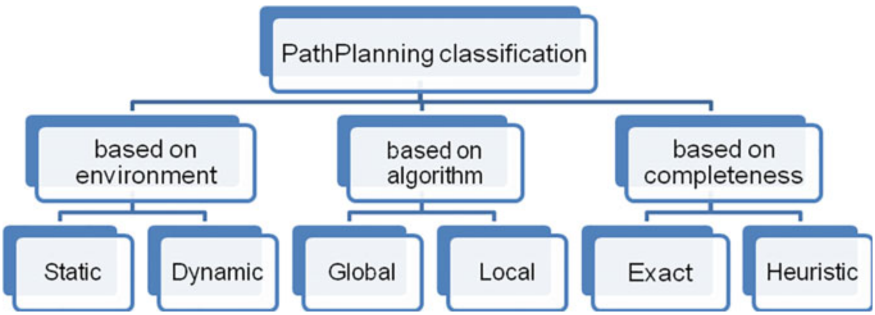


Fig. 1.3 Path Planning Categories

Table 1.1 Global and local path planning

Local path planning	Global path planning
Sensor-based	Map-based
Reactive navigation	Deliberative navigation
Fast response	Relatively slower response
Suppose that the workspace area is incomplete or partially incomplete	The workspace area is known
Generate the path and moving toward target while avoiding obstacles or objects	Generate a feasible path before moving toward the goal position
Done online	Done offline

is known as *global path planning* or *deliberative path planning*. The second class of path planning assumes that the robot does not have a priori information knowledge about its environment (i.e., uncertain environment). Consequently, it has to sense the locations of the obstacles and construct an estimated map of the environment in real time during the search process to avoid obstacles and acquire a suitable path toward the goal state. This type of path planning is known as *local path planning* or *reactive navigation*. Table 1.1 presents the differences between the two categories.

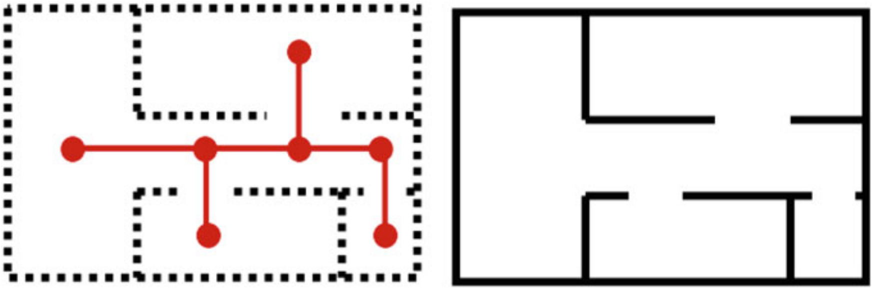
Completeness: Depending on its completeness, the path planning algorithm is classified as either exact or heuristic. An exact algorithm finds an optimal solution if one exists or proves that no feasible solution exists. Heuristic algorithms search for a good-quality solution in a shorter time.

Robot path planning also could be classified according to the number of robots that exist in the same workspace to do the same mission. In many applications, multiple mobile robots cooperate together in the same environment. This problem is called *Multi-Robot Path Planning*. Its objective is to find obstacle-free paths for a team of mobile robots. It enables a group of mobile robots to navigate collaboratively in the same workspace to achieve spatial position goals. It is needed to ensure that any two robots do not collide when following their respective paths.

1.4 Spatial Representations Commonly Used in Path Planning

Roughly, map-based path planning models fall into two categories depending on the way of looking at the world [15].

Qualitative (Route) Path Planning: (Figure 1.4a) In this category, there is no a priori map that represents the world, but it is rather specified by routes from the initial to target location. The world is represented as a connection between landmarks, and a sequence of connected landmarks will represent the route. This approach is similar to how humans describe a route in their natural language (e.g., go straight until reaching



(a) Qualitative Path Planning (b) Metric Path Planning

Fig. 1.4 Spatial representations commonly used in path planning

the XYZ restaurant, then turn toward the left, walk until finding the kindergarten, then turn right). Landmarks can be any kind of recognizable and perceivable objects that can uniquely identify a location.

Metric (Layout) Path Planning: (Figure 1.4b) The world is specified using a layout representation that is the map. The map provides an abstract representation to the world (e.g., street layout, intersections, roads). It has to be noted that it is possible to generate route based on layout representation of the environment, but not in other way. In robotics, metric path planning is more attractive than qualitative path planning as it is possible to represent the environment in a clear structure that the robot can use to plan and find its path. Furthermore, it allows the robot to reason about space. In fact, metric maps decompose the environment into a set of distinct points, called waypoints, which are fixed locations identified by their (x,y) coordinates. Planning the path will then consist in finding the sequence of connected waypoints that lead to the goal position while minimizing the path cost. The path cost can be defined as the path length, or path with minimum energy consumption, or the path delay, etc., depending on one of the problem requirements.

1.4.1 Environment Characterization

The robotic environments are characterized in terms of the shape of their obstacles. There are two main types of environments:

Structured environment: in which obstacles have a structured shape and nicely placed within the map. In such a case, the robotic map can easily specify the way the robot can move avoiding obstacles. For instance, in [?], obstacles do not have the actual shape and are represented by dots (for position only) or circles (for position and size). In some other research works [16], environments with only rectangular obstacles are dealt with. In some approaches [17], grids and quad tree are applied to the robot environments for discretization, and obstacles are represented approximately by fitting into the cells.

Unstructured environment or semi-structured: Real robot environments are usually unstructured in which obstacles may have different shape and sizes and be placed in inclined orientation. In such a case, the path planning problem is relatively complex. The algorithm needs to compute a feasible and an optimal path. [18] proposed a real-time path planning of autonomous vehicles for unstructured road navigation.

1.4.2 Path Planning Complexity

If we consider the general formulation of the motion planning problem, where the robot is not simply a point, it has been rigorously proven in this case [19] that the problem is PSPACE-hard (and hence NP-hard). The reason for this is that the configuration space has an unbounded dimension. As for a point robot, the dimension of the working space is bounded (generally 2 or 3), which makes the shortest path problem solvable in polynomial time: ($\mathscr{O}((n)\log(n))$ as an upper bound) [20].

As mentioned in Sect. 1.3, path planning problem could be solved using either exact or heuristic methods. The question is why exponential techniques are used to solve a polynomial problem?

This could be explained by the following reasons:

- Exact methods such as the well-known polynomial Djikstra's algorithm [21] perform a lot of irrelevant computations for reaching the goal. It is not going in the right direction.
- The state space of the problem may be large due to a fine-grain resolution required in the task, or the dimensions of the search problem are high.

It is preferable to use intelligent exact techniques such as Astar (A^*) [22] to guide the search toward promising regions (regions leading to optimal paths) and so avoiding to perform irrelevant computations. On the other hand, the exact methods may only be able to work over low-resolution workspace; if the dimension of the workspace increase, we may observe an increase in computational time.
We can say that in theory the path planning problem as described above has a polynomial complexity, but there is no efficient polynomial technique to solve them in practice due to the above reasons.

1.5 Conclusion

In this chapter, we give a general overview of the path planning problem; the different categories of this problem, approaches used to solve it, its complexity, etc. A lot of intelligent algorithms have been proposed to solve efficiently this problem. These algorithms span over a large number of techniques. This diversity makes hard for a robotic application designer to choose a particular technique for a specific problem. Usually, researchers design and implement a particular algorithm while other techniques might be more effective. This raised the need to devise a classification and taxonomy of the different algorithms being used in the literature. This is the subject of the next chapter.

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