Different Cell Decomposition Path Planning Methods for Unmanned Air Vehicles-A Review

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Different Cell Decomposition Path Planning Methods for Unmanned Air Vehicles-A Review

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Abstract. An Unmanned Aerial Vehicle (UAV) or robot is guided towards its goal through path planning that helps it in avoiding obstacles. Path planning generates a path between a given start and an end point for the safe and secure reach of the robot with required criteria. A number of path planning methods are available such as bio-inspired method, sampling based method, and combinatorial method. Cell decomposition technique which is known as one of the combinatorial methods can be represented with configuration space. The aim of this paper is to study the results obtained in earlier researches where cell decomposition technique has been used with different criteria like shortest travelled path, minimum computation time, memory usage, safety, completeness, and optimality. Based on the classical taxonomy, the studied methods are classified.

Keywords: Path Planning, Cell Decomposition, Regular Grid, UAV

1 Introduction

The use of unmanned air vehicle or autonomous robot in place of human beings to carry out dangerous missions in adverse environments has been gradually increased since last decades. Path planning is one of the vital aspects in developing an autonomous vehicle that should traverse the shortest distance from a starting point to a target point while in a given mission for saving its resources and minimizing the potential risks. Therefore, it is crucial for a path planning algorithm to produce an optimal path. The path planning algorithm should also hold the completeness criterion which means that a path can be found if that exists. Moreover, the robot's safety, memory usages for computing and the real-time algorithms are also significant [1-7]. Fig.1 illustrates the classification of path planning approaches.

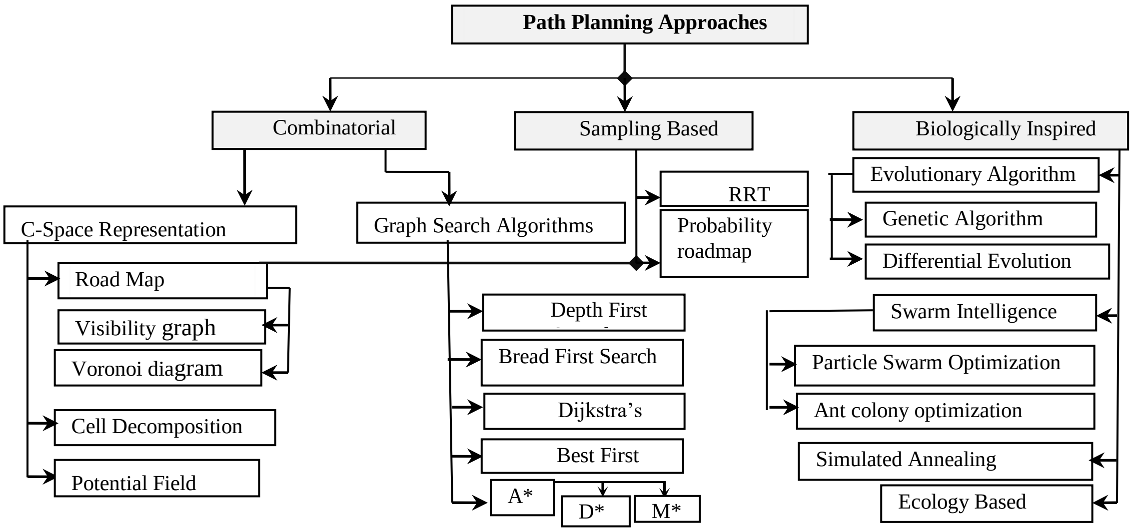


Fig.1. Classification of path planning approach [8]

The bio-inspired methods are the nature-motivated/biologically inspired algorithms. A number of instances of bio-inspired approaches are the Genetic algorithm (GA), Simulated annealing (SA), Particle Swarm Optimization (PSO) plus Ant Colony Optimization (ACO). GA uses the natural selection course of biological evolution that continuously fluctuate a populace of distinct results. Nonetheless, it cannot assure any optimal path. Local minima may occur in narrow environments and thus, it offers a lesser amount of safety and constricted corridor difficulty. GA is computationally costly and ultimately it is not complete [8].

SA algorithm is developed based on warming and cooling process of metals to regulate the internal configuration of its properties. Separate from very sluggish and very high cost functions, SA is not able to accomplish the optimal path [9-15]. PSO is a meta-heuristic population based approach and it has real-time outcome, but it tumbles into local optima easily in many optimization complications. Additionally, there is no general convergence concept appropriate for PSO in practice and its convergence period is mostly vague for multidimensional problems [16]. On the other hand, ACO emulates an ant to mark a path while the food source is confirmed. The ant separates its direction towards the food source with pheromones for tracing purpose. In ACO, the path in between the initial point and target point is arbitrarily produced. ACO does a blind exploration and therefore, it is not proper for efficient path planning due to the lack of optimal result [17-18].

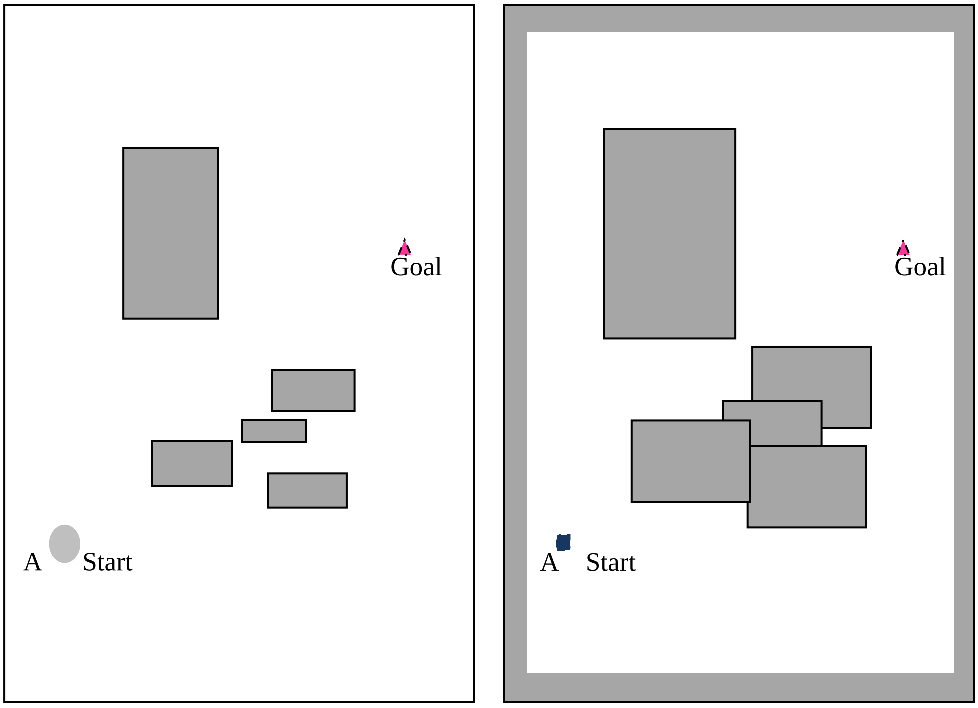
In sampling based path planning, a method Rapidly Exploring Random Tree (RRT) does not require the establishment of the design space. In RRT, the first step is to define the starting and the target points. Then, it considers the starting point as the base for the tree, based on which different new branches are grown-up till it reaches the target point [10-11]. RRT is simple and easy way to handle problems with obstacles and different constraints for autonomous/unmanned robotic motion planning. Depending on the size of the engendered tree, the computation time is also escalated. The resulting path commencing by RRT is not optimal all the time. Nonetheless, it remains pretty easy to find a path for a vehicle with dynamic and physical constrictions and it also creates least number of edges [19-20]. Probabilistic roadmap (PRM) method is a path-planning algorithm that takes random samples from the configuration space by examining the accessible free space and dodging the crashes to find a way. A local planner is used to join these configurations with close-by configurations. PRM is costly without any possibilities to acquire the path. [19-20].

Combinatorial path planning consists of mainly two methods, i.e. C-space representation technique and graph search algorithm. In this case, the first step is to create the configuration space of the environment. Then, a graph search algorithm, for example Dijkstra's and A-star (A*), is applied to search a path [7, 21].

Depth-first search (DFS) is good to pick up a path among many possibilities without caring about the exact one. It may be less appropriate when there is only one solution. DFS is good because a solution can be found without computing all nodes [7]. Breadth-first search that is suitable for limited available solutions uses a comparatively small number of steps. Its exceptional property finds the shortest path from the source node up to the node that it visits first time when all the graph's edges are either un-weighted or having similar weight. Breadth-first search is complete if one exists. Breadth-first search is good because it does not get trapped in dead ends [22] and this algorithm does not assure to discover the shortest path because it bypasses some branches in the search tree. It is a greedy search which is not complete and optimal. Dijkstra's algorithm is systematic search algorithm and gives shortest path between two nodes. In optimal cases, where there is no prior knowledge of the graph, it cannot estimate the distance between each node and the target. Usually, a large area is covered in the graph by Dijkstra's due to its edge selections with minimum cost at every step and thus, it is significant for the situation having multiple target nodes without any prior knowledge of the closest one [23]. A* is not very optimal because it needs to be executed a number of times for each target node to get them all. A* expands on a node only if it seems promising. It only aims to reach the target from the current node at the earliest and does not attempt to reach any other node. A* is complete because it always finds a path if one exists. By modifying the used heuristics and node's evaluation tactics of A*, other path-finding algorithm can be developed [24].

Configuration space gives complete information about the location of all points in the coordination and it is the space for all configurations such as real free space area for the motion of autonomous vehicle and guarantees that the vehicle must not crash with obstacles. An illustration of a C-space for a circular vehicle is shown in Fig.2. It assumes the robot as a point and adds the area of the obstacles so that the planning can be complete in a more capable way. C-space is obtained by adding the vehicle radius while sliding it along the edge of the obstacles and the border of the search space. In

Figure 2(a), the obstacle-free area is represented by the white region inside the close area.



(a) (b)

Fig.2. A scenario represented in (a) original form (b) configuration space. Note that the darker rectangles in (a) are those with actual dimensions while in (b) are those enlarged according to the size of robot *A*. The white areas represent free space.

The robot in Fig.2(a) is represented by *A*. On the other hand, as the workspace is considered as C-space, as shown in Figure 2(b), it tells that the free space has been condensed while the obstacles' area has been inflated. Hence, C-space indicates the real free space region for the motion of autonomous vehicle or unmanned vehicle and it assures that the autonomous vehicle or robot must not collide with the obstacle.

2 Cell Decomposition CD) Method

Cell decomposition (CD) is a very useful method especially in outdoor atmosphere. In CD, C-space is first divided into simple and connected regions called cells. The cells may be of rectangular or polygonal shapes and they are discrete, non-overlapping and contiguous to each other. If the cell contains obstacle, then it is identified as occupied, or else it is obstacle free. A connectivity graph is erected at that point to link the adjacent cells [43]. There are several variations of CD including Regular Grid (RG), Adaptive Cell Decomposition (ACD) and Exact Cell Decomposition (ECD) [23]. The classification of CD is shown in Fig.3.

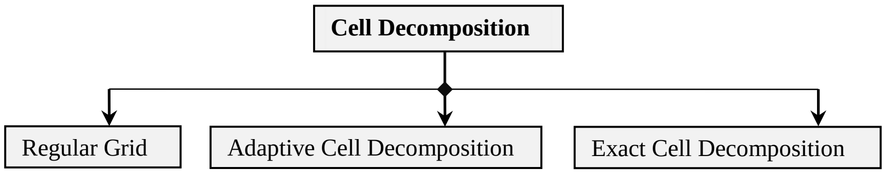


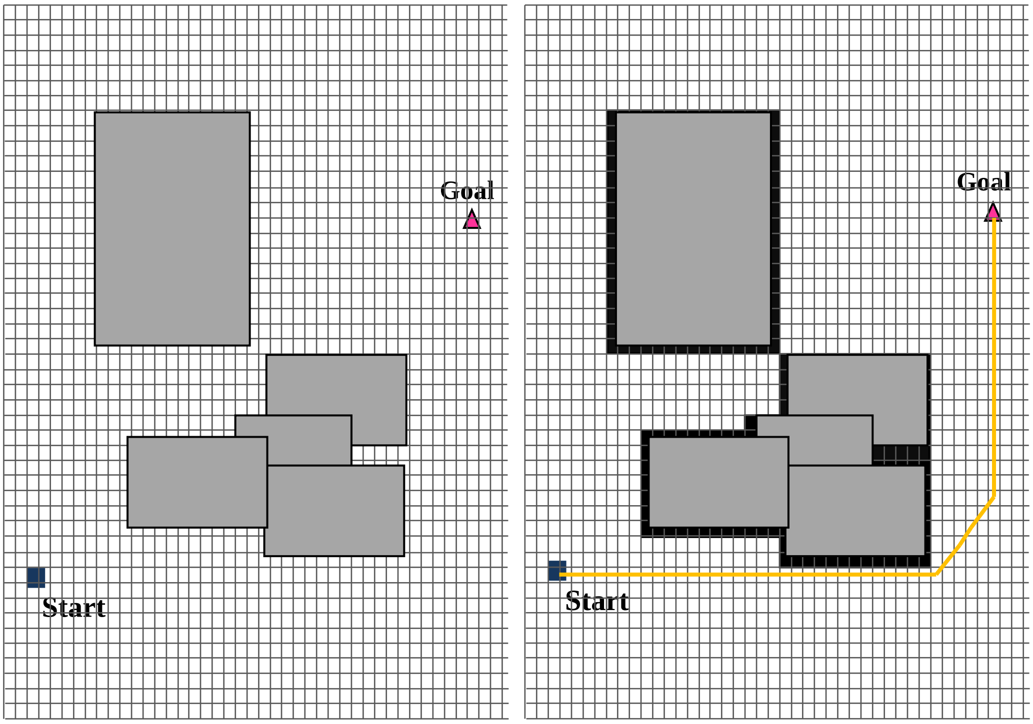
Fig.3. Classification of Cell Decomposition Method

2.1 Regular Grid (RG)

Regular grid (RG) technique was introduced by Brooks and Lozano-Perez [25] to find a collision-free path for an object moving through cluttered obstacles. In general, RG can be constructed by laying a regular grid over the configuration space. As the shape and size of the cells in the grid are predefined, RG is easy to apply. RG basically samples the domain and marks up the graph subsequently to know whether the space is occupied, unoccupied or partially occupied.

A cell is marked as an obstacle if an object or part of it occupies the cell; else it stays as free space. The node is located in the middle of every free space cell within the C-space. Connectivity graph is then constructed from all the nodes. Path planning using RG is illustrated in Fig.4. The path connecting starting point and target point is shown by solid yellow line.

RG method is popular because they are very easy to apply to a C-space and also flexible. The computation time can be reduced by increasing the cell size. On the other hand, the cell size can be made smaller to provide more detailed information and completeness.



(a) (b)

Fig.4. (a) Configuration Space obstacles (b) Obstacles represented by Regular Grid techniques. Note that the drivable area is considered impenetrable

Although RG is easy to apply, there are some drawbacks with this method. Firstly, it has the digitization bias wherever an obstacle that is too smaller than the cell dimension results in that whole grid square as filled or occupied. Consequently, a traversable space may be considered impenetrable by the planner. This scenario is illustrated in Figure 4 (b). Furthermore, if the cell is too big (hence grid resolution is too coarse), the planner may not be complete.

2.2 Adaptive Cell Decomposition(ACD)

The, adaptive cell decomposition (ACD) is built using quad-tree unlike RG. The cells of a quad-tree are identified either as free cells, which contain no obstacles, as obstacles cells, where the cells are occupied or as mixed cells, which represent nodes with both free space and obstacles. The mixed cells should be recursively sub-divided into four identical sub-cells until the resulted smaller cells contain no obstacles' region or the smallest cells are produced [26].

ACD maintains as much detail as possible while regular shape of the cells is maintained. It also removes the digitization bias of RG. An ACD representation employed for path planning is depicted in Fig.5. The collision-free path that connects starting point (Start) and target point (Goal) is depicted via solid yellow line.

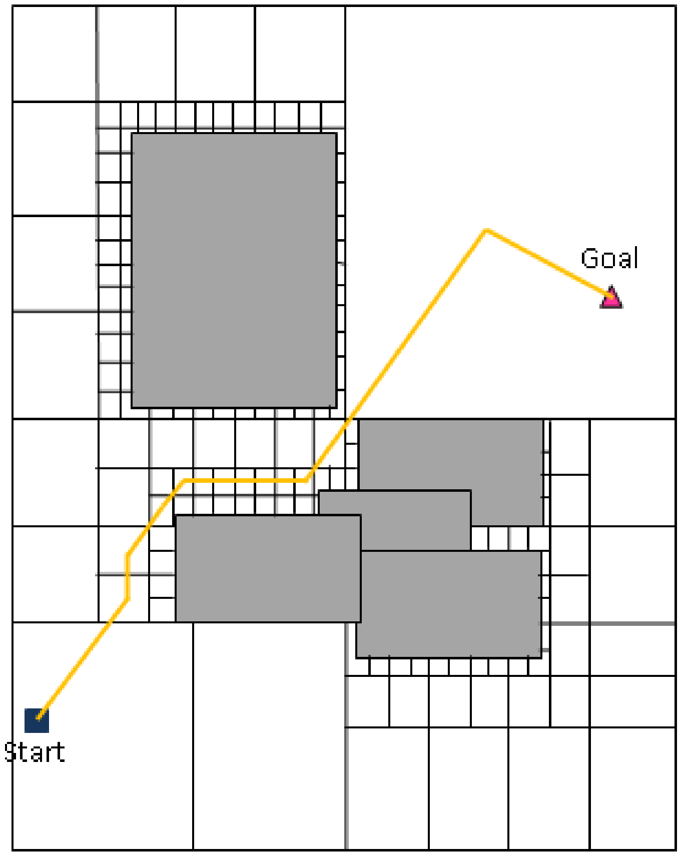


Fig.5. Path planning using quad-tree

2.3 Exact Cell Decomposition

Another variant of CD is Exact Cell Decomposition (ECD) method and it consists of two-dimensional cells to resolve certain dilemma linked with regular grids. The sizes of the cells are not pre-determined; nonetheless they are decided based on the location and shape of obstacles in the C-space [27]. The cell boundaries are determined exactly as the boundaries of the C-space, and the unification of the cells stands the free space. Therefore, ECD is complete that always finds a path if one exists. ECD is shown in Fig.6. The path connecting the starting (Start) and target (Goal) points is shown as solid yellow line.

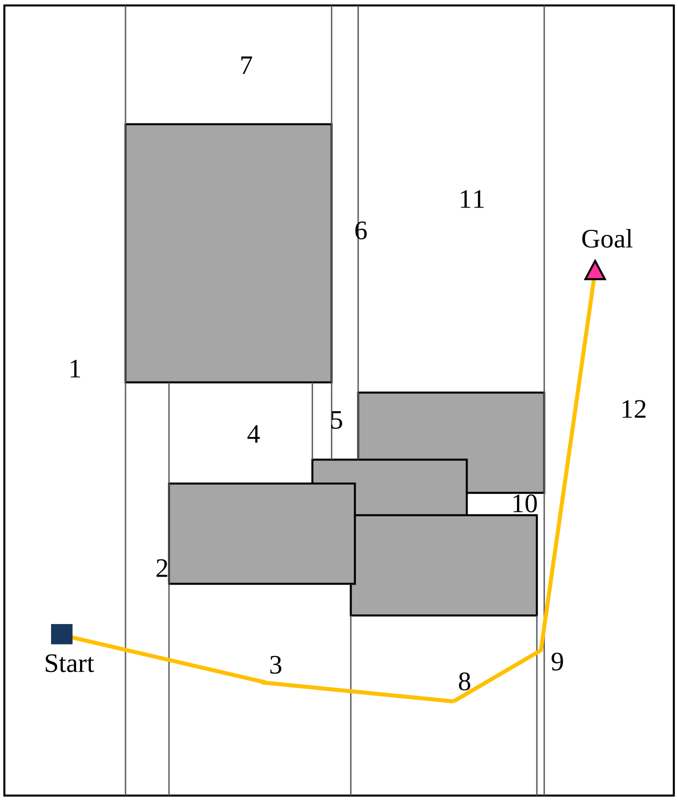


Fig.6. Path planning using exact cell decomposition

Opposed Angle-Based Exact Cell Decomposition is suggested and it is intended for the mobile robot path-planning issue through curvilinear obstacles for more natural collision-free efficient path [28].

Till date many researchers have used cell decomposition-based method to solve path planning problems. In [29], researchers recommended three innovative formulations to construct a piecewise linear path for an unmanned/ autonomous vehicle when a cell decomposition planning method is used. Another trajectory was obtained via path planning algorithms, by varying the involved cell decomposition, the graph weights, and the technique to calculate the waypoints [30]. A combined algorithm was developed by cell decomposition and fuzzy algorithm to create a map of the robot's path [31]. A technique suggested an ideal route generation outline in which the global obstacle-avoidance problem was decomposed into simpler sub complications, corresponding to distinct path homotopy that impacted the description of a technique for using current cell-decomposition methods to count and represent local trajectory generation problems for proficient and autonomous resolution [32].

Parsons and Canny [33] used cell decomposition-based algorithm for multiple mobile robots path planning, which shared the same workspace. The algorithm computed a path for each robot and it was capable of avoiding any obstacles and other robots. The cell decomposition algorithm was based on the idea of a product operation that was defined on the cells in a decomposition of a 2D free space. However, the developed algorithm was only useful when infrequent changes occurred in obstacles set. Chen et. al. [8] introduced framed-quad-tree to create a map in order solve a problem to find a conditional shortest path over a new atmosphere in real time. Conditional shortest path is the path that has shortest path among all possible paths based on known environmental information. The path was found using a propagated circular path planning wave based on a graph search algorithm [34]. Jun and D'Andrea [35] used approximate cell decomposition-based method to accomplish a robot path planning task. The proposed approach used the initial information of the locations and shapes of the obstacles. The method decomposed the region into uniform cells, and changed the values of probabilities while detecting unexpected changes during the mission. A search algorithm was used to find the shortest path. One drawback of this method is that if the penalty is considered for accelerations and decelerations, the graph will become a tree and it will expand exponentially with the number of cells making them very slow. Lingelbach [36] applied the so-called Probabilistic Cell Decomposition (PCD) method for path planning in a high-dimensional static C-space for its easy scalability. Investigational consequences showed that the performance of PCD was acceptable in numerous circumstances for path planning of rigid body movement such as maze-like problems and chain-like robotic platform. However, the PCD had a degraded performance when the free space was small compared to the area of C-space. Zhang et.al [37] utilised ACD for path planning of robot to subdivide the C-space into cells. The localised roadmaps were then computed by generating samples within these cells. Since the complexity of ACD is increased with the number of degree of freedom (DOF) of robots, it is not practical to use the higher DOF robot. Arney [38] implemented ACD path planning approach, in which the efficiency was attained by using a method found in Geographic Information Systems (GIS) known as tesseral addressing. Each cell was labelled with an address during the decomposition process that defined the cell size, position and neighbours addresses. The planner had a priori information about environment and the generated path had an optimal distance from the unmanned/autonomous vehicles' present location to the target location. It is suitable for real-time path planning applications.

3 Discussion on Different Cell Decomposition Methods

The benefits of CD are that it provides assurance to find a collision-free path, if exists and is controllable. Therefore, it is a comprehensive algorithm for an unmanned or autonomous vehicle that can travel the path deprived of the risk of local minima incidence [39]. Yet, the shortcoming of CD is that if the formed cell is too rough, at that time it will not be feasible to achieve the smallest path distance or length. Instead, if the cell is too trivial, then computation is more time-consuming [1], [40], [41]. The CD approach also does not provide acceptable performance in a dynamic state and in real-time circumstance [39], [10], [40]. It is required for CD to fine-tune with the situation as necessary; e.g. in exact CD, the cells are not predefined, but they are selected based on the site and shape of the obstacles inside the C-space [42].

Although RG is easy to apply, but the planner may not be complete if cell is too big, i.e. finding a path where one exists is not guaranteed. If the obstacle's size is significantly lesser than the cell size, then also the outcome for the entire grid square is not obstacle free or occupied. One more drawback of RG is that it inefficiently represents the C-space as in sparse area many same sized cells are required to fill the empty space. As a result, planning is costly because additional cells are handled than they are actually required.

The outcome of ACD is a map that holds different size grid cells and concentrates with the cell boundaries to match the obstacle's boundaries closely. It produces lesser number of cells so that the C-space can be used more efficiently and hence, less memory and processing time are required. ACD maintains maximum details while regular shape of the cells is maintained.

ECD is complete. Still, the paths generated via ECD are not optimal in path length. There is no simple rule to decompose a space into cells. This method is not suitable to apply in outdoor environments where obstacles are often poorly defined and of irregular shape.

Table 1. Comparison of Different Cell Decomposition Methods

Method		Optimal Path	Computational Time	Real time	Memory	Safety	Completeness
CD	RG	×	√	×	×	√	×
	ACD	×	√	×	√	√	√
	ECD	×	×	×	√	×	√

4 Conclusion

The results from earlier researches on several path planning algorithms for cell decomposition methods are compared in this study where the nature of motion was given importance and these algorithms were discussed for their advantages and drawbacks. When an optimal energy efficient collision-free path that is complete can be calculated with lowest computation time by an algorithm, then that algorithm can be conferred as an efficient path planning algorithm. Since none of the algorithms covers all the criteria, hence the optimization of an energy efficient path planning depends on the criteria of the used algorithm such as completeness, computation time etc., and the significant requisites of the vehicle's mission and its objective. For example, RG path planning is expensive but easy to apply. ACD has the adaptive quality and ECD is complete but not suitable for outdoor environment.

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