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Trajectory Planning of Robots in Presence of Obstacles: a Review Study

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Abstract
Path planning of robots is an important and challenging task, especially in presence of obstacles. Thus, this matter is attracted a great deal of interests by robotic researchers. The current study deals with the path planning of robotic systems in obstructed environments. Some recent researches are studied, and some conventional methods on the obstacle avoidance of the robots are reviewed. The effectiveness and defects of the methods are discussed. Moreover, some advanced methods on the obstacle avoidance and the path planning of the fixed and mobile robots are reviewed and discussed.

Key Word and Phrases
Robots, Path Planning, Presence of Obstacles, Conventional Methods, Advanced Methods.

1. Introduction

Path planning of robotic systems is an important and challenging task, which plays a crucial role in robotic fields. Beside, the robotic systems operate in a wide range of environments, including variant type of obstacles. Thus, the systems must be able to plan their paths without colliding to obstacles.

To plan the point-to-point motion of the robots in the obstructed environments, a great deal of methods have been developed, which in this study is presented and discussed. The path planning in the presence of the obstacles are classified as global and local path planning [1]. In the local techniques, the environmental map is not completely known, and the trajectory planning of the mobile robot is mainly based on its variant sensors information [2].

However, since the accuracy of sensors is vital in the motion planning problems, the use of global techniques has been recognized as a possible solution to planning the trajectories of the robotic system. In the global techniques, the robot's environment is completely known and the trajectory planning is defined as the modeling of the obstacles. Hence, the method makes the robot moves in the environments without colliding to the obstacles.

The conventional approaches are basically categorized as: potential field method, road map method, and cell decomposition algorithm. Moreover, some advanced approaches are treated in this paper.

In addition, some advanced methods on the obstacle avoidance and the path planning of the fixed and mobile robots are reviewed and discussed including Genetic Algorithm, Neural Network, Fuzzy logic, Ant Colony, Particle Swarm Optimization, Wavelet Theory, Tabu Search. Figure 1 shows a schematic of methods on the obstacle avoidance of the robotic systems.

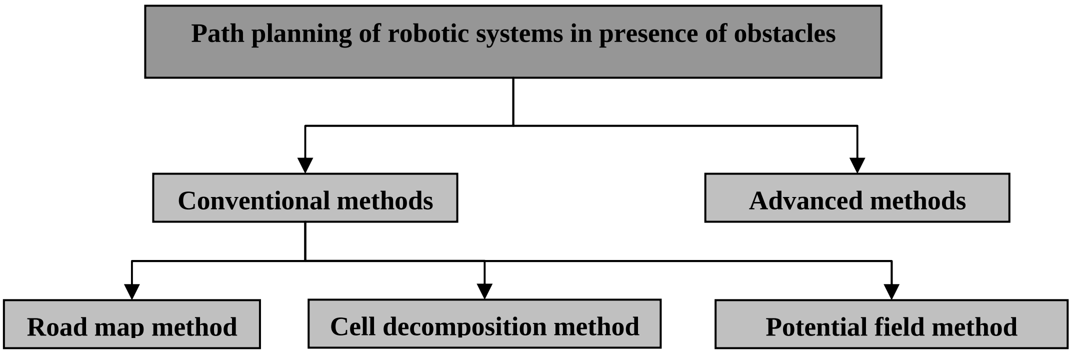

Fig. 1 A schematic of methods on obstacle avoidance of robotic systems.

2. Conventional Methods

In this section, some important conventional methods are presented such as potential field method, road map method, and cell decomposition algorithm.

Potential field (PF) method is a novel method, which has a elegant mathematics and simplicity. In this method, path planning methodology creates a field, or gradient, across the robot's map that directs the robot to the goal position from multiple prior positions [3]. The basic concept of potential field method is to fill the robot's workspace with an artificial potential field, where the robot is repulsed away from the obstacles and is attracted to its goal position. In this method, if the coordinate of the robot is considered as q, and the artificial potential field is considered as U, this filed is given as:

$$U(q) = U_{att}(q) + U_{rep}(q) \qquad (2.1)$$

where U_{att} is the attractive field of the goal, and U_{rep} is the repulsive field of the obstacles.

Then, the gradient of this artificial potential is assumed as a force vector which is applied to the dynamic of the system [3]:

$$F(q) = -\nabla U(q) \qquad (2.2)$$

The first formulation of potential field method has been addressed to Khatib [3]. He presented the PF method for the path planning of the mobile robots and manipulators in an obstructed environment. His proposed potential field formulation is given as [4]:

$$U_{att}(q) = \frac{1}{2} k_{att} . \rho_{goal}^{2}(q)$$

$$U_{rep}(q) = \begin{cases} \frac{1}{2} k_{rep} \left(\frac{1}{\rho(q)} - \frac{1}{\rho_0} \right)^2 & if\ \rho(q) \le \rho_0 \\ 0 & if\ \rho(q) > \rho_0 \end{cases} \qquad (2.3)$$

Newman and Hogan [5] used dynamic potential functions to control of high speed robot motion. Borenstein and Koren [6] proposed an obstacle avoidance procedure for fact mobile robots based on PF method. Moreover, same scientists [7] discussed the inherent limitations such as local minima, multiple obstacles. Thus, a lot of procedures and potential functions are proposed to rectify these limitations [8, 9]. Kim and Khosla [10] proposed a harmonic potential function to avoid the limitations of PF method. Moreover, a curvature-velocity method for local obstacle avoidance is presented in [11]. Ge [12] proposed a new potential function to collision avoidance of the mobile manipulators. Park et al. [13] employed the PF and the simulated annealing method for obstacle avoidance of mobile robots. An analytical algorithm for the collision-free motion planning of the wheeled mobile robots is presented in [14] based on potential field method. In this work, only kinematic model of the mobile robot is considered which is simple and straight forward. However, since inertia and torque constraints are neglected in this study, Shimoda et al. [15] used the PF based navigation for high speed unmanned ground vehicles on uneven terrain. Moreover, a study of a new method for improving artificial potential field in mobile robot obstacle avoidance is presented in [16]. Huang [17] studied a velocity planning for a mobile robot to track a moving target. In this paper, the potential field method is applied for both path and speed planning, or the velocity planning, for a mobile robot in a dynamic environment where the target and the obstacles are moving. The robot's planned velocity is determined by relative velocities as well as relative positions among robot, obstacles and targets. Furthermore, Korayem and Nazemizadeh [18] presented an optimal motion planning of the non-holonomic mobile robots in the presence of multi obstacles based on PF method. They applied the potential function to the index performance of the optimal problem, to avoid the PF limitations, and then used an indirect method to solve the problem. Thus the cost function *J* of optimal control problem is defined as [19]:

$$J = \int_{t_0}^{t_f} \left(\frac{1}{2} \| X \|_W^2 + \frac{1}{2} \| U \|_R^2 + \frac{1}{2} \| L_i \|_{w_{ob_i}}^2 \right) dt \tag{2.4}$$

where $\|X\|_W^2$ is the generalized squared norm of the state vector with respect to a state weighting matrix *W*, and $\|U\|_R^2$ is the generalized squared norm of the control vector with respect to a control weighting matrix *R*. The parameter $\|L_i\|_{wob_i}^2$ is related to the collision avoidance between the mobile robot and the i^{th} obstacle. Their proposed method can effectively avoid multiple obstacles, as shown in Fig. 2.

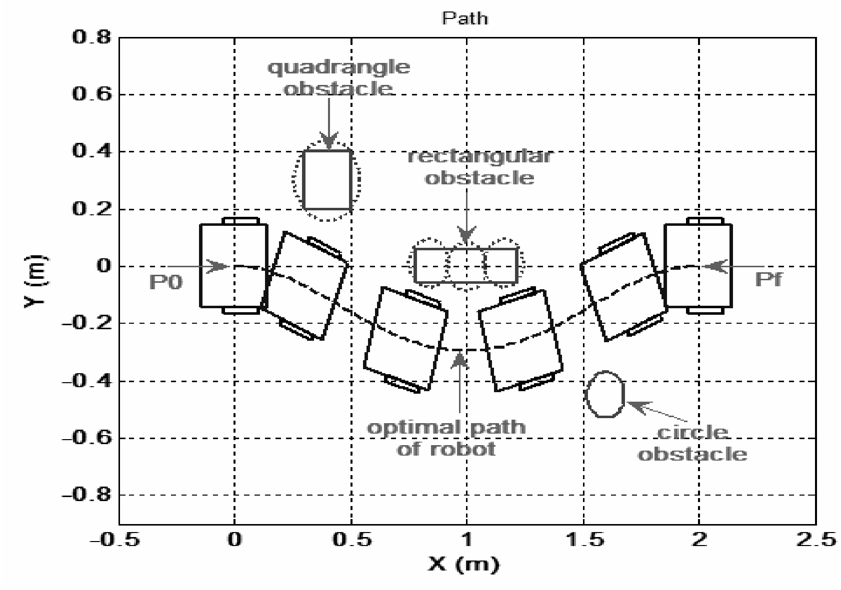

Fig 2 Multiple obstacle avoidance of the non-holonomic mobile manipulator [19]

Furthermore, Korayem and Nazemizadeh [20] developed a new formulation of potential functions using enclosed optimal ellipsoids to model the mobile manipulator parts and the environmental obstacles. In their method, parameter $\|L_i\|_{w_{ob_{ij}}}^2$ is referred to the potential function between the i^{th} obstacle and the j^{th} part of the mobile manipulator. This parameter is defined as [20]:

$$\|L_i\|^2_{w_{ob_{ij}}} = w_{ob_{ij}} \frac{1}{{d_{ij}}^2} \tag{2.5}$$

where d_{ij} is a dimensionless parameter, and is defined using the parametric equation of spatial ellipsoids, and is defined as [20]:

$$d_{ij} = \left(\frac{x^2_{ob_i}}{a^2} + \frac{y^2_{ob_i}}{b^2} + \frac{z^2_{ob_i}}{c^2} - 1 \right)^{\frac{1}{2}} \tag{2.6}$$

where $p_i(x_{ob_i}, y_{ob_i}, z_{ob_i})$ is the local coordinate of the obstacle. Hence, in this method the collision avoidance is formulated as a dimensionless parameter over a repulsive force, the inherent limitations of the potential field method are rectified. They validated their method via simulation results and experiments on a wheeled mobile robot known as the Scout robot (Fig. 3).

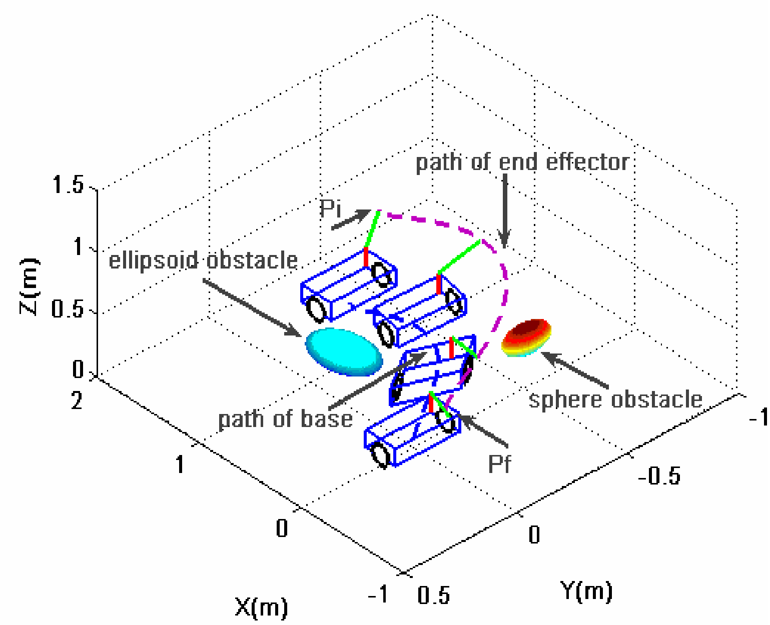

Fig 3 The Scout robot in the presence of spatial obstacles [20]

Also, Nazemizadeh et al. considered the jerk-bounded optimal path planning [21], and moving obstacle avoidance [22] based on optimal control theory and potential functions formulations.
Another method is known as road map method. In this procedure, the continuous environment is modeled into a set of routes within the free space. Then, these set of roads (including straight lines and curves) construct a network of paths, named road map. On the other word, the road map is a network of short segments which totally set up a road network [23]. Thus, the free space is converted to a set of admissible roads. Besides, the challenge is to construct these set of roads that together enable the robot to go anywhere in its free space. The approaches of modeling the free space to a set of can be treated as different approaches. In the case of the Visibility graph, roads come as close as possible to obstacles and resulting paths are minimum-length solutions. In the case of the Voronoi diagram, roads stay as far away as possible from obstacles [23]. The Visibility graph (VG) is constructed by a collection of lines in the free space that connects an edge of an obstacle to that of another. It means that two vertices are connected in the graph if they are mutually visible [24]. Asano et al. [25] used the Visibility approach to set a road map among polygon obstacles, and then presented a shortest path between start and goal points. Moreover, an efficient algorithm for planning collision-free motion of a convex polygonal object in 2-dimensional space amidst polygonal obstacles is presented in [26, 27] based on VG. Rekleitis et al. [28] used a VG- like procedure for path planning of multiple robots. Moreover, an enhanced

version of this method is developed in [29] to collision-free path planning of mobile robots in dynamic environment. The following figure show a Visibility graph for three polygon obstacles.

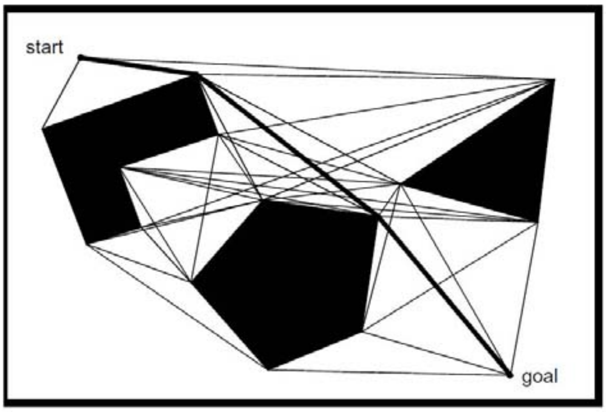

Fig 4 The Visibility graph for three polygon obstacles [2]

Another approach is known as Voronoi diagram (VD). In despite of VG approach, in VD method, the road map construction tends to maximize the distance between the robot and the obstacles in the map [30]. The Voronoi diagram consists of the lines constructed from all points that are equidistant from two or more obstacles. Canny [31] proposed VD approach for path planning in cluttered environments. Schwartz and Sharir [32] studied a VD approach to plan the path of an object amidst polygon barriers. Moreover, an algorithm to move a disc among polygons using the Voronoi diagram is reported in [33]. Amato and Wu [34] employed an advanced VD method for path and manipulation planning of robotic systems. Furthermore, an optimal path planner with obstacle avoidance strategy is developed in [35]. Dong et al. [36] proposed an advanced path planning method for mobile manipulators based on VD, and Breitenmoser et al. [37] studied convergence of VD method for non-convex environments with a group of networked robots. As the presented researches are based on a graph model of Network of roads using vertices of obstacles, the backbone of these models is dependent upon the nature and clutter of the environment. Thus, model environment mapping methods for a convex environment offer elegant solutions, but these methods require accurate sensor information and are therefore difficult to implement in practice.

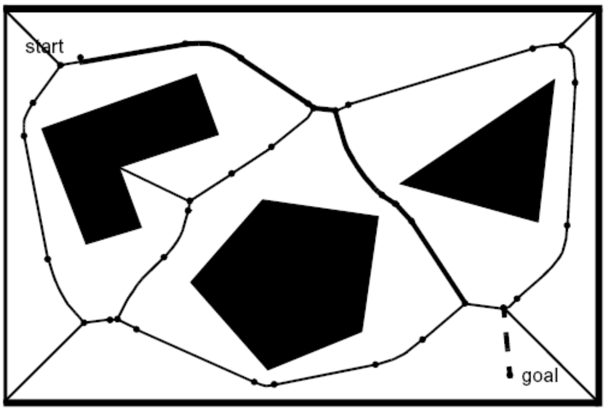

Fig 5 The Voronoi diagram for three polygon obstacles [2]

The other method is cell decomposition method, which is studied here. In fact, the main idea of the cell decomposition method (CDM) is to discriminate between geometric areas, or cells, that are free and areas that are occupied by obstacles [38]. The basic cell decomposition path-planning algorithm can be summarized as: dividing the workspace into a set of free and occupied cells or grids, connecting adjacent free cells and constructing a graph named connectivity graph, and plan the shortest path among the paths of connectivity graph. In the literature review, an important aspect of cell decomposition methods is known as the placement of the boundaries between cells [1]. If the boundaries are placed as a function of the structure of the environment, such that the decomposition is lossless, then the method is termed exact cell decomposition. If the decomposition results in an approximation of the actual map, the system is termed approximate cell decomposition. Keil and Sack [39] decomposed the environment via the vertices of polygon obstacles which is assumed as the exact cell decomposition. Brooks [40] developed a three dimensional global path planner for a PUMA robot arm based on CD method. Furthermore, a procedure to fill the whole region with obstacle avoidance for a robot using a raster scanning strategy is developed in [41], which is related to the sensor based decomposition. Fujimura and Samet [42] presented a hierarchical strategy for path planning among moving obstacles based on CD algorithm. Choset [43] proposed a novel cellular decomposition approach by breaking down the workspace. This solution combines the advantages of cell decomposition and template based approaches, and minimizes the number of cells used in cell decomposition. Moreover, an improved CD method is presented in [44], which tends to ensure the convergence of method. Atkar et al. [45] applied the exact cellular decomposition to complete coverage of a closed orientable surface in three dimensions. Chenghui and Ferrari [46] developed a novel approximate cell-decomposition method in which obstacles, targets, and sensor's platform are represented as closed and bounded subsets of the Euclidean workspace. Their method constructed a connectivity graph with observation cells that is pruned and transformed into a decision tree from which an optimal sensing strategy can be computed. Moreover, a simple feedback law is proposed over a given cell decomposition of obstructed environments is presented in [47]. Swingler and Ferrari [48] proposed a cell decomposition approach to cooperative path planning and collision avoidance. Furthermore, a path planning method for palletizing tasks of an industrial 6-axis robot using workspace grid decomposition is presented in [49]. Hence the cell decomposition algorithms explicitly computes the configuration space of the mobile robot, decomposes the resulting space into cells, and then searches for a route in the free space cell graph. However, the algorithm suffers from the drawback of high time complexity [50].

3. Advanced Methods

In this section, some advanced methods are presented. In order to improve the efficiency of Classic methods, Probabilistic algorithms have been developed, including Probabilistic Roadmaps and rapidly exploring Random Trees [51-[54], with major advantages is high-speed implementation. In these procedures, in an instance of time, a graph is constructed to obstacle avoidance at each time interval, and then these collision-free paths are attached to each others.

Furthermore, there are many Heuristic and Mete-heuristic algorithms for mobile robot path planning such as Genetic Algorithm [55, 56], Artificial Neural Network [57, 58], Fuzzy Logic [59, 60], Ant Colony [61, 62], Particle Swarm Optimization [63, 64], Wavelet Theory [65], Tabu Search [66, 67]. These methods are known as heuristic methods which can be combined in some cases. By the following figure, a solution of the maze problem is presented based on neural network

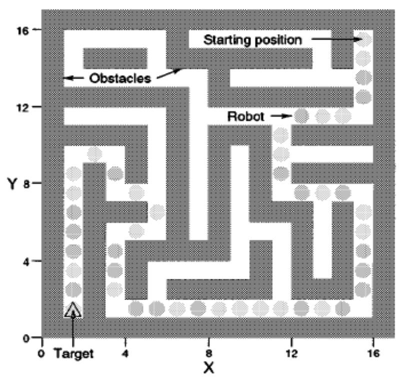

Fig 6 Solution of the maze problem based on the neural network[68]

4. Conclusions

This study has presented a review on some conventional method for path planning of robotic systems in cluttered environment such as potential field method, road map method, and cell decomposition method.

Also, the effectiveness and defects of these methods have been discussed. Moreover, some advanced methods for the obstacle avoidance and the path planning of the fixed and mobile robots were reviewed and shortly discussed.

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