Complete Coverage Navigation of Cleaning Robots Using Triangular-Cell-Based Map

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***Abstract*—This paper presents a novel approach for navigation of cleaning robots in an unknown workspace. To do so, we propose a new map representation method as well as a complete coverage navigation method. First, we discuss a triangular cell map representation which makes the cleaning robot navigate with a shorter path and increased flexibility than a rectangular cell map representation. Then, we propose the complete coverage navigation and map construction methods which enable the cleaning robot to navigate the complete workspace without complete information about the environment. Finally, we evaluate the performance of our proposed triangular cell map via the existing distance-transform-based path-planning method comparing it to that of the rectangular cell map. Also, we verify the effectiveness of the proposed methods through computer simulations.**

***Index Terms*—Cleaning robot, complete coverage, mobile robot, path planning, templates, triangular cell map representation.**

I. Introduction

IN RECENT years, an increasing amount of robotics research has focused on the problem of planning and executing motion tasks autonomously, i.e., without human guidance. Of all the research, work on mobile robots has often focused on the development of various methodologies for point-to-point transportation and manipulation tasks. Many challenging research problems have arisen in the application of the mobile service robots for floor cleaning or related tasks in public areas such as corridors, halls, and platforms [1]. The floor cleaning problem is especially interesting and challenging because of its applicability to various industrial and public fields. Although most cleaning and sweeping machines are still guided by human operators, there already exist several semi-autonomous cleaning robots for commercial usage [2].

A cleaning robot must navigate the complete workspace in order to clean a global workspace map. That is to say, there must be a complete coverage navigation algorithm where the cleaning robot navigates a full workspace in an unknown environment using only sensor data. This complete coverage navigation algorithm has often focused on the navigation of service robots which work in floor cleaning tasks [11]–[19]. The representative ones for complete coverage navigation are the cell-based [3], [10] and the template-based approaches [4]. However, these kinds of methods have several limitations and drawbacks. They require complete or partial information of the workspace or a planned path which cannot be applied directly to the unknown environment [4], [6], [7], where the location, shape, and size of obstacles are unknown, and where there is no map or model of the workspace initially available. Also, the coverage redundancy may be high or increased by the location of obstacles [5]. Applications where there is no available workspace model usually rely on sensor systems, such as laser range finders and infrared and sonar range sensors to collect information [8], [9]. For this reason, some map construction methods such as the grid-based certainty map and network/graph use sensor systems [10].

For a cleaning robot to navigate completely in an unknown environment, two basic requirements, map representation and path planning, are needed. The former requirement is provided by the on-board sensory system that gathers information about both the robot itself and the surrounding environment. The latter requirement is met by motion planning which enables a robot to navigate the global workspace completely.

With the observations mentioned above, we propose a complete coverage navigation method for cleaning robots in a totally unknown environment, using only sensor data. The complete coverage path-planning methodology proposed in this paper is composed of a combined algorithm of the cell-based method and the template-based method. The cleaning robot repeats its motion from one cell to another in accordance with a set of predefined rules on a cell-based map which enables the cleaning robot to make complete coverage navigation. A cleaning robot generally moves to one of the surrounding cells from the present cell on a cell-based map. Since all cells on the rectangular-cell-based model are square, the cleaning robot has eight directions for its movement. However, if the directions for movement can increase, the cleaning robot can move more flexibly to avoid the obstacles and to follow an optimal path. Therefore, we present a triangular-cell-based map representation that has 12 directions for movement, which enables the cleaning robot to navigate with shorter path and more flexibility. Among the various polygons, only the triangular cell has this advantage.

Finally, we compare the performance of our proposed triangular cell map with that of the rectangular cell map via the existing distance-transform-based path-planning method. We also verify the effectiveness of our complete coverage navigation method through computer simulations of several examples.

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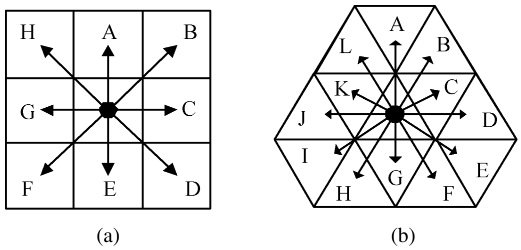


Fig. 1. Accessible directions of rectangular- and triangular-cell-based decomposition.

II. Distance-Transform-Based Path-Planning Method on Triangular Map

In reality, a cleaning robot must navigate a workspace completely to clean without any unclean regions. For a cleaning robot to do so, an efficient local path-planning method is needed, which enables a cleaning robot to find unclean regions and to move to them. In this section, we describe the distance-transform-based path-planning method [6] used in our complete coverage navigation algorithm. The advantage of our proposed triangular map representation over the rectangular map representation is emphasized through this local path-planning method.

A. Triangular-Cell-Based Decomposition of Workspace

In order to plan paths, the cleaning robot must know the workspace very well after gathering the information of the environment. In this paper, we use cell-based map representation and ultrasonic sensors for map construction.

Generally, a decomposition of the workspace is based on rectangular cells. The existing rectangular map has eight different directions for the next movement of the cleaning robot as shown in Fig. 1(a). Generally, as the directions where the cleaning robot can navigate increases, a better path can be found for the cleaning robot, and moreover the cleaning robot can navigate more flexibly to avoid collision when unexpected moving obstacles appear. The triangular map representation method has 12 different directions as shown in Fig. 1(b). We will show the efficiency of this method in the next section through an example.

B. Distance-Transform-Based Path-Planning Method

The distance-transform-based path-planning method considers the task of path planning as finding paths from the goal location back to the start location. This planning procedure works well in the environment with a uniform grid by propagating the distance value through free space from the goal cell. First, the method assigns a distance value from the target point to all the free space cells.

Generally, from the goal cell, the distance values are spread to the start cell with adding one. In case of adding one to the distance value of all neighbor cells, there is the selection problem for the shortest path because of the same distance value. This problem can be solved by assigning the different distance value according to the cell location. The distance values of orthogonal and diagonal neighbor cells are spread from the goal cell to the start cell, with adding three and four, respectively. Then, there are no cells having the same distance value in the planned path. For this reason, we assign the different distance values on the triangular-cell-based map as shown in Fig. 2(b).

The distance wave front flows around obstacles and eventually through all free space in the environment. When the distance values are assigned to all the cells as shown in Fig. 2, a cleaning robot can search for the cell with the smallest distance value toward eight or 12 directions and find the next path, i.e., the shortest path to the goal is traced by walking downhill via the steepest descent path. If there is no other cell with a smaller distance value than the distance value of the current cell, there does not exist any path to a target point. Fig. 2(a) shows the resultant path planned by the distance-transform-based path-planning method on a rectangular cell map.

On the triangular-cell-based map, the next movable cell is determined considering the distance value of all neighbor cells and the distance from the present cell to all neighbor cells, and it has the smallest sum of these two values. When several neighbor cells have the same sum, the next movable cell can be arbitrarily selected among them because all possible paths have the same length eventually. In Fig. 2(b), although there are several possible paths, the total length of each path is the same. Fig. 2(b) represents the resultant path planned by the distance-transform-based path-planning method on the triangular cell map. It can be seen that the path of Fig. 2(b) is shorter and more flexible than that of Fig. 2(a) due to the efficiency of the triangular cell. This path-planning method is applied to the proposed complete coverage navigation in the next section. If there is an area that is not swept, the cleaning robot must move to it. The distance-transform-based path-planning method, which plans the local path, is used for searching and moving to the closest cell in an unclean area.

III. Complete Coverage Navigation Method

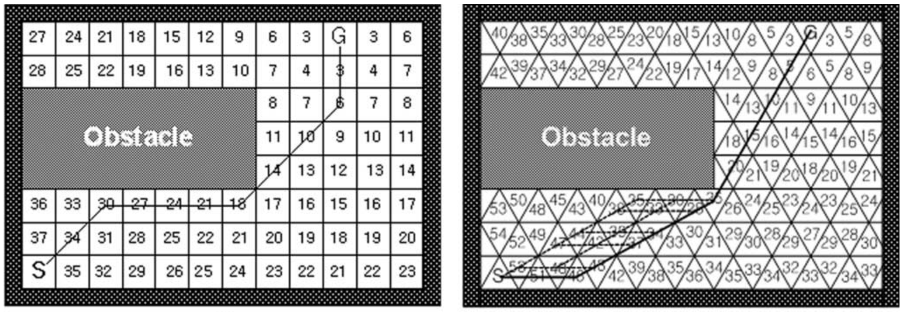
Since the purpose of a cleaning robot is to sweep or scrub the whole given workspace, complete coverage is most important for implementing a cleaning robot. In this section, we describe a complete coverage navigation procedure by which a cleaning robot can navigate the complete workspace although it has no perfect information about the environment.

A. Preliminaries for Complete Coverage Navigation

In order to describe the procedure, we have to present some basic concepts and definitions. Constraints and objectives of the method are introduced first, followed by some terminology used in the procedure.

- ***Constraints and objectives of complete coverage navigation***

  The principal criteria and constraints that must be taken into account in order to carry out a correct and efficient complete coverage navigation include the following.
  - *Completeness:* The moving trajectory of a cleaning robot must guarantee the complete sweep of the free accessible surface.
  - *Convergence:* The ending positions are always attainable.
  - *Unknown environment:* The swept region and the number of obstacles are finite and unknown. The en-



(a) (b)

Fig. 2. Result path planned on (a) rectangular map and (b) triangular map.

vironment is finite and closed, and the starting position is not fixed.

- *Energy and time optimization:* The cleaning time and overlapping paths must be as minimum as possible.
- *Robustness:* With no constraints on the size and position of obstacles, sensors must detect them correctly.
- *Feasible trajectory for a cleaning robot:* The complete coverage navigation plan is composed of sequential and continuous operations, and simple motion paths are preferred.
- *Simplicity:* The complete coverage navigation algorithm must be preferably systematic and structured, avoiding complex mixtures of cases and conditions.

- ***Space model***

  In this complete coverage navigation algorithm, the environment is modeled by a triangular-cell-based map, where the height of the triangular cell on the map has the same size as the cleaning robot. Initially, all cells of a global map are marked as unknown with three possibilities: free space cell (FSC), obstacle space cell (OSC), and unknown cell (UKC). During the navigation of a cleaning robot on the map, the cell information is obtained by an externally installed sensor such as ultrasonic sensor.

- ***Covered region and uncovered region***

  A cleaning robot must navigate the complete workspace that consists of the accessible region except for OSC. The types of all the cells on the entire workspace are memorized and the cleaning robot moves to the next accessible cell using the complete coverage navigation algorithm. In order to accomplish a complete coverage navigation procedure, we formalize the concept of "covered region" (CR) and "uncovered region" (UCR), where CR is defined as the region which has been already navigated by a cleaning robot and UCR is defined as the accessible region which has not yet been navigated by the cleaning robot.

- ***Basic motion for the cleaning robot***

  The basic motion of the cleaning robot on the triangular cell-based-map is shown in Fig. 3. When a cleaning robot sweeps in an unclean region, it crosses the full length of the region in a straight line, turns around, and traces a new straight line path adjacent to the previous one. By repeating this procedure the cleaning robot is guaranteed to sweep the unclean region. This motion is used in the region-filling navigation step continued in the complete coverage navigation procedure which is described below.

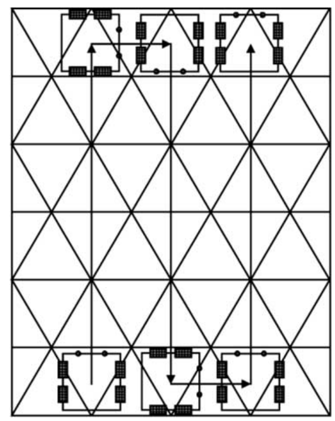


Fig. 3. Basic motion of cleaning robot on the triangular-cell-based map.

B. Complete Coverage Navigation Procedure

In order to sweep the entire workspace, a cleaning robot must perform complete coverage navigation. Since most of the existing methods for complete coverage navigation use the complete or partial information about the workspace, these methods cannot be applied to a totally unknown environment [6], [7]. The complete coverage navigation method presented in this paper provides a way to completely navigate without any information about the workspace. A cleaning robot moves from the current location to the next in accordance with the predefined rules, and through repeating this process it thus navigates the entire workspace.

The proposed complete coverage navigation method is based on the following three steps:

Step 1—Wall-Following Navigation: The proposed complete coverage navigation method is implemented without prior knowledge about the environment. At first, a cleaning robot performs the wall-following navigation procedure for obtaining the contour and size of the indoor environment. Through this procedure, the entire workspace is determined and decomposed into the triangular cell based map. Fig. 5(a) illustrates the Step 1 procedure.

Step 2—Region-Filling Navigation Using Seven Templates: After the wall-following navigation procedure of Step 1, a cleaning robot performs the region-filling navigation by using seven templates as shown in Fig. 4. In this procedure,

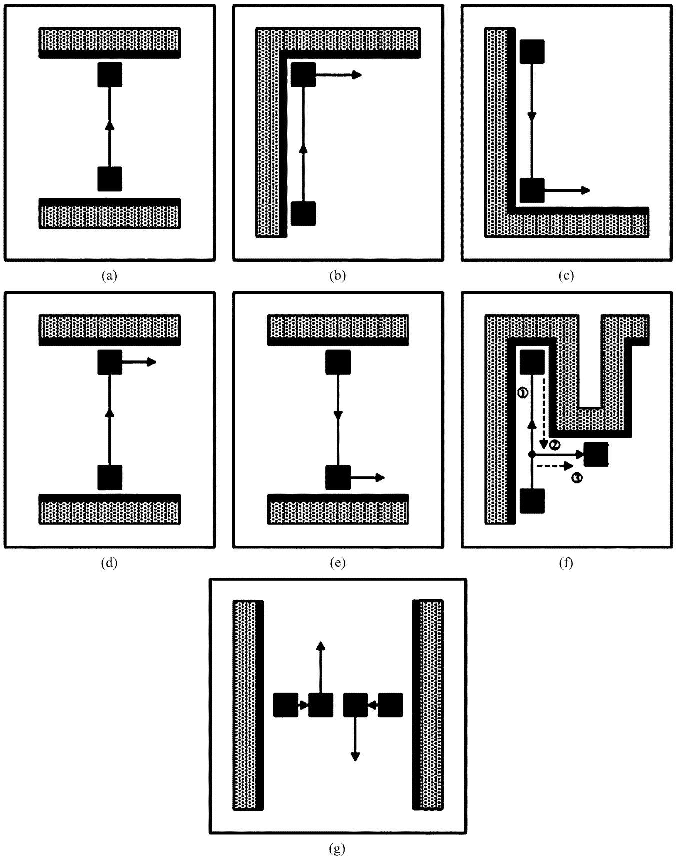


Fig. 4. Seven templates used for region filling navigation. (a) Template FN. (b) Template RT. (c) Template LT. (d) Template ERT. (e) Template ELT. (f) Template BT. (g) Template ELT-1.

a cleaning robot navigates the workspace through basic linear motions from one point to another as shown in Fig. 5(b). In this motion, a cleaning robot selects the next movable cell among cell A, cell D, cell G, and cell J on the triangular-cell-based map shown in Fig. 1. When the existence of an obstacle at Right and Left cells is considered, if there exists the obstacle at cell C or cell D, a cleaning robot cannot move to cell D. In this case, a cleaning robot regards the Right cell as the obstacle.

A set of seven templates, FN (Forward Navigation), RT (Right Turn), LT (Left Turn), ERT (Empty Right Turn), ELT (Empty Left Turn), BT (Back Trace), and ELT-1 (Empty Left Turn-1), is proposed as the minimum number to achieve the workspace coverage of a region which contains obstacles in its interior. Table I represents the templates according to the property of the enclosed three cells (Front, Right, Left) and the direction at the present position of a cleaning robot.

Step 3—Finding and Moving to the Uncovered Region: After Step 2 is completed, the cleaning robot moves to the closest cell in the uncovered region from the end position of Step 2. The distance-transform method is used for searching the closest cell. From the end position of Step 2, if the distance values are given to each cell for all over the free workspace, the closest cell in the uncovered region has the smallest distance value among distance values in the uncovered region, and the closest cell in the uncovered region is found. The distance value is then given again to the entire free workspace from this cell. The shortest path to the closest cell in the uncovered region from the end position of Step 2 is traced by walking downhill via the steepest descent path. Fig. 6 illustrates the procedure given in Step 3 that enables a cleaning robot to find the closest cell in the uncovered region and move to it.

Next, the region-filling navigation procedure is applied again. If this process is repeated, a cleaning robot can perform the complete coverage navigation.

From the result shown in Fig. 7, we confirm that a cleaning robot can navigate the entire workspace with the proposed complete coverage navigation method.

In this navigation method, if there exists an obstacle at cell C, a cleaning robot cannot move to cell B or cell D on the triangular-cell-based map shown in Fig. 1. Also, in the distance-transform-based path-planning method, the distance value is not directly spread to cell D if cell C has an obstacle. However, we assume that a cleaning robot can move to cell A even if cell C has an obstacle. In our complete coverage navigation method, if there is an obstacle at cell C, a cleaning robot moves to cell B by a roundabout path in Step 1 and Step 3 and turns a movable direction according to the seven templates and basic motion shown in Figs. 3 and 4 in Step 2. In Step 1 and Step 2, the triangular-cell-based map does not have any advantage compared with the rectangular-cell-based map. However, when a cleaning robot finds and moves to the closest cell in the uncovered region, the efficient path can be planned due to the advantage of the triangular-cell-based map in Step 3, performed as our global path-planning method.

C. Completeness and Convergence

The completeness is the major measure representing the performance of a complete coverage navigation method. A cleaning robot must navigate the entire workspace through the shortest possible path and be able to navigate the entire workspace.

Lemma 1: If the entire workspace is closed, then the unknown region is finite.

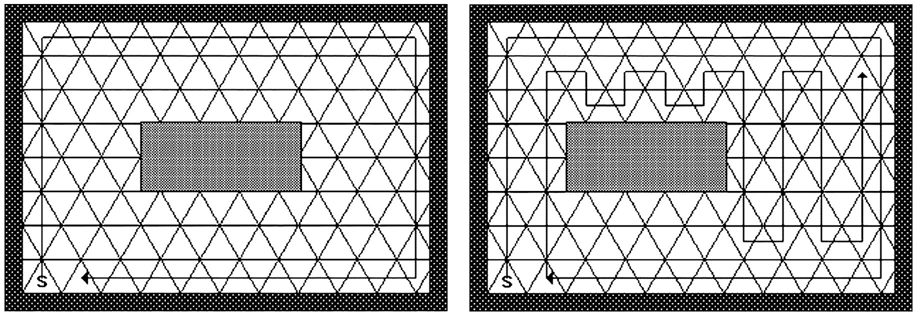
Since the workspace is finite, the accessible free region and the obstacle region are finite. The union of the free region and the obstacle region must contain the unknown region. Therefore, the unknown region is finite.

Lemma 2: At least one cell in the covered region is on the border of one among the neighbor cells of the uncovered region.

Lemma 3: If the distance value is spread over region from the present cell, a cell with minimum distance value in the unknown region is the closest cell in the uncovered region from the present cell.

At least one cell in the uncovered region is contiguous to the covered region. In order to find the closest cell in the uncovered region, the distance value is spread over the region if the distance value is spread from the present cell in the covered region. Since at least one cell among the boundary cells of the unknown region is the cell in the uncovered region, a cell with the minimum distance value in the unknown region is the closest cell in the uncovered region from the present cell. Therefore, if an uncovered region exists, the cleaning robot can certainly find the closest cell in the uncovered region and move to it.

Theorem: If the initial position of the cleaning robot in the free-space region is defined, the complete coverage navigation algorithm guarantees the completeness of the filling procedure.

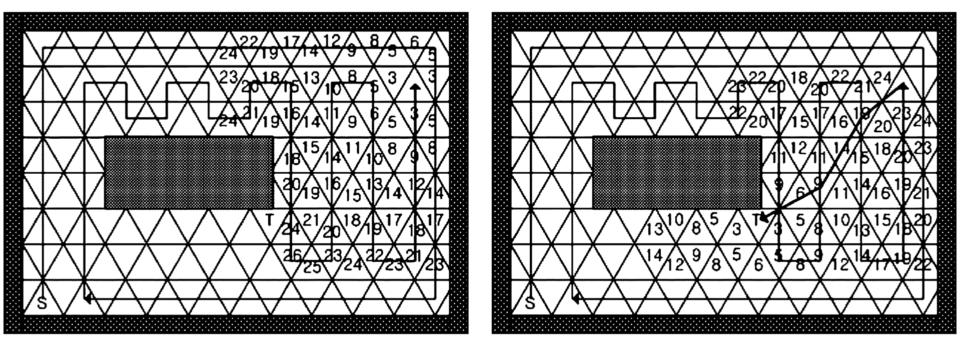


(a) (b)

Fig. 5. (a) Wall-following navigation and (b) region-filling navigation.

TABLE I
TEMPLATES USED FOR CLEANING TASK MOTIONS

Templates		Existence of obstacle or Covered region			
		Front	Right	Left	Direction
FN		NO	YES	×	×
			×	YES	
RT		YES	NO	YES	×
LT		YES	YES	NO	×
ERT		YES	NO	NO	UP
ELT		YES	NO	NO	DOWN
BT	Turn	YES (Obstacle)	YES (Obstacle)	YES (Obstacle)	×
	Navigate	YES (Covered Region)	YES (Obstacle)	YES (Obstacle)	
ELT-1		NO	NO	NO	×



(a) (b)

Fig. 6. (a) Finding and (b) moving to the uncovered region in Step 3.

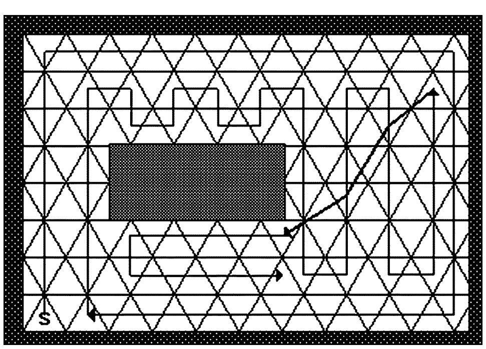


Fig. 7. Result of the complete coverage navigation.

This theorem follows directly from Lemmas 1, 2, and 3. When no more uncovered regions are detected, the covering procedure is completed.

IV. EXAMPLES AND SIMULATION RESULTS

In this section, first we compare the performance of our proposed triangular-cell-based map with that of the rectangular-cell-based map via the existing distance-transform-based path-planning method in order to evaluate the efficiency of the former. Then, we verify the effectiveness of our proposed complete coverage navigation method through computer simulations of several examples.

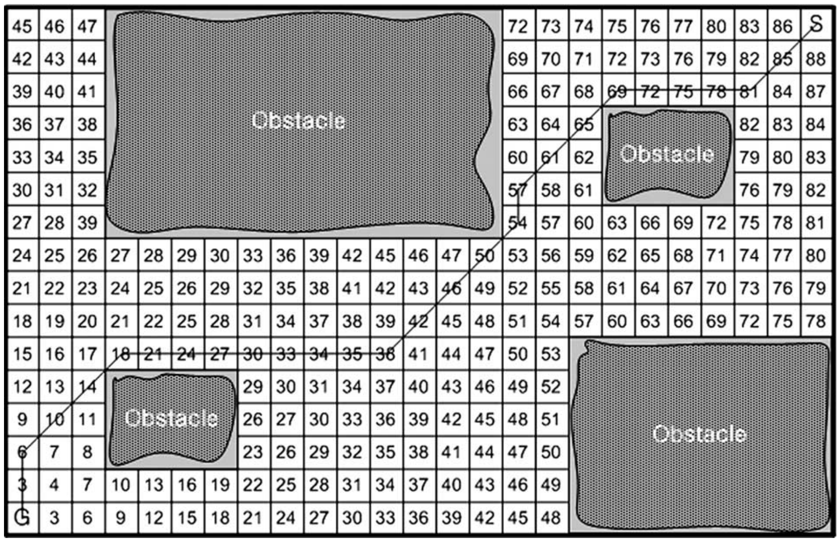


Fig. 8. Path planned on rectangular-cell-based map.

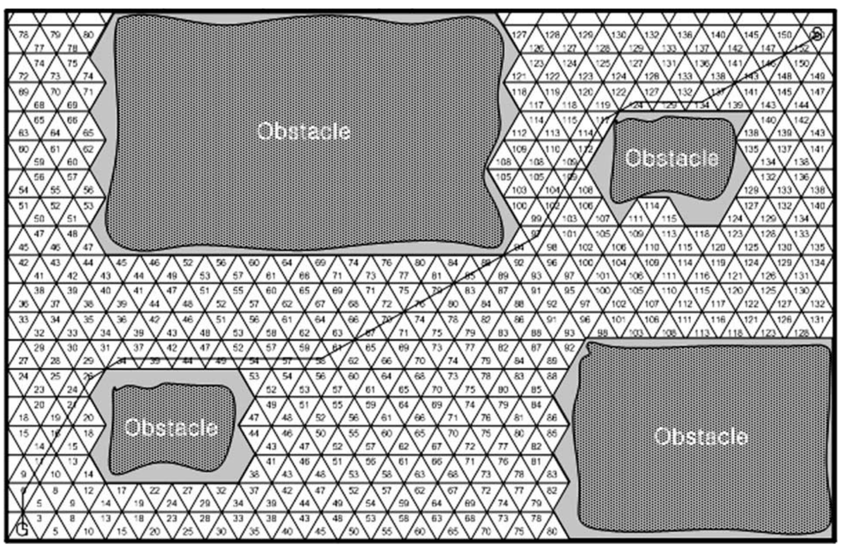


Fig. 9. Path planned on triangular-cell-based map.

A. *Efficiency of the Triangular-Cell-Based Map*

In order to verify the efficiency of the triangular-cell-based map, we use the same example of workspace, which has four obstacles, for both the triangular-cell-based map and the rectangular-cell-based map. In addition, the size of the workspace is assumed to be 16 m $\times$ 25 m.

Fig. 8 shows the result of the path from the starting point S to the target point G planned on the rectangular-cell-based map by the distance-transform-based path-planning method. In this figure, the navigation distance of the cleaning robot is 32.27 m. Fig. 9 shows the result of the path from the starting point S to the target point G planned on the triangular-cell-based map by the same method as Fig. 8. In this figure, the navigation distance of the cleaning robot is 30.23 m.

From the results of Figs. 8 and 9, it is verified that the triangular-cell-based map makes the navigation path shorter and more flexible. This advantageous result of the triangular-cell-based map comes from the fact that the triangular-cell-based map has more directions for movement in path planning than the rectangular-cell-based map.

In the case of Fig. 9, the side length of the rectangle and the triangle cell is set to be equal. This causes the total number of triangular cells to increase, and more memory space is required to implement the map compared to the rectangular-cell-based map. This is a weak point of the triangular-cell-based map for path planning. In order to overcome this weakness, the size of the triangular cells is enlarged so that the total number of triangular cells is equal to that of the rectangular cells.

Fig. 10 illustrates the path planning using the increased size of the triangular cells for cleaning robot navigation, where the navigation distance of a cleaning robot is 29.57 m. Compared with the result of Fig. 9, Fig. 10 shows the navigation distance to be reduced even though the enlarged triangular cell is used.

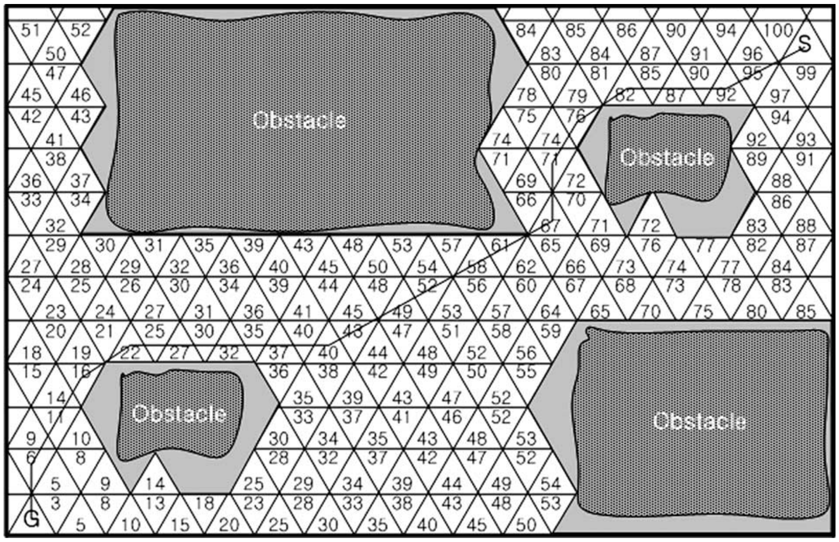


Fig. 10. Path planned on the enlarged triangular-cell-based map.

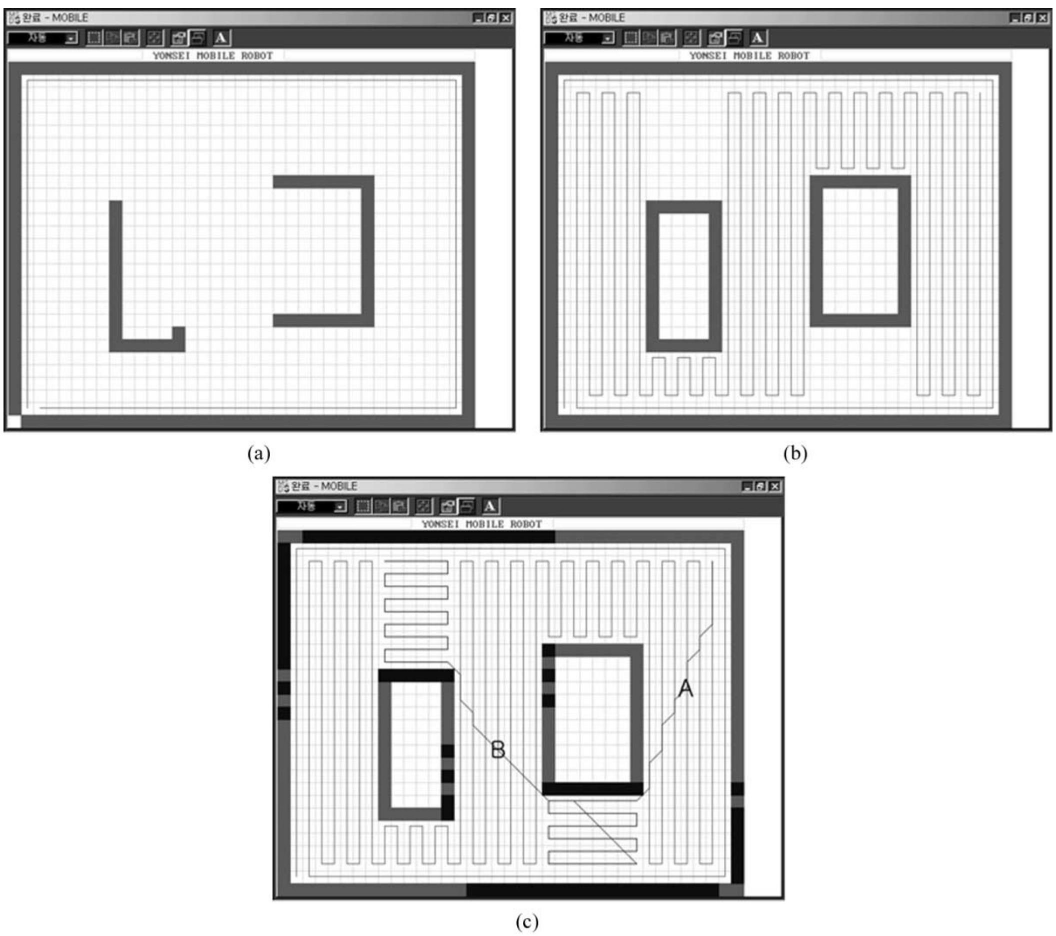
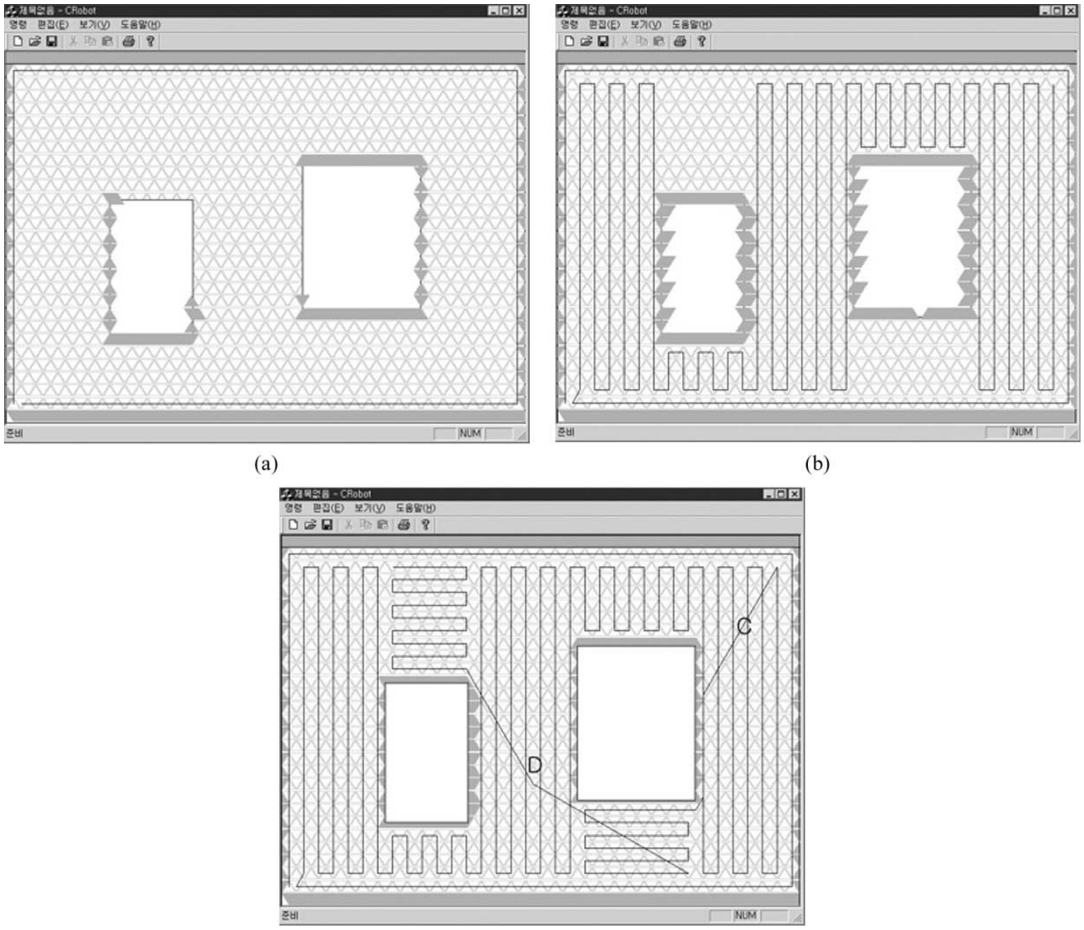


Fig. 11. Complete coverage navigation on the rectangular-cell-based map. (a) Wall-following navigation. (b) Region-filling navigation. (c) Complete coverage navigation.

From this fact, the selection of the size of the triangular cell is an important factor.

B. Complete Coverage Navigation

We will verify the effectiveness of the proposed complete coverage navigation method through the following computer simulations. As shown in Figs. 11 and 12, we use the same work environment, which has two obstacles, for both the triangular-cell-based and the rectangular-cell-based maps. Fig. 11 illustrates the results of the complete coverage navigation method for the cleaning robot on a rectangular-cell-based map. The result in Fig. 11(a) represents the Step 1 procedure in



(a) (b) (c)

Fig. 12. Complete coverage navigation on the triangular-cell-based map. (a) Wall-following navigation. (b) Region-filling navigation. (c) Complete coverage navigation.

which the cleaning robot starts at the lower left corner and performs the wall-following navigation. From this procedure, the cleaning robot can obtain the information on the size of the indoor environment and the partial information on obstacles. Fig. 11(b) represents the result of the Step 2 procedure, in which the cleaning robot performs the region-filling navigation using basic linear motions. Fig. 11(c) shows the result of the overall complete coverage navigation method including finding and moving to the closest cell in the uncovered region. One may notice that A and B are not smooth but piecewise due to the limited navigation direction of the rectangular-cell-based map.

Fig. 12(c) shows the result of the overall complete coverage navigation and feasibility of the proposed navigation method on the triangular-cell-based map. The wall-following navigation and region-filling navigation as shown in Fig. 12 are the same results as the resultant trajectories on the rectangular-cell-based map. In particular, comparing C and D shown in Fig. 12(c) with A and B of the rectangular cell map representation shown in Fig. 11(c), one can conclude that the new triangular-cell-based map representation can plan the shorter and more flexible path of the cleaning robot due to the increased navigation directions on the triangular-cell-based map.

V. Conclusion

In this paper, a novel navigation method was presented for a cleaning robot, which can work well in a completely unknown workspace. First, we presented a new triangular-cell-based map representation that enables a cleaning robot to have more navigation directions. While the rectangular-cell-based map has eight navigation directions, the triangular-cell —based map increases the navigation directions to 12. This increase makes the navigation path shorter and more flexible. Second, we proposed a complete coverage navigation and map construction method, which enables a cleaning robot to navigate the complete workspace without any information about the environment. To generate a complete coverage navigation path without prior information of the environment, the wall-following navigation was first performed. Through this procedure, a cleaning robot can obtain the information of the contour of the environment. Then, basic templates were introduced as means for local navigation. To find the uncovered region and determine the local direction, the distance-transform method was also adopted.

From the simulation results of several examples, we verified the effectiveness of the our navigation approaches. Even though the environment used in the simulation was a simple workspace with only four obstacles, it is expected that the efficiency of the proposed triangular-cell-based map will be increased for more a complicated workspace.

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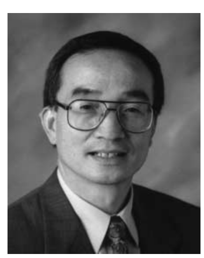

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