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An Effective Trace-Guided Wave-front Navigation and Map Building Approach for Autonomous Mobile Robots

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ABSTRACT

This paper aims to address a trace-guided real-time navigation and map building approach of an autonomous mobile robot. Wave-front based global path planner is developed to generate a global trajectory for an autonomous mobile robot. Modified Vector Field Histogram (M-VFH) is employed based on the LIDAR sensor information to guide the robot locally to be autonomously traversed with obstacle avoidance by following traces provided by the global path planner. A local map composed of square grids is created through the local navigator while the robot traverses with limited LIDAR sensory information. From the measured sensory information, a map of the robot's immediate limited surroundings is dynamically built for the robot navigation.

The real-time wave-front based navigation and map building methodology has been successfully demonstrated in a Player/Stage simulation environment. With the wave-front-based global path planner and M-VFH local navigator, a safe, short, and reasonable trajectory is successfully planned in a majority of situations without any templates, without explicitly optimizing any global cost functions, and without any learning procedures. Its effectiveness, feasibility, efficiency and simplicity of the proposed real-time navigation and map building of an autonomous mobile robot have been successfully validated by simulation and comparison studies. Comparison studies of the proposed approach with the other path planning approaches demonstrate that the proposed method is capable of planning more reasonable and shorter collision-free trajectories autonomously.

Keywords: Wave-front path planning, trace-guided, navigation, map building, global path panning, LIDAR-based navigator

1. INTRODUCTION

Robotic path planning and map building is one of the issues in the field of robotics that attempts to find and optimize the path from the initial position to the final position while the local map is dynamically built up as the robot moves. Autonomous mobile robot navigation is an essential issue in robotics. Real-time navigation and map building is a challenging task for autonomous mobile robots, especially in unknown and dynamical environments. For real-time autonomous navigation, the autonomous mobile robot is able to sense its environment, interpret the sensed information to obtain the knowledge of its location and the environment, plan a real-time collision-free trajectory from an initial position to goal, and send effective control commands for the robot direction and velocity to reach the goal.

There have been a great number of studies conducted on autonomous robot navigation and mapping with obstacle avoidance such as fuzzy logic ([1][12]), Ant Colony Optimization ([2-3]), neural network methods ([4-8], [12]), potential field model ([9-10]), genetic algorithm (GA) ([9]), distance transform method ([10]), Particle Swarm Optimization approach ([11]), Delaunay Triangulation ([13]), distance transform ([15-17]), VFH methods ([18-19]), and D*-search method ([20-21]). Fahmi et al. [1] developed a fuzzy logic controller based behavior architecture to drive an autonomous robotic wheelchair to complete goal seeking, wall following, obstacle avoidance and navigation tasks. Sensor fusion algorithm is proposed for robotic wheelchair control equipped with a microcontroller-based embedded system for motion control and sensors information acquisition, localization and communication. Xing et al. [2] described the applications of Ant Colony Optimization (ACO) to intelligent vehicles. This has revealed important insights into the potential of applying ACO algorithms to UGVs. The reason why much of the innovations on the ACO have been devised in vehicle path planning is that ACO paradigm is more robust, faster, and has a better probability in achieving the globally optimal solution thus it is successfully applied to UGVs. Tan et al. [3] developed an ACO algorithm for

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robotics navigation to optimize and adjust the global trajectory searched by Dijkstra model that generates a sub-optimal collision-free path. The ACO algorithm is employed to adjust and optimize the positions of the path nodes on this sub-optimal path, so as to generate the globally optimal path.

Neural network method is an efficient approach for robotics navigation. Fujii et al. [4] suggested a multi-layered approach for collision-free navigation via reinforcement learning. However, the planned robot motions using learning based approaches are not optimal, particularly at the initial learning phase. Yang and Meng [5] proposed a biologically inspired neural network approach for real-time path planning with obstacle avoidance of a mobile robot and a multi-joint robot manipulator in a non-stationary environment. The planned robot motion in a static environment is globally optimal although there is no explicit optimization of any global cost functions. The optimality of the real-time robot trajectory is planned through the dynamic activity landscape of the neural network without any prior knowledge of the dynamic environment, without explicitly searching over the free workspace or the collision paths, and without any learning procedures. Therefore it is computationally efficient. Luo and Yang extended the neural dynamics model to coverage-type motion planning of an autonomous mobile robot and also this approach is applied to solve vicinity problems of obstacles in complete coverage navigation ([6-7]). However, the neural network models described previously are only suitable for navigation in non-stationary environments without map building. Luo and Yang [8] recently developed heuristic algorithms based on a biologically inspired neural network model, which concurrently perform navigation and map building under unknown environments.

Some research models integrate two approaches to take advantage of the various features. For instance, Savage et al. [9] developed a potential field method associated with a genetic algorithm (GA) for navigation of autonomous robots. In their model, a genetic algorithm (GA) is employed for optimizing the potential field by encoding the chromosome of each individual for the potential field generated by waypoints, obstacles, and goals. Wang et al. [10] proposed a hybrid navigation model in combination of a global path planner of a distance transform and a local navigator of potential field methods under unknown environments by combining advantages of two methodologies. Chung et al. [11] combined Particle Swarm Optimization and fuzzy logic methods for a wheeled mobile robot navigation and wall-following. Fuzzy logic is utilized to avoid local dead-end. Zhu and Yang [12] integrated advantages of fuzzy logic and neural network methodologies. In their model, a neuro-fuzzy-based approach for robotic navigation coordinating the sensor information and robot motion together is proposed, in which a learning algorithm based on neural network techniques is developed to tune the parameters of membership functions for the fuzzy logic system. The fuzzy logic system is designed by two basic behaviors, target seeking and obstacle avoidance. However, a number of previous models lack of ***map building*** in their methodologies due to its difficulty of concurrent navigation and mapping. Chen et al. [13] proposed an enhanced dynamic Delaunay Triangulation-based motion planning approach for mobile robots to plan and navigate a path successfully under lane line type environments. Using processed data from a LADAR, camera, compass and GPS unit, a composite local map containing both obstacles and lane line segments is built up and Delaunay Triangulation is continuously run to plan a trajectory. In term of mapping, for instance, Ozkil et al. [14] proposed an approach by utilizing a topological map for global motion planning and metric maps for local navigation. Occupancy grids by a laser range finder to represent local information about partial areas are produced by metric maps whereas the global topological map is employed to indicate the connectivity of the region in the environment and the interconnectivity of the local maps.

In this paper, a local map composed of grids is dynamically built through the robot navigation with restricted LIDAR sensory information. The robot is able to dynamically build a map of its immediate limited surroundings. The onboard robot sensors such as LIDAR have only a limited reading range and the obtained sensory information is used for its navigation. In this paper, a trace-guided real-time navigation and map building approach for an autonomous mobile robot is proposed. Wave-front based global path planner is developed to generate a global trajectory in workspace. Pheromone traces are remained along the planned global trajectory. As a result, the traces provide the autonomous mobile robot with a sequence of starting points and goals by a developed local navigator. An autonomous mobile robot like an ant is capable of traversing along the pheromone traces to gradually reach the final destination. A commonly used local navigation algorithm, the Vector Field Histogram (VFH), is relatively fast and thus suitable when computational capabilities on a robot are limited. In this paper, a modified Vector Field Histogram (M-VFH) is developed as a local navigator to guide the robot to perform point-to-point navigation locally with obstacle avoidance by means of LIDAD sensor information to follow pheromone markers, which is not sensitive to sensor noise and other disturbances.

The real-time wave-front based navigation and map building methodology has been successfully demonstrated in a Player/Stage simulation environment. With the wave-front based global path planner and M-VFH local navigator, a safe,

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short, and reasonable trajectory is successfully planned in a majority of situations without any templates, without explicitly optimizing any global cost functions, and without any learning procedures. Its effectiveness, feasibility, efficiency and simplicity of the proposed real-time navigation and map building for an autonomous mobile robot have been successfully validated by simulation and comparison studies. Comparison studies of the proposed approach with the other path planning approaches demonstrate that the proposed method is capable of planning more reasonable and shorter collision-free trajectories autonomously.

2. THE PROPOSED NAVIGATION AND MAPPING MODEL

The wave-front based global path planner is developed to generate a global trajectory of an autonomous mobile robot. Modified Vector Field Histogram (M-VFH) is employed based on the LIDAR sensor information to guide the robot locally to autonomously traverse with obstacle avoidance by following pheromone traces provided by the global path planner. In this section, after a wave-front based global path planner is described first, LIDAR-based local navigator with mapping is addressed.

2.1 Wave-front Based Global Path Planner

Wave-front based motion planning approach has been extensively applied for motion planning of mobile robots ([15-16]), which was originally devised as a tool to propagate distance in tesselated space from the shape boundaries into their centers while studying shape of objects in 2D images ([15]). The wave-front based motion planning algorithm is a simple-to-implement and efficient methodology for robot navigation in fixed-size cell arrays ([17]).

In the wave-front based path planning algorithm, a distance wave-front is propagated through entire free space grids from the target grid to stating pointing grid under the whole environment. The path planner marks for each grid its Manhattan distance to the target grid to take advantage of its wave-front expansion from the target grid outward. The process continues until the grid of representation of the starting position with the mobile robot is reached. From initial grid, the path planner is able to estimate a trajectory in the steepest descent mode. For any initial grid corresponding to the initial position of the mobile robot, the shortest path to the target is traced by traversing downhill via a gradient descent trajectory in the entire workspace illustrated in Figure 1 ([15-17]) from **S** (14,10) to the destination **F** (1,1).

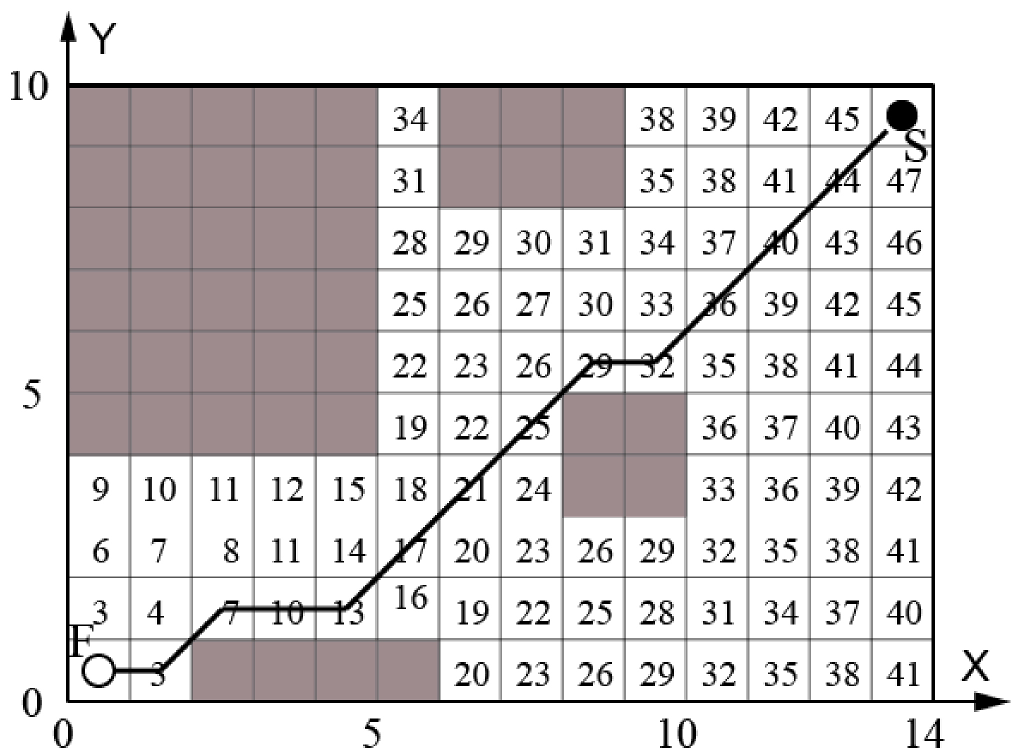

Figure 1 The planned trajectory by the wave-front expansion based path planning algorithm ([17])

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2.2 LIDAR-based Local Navigator and Map Building

Usually, the local map is dynamically obtained from data of LIDAR, GPS and camera. The LIDAR data consists of two sections shown in Figure 2: one is the angle scanned by the LIDAR and the other is length. A reactive local navigation algorithm commonly used in mobile robotics is the M-VFH ([18-19]). This algorithm and many of its variants are computationally efficient, an important consideration for real-time operation that makes it popular. The VFH algorithm outputs a preferred target sector for the robot to move towards. The recommended direction is derived from an analysis of a polar obstacle density histogram constructed from sensor scans of the obstacle field in front of the robot. This decision is generated from current sensor data; that is, the base algorithm has no memory of prior decisions. Thus, one of the attendant disadvantages of the algorithm is that the robot can get trapped when attempting to get past a concave obstacle structure. This typically manifests itself as a back-and-forth oscillation around the curve of the structure. In the past, heuristics have been added to overcome this problem but their proper tuning has always been a challenge.

The VFH method developed a concept, called the *polar histogram,* a kind of intermediate data-representation. The VFH algorithm provides mobile robots with a sufficiently detailed spatial representation of the environment with densely cluttered obstacles ([18]). In order to compensate for the inaccuracies of some sensors such as the ultrasonic sensors, the statistical data of the histogram grid is stored by the polar histogram. However, the amount of data that needs to be processed in real-time is decreased. Ulrich and Borenstein [19] developed a modified version of VFH+ navigation algorithm, which utilizes a four-stage data reduction technique to calculate the new direction of motion. The robot navigation is performed using this modified version of VFH+ navigation algorithm. To avoid obstacles, the VFH+ is utilized as a local reactive navigation algorithm based directly on the sensor data (LIDAR, SONAR, GPS, etc.). In this paper, this polar histogram is divided into 54 sectors as every sector is 5° and the LIDAR has a range of 270° in Figure 2. The obstacles are enlarged to further eliminate the chance of the robot colliding any obstacles and to provide smoother motion for the robot. This creates a smoother path for the robot and reduces navigation time ([13]). The best sector to go through is then used to guide the robot based on a weighted formula that combines deviation from desired direction and associated obstacle densities.

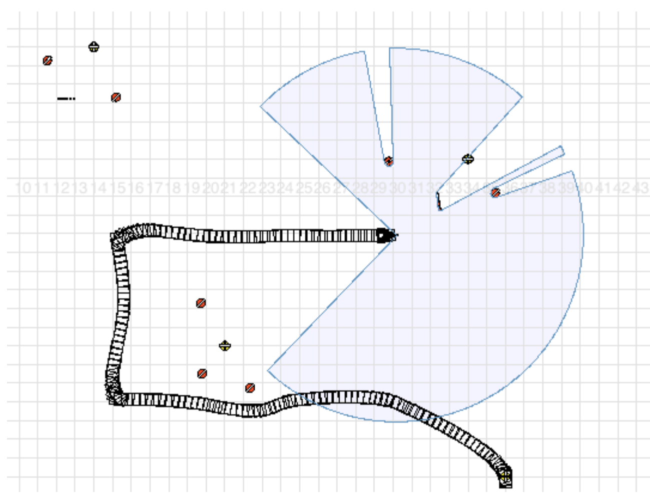

Figure 2 The LIDAR scanner of 270° for local navigation

3. TWO-LAYER TRACE-GUIDED ROBOT NAVIGATION AND MAP BUILDING

Once a path from wave-front algorithm has been obtained, a number of trace points along it are extracted so as to use the M-VFH algorithm. These points are converted into GPS coordinates and presented to M-VFH as consecutive goals. M-VFH then generates motion commands which are passed on to the drive controllers to move the robot towards these intermediate goals. Once the robot is close to an intermediate goal, we consider it achieved and substitute the next intermediate goal along the desired path. Once a trajectory is planed globally, the traces are remained along the trajectory in Figure 3. The mobile robot is directed by following the trace while it dynamically builds up the local map. There are several options to mark traces by even intervals or at turning points. In Figure 3, the traces are marked representing by red dots along the trajectory planned by the wave-front path planner.

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The wave-front propagates from the goal position, marking all free space grids with an incrementing distance value. Once all non-obstacle grids have been marked, the resulting path is created by gradient descent. The M-VFH algorithm outputs a preferred target sector for the robot to move towards. The recommended direction is derived from an analysis of a polar obstacle density histogram constructed from sensor scans of the obstacle field in front of the robot. While the robot transverses in the workspace, the global environmental information is unavailable for the robot due to the inability of the sensor range. Square grid map representations are suggested for real-time map building and navigation. The proposed method does not need any templates, even in unknown environments. A local map composed of square grids is created through the local navigator while the robot traverses with LIDAR information. From the measured sensory information, a map of the robot's immediate limited surroundings is dynamically built for navigation. In order to generate safer, more reasonable collision-free trajectories, some heuristic algorithms are developed to optimize the path by effectively integrating the global path planner and local navigator. Due to the ability of the LIDAR with the local navigator, the robot is able to avoid moving and unforeseen obstacles while the robot traverses in the workspace.

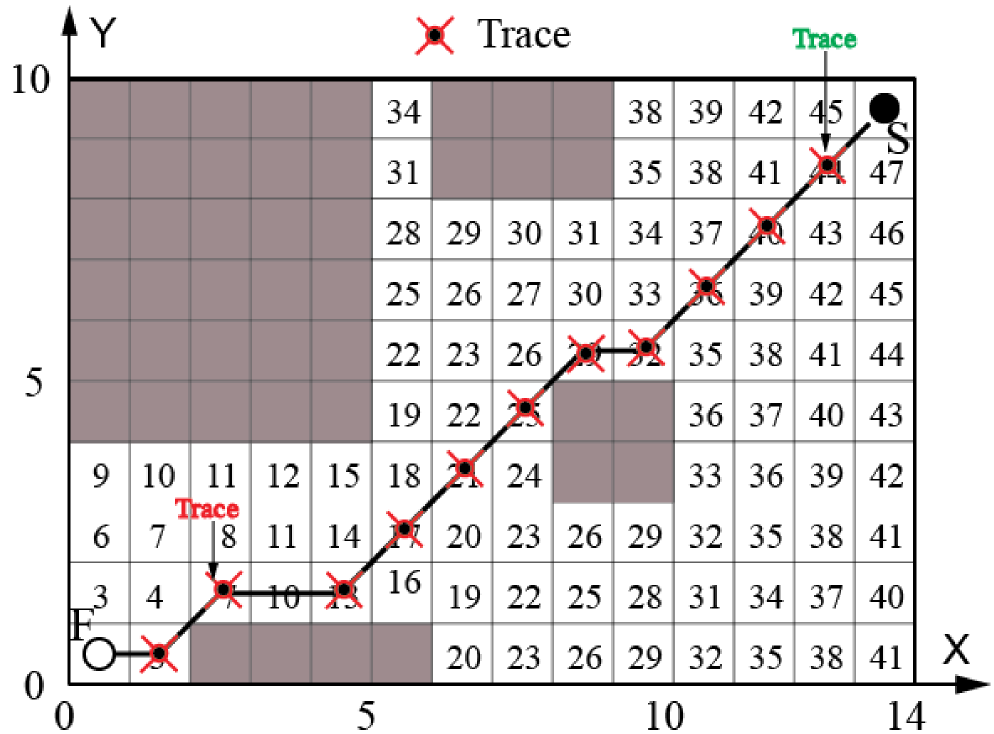

Figure 3 The illustration of traces along the planned trajectory by the wave-front expansion algorithm

4. SIMULATION AND COMPARISON STUDIES

In this section, the proposed model will be validated by simulation and comparison studies for autonomous mobile robot navigation. The wave-front based path planner and LIDAR-based local navigator are programmed in Matlab. The proposed approach enables an mobile robot to reach the target along trajectory with obstacle avoidance. Simulation and comparison studies are performed in this section to validate the effectiveness and efficiency of proposed autonomous robot navigation algorithms. In this section, the proposed map-building and robot navigation model is compared with the D*-Lite based model ([20] [21]) by simulations on Player/Stage platform. The workspace is decomposed into cells. A hybrid navigation model with Distance Transform Path Planner as the global path planner and Potential Field navigation method as the local navigator is proposed ([10]) to take advantage of both features. For comparison purpose, the workspace in their model is utilized to run our model illustrated in Figure 4, populated three obstacles in the unknown environment. If applying D*-Lite methodology and M-VFH, the simulation result is illustrated in Figure 5. The starting point is at **S** (0.5,0.5) and the target is at **F** (8.5, 4.5). The planned trajectory is shown in Figure 5(A) and the built maps in various stages dynamically built locally by LIDAR-based mapping model are imaged in Figures 5(B), and (C). Finally, the robot reaches the target at **F** (8.5, 4.5), whose map is imaged in Figure 5(D).

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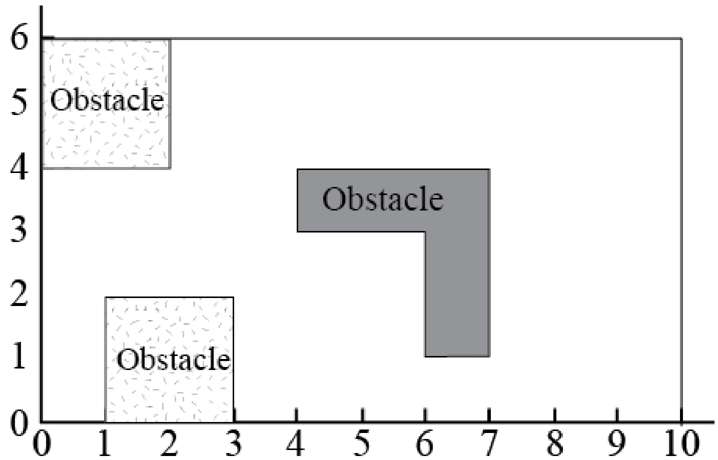

Figure 4 The illustration of robot navigation workspace ([10])

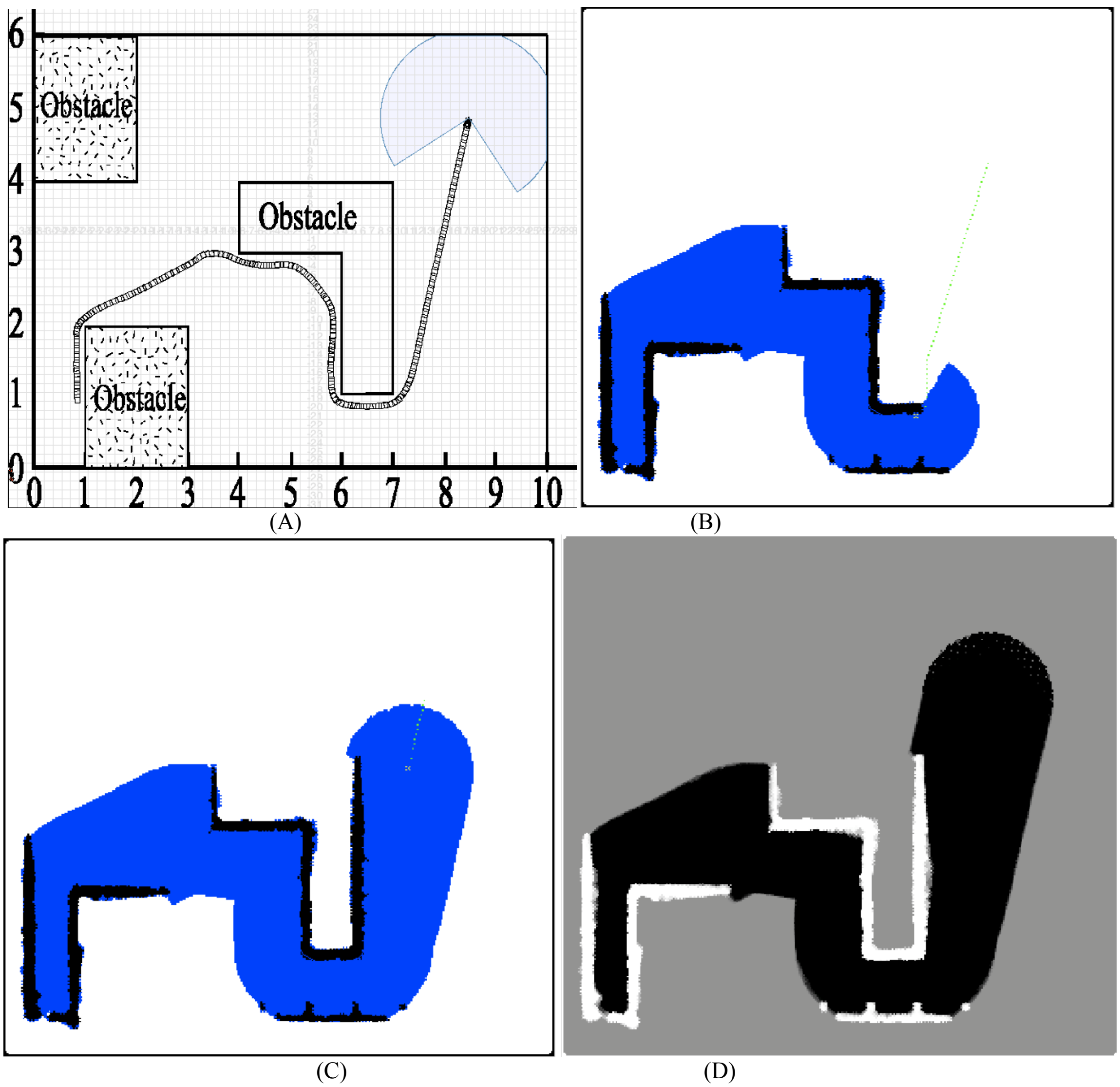

Figure 5 The simulation results of planned trajectory and built map by D*-Lite model

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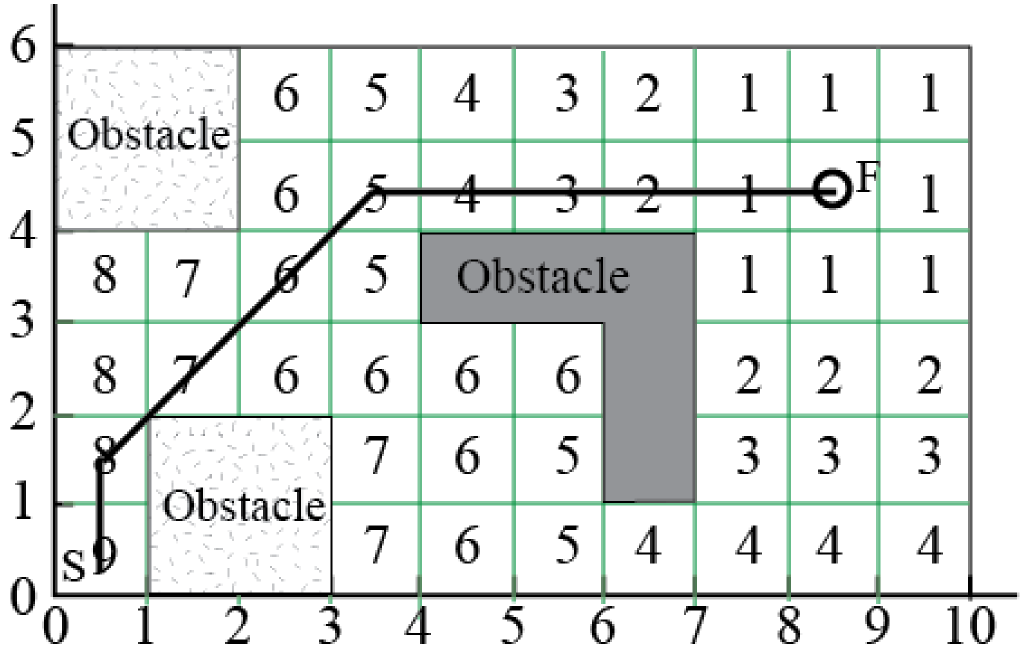

Figure 6 The planned trajectory by the wave-front based global path planner

The proposed wave-front in association of M-VFH model is applied in the identical environment as mentioned above. The planned trajectory by the wave-front global path planner is illustrated in Figure 6, in which the environment is decomposed into cells filled out numbers by the wave-front based algorithm. Once the trajectory is planned globally, traces are marked to assist in the LIDAR-based local navigator to send commands to control the robot reach each trace point. The traces are represented in X-type dotes shown in Figure 7.

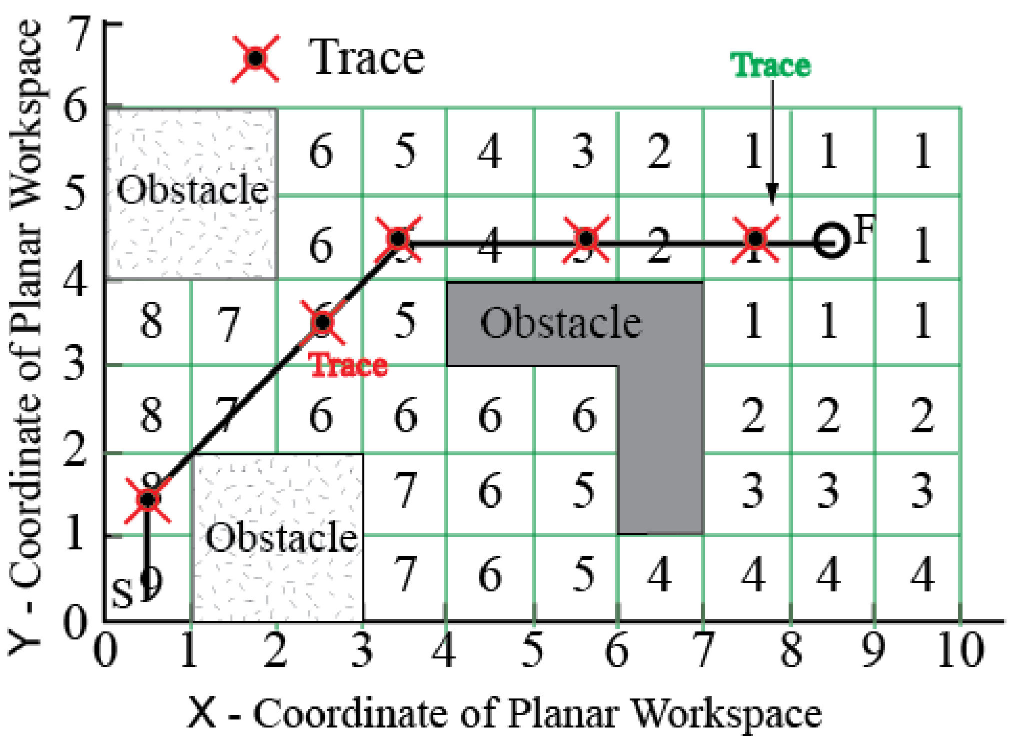

Figure 7 The planned trajectory by the wave-front based global path planner with marked traces

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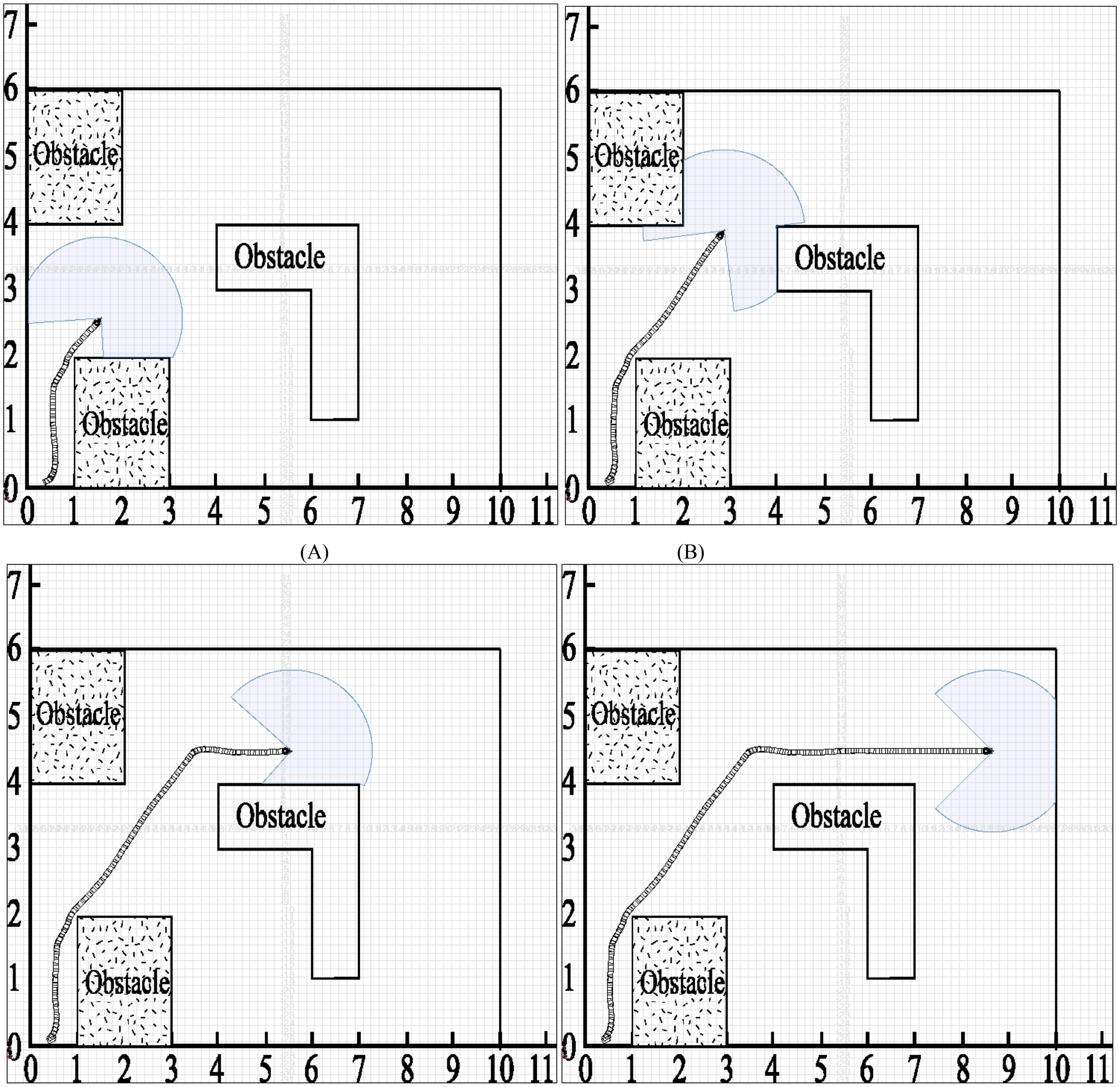

(A) (B) (C) (D)

Figure 8 The simulation results of planned trajectory by the proposed model

In Figure 8, the motion of the mobile robot driven the proposed model is depicted, in which the robot starts from the initial point **S** (0.5,0.5). After the global trajectory is acquired, the robot is driven by the LIDAR-based local navigator by following the traces. Finally, the robot reaches the goal **F** (8.5, 4.5) in Figure 8(D). The built maps in several phases are imaged in Figure 9.

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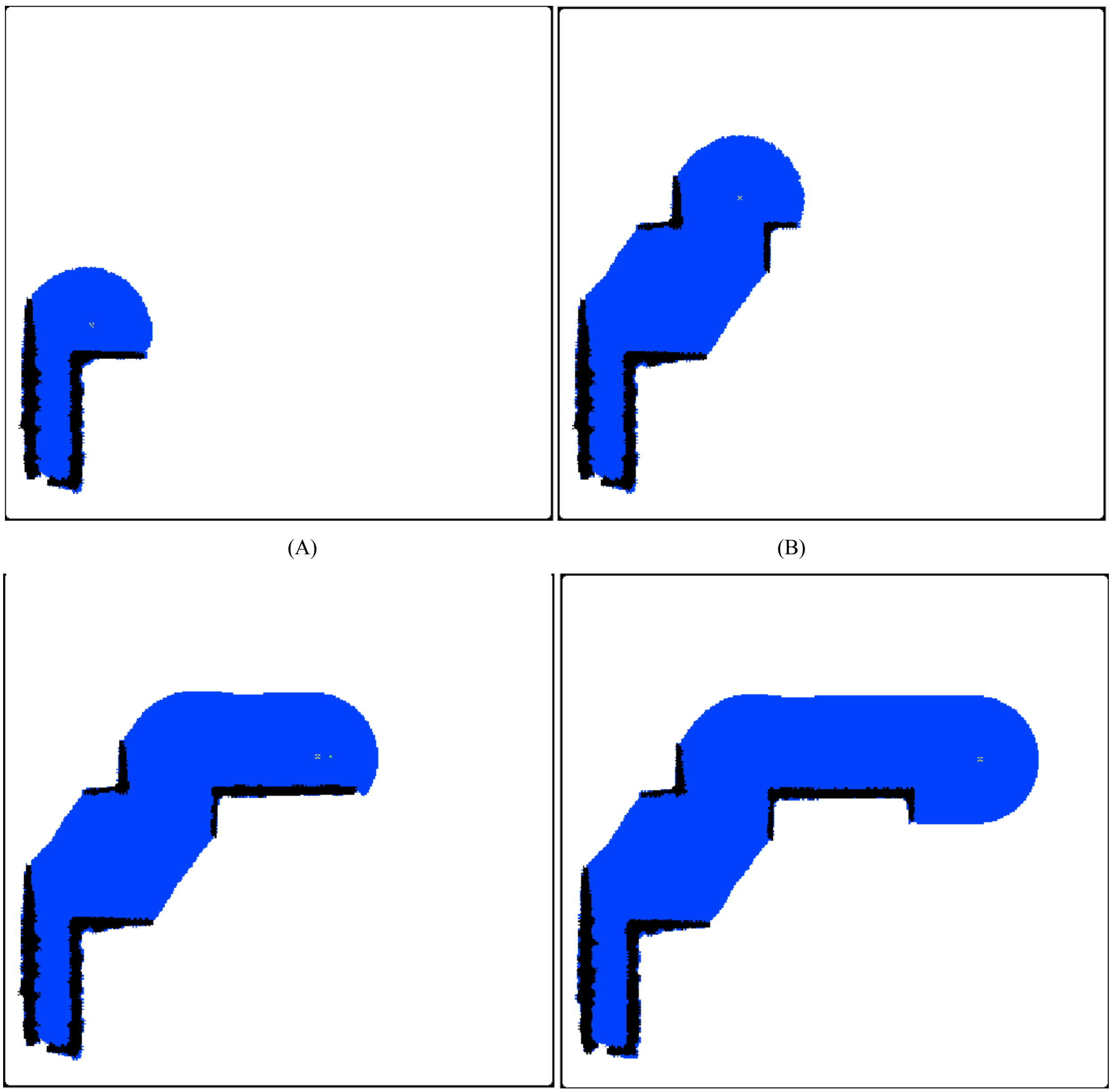
5. CONCLUSION

In this paper, the real-time wave-front based navigation and map building methodology has been successfully demonstrated in a Player/Stage simulation environment. With the wave-front based global path planner and M-VFH local navigator, a safe, short, and reasonable trajectory is successfully planned in a majority of situations without any templates, without explicitly optimizing any global cost functions, and without any learning procedures. Its effectiveness, feasibility, efficiency and simplicity of the proposed real-time navigation and map building for an autonomous mobile robot were successfully validated by simulation, comparison studies and experiments. Comparison studies of the proposed approach with the other path planning approaches demonstrate that the proposed method is capable of planning more reasonable and shorter collision-free trajectories autonomously.



(A) (B)

(C) (D)

Figure 9 The built map by the proposed model

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