Global Topological Map Building Using Local Grid Maps

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Abstract: Two major paradigms for map building are grid maps and topological maps. Topological maps have drawn more attention because they are compact, provide natural interfaces, and are applicable to path planning easily. These merits of a topological map become increasingly important as the size of the environment gets large. However, a conventional method which builds a topological map using a global grid map cannot fully overcome the problems of memory and computational burden existing in a grip map approach. Furthermore, fast update is not available in this approach. In this paper, therefore, to overcome these problems, we present a method for updating a global topological map from the local topological maps. These local topological maps are created through a thinning algorithm from a local grid map, which is built based on the sensor information at the current robot position. A thinning method requires simpler computation than the Voronoi diagram. It is very difficult to perceive all parts of an object due to the limitations of sensors, thus leading to a 'hidden area.' To solve this hidden area (visibility) problem, therefore, all nodes are considered as 'temporary' and redundant nodes among these are discarded. A series of experiments have been conducted using a two-wheeled mobile robot equipped with a laser scanner. It is shown that the proposed scheme can create satisfactory topological maps.

Keywords: map building, topological map, thinning, visibility, Voronoi diagram, path planning, mobile robot, laser scanner

1. Introduction

Map building is the task of modeling a robot's environment and localization is the process of determining the position and orientation of a robot with respect to the global reference frame. These are the key elements for an autonomous mobile robot system.

There are two major paradigms for mapping the indoor environment: a grid map and a topological map. The former can produce an accurate map in a relatively simple manner, but requires large memory, is inefficient, and time-consuming. The latter, on the other hand, provides more efficient and compact map requiring much less memory, but is difficult to apply to localization.

In most cases a global topological map is built from a global grid map [1]. This hierarchical approach can utilize advantages of the grid and the topological maps, but still has the problem of large memory requirement involved in a grid map. Moreover, updating these hierarchical maps is very difficult.

As an alternative to this approach, the direct topological map building using the Voronoi diagram [2] was proposed by some authors ([3], [4], [5], [6]). Simhon [3] proposed a hybrid topological-metric model using local metric description of 'islands of reliability'. In [4], Nagatani proposed sensor-based exploration procedure allowing a mobile robot to trace the Voronoi diagram of the partially observed environment from sensor inputs. He used the 'meet points' at the intersection of edges of the Voronoi diagram. Zwynsvoorde described in [5] global topological map building using local Voronoi-like graphs. He defined the 'escapes-line' and discarded the nodes involved at least one 'escape-line.' It is difficult, however, to apply the Voronoi diagram to arbitrarily shaped objects and needs long computation time.

In this paper, an improved method for constructing a topological map is proposed. It can utilize the advantages of the topological map such as compactness. A local grid map from current sensor data is first constructed. From this map, a local topological map is then built using a thinning method which is the alternative to the Voronoi diagram. Finally, local topological maps are integrated and updated to the global one. Geometrical information of the nodes of the local topological maps enables the nodes to serve as landmarks in matching the local maps. To solve this hidden area (visibility) problem, therefore, all nodes are considered as 'temporary' and the redundant nodes among these nodes are discarded. This scheme is also used in localization based on the topological map later.

In most research on localization, grid-based methods with detailed information are used. Probability-based methods for localization (e.g., Monte Carlo [7], Condensation [8], probability grids [9], etc.), therefore, are all based on grid maps. Localization using a topological map was undertaken in [10], [11]. The problem with a topological map in localization, however, is that a robot may not recognize its state with momentary sensor information because geometric information in the topological map is ambiguous. To overcome this difficulty applying the topological map to localization, additional nodes need to be added to the global topological map so that information of the topological map can be increased, which is possible with a thinning method.

Since the detailed model of the environment between nodes is not available in a topological map, the wave-front algorithm is used for navigating node to node. Using this method, a mobile robot can move to the next node optimally while avoiding the obstacles [12].

The paper is organized as follows. Section 2 presents local topological map building using a thinning method including visibility analysis. Section 3 deals with the updating process to the global topological map. Various test results in the real environment are discussed in Section 4.

2. Local Topological Map Building Using Thinning

A topological map is used as a main map for path planning and localization in this research. In the feature-based topological map, the environment is modeled by a set of geometric primitives such as nodes and arcs. It has several advantages such as compactness, fast computation, natural expression to a human, and so on. Topological maps, however, are not appropriate for localization which requires comparison of the current map with the reference map because they have only limited feature information compared to grip maps. Localization performance can be improved by adding more node information through a thinning method (explained later on).

To build a topological map based on a grid map (binary map), a Voronoi diagram is commonly used. A Voronoi diagram is the partitioning of a plane with *n* points into *n* convex polygons such that each polygon contains one point exactly and every point in a given polygon is closer to its central point than to any other points. A Voronoi diagram is also known as a Dirichlet Tessellation, and the cells are called Dirichlet regions or Voronoi polygons. But it is complex and difficult to apply to arbitrarily shaped objects. In building a topological map, therefore, a thinning method is proposed in this paper, which needs simpler computation than the Voronoi diagram but can show similar performance.

2.1 Thinning Method

A thinning method is one of the most popular image processing algorithms, which are used to detect the skeleton of images. In many image processing applications such as recognition of biological cell structure, thickness of the shapes does not contribute to the recognition process.

Binary images (or maps) to which a thinning method is applied should meet the following conditions:

1. Connected image regions must thin to the connected line structure with 1 cell wide.
2. The minimal number of cells around the resulting empty cell is 8.
3. Approximated end line locations should be maintained.
4. The thinning results should approximate the medial line of an object.
5. Short branches (abundant) due to unevenness of the boundary should be minimized.

Figure 1 illustrates of an example of a thinning process. The objects on the left can be described satisfactorily by the structure composed of connected lines (i.e., 'T' shape drawn with the thin lines on the right). Note that connectivity of the structure is still preserved even for representation with thin lines. In the case of mobile robots, the connected lines are paths on which a robot navigates without colliding with other objects.

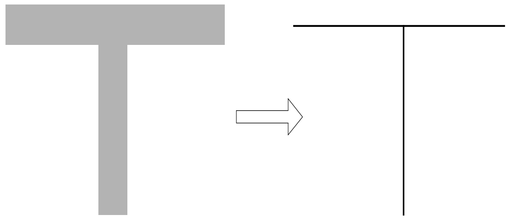


Fig. 1 Example of thinning.

In this paper, Zhang-Suen's thinning method [13] is adopted. It has served as a basis of comparison with various thinning methods for many years, and is fast and simple to implement. It is a parallel method, meaning that the new value for any pixel can be computed using only the values known from the previous iteration. Figure 2 illustrates the thinning process, where an object is represented in its skeleton.

With the mask for the center cell (p_1) under consideration indicated in Fig. 2, the following conditions apply to 8 neighboring cells (p_2 ~ p_9) around p_1. Note that '0' denotes an empty cell and '1' an occupied cell (i.e., binary map or image). The thinning procedure proceeds by eliminating the occupied cells that meet these conditions.

p_9	p_2	p_3
p_8	p_1	p_4
p_7	p_6	p_5

Fig. 2 Center cell p_1 and its thinning mask.

[Step 1]

① $2 \leq N(p_1) \leq 6$ (has at least two black neighbors and not more than six),
② $S(p_1) = 1$ (connectivity number is 1),
③ $p_2 \cdot p_4 \cdot p_6 = 0$,
④ $p_4 \cdot p_6 \cdot p_8 = 0$

$N(p_1)$: # of cells being not zero. (i.e., $N(p_1) = p_2 + p_3 + \cdots + p_8 + p_9$.)

$S(p_1)$: # of changes from 0 to 1 in the sequence of $p_2, p_3, \cdots, p_8, p_9$

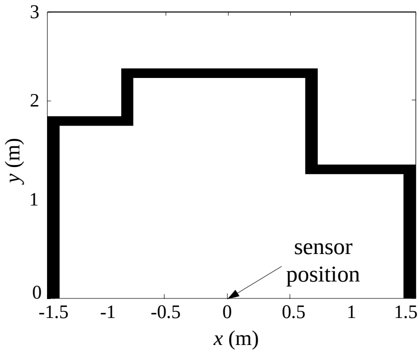
[Step 2]

① and ② are the same as [step 1]
③ $p_2 \cdot p_4 \cdot p_8 = 0$,
④ $p_2 \cdot p_6 \cdot p_8 = 0$

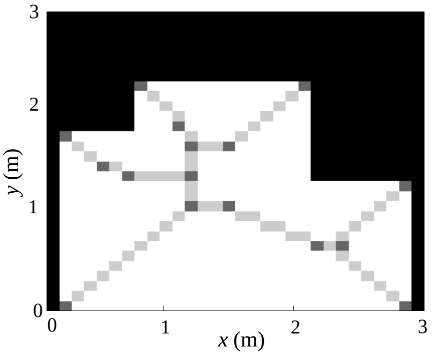
Note that step 1 is conducted for the entire grid map and the corresponding grid cells are eliminated. Then step 2 is carried out for elimination of other cells meeting the conditions. The nodes, the representative points of the local environment, are extracted from the arcs (i.e., path) obtained above. Because the position and the number of nodes are related to accuracy and usefulness of a topological map, an appropriate selection rule of nodes is very important. In this paper, the nodes are selected at the end points of the arc, the corner points where the arc slope varies, and the branch points where more than three arcs intersect.

2.2 Simulation Results

Fig. 3(a) shows the raw range data obtained by a laser scanner. The laser scanner is assumed to be placed at the origin. Fig. 3(b) shows the binary map with range data, its arcs and nodes are obtained by the thinning method. It is assumed that the back of the points sensed by the laser scanner is filled with the obstacles. In the global topological map, geometric information of the node (x, y) with respect to the reference (global) frame and connectivity between two nodes are stored.



(a) Laser scanner range data



(b) Collision-free path obtained by thinning and its nodes

Fig. 3 Thinning and local topological map building.

A thinning method can provide additional nodes to the local topological map. Fig. 4 demonstrates comparison of the topological map using a Voronoi diagram (left) with that using a thinning method (right). Four more nodes are created when a thinning method is employed. More geometrical information due to these additional nodes improves performance of localization and map matching.

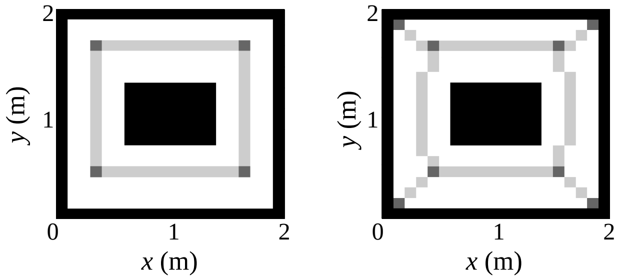


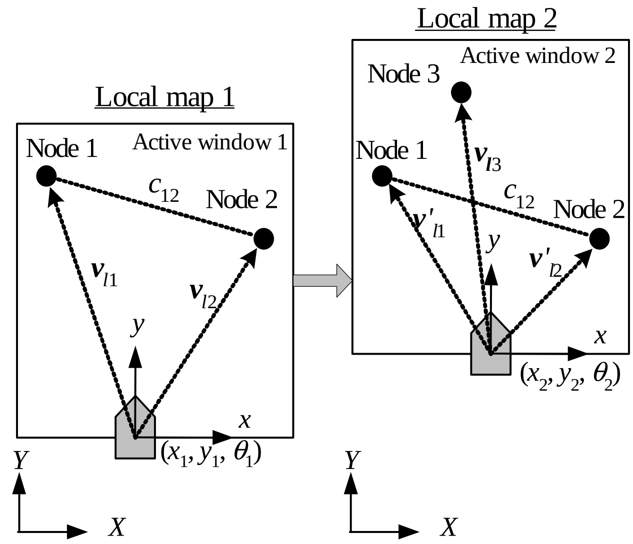
Fig. 4 Topological map using Voronoi diagram (left) and thinning method (right).

3. Global Topological Map Building

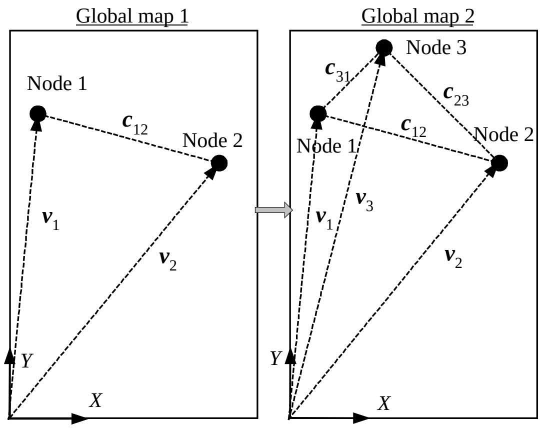
3.1 Global Topological Map Building

A method for updating a local topological map to the global one is presented below. The local topological map contains geometrical information of the nodes and connectivity between nodes. The update process of a global topological map is basically performed by matching the nodes of the local topological maps to those of the global one.

Figure 5 illustrates the local and global topological maps at the instants t_1 and t_2. Suppose that the robot detected node 1 and node 2 at the position (x_1, y_1, θ_1) at t_1 within the active window 1. This local topological map 1 is updated to form the global map 1. The robot then moves to the next position (x_2, y_2, θ_2) and detected node 1, node 2 and node 3 within the active window 2 at t_2. Since node 1 and node 2 are common to both global maps, only node 3 is updated to form the global map 2. The updating process will repeat until the entire region of the environment is covered.



(a) Local topological maps at each instant.



(b) Global topological maps updated at each instant.

Fig. 5 Detected nodes and their vectors and connectivity between nodes at each instant.

2.3 Visibility Analysis

In general, a sensor can cover only limited distances and angular ranges, so there exists a ‘hidden area’ that cannot be seen by a sensor. Fig. 6 describes the occlusion due to sensor limitation. Occlusion and sensor limitation cause inaccurate environment modeling and formation of unnecessary (redundant) nodes, which should be removed by some means later. In this paper, the nodes that are not created in the next local map are considered redundant and eliminated from the map.

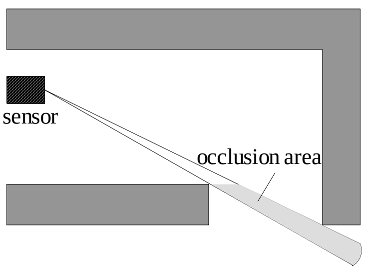


Fig. 6 Occlusion due to sensor limitation.

As illustrated in Fig. 7, some experiments were done for the situation in which occlusion occurs and range data at 3 different positions were collected as the robot moves forward. In Fig. 8, all nodes are considered temporary, and the current local map is compared with the previous one. Then, the nodes which are not created in the current map are removed since they are redundant and update of the local map to the global one is performed. For example, in Fig. 8(a), the node denoted as “R” corresponds to a redundant one created because of occlusion at sensor position 1. This node is not created again in local map 2 taken at sensor position 2. On the other hand, local map 2 shows 4 nodes denoted as “R” which are generated as a result of the thinning process. These nodes are also redundant and thus removed since they are not created in local map 3. A global topological map can be built fast and correctly through a thinning algorithm.

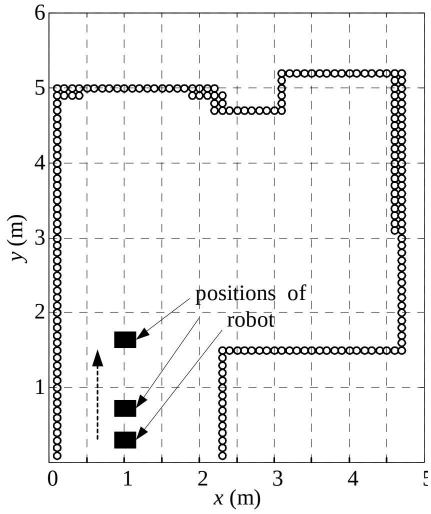
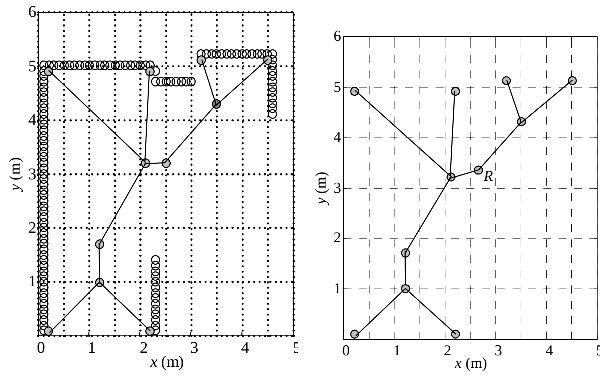
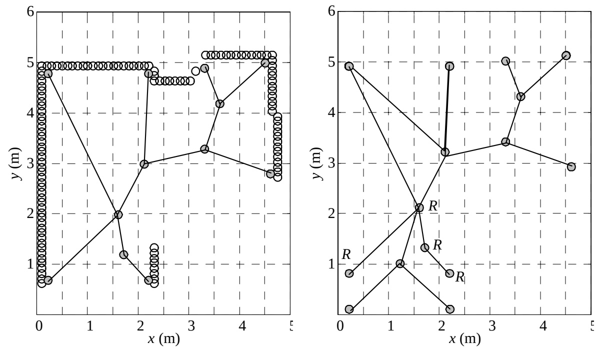


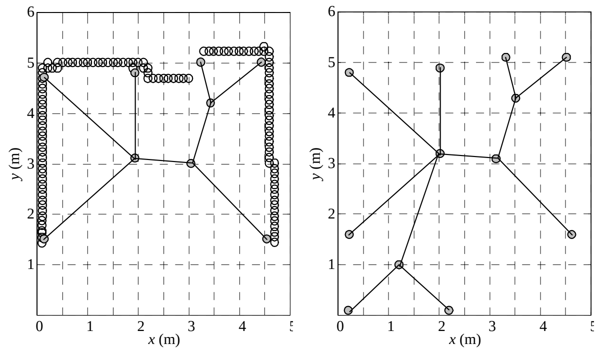
Fig. 7 Global grid map and sensing position.



(a) Local and global topological maps 1.



(b) Local and global topological map 2



(c) Local and global topological map 3

Fig. 8 Local and global topological map at each instant.

4. Experimental Results and Discussions

To verify validity of the proposed algorithm, various tests on topological map building and global localization have been conducted. The Pioneer II DX mobile robot equipped with a Sick laser scanner was used for the test.

The environment for the test is about 20*10m large. The laser range data are gathered manually by placing the robot at the specified locations. Fig. 10 is a laser-based global grid map of the environment under consideration. Note that this grid map is shown only for the purpose of better understanding of the environment, and is not used to construct the global topological map.

Fig. 9 Pioneer 2-DX mobile robot quipped with ultrasonic sensors and PC.

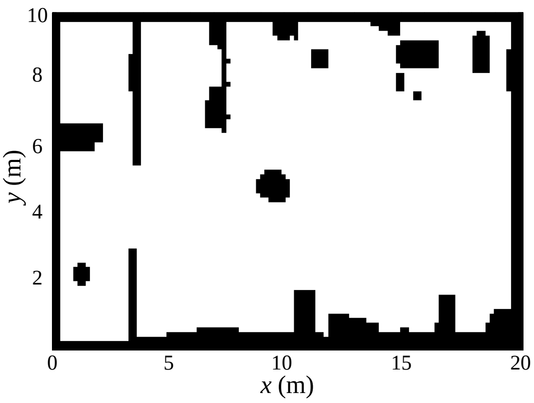
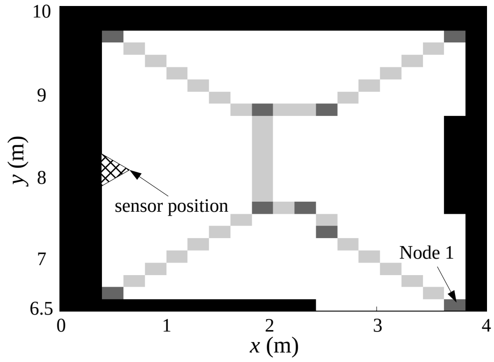
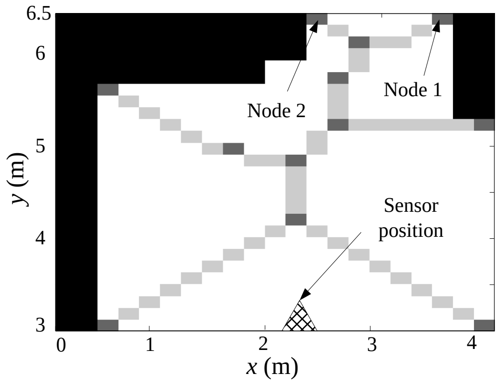


Fig. 10 Global grid map of the environment under consideration.

Local topological maps have been built at the predetermined locations (about 10 ~ 15) with a laser scanner in this environment. These maps are continuously updated to the global topological map. The process of building the global topological map is shown in Fig. 11 and 12. Fig. 11 represents the local topological map built at each sensor position. The position is expressed by the grid number. Since the grid size is 10cm*10cm, Fig. (a) is the map at (3m, 8m) and (b) is at (2.3m, 3m). Fig. 12 shows the process of updating each local topological map to the global one. In local map 1, node 1 is a temporary node and node 1 and 2 are of local map 2. But node 1 is common to both local maps 1 and 2, so the geometrical information of this node makes updating process of two local maps easily. Node 2, which is shown only in map 2, is a redundant node which should be deleted after update. This node is formed because it is around the end of the active window in local map 2, but is not necessary in the global map since it is no longer the edge of the active window and part of empty space. Fig. 13 shows the final global topological map and it has only the geometrical information of nodes and connectivity between two nodes.



(a) Local map 1 for sensor position at (30, 80, 0˚)



(b) Local map 2 for sensor position at (23, 30, 90˚)

Fig. 11 Binary map and its local topological map at each sensor position.

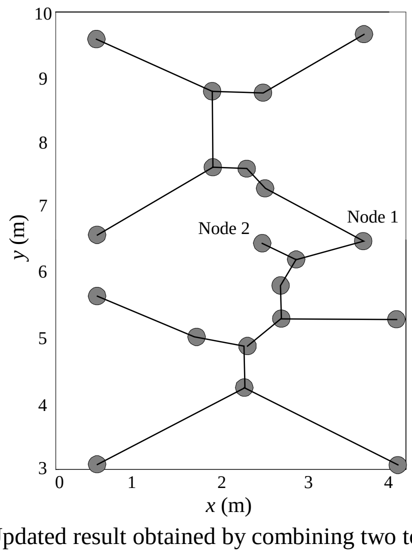


Fig. 12 Updated result obtained by combining two topological maps 1 and 2

Fig. 14 shows the result of path planning using a topological map. In the figure, the letters S and F indicate the start and final nodes, respectively. There are many reachable paths from S to F, but the shortest path without collision, which is obtained by the A* algorithm, is represented by the dotted line in Fig. 14. The topological map can be easily applied to the task such as path planning.

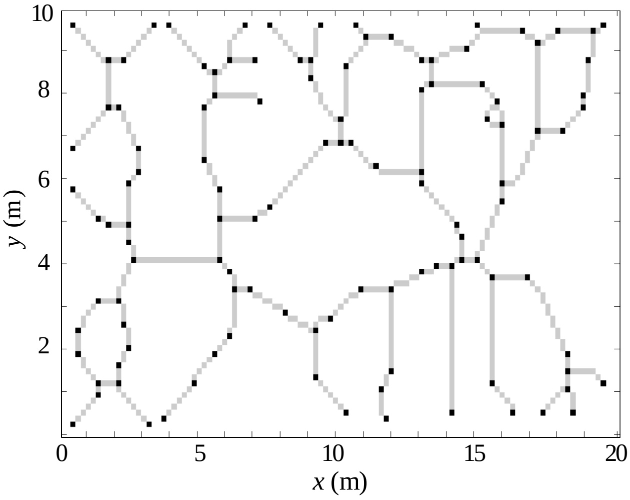


Fig. 13 Final global topological map.

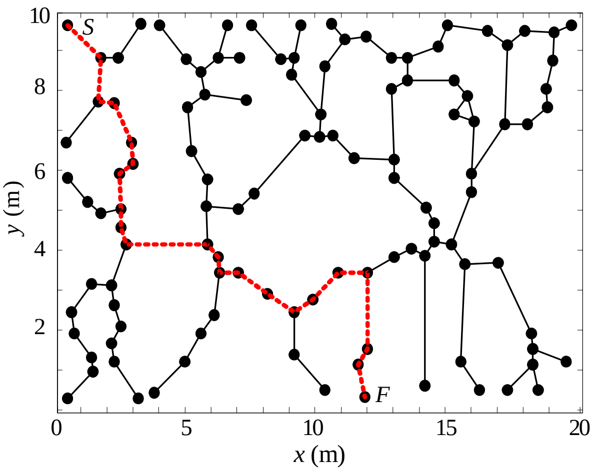


Fig. 14 Optimal path planning (from *S* to *F*).

5. Conclusions

In this research, fast and simple approach to map building is proposed for a mobile robot equipped with a laser scanner. A robot gathers sensor data at the predetermined positions and builds the binary grid map from which a local topological map is constructed using a thinning method. The global topological map is then built from the local topological maps. The following conclusions are drawn.

1. The global topological map using a thinning method needs much simpler computation than that using a Voronoi diagram.
2. A thinning method can create additional nodes in the resulting topological map than a Voronoi diagram, thus providing more information on the environment.
3. Each node created in a local map is considered as 'temporary' and redundant nodes are discarded according to the relations with their neighboring nodes.
4. Path planning can be easily achieved with a topological map.

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