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Topological Graph Based Boundary Coverage Path Planning for a Mobile Robot

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Abstract: A path planning method for the optimal boundary coverage of building interiors using a mobile robot is proposed. First, the data association problem of indoor modeling caused by localization uncertainties of an information gathering system such as a mobile robot is explained. Then, an expanded obstacle map is proposed to cope with the data association problem, in which the boundaries of the expanded obstacles are utilized as the path of a mobile robot. And also, the path enables a mobile robot to gather information on the obstacles at a certain distance. Next, a topological graph is utilized for the optimization of the travel path. Finally, simulation results are shown to verify the proposed algorithm.

Keywords: Boundary coverage path planning, Expanded obstacle map, Indoor modeling, Topological graph.

1 INTRODUCTION

This paper aims at developing a boundary coverage path planning method which allows a robot to gather ambient information at a certain distance in various structures of indoor environments.

The typical coverage path planning for cleaning and examination of indoor environments is focus on planning the path which allows a robot to pass all accessible area in a given environment. The cell decomposition method is one of the famous approaches for the area coverage path planning. Boustrophedon Cellular Decomposition (BCD) based method carries out optimal coverage of known environments using Reeb graph based critical points [1]. In order to explore surface using UAV, BCD based coverage path planning method was also proposed [2]. In order to solve a boundary coverage problem using multi-robot with an omnidirectional inspection sensor, K. Easton et al. proposed solution of kRPP(k-Rural Postman Problem) using simplified sensor model based graph representation [3]. This approach is most suitable for boundary inspection. But the inspection is not conducted at a certain distance.

On the other hand, the boundary coverage proposed in this paper is for the point cloud generation which expresses environments based on a set of vertices and for gathering information for texture mapping. In order to generate accurate point cloud, a robot should travel via points which allow the robot to collect relative position information of a given environment. And if texture information is collected successively at a regular distance, the frame transform using projective geometry can be reduced and the pixel density of images can be maintained uniformly and finally the image stitching error can be reduced. But the indoor environment with narrow hallways and a complex indoor structure prevents optimal positioning of a mobile robot for collecting ambient information.

Given these considerations, an expanded obstacle map which consists of obstacles with constant offset boundary and a path planning method using a topological graph are proposed to cope with these problems. As a result, a mobile robot can gather environment information at a certain distance continuously and come back to the start location by the minimum traversing distance via all boundaries of obstacles since it navigates the boundary coverage path which is an Eulerian circuit.

The rest of the paper is organized as follows. The following section introduces the data association problem of indoor modeling. Section 3 addresses the algorithm for boundary coverage path planning. Final section sums up with some concluding remarks.

2 DATA ASSOCIATION PROBLEM OF INDOOR MODELING

The point cloud generation using a mobile robot can be summarized as the following three steps.

1. Localization and mapping are conducted based on encoders, a gyroscope, and a horizontal LRF.
2. If the travel distance is long, the position error can be accumulated and it causes a loop closure problem. In order to cope with this problem, the graph SLAM can be utilized for minimizing the accumulated error [4]. As a result, if all the paths of a mobile robot are obtained, the pose of a robot at each sampling time can be calculated.

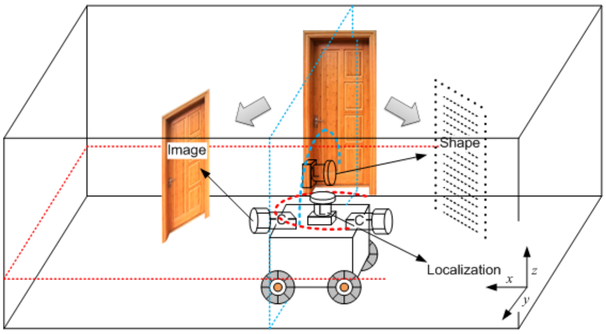


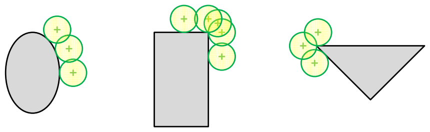
Fig. 1 Indoor modeling using a mobile robot.

3. Integrating the information from a vertical LRF based on a robot pose, the point cloud can be generated.

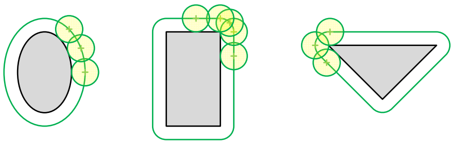
As a result, in order to generate the point cloud and to gather image information for texture mapping, it is required that a mobile robot navigates along the path on which it can gather ambient information optimally based on the structural characteristics of the surrounding space. Also, in order for reducing the frame transform using projective geometry and keeping the pixel density of visual image uniformly, it is required that image information for texture mapping is gathered continuously at a certain distance. But, the navigation with no regard for changing space disturbs the generation of point cloud with uniform density, and the inaccurate data association between the image and the position data may cause an image stitching problem in the texture mapping.

Fig. 1 shows the scanning patterns of a mobile robot with two laser scanners when it navigates in a corridor for gathering information required for the point cloud generation. The LRF which scans xy horizontal plane can be used for building an obstacle map based on 2D information of the environment. On the other hand, the information from the LRF mounted along z axis is dependent on the robot pose because it gathers information based on line scanning which is vertical to the direction of the robot. That is, since the line scanning is carried out as the blue dot line shown in Fig. 1, the information gathering is seriously affected by the structure of environment and the pose of the robot. Hence, the navigation of the mobile robot should be conducted in order for the second LRF to never miss the boundary of the obstacle.

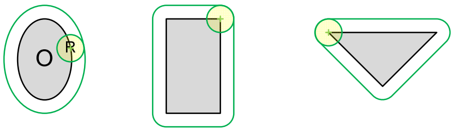
To cope with these problems, the path planning method for the boundary coverage which allows a robot to gather environment information optimally using a given 2D map is proposed in the next section.



(a) Boundary following at a certain distance.



(b) The path of a robot center becomes the boundary of an expanded obstacle.



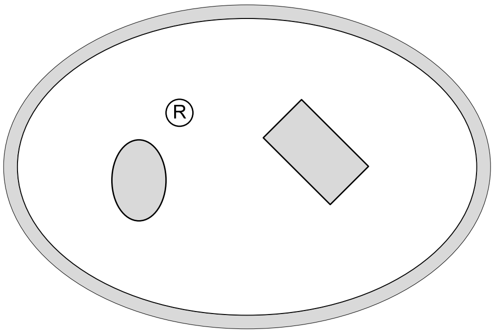
(c) Minkowski sum.

Fig. 2 Expanded obstacles.

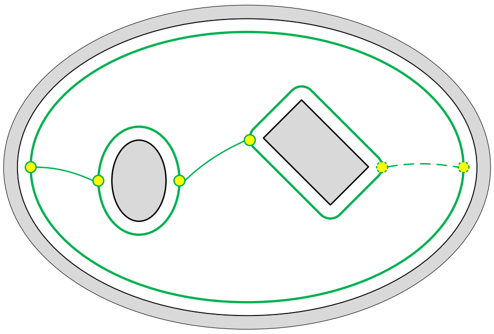
3 BOUNDARY COVERAGE PATH PLANNING

The boundary coverage path planning method aims at generating the shortest path which allows a robot to travel via all the boundaries of obstacles in various indoor environments. In this paper, the boundaries of obstacles are generated based on expanded obstacles, and then the boundary coverage path is planned by using a topological graph. Hence, the proposed path planning method is composed of the following three steps.

First, expanded obstacles are generated based on the optimal distance which is required for information gathering. If a mobile robot navigates around an obstacle at a certain distance, then the path is generated as shown in Fig. 2 (a). The radius of the robot is the optimal distance. If the center points of the robot are connected, a certain distance offset from the obstacle is generated as shown in Fig. 2 (b). Hence, a robot with optimal sensing area in the obstacle map can be dealt with as a point robot in the expanded obstacle map. This means that if a point robot navigates along the boundary of an expanded obstacle, then the robot can gather environment information optimally. In this paper, an expanded obstacle is calculated by Minkowski sum, which is described by Eq. (1). Fig. 2 (c) shows Minkowski sum for various polygonal obstacles [5].



(a) Obstacle map



(b) Critical points and edges for disjoint obstacles

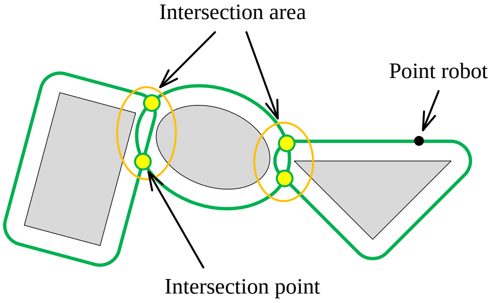
Fig. 3 Critical points and edges for disjoint polygonal obstacles.

$$O \oplus R = \{x + y \mid x \in O,\ y \in R\} \qquad (1)$$

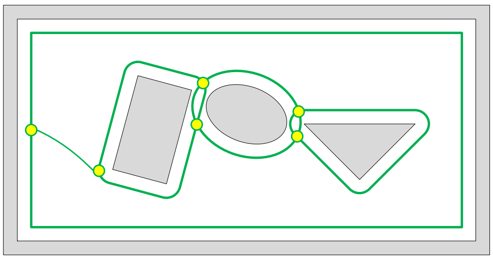
Next, the critical points based on Boustrophedon Cellular Decomposition (BCD) [1] are founded and the edges which connect critical points are replaced by the boundaries of expanded obstacles. Then the critical points and the boundaries are utilized as vertices and edges of the topological graph $G = (V, E)$. If expanded obstacles overlap each other and the intersection area doesn't overlap the obstacle, then the intersection points are included in the vertexes of the graph G because the point robot can gather environment information along the intersection boundaries.

Fig.3 (a) shows the expanded obstacle map of inner and outer obstacles. And Fig. 3 (b) shows critical points and edges of the expanded obstacle map. Without loss of generality, if the search is started from the left side, the last two critical points are not included in the vertex of the input graph because they are connected to the boundary of the obstacle which is already connected by other critical point.

Fig. 4 (a) shows the overlap of the boundaries in the expanded obstacle map caused by that two obstacles are located too close in the obstacle map. If the intersection area doesn't overlap the obstacle, then the intersection points are included in the vertices of the graph G because the point robot can gather environment information along the intersection boundary. Fig. 4 (b) shows critical points and edges for overlapping polygonal obstacles.



(a) Obstacles with intersection area



(b) Critical points and edges

Fig. 4 Critical points and edges for overlapping polygonal obstacles.

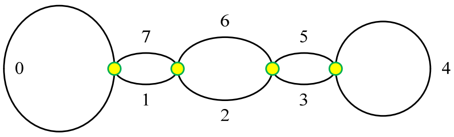
Finally, the boundary coverage path is calculated by Chinese postman problem with the topological graph [6], which is an Eulerian circuit. Since the Eulerian circuit is an Eulerian path which starts and ends on the same vertex, the obtained path is a closed path traversing via every edge at least once. The boundary coverage path can be obtained by the following linear programming problem:

$$\text{Minimize } z = \textstyle\sum_{e \in E} (c_e x_e) \qquad (2)$$

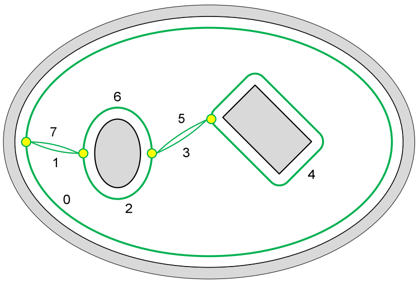
And the following conditions should be satisfied.

$$\begin{aligned} & x_e \geq 0,\ \ e \in E \\ & w_n \geq 0,\ \ n \in V \\ & \textstyle\sum_{e \in E} a_{ne} x_e - 2w_n = b_n,\ \ n \in V \end{aligned} \qquad (3)$$

where c_e is a real number representing the cost of edge e, a_{ne} is 1 if edge e meets node n, and 0 otherwise, x_e is an integer, the number of extra times the edge e is traversed, b_n is 0 when degree of n is even, 1 otherwise, and w_n is an optional integer, which can be thought as adjoining loops to the graph at each node.



(a) Topological graph for disjoint obstacles.



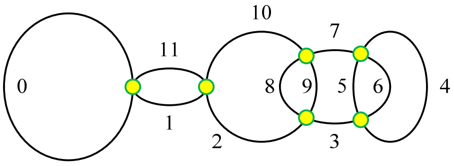
(b) The boundary coverage path for disjoint obstacles.

Fig. 5 Boundary coverage path planning using a topological graph for disjoint obstacles.

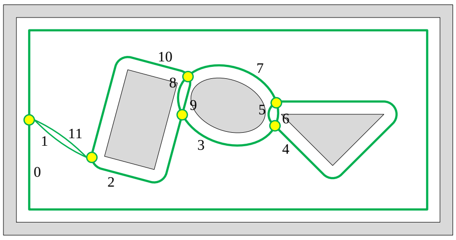
As a result, the boundary coverage paths which have the characteristics of an Eulerian circuit are obtained. Fig. 5 shows the result of disjoint polygonal obstacles. Fig. 5 (a) shows the topological graph of the boundary coverage path and Fig. 5 (b) shows the boundary coverage path, in which the gray polygonal area is an obstacle, the green bold line is the boundary of the expanded obstacle, the green thin line is the edge which connects the critical points of disjoint polygonal obstacles, the yellow circle is the critical point, and the number means the order of the path following. Fig. 6 (a) shows the topological graph of the boundary coverage path of overlapping polygonal obstacles. Fig. 6 (b) shows the boundary coverage path.

4 CONCLUSION

In this paper, a mobile robot with cameras and laser scanners for indoor modeling has been introduced and a boundary coverage path planning algorithm using expanded obstacles and topological graphs has been proposed for the information gathering of building interiors at a certain distance. The topological graph based on the critical points and the boundaries of the expanded obstacles was utilized as an input graph for Chinese postman problem for planning the optimal boundary coverage path, which allows a mobile robot to traverse all the boundaries of obstacles at least once. Case study results have been shown for verifying the proposed algorithm.



(a) Topological graph for overlapping obstacles



(b) The boundary coverage path for overlapping obstacles.

Fig. 6 Boundary coverage path planning using a topological graph for overlapping obstacles.

ACKNOWLEDGMENT

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