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Obstacle representation by Bump-surfaces for optimal motion-planning

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Abstract

This paper introduces a new method for global, near optimal, motion-planning of a robot (either mobile or redundant manipulator) moving in an environment cluttered with a priori known prohibited areas which have arbitrary shape, size and location. The proposed method is based on the novel notion of Bump-surfaces (or B-surfaces) which represent the entire robot environment through a single mathematical entity. The motion-planning solution is searched on a higher-dimension B-surface in such a way that its inverse image into the robot environment satisfies the given objectives and constraints. The computed solution for a mobile robot consists of a smooth curve without self-loops which connects the starting and destination points with the shortest possible path. The same approach is also used for *n*th degree-of-freedom manipulators where the end-effector reaches the destination position following a smooth short path avoiding the prohibited areas. For clarity reasons the proposed method is introduced in this paper for the case of a two-dimensional (2D) planar terrain with static obstacles, while a generalization to motion-planning problems on curved terrains is also discussed. Extensive experiments are presented and discussed to illustrate the efficiency and effectiveness of the proposed motion-planning method in a variety of complex environments.

Keywords: Motion-planning; Path-planning; Mobile robots; Articulated robots; Manipulators; Obstacles; Genetic algorithms; Conjugate gradient

1. Introduction

The problem of finding a valid path between a starting and a target point in an environment cluttered with static obstacles attracted the attention of many researchers. When the free space between the obstacles is much wider than the objects' size this problem is called Gross-Motion Planning [1] and the present paper deals

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with such problems, but for simplicity the abbreviation Motion-Planning is used. It is worth to notice that in this work the definitions proposed by Hwang and Ahuja [1] are adopted. The shortest path of the moving object is considered as a special case of the motion-planning problem and less publications deal with this problem than the general motion-planning. The published methods are used in a variety of applications such as robot navigation, automated travelling advisory system, circuit board and piping layout, graphics animation and virtual reality. The complexity of the general motion-planning problem is enormous, so a variety of simplifications have been suggested to reduce the complexity and solve the problem using heuristic techniques.

Latombe [2] classified motion-planning methods appeared in the literature in three main categories: road map or skeleton methods, cell decomposition methods and potential fields methods. In most of the methods, a pre-processing stage is necessary before computing the solution of the actual motion-planning problem, where the environment information concerning the obstacles and the free space is represented appropriately to make the solution of the path-planning problem less complicated. The moving object can take a great variety of shapes and sizes complicating the path-planning problem. Lozano-Perez [3] introduced the configuration space approach to simplify this complexity. Using this approach the moving object is transformed to a point while the obstacles are expanded appropriately. Although the implementation of such a transformation is quite complex and time consuming, this is performed once and off-line for a static environment. Later some research work has been devoted to extend the formulation of configuration space to non-convex polygons and to articulated robots. In one of the latest works, a method is proposed for C-space evaluation applicable to mobile and articulated robots [4]. On the other hand, some of the path-planning methods have been used directly without this pre-processing stage of the configuration space formulation.

In skeleton methods, the free space between the obstacles can be represented using generalized cones [5], visibility graphs [6], Voronoi diagrams [7] and roadmaps [8]. Using these methods the free configuration space is reduced to a network of lines and the path planning algorithm has to move the robot from the start to goal point through the edges of this network. The visibility graph and Voronoi diagrams are mostly used for two-dimensional (2D) motion planning [1] and are limited to simple configuration spaces [9]. The equidistance diagram [9] has been proposed which was inspired from the Voronoi diagrams in order to reduce the computational time. The randomised roadmap methods are currently the most promising for motion-planning. The probabilistic roadmap planner samples the configuration space for points in the free space and then a local planner connects these points into a graph of valid paths. This approach has been applied efficiently in a variety of cases, but due to probabilistic nature it is difficult to analyze it and little is known about the speed of convergence [10]. The complexity of the probabilistic roadmap planners depends strongly on the path difficulty and less on the complexity of the scene or the dimension of the configuration space [11]. On the other hand, there are still problems in the application of the probabilistic roadmap methods concerning the quality of the path such as: the path is not smooth, it can make long detours and contains many redundant motions [11]. In order to improve the quality of the path, remedy techniques are necessary.

In the cell decomposition approaches, the free space is decomposed into a set of simple cells and the adjacency between the cells is determined forming a graph of free cells. Then a continuous path is computed into the free space using search algorithms. Instead of the simple grid methods (exact), quadtree or octree (approximate) free space representation has been introduced to reduce the high memory requirements [12]. These methods are quite efficient when the edges of the objects are parallel to the edges of the quadtrees. When the dimension of the configuration space or the complexity of the scene are high then the number of cells become too big increasing the memory requirements. A later technique [13] reduces considerably the memory requirements by introducing an augmented octree representation. Chen et al. [14] introduced the idea of framed quadtree in order to develop an algorithm for the shortest path determination. Later this idea has been further elaborated by combining the framed quadtrees to reduce the number of free cells to be searched for shortest path determination [15].

The maps derived using the roadmap or cell decomposition methods are used to record the position of the moving object (robot) and to plan paths for it to follow. Graph theory is used to find a valid or an optimal path. Using Voronoi diagrams or generalized cones the valid