AUTONOMOUS VEHICLE NAVIGATION AND MAPPING WITH LOCAL MINIMA AVOIDANCE PARADIGM IN UNKNOWN ENVIRONMENTS

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ABSTRACT—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. One of the attendant disadvantages of this algorithm is that a robot can get trapped when attempting to get past a concave obstacle structure. The Navigation Challenge course now has several such structures, including some that partially surround waypoints. Elaborate heuristics are needed to make VFH viable in such a situation and their tuning is arduous. An alternate approach that avoids the use of heuristics is to combine a dynamic path planning algorithm with VFH. In this paper, the D*Lite path planning algorithm is used to provide VFH with intermediate goals, which the latter then uses as stepping stones to its final destination. Results from simulation studies as well as field deployment are used to illustrate the benefits of using the local navigator in conjunction with a path planner.

Key Words: D*Lite, Vector Field Histogram (VFH), path planning, navigation, breadcrumbs, intelligent mobile robots, local minima, unknown environments

1. INTRODUCTION

When robots work in unknown environments, map building is required for the vehicles to effectively and efficiently explore the workspace with obstacle avoidance. Path planning is an essential requirement for intelligent robots in many robotic applications. Consequently, real-time concurrent map building and vehicle path planning are desirable for efficient performance in many robotics applications. In some real world applications, environment course has evolved into a complex form, in which there are several concave obstacle, barrels, etc. 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.

There have been some studies on map building and navigation [1-3] under unknown environments. Wang and Liu successfully proposed a fuzzy-logic-based approach to implement the behavior design and coordination for map building and navigation under unknown environments [1]. Their navigation model has been applied to robot motion planning in some cases such as a large concave, U-shaped, unstructured, maze-like environments. A hybrid intelligent system integrating Genetic Algorithms (GA), Fuzzy Logic (FL), Neural Networks (NN) and Expert Systems (ES) for collision-free motion planning of intelligent vehicles under unknown environments is developed by Hachour [2]. An intelligent 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 four algorithms, their parameters need to be tuned and that is difficult and time-consuming. Chiang et al. developed a hybrid method called Boundary Following Fast Marching Method (BFFMM) for path planning in an unknown environment by utilizing local sensory perceptions only [3]. In this paper, we will compare our model with these three models [1-3].

D*Lite is an efficient path planning algorithm that handles navigation through unknown terrain and accommodates dynamic obstacle discovery as the robot moves and scans new areas. When the map changes through discovery of a new feature, it modifies the existing path to accommodate the discovery rather than finding a new path from scratch. D*Lite also requires the maintenance of a map, which acquires greater definition as the robot moves, thus facilitating improved motion planning. It is important to note that while D*Lite, a graph theory-based algorithm, is much more computationally efficient than its predecessor, the Dijkstra algorithm; it still imposes a serious computational burden, particularly in the context of real time implementation on fast-moving robots. An alternate approach that avoids the use of heuristics is to combine a dynamic path planning algorithm with VFH. In this paper, the D*Lite path planning algorithm is used to provide VFH with intermediate goals, which the latter then uses as stepping stones to its final destination. Results from simulation studies as well as field deployment are used to illustrate the benefits of using the local navigator in conjunction with a path planner.

This paper discusses the introduction of D*Lite-based path planning to enhance the performance of the VFH algorithm while navigating a complex course with features that have the potential of trapping the robot. Comprehensive results from simulation studies as well as field deployment on an actual robot will be presented and discussed.

2. D*LITE PATH PLANNER

The D* path planning algorithm for mobile robots was pioneered by Stentz in [9], which is a kind of Dynamic A* algorithm due to its similarity with A* algorithm [10]. 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 environments. 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 [11]. Therefore, D*Lite and its variants have been extensively applied for autonomous vehicle motion planning [8][11].

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 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 concurrent map building and path planning of autonomous vehicles in a completely
unknown environment. 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 bread-crumbs. With the exploration of a terrain by the vehicle, a map is dynamically generated and trajectories are planned dynamically.

![Diagram](image)

**Figure 1. Software development environment on Player/Stage**

### 3. VECTOR FIELD HISTOGRAM (VFH) ALGORITHMS

A commonly used reactive local navigation algorithm is the Vector Field Histogram (VFH) and its enhancements. The VFH algorithm outputs a preferred target sector for the robot to move towards based on the concept of a polar obstacle density histogram constructed from the obstacle field in front of the robot. This decision is generated based on the current data; that is, the base algorithm has no memory of decisions made previously. 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.

Khatib proposed the concept of artificial potential fields that can be applied for path planning of mobile robots with real-time obstacle avoidance [5]. 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 [6]. Borenstein and Koren developed the Virtual Force Field (VFF) method by integrating the concept of potential fields with certainty grids [4]. The VFF model is capable of planning continuous, smooth and rapid trajectory for mobile robots with unforeseen-obstacle avoidance [11]. Navigated by VFF model, mobile robots travel more rapidly and stably [5]. 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 [7].
The robot navigation is carried out using a modified version of VFH+ algorithm in this work as the local navigation tool, which utilizes a four-stage data reduction technique to calculate the new direction of motion [12]. To avoid obstacles, the VFH+ is utilized as a local reactive navigation algorithm based directly on the sensor data (LIDAR, SONAR, GPS, etc.) [11]. 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.

4. CONCURRENT MAP BUILDING AND VEHICLE MOTION PLANNING

4.1 Autonomous Vehicle Navigation by D*Lite and VFH

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. In this challenge obstacle grouping is not incorporated, as the challenge does not necessitate tight maneuvers, rather it requires smooth driving and careful path planning. 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.

4.2 Map Building

Map building is an important capability for autonomous robots that facilitates good decision making. It is particularly beneficial in the Navigation Challenge, 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 “considers” it is in a trap. Map building requires an accurate estimate of the robot pose (X, Y, Yaw) 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.

5. SIMULATION AND EXPERIMENTAL RESULTS

The proposed model is capable of planning a reasonable path for intelligent robots autonomously without any human intervention. In this section, to verify the capabilities of the
proposed model, simulation studies and comparison studies were performed that are completed on a software platform, Player™/Stage, in which our algorithms are developed, debugged, tested and simulated. Some simulation studies in U-shaped, unstructured and multi-obstacle outdoor environments have been accomplished in this paper. Comparison studies on the Player/Stage platform demonstrate that the proposed method is capable of planning more reasonable, less cost and shorter collision-free paths in unknown environments.

5.1 Simulation and Comparison Studies

As stated previously, the software development environment was based on Player/Stag; the features and merits of this choice have been discussed. Stage provides a powerful simulation environment that can be used to develop and test algorithms in environments similar to those expected in actual competition. A substantial benefit accrues from the use of such a simulation system - the team can construct highly complex course scenarios, test and assess the performance of algorithms, and make necessary corrections much faster than with the actual vehicle. The simulation result is shown in Figure 2.

![Simulation result of vehicle navigation by D*Lite and VFH algorithms](image)

Figure 2. Simulation result of vehicle navigation by D*Lite and VFH algorithms

The proposed model is applied to a U-shaped case, in which there are two U-shaped obstacles [1]. The simulation result of a U-shaped case by fuzzy logic-based model for a mobile robot is shown in Figure 3 [1]. For comparison purpose, the mobile robot navigated by the proposed model traverses in the same double U-shaped environment. The mobile robot is able to plan a more reasonable and much shorter trajectory from the initial position to the goal shown in Figure 4. The mobile robot driven by the D*Lite and VFH algorithms was not trapped in the dead ends. Figures 4A and 4B show different phases as the mobile robot moves. Breadcrumbs generated by the D*lite algorithm are marked by the white points in Figures 4A and 4B (phase 1 and phase 2). As unknown terrain is explored by the intelligent vehicle, a new map is dynamically built up and breadcrumbs are dynamically created by the D*Lite. Finally, the collision-free route from the initial point inside U-shaped wall to the goal outside wall is planned by the proposed model that is illustrated in Figure 4C.

The proposed model is then applied to a multi-obstacle case, in which there are multiple obstacles under unknown environment [2]. The simulation result of the multi-obstacle case by a hybrid intelligent system model developed by Hachour for a mobile robot is shown in Figure 5A [2]. For comparison purpose, our proposed model is utilized to navigate the mobile robot to move in this multi-obstacle environment. From the simulation result, we find that the mobile robot is capable of planning a more reasonable and much shorter collision-free route shown in Figures 5B and 5C that illustrate the built map and planned trajectory in different stages as the mobile robot traverses in the unknown environment. Breadcrumbs created by the D*Lite algorithm are marked
by the white points in Figures 5B and 5C. The built map with simulation result of a multi-obstacle case by the proposed model close to the goal is illustrated in Figure 5D.

![Figure 3. Simulation result of a U-shaped case by fuzzy logic-based model (from Wang and Liu, 2008 [1])](image)

**Figure 3. Simulation result of a U-shaped case by fuzzy logic-based model (from Wang and Liu, 2008 [1])**

![A](image) ![B](image) ![C](image)

**Figure 4. Simulation result of a U-shaped case by the proposed model: A: phase 1; B: phase 2; C: phase 3**

A fast marching method (FMM) for mobile robot path planning is introduced by Chiang et. al [3]. The trajectory planned by the mobile robot with FMM model in a structured room-like environment is illustrated in Figure 6A. The simulation of motion planning on the same environment by the proposed model is performed to compare with the FMM model. Through observation, the trajectory planned by the D*Lite associated with the VFH algorithm is more reasonable than that implemented by the FMM model illustrated in Figures 6B and 6C, in which the breadcrumbs created by the D*Lite algorithm are represented by white dashed lines depicted in Figures 6B and 6C updated as unknown areas are explored by the mobile robot. Blue solid lines display the actual trajectories of the mobile robot in Figures 6C and 6D. The trajectory planned by the proposed model is more reasonable than the route created by the FMM model [3].
Figure 5. Simulation result of a multi-obstacle case by a hybrid intelligent system model. A: The result by Hachour’s model (from [2]); B: The result by the proposed model, phase 1; C: The result by the proposed model, phase 2; D: The result by the proposed model, phase 3

5.2 Experiments

With our proposed model, such a mobile robot shown in Figure 7A can successfully navigate in a complicated unknown environment containing semicircle, barrels, and fence etc. The experiments by an actual vehicle validated that the proposed model can successfully navigate the mobile robot in the complicated environment of (see Figure 7B). The fact that our robot navigation algorithm is successfully simulated and tested on actual complicated courses is a great example of how the proposed D*Lite algorithm, local VFH and breadcrumb technique are efficient and robust.

6. CONCLUSION

In this paper, the D*-Lite algorithm associated with local VFH navigation methodology was developed and applied for real-time concurrent map building and motion planning of autonomous vehicles in a completely unknown environment, which is an effective strategy to avoid traps, as well as to utilize known information to generate the most optimal paths. A grid-based local map was dynamically created during exploration based on use of a 270 degree LIDAR sensor and integrated into a global map. Results from simulation studies as well as field deployment were used to illustrate the benefits of using the local navigator in conjunction with a path planner.
Simulation studies involving U-shaped, unstructured and multi-obstacle environments have been accomplished. Comparison studies on the Player/Stage simulation platform demonstrate that the proposed method is capable of planning more efficient collision-free paths in unknown environments.

![Simulation of motion planning under the structured environment](image)

**Figure 6. Simulation of motion planning under the structured environment**

- A: by FMM model (from [3]); B: by the proposed model (phase 1);
- C: by the proposed model (phase 2); D: by the proposed model (last phase)

**REFERENCES**

Figure 7. The intelligent vehicle utilized to implement the proposed navigation algorithm and its environment. A: The intelligent vehicle; B: The unknown workspace


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