Complete coverage path planning of mobile robots for humanitarian demining

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***Abstract*— The paper presents a path planning algorithm for a non-circular shaped mobile robot to autonomously navigate in an unknown area for humanitarian demining. For that purpose the path planning problem comes down to planning a path from some starting location to a final location in an area so that the robot covers all the reachable positions in the area while following the planned path. Based on our previous complete coverage algorithm of known areas we have developed a complete coverage algorithm capable of operating in unknown areas with known border dimensions. The proposed algorithm uses occupancy grid map representation of the area. Every free cell represents a node in the graph being searched to find the complete coverage path. The proposed algorithm finds the complete coverage path in the graph accounting for the dimensions of the mobile robot, where non-circular shaped robots can be easily included. The algorithm is implemented under the ROS (robot operating system) and tested in the stage 3D simulator for mobile robots.**

***Index Terms*— autonomous mobile robots, path planning, coverage path planning, exploration**

I. Introduction

The path planning problem of a mobile robot for humanitarian demining application comes down to planning a path from a start position to a final position in an area so that the robot inspects all the reachable positions (nodes in a graph) while following the planned path. The problem of finding the path that visits all nodes in a graph is called the complete coverage path planning [7]. Finding an optimal path that visits every node in a graph exactly once is NP-hard problem known as the traveling salesman problem. Therefore, approximate or even heuristic solutions are used for the complete coverage path planning task.

A common approach to complete coverage planning is decomposing the environment into subregions [6], selecting a sequence of those subregions, and then generating a path that covers each subregion in turn. Most methods assume convex polygonal environments and perform exact cell decomposition [5], [1], [11], which can be very time consuming in changing environments. Methods based on the approximate cell decomposition (i.e. grid maps) are less time consuming, but suppose that the mobile robot has the dimensions of exactly one cell within the grid map [4], [12].

Most complete coverage planning algorithms assume circular shaped mobile robot, and there is little work reported for complex non-circular shaped mobile robots. This paper presents a new complete coverage path planning algorithm for complex shaped mobile robot and is capable of operating in unknown areas of known border dimensions for the application of humanitarian demining. The algorithm is an extension of our previous complete coverage D* algorithm (CCD*) developed for circular shaped robots operating in known indoor environments with moving obstacles [2]. The proposed algorithm uses decomposition of the unknown area into squared cells of equal size and finds the complete coverage path that covers all reachable cells. The complete coverage path is integrated with the dynamic window obstacle avoidance algorithm [3] to produce smooth robot trajectory considering robot's kinematic and dynamic constraints.

The rest of the paper is organized as follows. Section II describes robot and environment representation for the humanitarian demining. Section III presents the proposed complete coverage planning algorithm. Test results are given in Section IV and conclusion in Section V.

II. Robot and environment representation

A. The robot

In this paper, we assume usage of the humanitarian demining mobile robot MV-4 of DOK-ING company (Fig. 1), although developed algorithm is generally applicable to other robots. The dimensions of the prime mover together with the attached flail tool for activating mines are given in Table I (taken from `www.dok-ing.hr`). The simulation setup with the robot model is shown in Fig. 2. The simulated robot has on-board laser range sensor with 360° field of view. The maximal range used for mapping of unknown obstacles are set to 8 m, although outdoor laser range sensors provides much higher ranges (e.g. 30 m). The limitation of only 8 m ranges data assure more reliable map update especially in an uneven terrains (detecting of the ground). The robot has differential drive, i.e., it can rotate in place, and can move in forward and backward direction.

TABLE I

Technical data for the MV-4 mine clearance system.

Dimensions	(Length x Width x Height) mm
Prime Mover	3005 x 1530 x 1470 mm
Prime Mover With Flail (Clearing arm pulled in)	4455 x 2015 x 1470 mm
Prime Mover With Flail (Clearing arm extended)	5145 x 2015 x 1470 mm

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Fig. 1. The MV-4 mine clearance system. Courtesy of DOK-ING company `www.dok-ing.hr`.

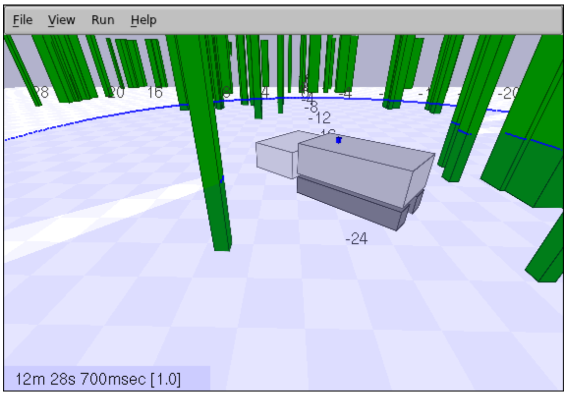

Fig. 2. The simulation setup in the Stage simulator – 3D view of the robot model and the part of the random environment.

B. The occupancy grid map

Two-dimensional (2D) occupancy grid maps are usually used to represent a continuous environment by an equally-spaced grid of discrete points [10]. The whole unknown area with known borders is divided into squared cells of equal size. Each cell contains occupancy information of the part of the environment that it covers, which is continuously updated as the robot detects obstacles within the corresponding cells.

The real shape of the robot represented in the grid map is shown in Fig. 3. It is usually assumed that the robot shape can be approximated by the circle, which position coordinates are planned. In order to avoid robot orientation planning, in this paper we assume that the real shape of the robot can be approximated by two circles. One circle covers the robot's vehicle (prime mover), and another circle covers the robot's flail tool for demining. By introducing the two circles and with certain adaptation of the obstacle avoidance module it is sufficient to plan only position coordinates. The larger circle (R_1 in Fig. 3) is used for obstacle enlargement. The robot's position is considered to be in the center of the prime mover. For the path planning it is assumed that the robot needs to inspect the whole area by its tool and not by its mask. Further, it is assumed that the visited nodes are within the approximated squared shape of the tool, which is a little bit narrower than the real tool dimensions. On the other hand, while following the planned path, nodes that are visited are determined conservatively, i.e., the ones that are covered with the real shape of the robot.

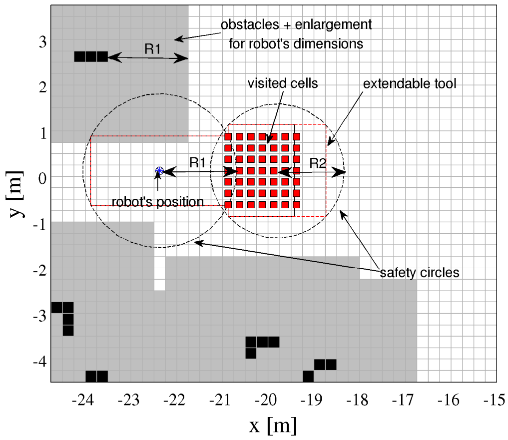

Fig. 3. The occupancy grid map with the robot real shape. The size of the cell is $e_{\text{cell}} = 0.25$ m.

III. The complete coverage planning for humanitarian demining

The proposed complete coverage planning algorithm for humanitarian demining is actually a modified version of our original complete coverage D* algorithm [2]. While original CCD* algorithm is limited to path planning of circular shaped robots in known area, introduced modifications enables path planning of non-circular shaped robots in unknown areas.

A. The CCD* algorithm's modifications

Modifications of the CCD* algorithm, which enable path planning for complex robot's shape, include first planning the coverage path for the tool's center, i.e., the node in the center of the tool's squared shape (see Fig. 3), and afterwards deriving for the robot's position. The first node in the coverage tool's path is the tool's center point when the robot is in the start position, and the first node in the coverage robot's path is the start node. The tool's center point is displaced from the robot's center point. The CCD* algorithm is called for the tool's position T and the path $\mathcal{P}_T$ is determined. Afterwards, by performing certain coordinate transformation the path of the robot's center point $\mathcal{P}_R$ is determined.

When an on-board range sensor detects obstacles, corresponding cells become occupied. Additionally, cells between the robot and the detected obstacles become free. Afterwards, the path replanning process is initiated and certain parts of the area are included or removed from the path. To track which cells are visited by the robot while following the complete coverage path, functions $\textbf{visited}_R(n) = \{0, 1\}$ and

$\textbf{overlapped}_R(n) = \{0, 1\}$ are used. Before each execution of the complete coverage path calculation values of functions $\textbf{visited}(n)$ and $\textbf{overlapped}(n)$ are rewritten by the new ones $\textbf{visited}_R(n)$ and $\textbf{overlapped}_R(n)$, respectively. The new coverage path is recalculated by the same procedure but with smaller number of non-visited nodes in the graph.

B. Illustration of algorithm's iterations

First, the D* search [9] is performed from the start node S to calculate the cost values g for every reachable node. The first node in the coverage tool's path is the tool's center point, and the first node in the coverage robot's path is the start node. The tool's center point is distanced from the robot's position for the fixed length l_T along the x-axis of the robot's local reference frame (robot's direction of moving forward). In the path planning step, smaller mask of squared shape (inner part of the real tool shape) is used for determining visited nodes (see Fig. 3), as opposed to the path following step where all cells that are covered by the real shape of the robot are used. Only for the first step of the algorithm visited and overlapped values are determined for complete robot mask. In all other steps those values are determined only for the tool.

The next node in the coverage tool's path is chosen from the candidate nodes in the same way as in the original CCD* algorithm for the robot's path. The candidate nodes are defined to be non-overlapped nodes that are reachable and distanced from the previous node in the coverage tool's path for the tool square size in four straight directions through the grid. The next node is the one with the smallest cost value g. An example of the first iteration of producing the coverage path is shown in Fig. 4.

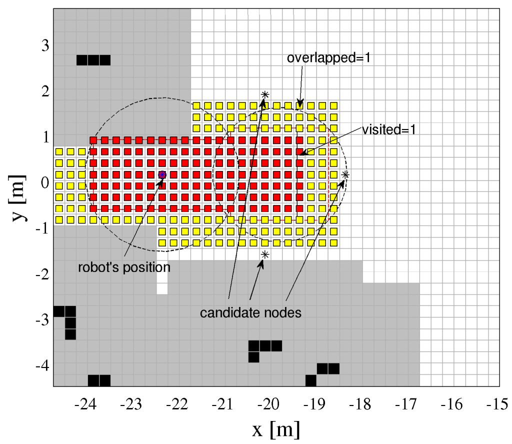

Fig. 4. The first iteration of the coverage path – assigning the visited and overlapped nodes and determining the candidate nodes.

When each node in the tool's path is determined, for example the i-th node of the tool's path, the i-th node of the robot's path is calculated to account for displacement between the robot's position and the tool's position. The point in the tool's path is translated backwards for the length l_T along the connection line between the $(i-1)$-th point in the robot's path and i-th point in the tool's path. If the length of the connection line is smaller than the displacement length l_T, then the i-th point in the robot's path gets repeated its previous $(i-1)$-th point. By this procedure the robot's path is smoothed and becomes more appropriate to follow by the path following module. An example of this procedure is shown for the third iteration of the algorithm in Fig. 5. Described iterations continue until there is no

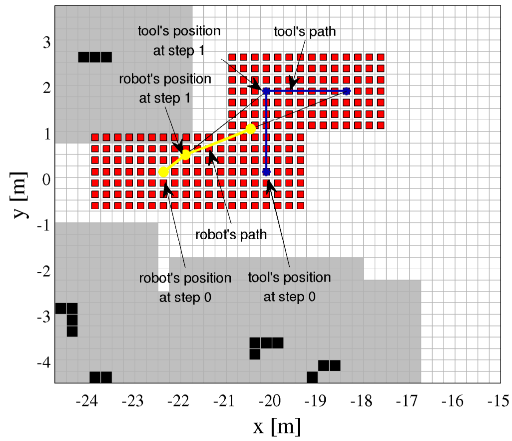

Fig. 5. The third iteration of the coverage path – determining the robot's path from the tool's path.

surrounding candidate nodes. Then, like in the CCD* algorithm, another search is performed from the last node of the tool's path to find the closest non-visited node. Algorithm stops when there are no non-visited node left.

IV. Test results

The proposed algorithm was implemented in ROS (the robot operating system and the Stage simulator www.ros.org) with the MV4 robot model described in section II. The AMCL algorithm (Adaptive Monte Carlo Localization) was used for robot localization. For path following a dynamic window based algorithm, described in our previous work was used [8] with certain adaptations for two circle shaped robot. The robot was allowed to go backwards in some deadlock scenarios. A randomly generated map was used with dimensions 50 m x 50 m as the simulation map of an unknown area, see Fig. 2. The laser range readings used in the simulation has full field of view (360 degrees) and was limited to 8 meters to cope only with obstacles in local vicinity of the robot. While the robot was moving, it detected unknown obstacles and replanned the complete coverage path.

Figure 6 shows three of many replannings while moving through the unknown area. The first one (left)

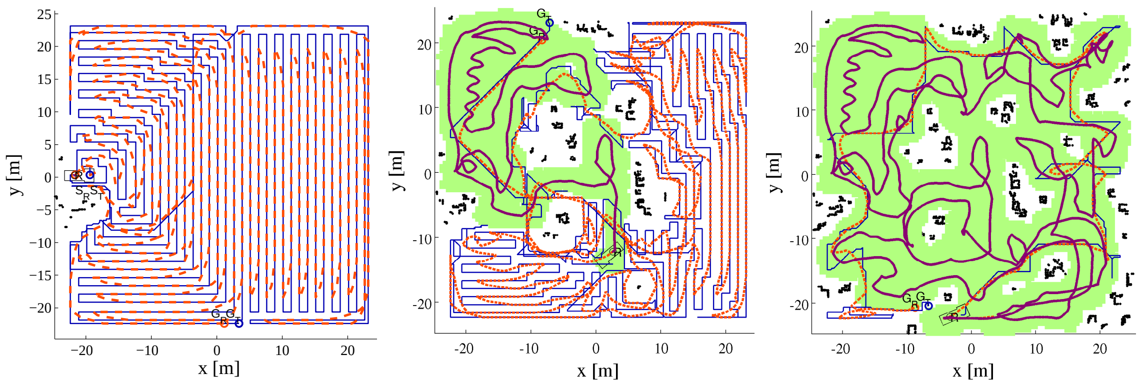

Fig. 6. Three snapshots of (many) replanning steps while the robot is moving through the unknown area and detecting unexplored obstacles – visited area is colored green, the new tool's path is noted by solid line, the new robot's path is noted by dashed line, and driven trajectory is bolder curve.

is the initial planning. End nodes of the tool's path and the robot's path are noted by G_T and G_R, respectively. The path was changing at each replanning step and had more path direction changes with more obstacles detected. Due to non-perfect path following some parts of the area remind non-visited. Those parts were included in the new complete coverage path with the next replanning step. However, some cells were very hard to visit due to complex shape of the robot and rotation on the spot near certain obstacle configuration was not admissible by the dynamic window algorithm. Total time needed to visit green area in the snapshot 3 took about 80 minutes, and for the final covering it took 110 minutes. The robot was traveling with average speed of 135 mm/s. Maximal allowed speed was 500 mm/s for forward motion and 100 mm/s for backward motion. Maximal orientation speed was limited to 100 °/s. From snapshot 3 the robot tried to visit cells near the border of obstacles, which was not successful in all cases since the robot needed also to rotate in place to reach the non-visited cells, which was not planned by the algorithm. Finally, the robot covered total number of 30712 cells (1919.5 m^2) of the total number of 30718 reachable cells, i.e., only 6 cells remained non-visited. The total length of the robot's driven trajectory was 938.4 m.

V. Conclusions

In this paper a new complete coverage path planning algorithm for humanitarian demining has been proposed. It was shown that it effectively plans the robot's path ensuring that the flail tool visits all reachable regions (cells) of the inspected area. The test results of the proposed algorithm have shown satisfactory behavior of the algorithm in the environment populated with unknown static obstacles. A few cells have stayed non-visited due to non-perfect path following. In our future work, a better path following algorithm will be developed and additional constraints will be included in the planning algorithm such as the minimization of the number of path direction changes and planning also orientations for certain points near the obstacles.

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References

[1] H. Choset. Coverage of known spaces: the boustrophedon cellular decomposition. *Autonomous Robots*, 9(3):247–253, 2000.

[2] M. Đakulović, S. Horvatić, and I. Petrović. Complete Coverage D* Algorithm for Path Planning of a Floor-Cleaning Mobile Robot. In *Proceedings of the 18th IFAC World Congress*, pages 5950–5955, 2011.

[3] D. Fox, W. Burgard, and S. Thrun. The dynamic window approach to collision avoidance. *Robotics & Automation Magazine, IEEE*, 4(1):23–33, 1997.

[4] Y. Gabriely and E. Rimon. Competitive on-line coverage of grid environments by a mobile robot. *Computational Geometry*, 24(3):197–224, 2003.

[5] W.H. Huang. Optimal line-sweep-based decompositions for coverage algorithms. In *IEEE International Conference on Robotics and Automation (ICRA 2001)*, pages 27–32, 2001.

[6] J.C. Latombe. *Robot Motion Planning*. Kluwer Academic Publishers, Dodrecht, Netherlands, 1991.

[7] S.M. LaValle. *Planning algorithms*. Cambridge Univ. Pr., 2006.

[8] M. Seder, K. Maček, and I. Petrović. An integrated approach to real-time mobile robot control in partially known indoor environments. In *32nd Annual Conference of IEEE Industrial Electronics Society (IECON 2005)*, pages 1785–1790, 2005.

[9] A. Stentz. Optimal and efficient path planning for partially-known environments. In *IEEE International Conference on Robotics and Automation (ICRA 1994)*, pages 3310–3317, 1994.

[10] S. Thrun, W. Burgard, and D. Fox. *Probabilistic robotics*. Cambridge, Massachusetts: MIT Press, 2005.

[11] S.C. Wong and B.A. MacDonald. A topological coverage algorithm for mobile robots. In *IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS 2003)*, volume 2, pages 1685–1690. IEEE, 2003.

[12] A. Zelinsky, RA Jarvis, JC Byrne, and S. Yuta. Planning paths of complete coverage of an unstructured environment by a mobile robot. In *Proceedings of International conference on Advanced Robotics (ICAR 1993)*, pages 533–538, 1993.