Complete Area Coverage Path-Planning with Arbitrary Shape Obstacles

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***Abstract*—This article presents a quadtree data structured method for complete area coverage (CAC) path-planning in known environment with arbitrary shape obstacles by applying the concepts of contour map and spanning tree. Contour map can reduce the number of turns effectively. The results of this proposed method can achieve no overlapping with complete area coverage. The robot will start and end at the exact same point.**

***Index Terms*—complete area coverage; contour maps; quadtree; spanning tree**

I. INTRODUCTION

As technology continues to advance, robotics and automation are becoming more important. Its purpose is to improve the effectiveness of automation and robotics tasks at the same time. Therefore, a variety of robots have been derived and more people are investing in the development of robotics. Humans hope that one day they can use robots to assist themselves to perform some dangerous, dirty, and difficult works, application examples that uses robots to achieve automation include robotic arms, construction robots, underwater exploration robots [1], handling dangerous goods, guided robots [2], path planner [3-4], navigation [5] and etc.

Autonomous Mobile Robots are generally capable of walking freely in open spaces and performing their own tasks. They must have the ability to automatically route, that is, to construct environmental maps and avoid obstacles with path planning. The research methods proposed to achieve this function are often based on sensors or visual systems such as Light Detection and Ranging (LIDAR) in autonomous ground vehicles. In the literatures, many scholars who have invested in robotics research have published many research results in this area [6-14]. In recent years, a large number of household cleaning robots have been commercialized. The basic requirement is to avoid obstacles and complete the cleaning of the work space in the shortest amount of time. However, due to the limit of unknown environment, to complete the comprehensive floor cleaning work, navigation, obstacle avoidance, and cleaning strategy has become major challenges.

The so-called global coverage problem means that the robot travels the entire area except the obstacles efficiently. Similar to the point-to-point algorithms, global coverage algorithms can be used in a wide range of applications, such as cleaning (dust, leaves, snow, etc.), harvesting (grains, grass, etc.), painting problems [15], ploughing, spreading (pesticide seed coating), prospecting, search and rescue, underwater detection, demining, etc.

This paper aims to achieve the cleanliness of the entire floor map and has developed a Complete Coverage Path-Planning (CCPP) algorithm for robots, using the robot's own sensors to identify the surrounding environment and avoid the obstacles. To enable the cleaning robot to move around in the home environment, the cleaning robot must clean up the entire space and plan a path covering the entire area as well as avoid overlapping to complete the required cleaning task.

Before the cleaning robot was commercialized, there were some studies on the application of the floor cleaning method in unknown environment. In 1997, Carvalho et al. [16] explored a comprehensive cleaning method for

Manuscript received September 9, 2019; revised November 1, 2019.

doi: 10.18178/joace.7.2.80-85

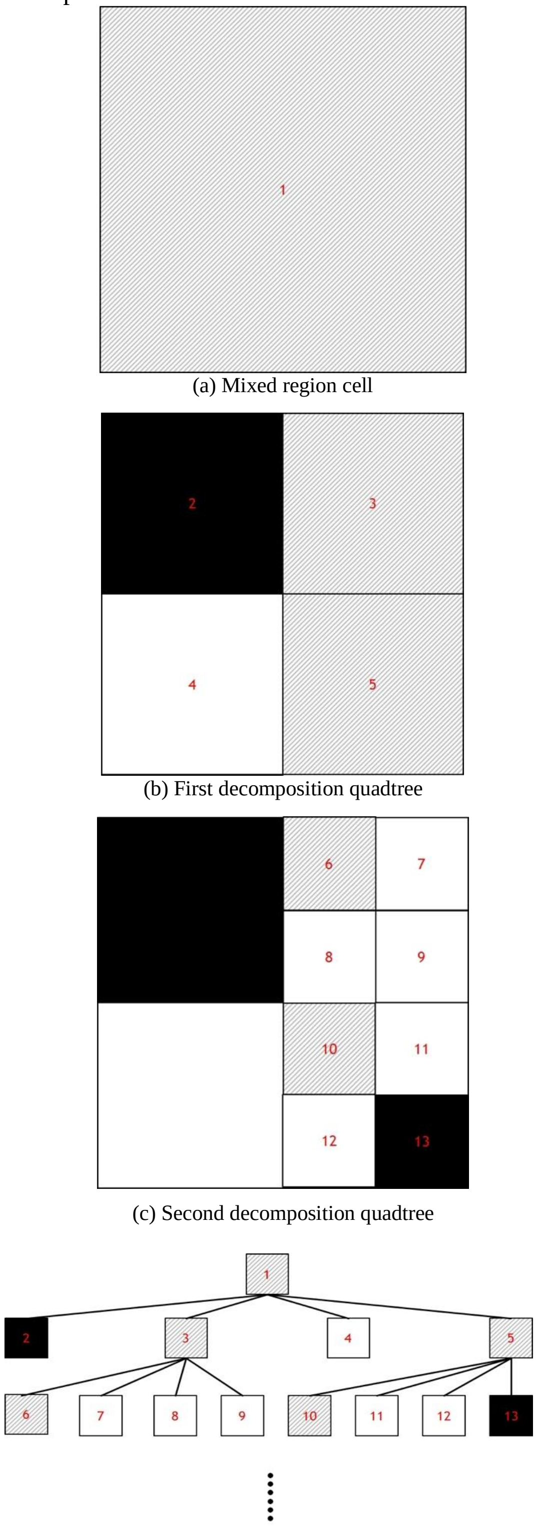
setting unknown obstacles on known 2D environmental maps. Ultrasonic detection of obstacles, TM (Towards Marker), UT (U-turn), SS (Side Shift), UTI (U-turn Interlaced), and BT (Backtracker) are five cleaning path modes for complete area cleaning methods. In 1998, Lang and Chee [17] used a 5-unit model such as integrated positioning unit, sensing fusion unit, map building unit, path planning unit, obstacle avoidance, and navigation unit as the system architecture for cleaning robot. Different from the previous control methods, the running speed and the turning rate are implemented by using the fuzzy rule. In 2014, Jan et al. [18] proposed a method with vertical cell-decomposition with convex hull for real time complete area coverage navigation of an autonomous mobile robot.

However, commercialized home robots are often based on convenience, cost, and practicality. In 2002, Oh and Watanabe [19] proposed a simple, efficient navigation for small household cleaning machine that uses only proximity sensors to perform navigation, using three walking rules: (1) Random; (2) Zigzagging: such as the way cattle walk; (3) Rectangular spiral, used in the general unknown home environment, and the effect of garbage removal is analyzed for each of the three paths. It is known from the experimental results that the correctness of the turning angle and the automatic adjustment of the direction when traveling. It is possible to obtain a better cleaning effect by enabling parallel movement with the walls to maintain a certain distance. Then it is applied to commercial cleaning robots such as "Roomba" [6] and "Roboking" [7]. Take "Roomba" as an example, its traveling rules are (1) spiral magnification (2) edge following (3) crisscross. First, adopt (1) spiral amplification mode to cover the space with a gradually expanding spiral operation mode. When the obstacle sensor touches a large obstacle such as a wall or furniture in the process of spiral enlargement, it will change to (2) follow the edge, following mode and follow the wall or furniture. After cleaning a part of the space along the wall or furniture, Roomba will change to (3) crisscross mode to sweep through the space, then turn 90 degrees, traveling to another area and repeat the rules above. The route cleans the next area so that the route is repeated until the cleaning time is over.

II. Background

Some of the well-known concepts used in this proposed algorithm includes quadtree, are addressed in this section.

Quadtree [20] is a popular data structure for digital image processing, one of its purposes is to divide and define space. The quadtree is a tree with four subtrees on each node except the leaves. Fig. 1 demonstrates a cell divided into four quadrants. It has a wide range of application such as spatial indexing, image processing, mesh generation, and so on. This data structure was developed by Finkel and Bentley in 1974. Spatial segmentation is an important issue in the coverage of complete areas. In order to plan the path efficiently, the quadtree is used in this paper to define the free space and obstacle range to solve the spatial division of the complete area coverage problem. Space decomposition can be classified as rasterization, vertical slicing, trapezoidal slicing, etc. The advantage of the quadtree is that it can completely define the position and range of irregular shapes, reduce the time and space of rasterization, and can clearly define free space and obstacle space.



(a) Mixed region cell

(b) First decomposition quadtree

(c) Second decomposition quadtree

(d) Quadtree representation

Figure 1. Quadtree

A spanning tree [15] is a subset of graph G that connects all the vertices with the least amount of number of edges. A spanning tree cannot be disconnected or contain any cycles. Therefore, every connected and undirected graph G contains at least one spanning tree. An explanation of the spanning tree process can be found in Fig. 2. Fig. 2(a) is a connected graph. Spanning tree can be found in Fig. 2(b). Minimum spanning tree (MST) is demonstrated in Fig. 2(c).

III. Algorithm

This section presents the proposed algorithm in details based on quadtree, connected graph, contour maps, and spanning tree to find the complete area coverage path for arbitrary shape obstacles.

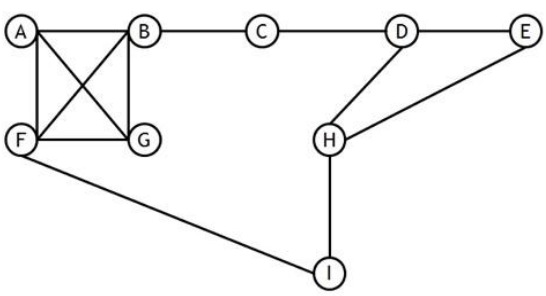
The list notations used in this algorithm can be found in Table I.

Algorithm: Complete area coverage path-planning with arbitrary shape obstacles

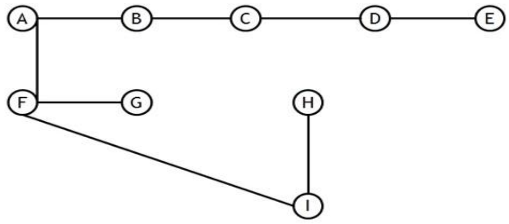
Step 1: Initialization
Initialize the obstacles by quadtree.
Step 2: Generate the connected graph
Call Function 1 Connected graph.
Step 3: Global routing
Call Function 2 Generate the roadmap.
Step 4: Detailed routing
Call Function 3 Planning the complete area coverage path in details.
END

TABLE I. Notations

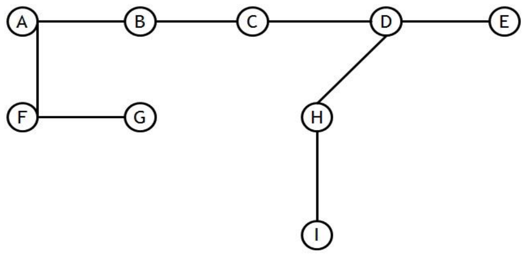
Notation	Definition
C	The coordinates set of the centroid; $c_i (x_i, y_i)$
G	The connected graph; $G = (V, E)$
G^{RM}	The sub graph of global routing sequence; $G^{RM} = (V^{RM}, E^{RM})$
G^C	The set of contour; $G^C = (V^C, E^C)$
G^{CM}	The set of contour map $G^{CM} = (V^{CM}, E^{CM})$
$G^{CM'}$	Modified contour map of spanning tree; $G^{CM'} = (V^{CM'}, E^{CM'})$
G^U	The union of branches and bridges; $G^U = (V^U, E^U)$
G^{Branch}	The sets of branches in G^{RM}; $G^{Branch} = (V^{Branch}, E^{Branch})$
G^{Bridge}	The sets of bridge in G^{RM}; $G^{Bridge} = (V^{Bridge}, E^{Bridge})$



(a) Connected graph



(b) Spanning tree



(c) Minimum spanning tree

Figure 2. Spanning tree

Function 1 Connected graph
Step 1: Calculate the centroids C for all the leaves.
Step 2: Connect all the centroids to their neighboring centroids to construct the connected graph G.
END

Function 2 Global routing
Step 1: Call Function 2.1 Finding contour map.
Step 2: Call Function 2.2 Find the sub graph for the global routing.
Step 3: Navigate the contour map and circumnavigate the branches and bridges to generate the global route sequence.
END

Function 2.1 Finding contour map
Step 1: Apply the concepts of gift wrapping and neighborhood to find the contour G^C in graph G.
Step 2: Repeatedly call step 1 to find the contour G^C and remove the edges connected to it from graph G until no more contour is found.
END

Function 2.2 Find the sub graph for the global routing
Step 1: Call Function 2.2.1 to obtain the modified MST.
Step 2: $G^U = G^{RM} - G^{CM'}$ is defined as the union of branches and bridges, all the edges in G^U are defined as bridges, if their terminal vertices are located at two continuous contours.
Step 3: Recover the removed edges in Function 2.2.1.
END

Function 2.2.1 Modified minimum spanning tree
Step 1: Repeatedly generate the partial spanning tree of contour map $G^{CM'}$ and temporarily remove the spanning tree from G.
Step 2: Sort the remaining edges.
Step 3: Apply the concept of Kruskal's MST algorithm to find the MST in graph G^{RM} based on the sorted edges obtained in step 2.
END

Function 3. Detailed routing

Step 1: Decompose the cells with V^{RM} by their corresponding degree.

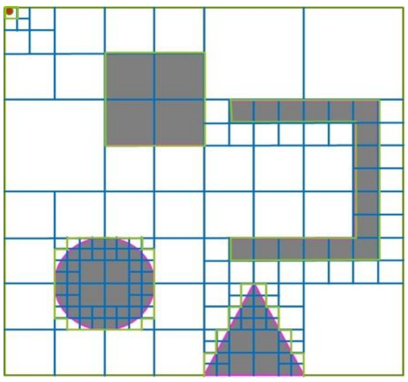
Step 2: Traverse along the zigzag patterned trajectory by the Global routing sequence.

END

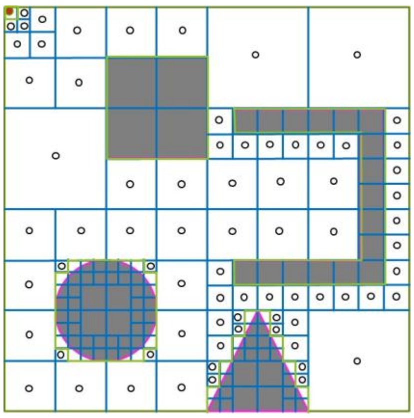
IV. ILLUSTATION OF THE ALOGROITHM

The detailed illustration of this proposed method is depicted in this section.

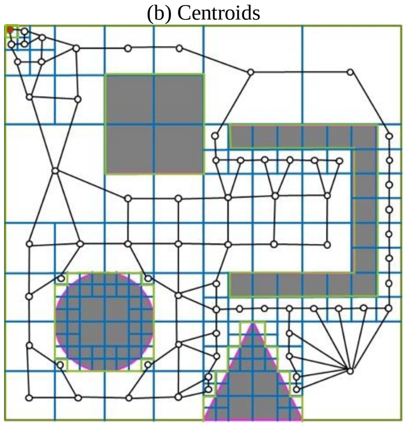
Fig. 3 illustrates the complete area coverage path-planning for arbitrary shape obstacles. Fig. 3(a) is the initialization. Fig. 3(b) presents the centroids. Connected graph is shown in Fig. 3(c). Fig. 3(d) demonstrates the contour map. The roadmap of global routing is demonstrated in Fig. 3(e). Fig. 3(f) decomposes the quadtree leaves for circumnavigation. The detailed path-planning route is displayed in Fig. 3(g).



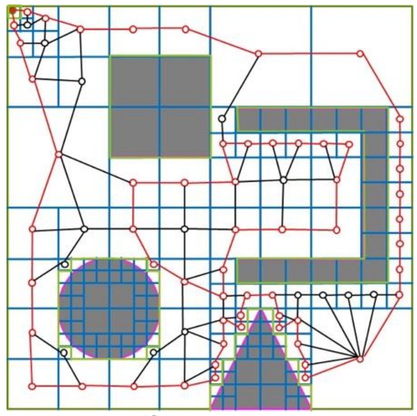
(a) Initialization



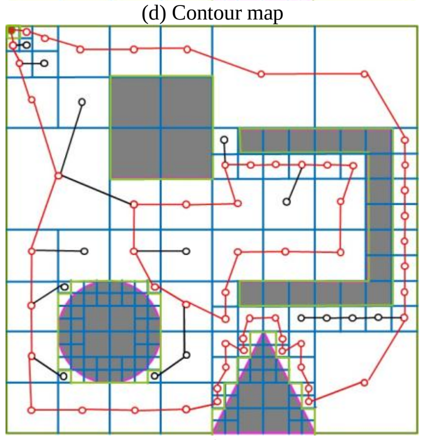
(b) Centroids



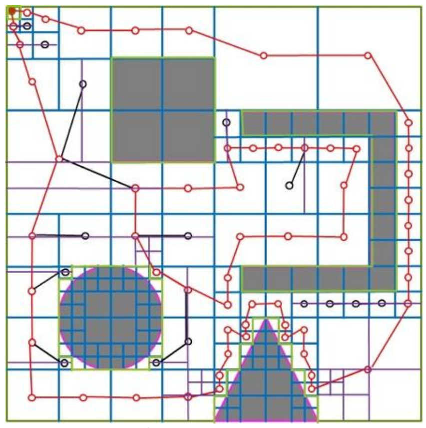
(c) Connected graph



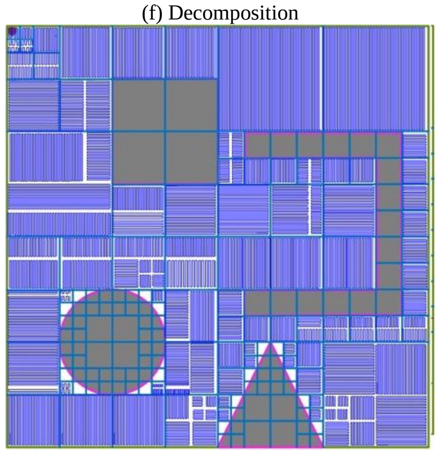
(d) Contour map



(e) Roadmap of global routing



(f) Decomposition



(g) Detailed path-planning

Figure 3. CAC path-planning for arbitrary shape obstacles

V. Conclusion

In this article, a novel quadtree decomposition data structure approach using contour maps and spanning tree is proposed for complete area coverage in known environment with arbitrary shape obstacles. The advantage of this proposed method is that after the robot completes the cleaning, it will return to the same point where it first started without any overlapping. The route planned by this algorithm is a complete area coverage path. Compared to other well-known global routing algorithms related to spanning trees, this method has a lower number of turns by using the concept of contour in our algorithm.

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