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Boundary Aware Navigation and Mapping for a Mobile Automaton

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***Abstract*—When autonomous mobile robots explore unknown terrain, map building is required for the vehicles to effectively and efficiently search the workspace with obstacle avoidance. In this paper, a boundary aware methodology is proposed for real-time autonomous robot navigation and mapping under unknown environments. An initial global trajectory is first created based on a re-planning technique before a LIDAR-based boundary aware local navigation approach is utilized to guide the robot locally with obstacle avoidance while building up its local map. Its effectiveness and efficiency of real-time simultaneous navigation and mapping for an autonomous robot were successfully validated by simulation and comparison studies.**

***Index Terms*—Global re-planning, boundary aware navigation path planning, Vector Field Histogram (VFH), local navigator, autonomous mobile robots.**

I. INTRODUCTION

Real-time navigation and mapping is an essential requirement for autonomous robots in plenty of robotic applications. As a result, real-time simultaneous map building and robot navigation are desirable for efficient performance in many robotics applications. In some real world applications, environmental information has evolved into a complex form. The basic navigation problem for autonomous robots is concerned with finding a safe and good-quality collision-free path from an initial point to a destination while a local map is constructed. Real-time navigation and map building is a challenging task for autonomous robot, especially in unknown cluttered and dynamical environments.

There have been a number of studies on navigation and map ([1-4]) under unknown environments. Lumelski and Stepanov ([1]) proposed a Bug-type algorithm for dynamic path planning in a workspace filled with irregular shape obstacles of a mobile robot. However, the computational effort is high with their algorithms to implement collision-free robot navigation. N. Buniyamin *et al.* [2] improved Lumelski and Stepanov's Bug algorithms by a point-to-point sensor technique. The robot is navigated by range scanning of the sensor locally.

Nakhaei Nia *et. al.* [3] successfully developed a hybrid intelligent system integrating fuzzy logic (FL), virtual force field (VFF), and boundary following (BF) for collision-free motion planning of an intelligent mobile robot under unknown environments. The functional and computational efforts of the design and integration of three modules have been taken. Their navigation model has been applied to robot motion planning in some cases such as a large concave, U-shaped, unstructured, maze-like environments ([3]). An autonomous robot is successfully navigated to move from an initial point to a desired target along an estimated trajectory with obstacle avoidance under unknown environments. However, as the system is obtained by integrating three algorithms, their parameters need to be tuned and that is difficult and time-consuming. However, these three papers lack of map building for navigation.

Koenig and M. Likhachev proposed a novel fast re-planning approach for goal-directed navigation in unknown environments, in which a mobile robot with heuristics searches from the goal vertex toward the current vertex of the robot by minimizing reorder the priority queue [4-6]. Borenstein Y. and Koren [7] proposed a local navigation algorithm, the Vector Field Histogram (VFH), which is relatively fast and thus suitable when computational capabilities on a robot are limited. 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 ([7]).

In this paper, a boundary aware approach is integrated with a re-planning based global path planner and a LIDAR-based local navigator to perform simultaneous collision-free navigation and map building of an autonomous robot. The role of the re-planning-based global path planner is to provide the sensor-based local navigator path planner (i.e., potential field, Vector Field Histogram, etc) with the necessary trajectory information for computation, such as obstacle configurations, current robot position, sub-goals if necessary, in addition to performing reactive local navigation algorithm. The local navigator continually creates local map and localization information by processing sensor data such as LIDAR-based data. As the global trajectory is being planned, a boundary-aware module is developed responsible for simultaneously performing local navigation and mapping in order to determine the local path for the robot. In this paper, the effectiveness and efficiency of real-time simultaneous navigation and mapping will be validated by comparing our model with three models described above ([1-3]).

The rest of this paper is organized as follows. The simultaneous map building and robot navigation is described in Section II. In Section III, The simulation and comparison

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studies of the proposed real-time simultaneous map building and collision-free navigation of an autonomous robot in various unknown terrains are addressed. Finally, important properties of the proposed approach are concluded in Section IV.

II. SIMULTANEOUS MAP BUILDING AND ROBOT NAVIGATION

In this section, a global path planner, a LIDAR-based local navigator, mapping for boundary aware navigation will be addressed.

A. Re-planning-based Global Path Planner

In this paper, a re-planning-based global path planner is employed to generate a global trajectory for the robot. The D* path planning algorithm for mobile robots was pioneered by Stentz in ([4]), which is a kind of Dynamic A* algorithm due to its similarity with A* algorithm ([5]). D*Lite algorithm for mobile robots is a successful combiner of A* algorithm, incremental search and heuristic search to plan near-optimal paths in partially known terrain s. D*Lite is algorithmically similar to the successful D* path planner implemented the same behavior but it is more extendable and rapid as it is much simpler to understand ([6]). Therefore, D*Lite and its variants have been extensively applied for autonomous vehicle motion planning ([6][9]). Driven by D*Lite algorithm only, mobile robots have difficulty traversing across sharp corners with obstacles, and traveling in between two obstacles, and trapped in the U-shaped type obstacles. This issue is resolvable if a local Vector Field Histogram (VFH) navigation is involved. In this paper, a D*-Lite algorithm associated with the local VFH navigation methodology is developed and applied for real-time simultaneous map building and path planning of autonomous vehicles in a completely unknown terrain . Local map is dynamically created during exploration with 270° limited LIDAR information. The VFH is capable of considering the dynamics and shape of the robot and processing uncertainty from sensor and modeling errors by a statistical representation of the robot's environment through histogram grid. A path from a starting point to the goal is created by D*-Lite algorithm, in which the path is dynamically marked by *markers*. With the exploration of a terrain by the vehicle, a map is dynamically generated and trajectories are planned dynamically.

B. LIDAR-based Local Navigator

A reactive local navigation algorithm commonly used in mobile robotics is the Vector Field Histogram (VFH). 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. One way to mitigate the above problem is to generate a more global path with intermediate targets and obstacle memory. Therefore, in this research, it aims to consider the incorporation of the D*Lite algorithm to address these needs.

Khatib proposed the concept of artificial potential fields that can be applied for path planning of mobile robots with real-time obstacle avoidance ([9]). The concept of certainty grids for sensor fusion and sensor data accumulation with an extensively accepted map representation was first developed by Moravec and Elfes ([10]). Borenstein and Koren developed the Virtual Force Field (VFF) method by integrating the concept of potential fields with certainty grids ([7]). The VFF model is capable of planning continuous, smooth and rapid trajectory for mobile robots with unforeseen-obstacle avoidance. Navigated by VFF model, mobile robots travel more rapidly and stably ([10]). However, VFF is likely to get trapped in local minima. 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 ([9][10]).

In this paper, this polar histogram is divided into 54 sectors as every sector is 5° and the LIDAR has a range of 270°. The obstacles are enlarged to further eliminate the chance of the robot hitting any obstacles and to provide smoother motion for the vehicle. This creates a smoother path for the robot and reduces navigation time. The best sector to go through is then used to guide the vehicle based on a weighted formula that combines deviation from desired direction and associated obstacle densities. Once a path from D* Lite has been obtained, a number of points along it are extracted so as to use the VFH algorithm. These points are converted into GPS coordinates and presented to VFH as consecutive goals. 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. One would normally re-plan the path if an unknown obstacle presented itself.

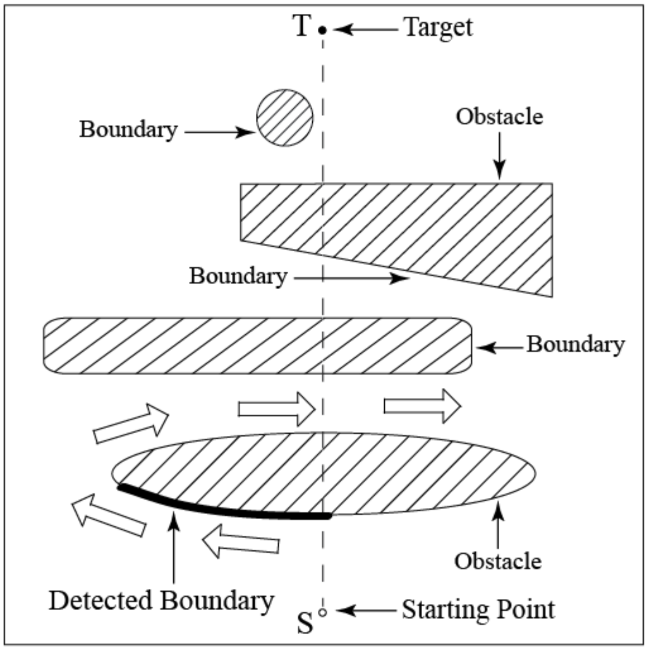


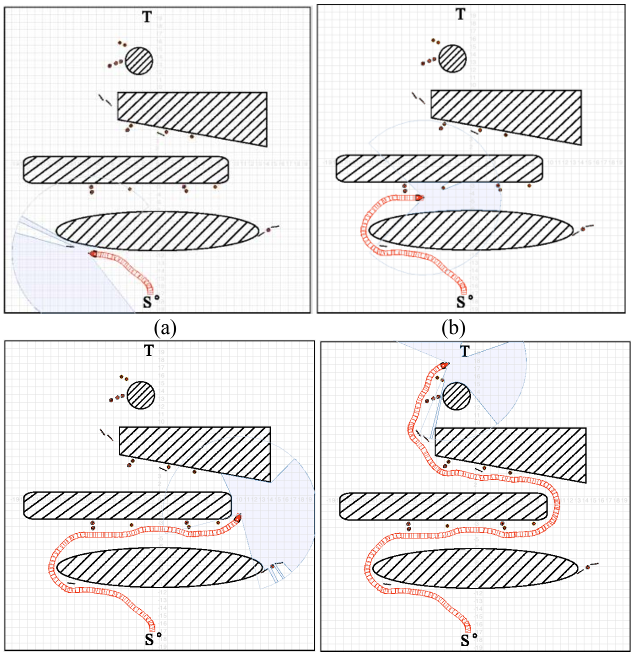
Fig. 1. Boundary aware navigation of a mobile robot

C. Boundary Aware Navigation and Mapping

Map building is an important capability for autonomous robots that facilitates good decision making. It is particularly beneficial in the navigation and mapping, since it enables the use of path planning algorithms to determine the optimal route between waypoints. The ability to maintain a global map is used to enable the robot to partially retrace its path when it senses it is in a trap. Map building requires an accurate estimate of the robot pose so that precise registration of the local map on the global map can be carried out. A Kalman Filter was implemented to estimate vehicle pose reliably by fusing data from the motor encoders, the DGPS, and the digital compass.

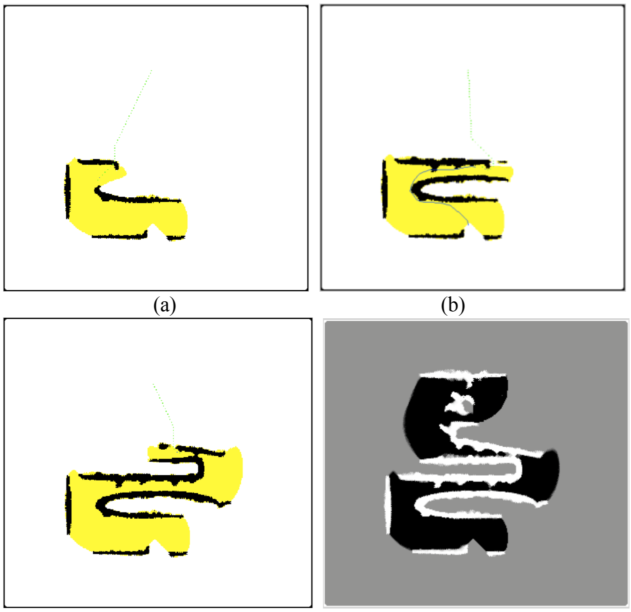
Given a set of waypoints and starting points, a matching lookup table for waypoint sequencing is created. The D*Lite algorithm then provides an initial path marked by breadcrumbs between pairs of waypoints, and the VFH navigation algorithm drives the robot according to those breadcrumbs. Path planning is carried out using the D*Lite algorithm, which provides the best route between waypoints. D*Lite can progressively re-plans the optimal route when the map is augmented with new information as the robot explores. Our program prints out these breadcrumbs, which update continuously according to the movement of the robot. The robot local navigation is carried out using the VFH algorithm. D*Lite associated with VFH algorithm and breadcrumb technique generate an efficient optimal path through a map building, in which the map is represented as a weighted graph. A path from a starting point to the goal is created by the D*-Lite path planning algorithm and delineated by strategically placed breadcrumbs. As the robot explores unknown terrain, a local map is dynamically generated while the global map is augmented. The boundary aware navigation is inspired by the Bug algorithm ([1]) but it differs from the latter in the sense that boundary aware approach is local algorithm by means of the local LIDAR sensor to detect the boundary for collision-free navigation. The workspace filled with four irregular obstacles with ***S*** as the starting point and ***T*** as the target of an autonomous robot is illustrated in Figure 1. The bold black lines in the elliptic obstacle represent the detected boundary of obstacles by 270° limited LIDAR sensor. The essential idea of the boundary aware algorithm is to detect the edge of obstacles by LIDAR sensor and follow the boundary of them while navigating the robot by the VFH local navigation. The broad arrows in Figure 1 illustrate the direction of the robot following the boundary of obstacles toward the target.

In order to describe the real-time boundary aware navigation and mapping, a simulation is performed in the workspace with some barrels in Figure1. Given a set of waypoints and starting points, a matching lookup table for waypoint sequencing is created. The D*Lite algorithm then provides an initial path marked by markers. In the workspace shown in Figure 1, there are some barrels placed beside circle-shaped, unstructured and elliptic obstacles. The mobile robot moves from starting point ***S*** towards the target illustrated in Figure 2(a). The LIDAR mounted on the robot has capability to detect the edge of the obstacle thus the robot is able to move following the boundary of the obstacles shown in Figure 2(b) and Figure 2(c). Finally, the robot reaches the Target ***T*** by planning a smooth collision-free trajectory shown in Figure 2(d). Accordingly, the generated maps in various stages are illustrated in Figure 3. The robot only detects partial boundaries of obstacles in Figure 3(a) while it is in the early stage. The map is built while the robot is navigated by the hybrid navigation methodology shown in Figures 3(b) and 3(c). Finally, the entire map is constructed when the robot researches the target illustrated in Figure 3(d).



(a) (b) (c) (d)

Fig. 2. Illustration of boundary aware navigation of a mobile robot



(a) (b) (c) (d)

Fig. 3. Illustration of boundary aware based mapping of a mobile robot

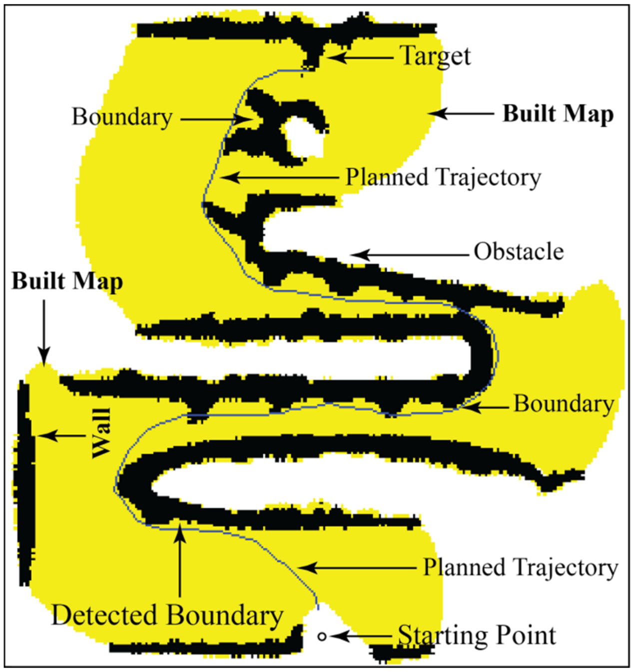


Fig. 4. Illustration of boundary aware based navigation and mapping of a mobile robot

While the robot is navigated by the proposed trajectory planning strategy, the entire map is built up shown in Figure 4, in which the detected boundaries, built map, detected wall, obstacles and planned trajectory are indicated

III. SIMULATION AND COMPARISON STUDIES

In this section, the proposed two-level navigation and mapping model is simulated in comparison of other methodologies. The proposed model is first utilized to compare with Bug algorithm ([1], [2]).

A. Comparison with Bug Algorithms

For comparison purpose, the mobile robot navigated by the proposed model traverses in the same double bug-shaped environment as Lumelski and Stepanov's model ([2]). The original workspace with bug-shaped obstacles simulated by Lumelski and Stepanov is illustrated in Figure 5 ([1]). The mobile robot is capable of planning a more reasonable and much shorter trajectory from the initial position to the goal shown in Figure 6.

The mobile robot driven by the D*Lite and VFH algorithms plans a shorter and more reasonable trajectory than Bug algorithm [1]. Figures 6(a), 6(b) and 6(c) illustrate various phases as the mobile robot traverses in the same environment filled with two bug-type obstacles. Figure 6(d) indicates that the robot reaches the target after it generates a boundary-following collision-free route. Correspondingly, generated local maps are illustrated in Figure 7. Breadcrumbs generated by the D*Lite algorithm are marked by the green points in Figures 7(a) and 7(b) (phase 1 and phase 2). As unknown terrain is explored by the intelligent robot, a new map is dynamically built up and breadcrumbs are dynamically created by the D*Lite. The collision-free trajectory from the initial point ***S*** to the target ***T*** is planned by the proposed model illustrated in Figure 6(d) while the autonomous robot dynamically constructs the map driven by the hybrid boundary-aware VFH local navigation and D*-Lite re-planning path planning methodology. Figure 7(a) depicts the initial phase of the robot, in which only a segment of the bug-shapes obstacle is detected thus partial map is constructed and more map is built in Figures 7(b) and 7(c). The final map is fulfilled when the robot reaches the Target in Figure 7(d).

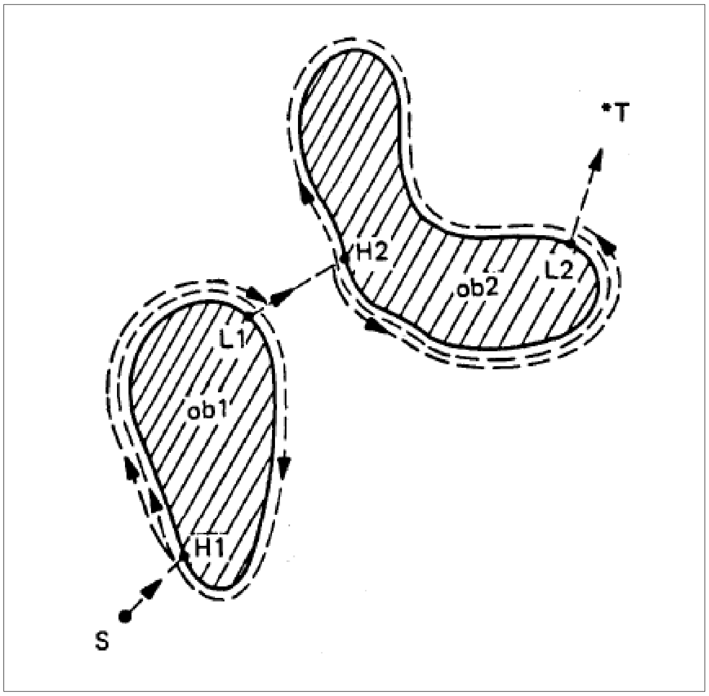


Fig. 5. Path planning example by Bug algorithm (from [1]

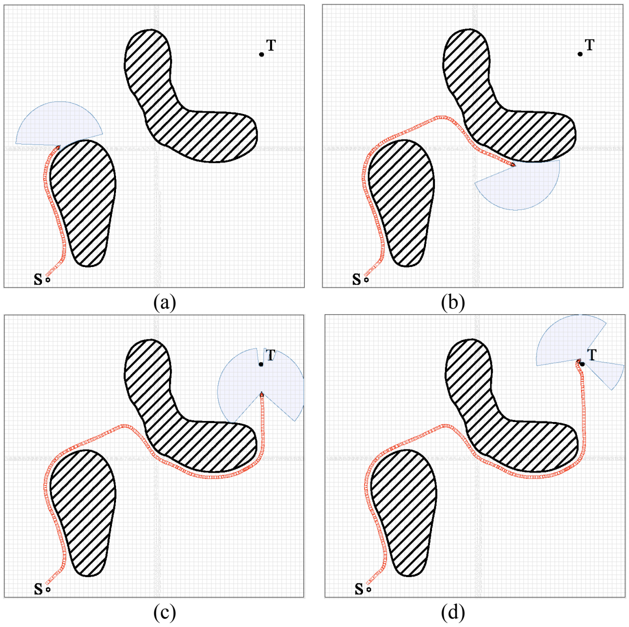


Fig. 6. Simulation of boundary aware based navigation of a mobile robot with bug-shaped obstacles

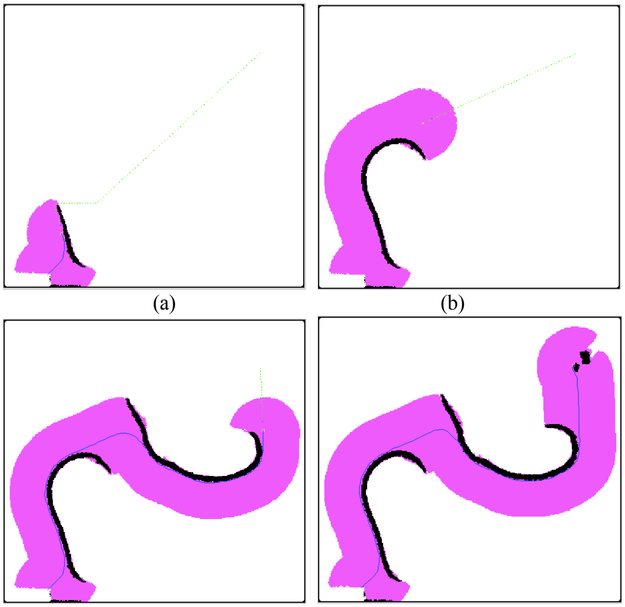

(a) (b)
(c) (d)

Fig. 7. Illustration of boundary aware based mapping of a mobile robot with bug-shaped obstacles

B. Comparison with Bug Algorithms

The proposed model is then simulated in comparison of a point-to-point sensor-based bug technique, in which there are multiple obstacles under unknown terrain [2]. Recall that Buniyamin *et al* proposed a point-to-point sensor-based bug methodology for unknown terrain robot path planning [2]. However, the main drawback of their method is that the developed navigation technique causes longer trajectory. The property of the point-to-point sensor-based bug approach increases many inevitable unreasonable trajectories. The navigation driven by their model depends *excessively* on the information of sensors thus it causes low failure tolerance.

The simulation result of the sensor-based bug model developed by Buniyamin *et al* for a mobile robot is shown in Figure 8 ([2]). For comparison purpose, our proposed model is utilized to navigate the mobile robot to move in this same unknown terrain, where there are four circle-shaped obstacles and one rectangular-shaped obstacle. The autonomous robot initiates from the starting point ***S*** in Figure 9 to search the target. The autonomous mobile robot is capable of planning a more reasonable and much shorter collision-free route shown in Figures 10, and 11 compared with the result in [2].

The simulation result of a multi-obstacle case by the proposed model close to the goal is illustrated in Figure 11. Figure 12 illustrates the built map in different stages as the mobile robot traverses in the unknown terrain. In Figure 12, white color areas indicate explored obstacles whereas the black areas represent map scanned by the 270° LIDAR sensor. The local map is dynamically built up until the robot traverses to the target, when the global map is formed.

Obviously, in their simulation, the robot traverses a path with a greater length than ours to cover a given workspace simulated in this section.

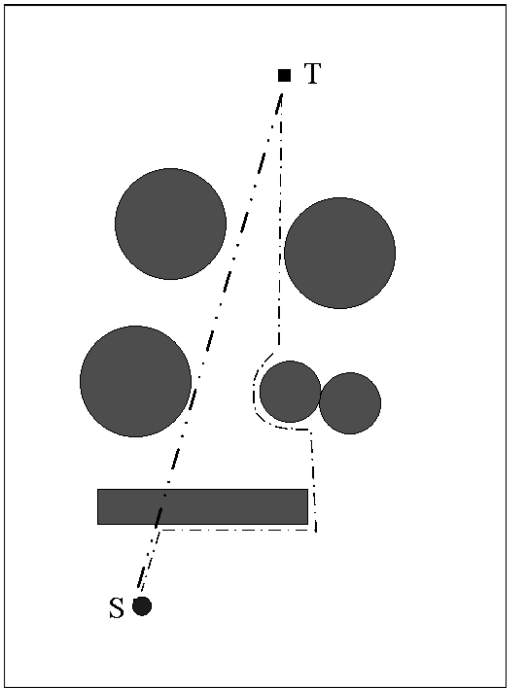


Fig. 8. Robot navigation by sensor-based point-to-point algorithm (from [2])

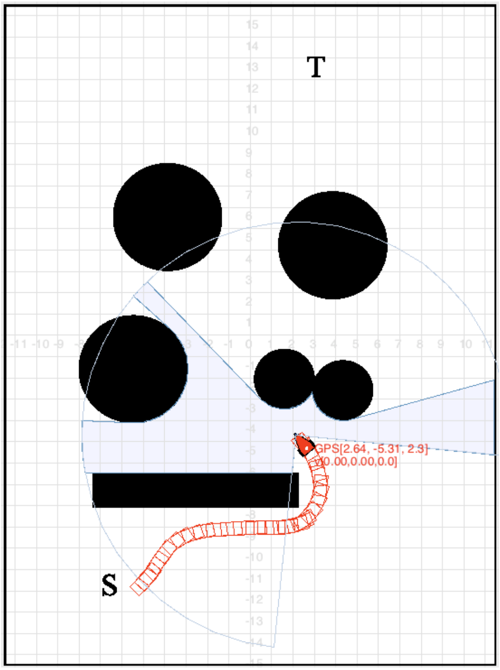


Fig. 9. Simulation of the robot navigation driven by our hybrid model in initial phase

IV. CONCLUSION

In this paper, real-time simultaneous boundary-aware-based mapping and navigation was developed for an autonomous mobile robot collision-free navigation by combining D*-Lite algorithm and a boundary-aware-based local VFH navigation in a completely unknown terrain. A grid-based local map was dynamically created during exploration based on use of a 270° LIDAR sensor and integrated into a global map. An initial global trajectory was first generated by means of a re-planning technique before a LIDAR-based boundary aware local navigation approach was utilized to guide the robot locally with obstacle avoidance while building up its local map. Simulation and comparison studies were performed to successfully validate its effectiveness and efficiency of real-time simultaneous navigation and mapping for an autonomous robot under ***unknown*** terrains.

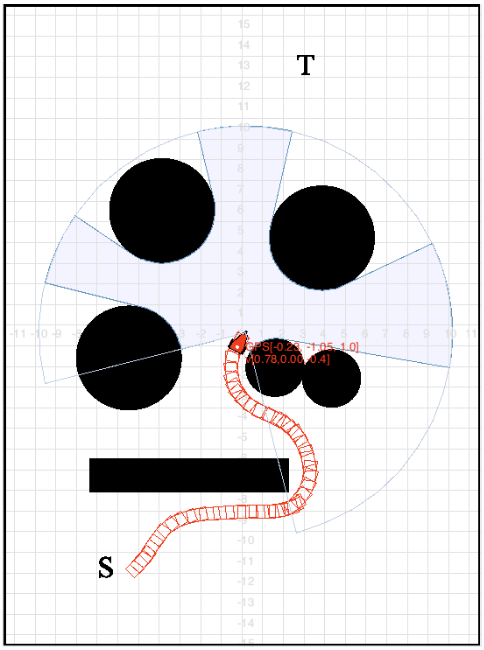


Fig. 10. Simulation of the robot navigation driven by our hybrid model

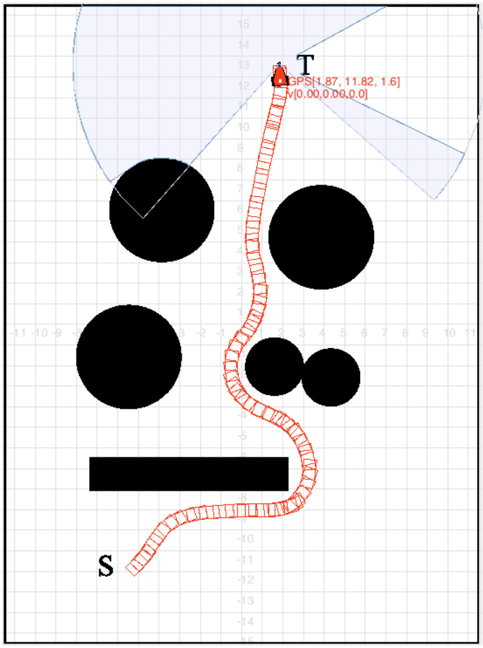


Fig. 11. Simulation of the robot navigation driven by our hybrid model

Fig. 12. The built map of the robot driven by our hybrid model

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