Obstacle Avoidance and Path Planning Schemes for Autonomous Navigation of a Mobile Robot: A Review

J. A. Oroko and G. N. Nyakoe

Abstract—Autonomous navigation of a mobile robot involves self-steering of a robot from one place to another based on computational resources on-board the robot. There are many different ways to approach mobile robot navigation, with path planning and obstacle avoidance playing a key role. This paper discusses three methods used in obstacle avoidance and path planning i.e., the Bug algorithms, the Potential Field methods and the Vector Field Histogram method which are all active sensor-based methods. A more robust system for use to achieve autonomous navigation in any environment can be developed by fusing technologies or schemes by taking advantage of the merits of the different systems while limiting their drawbacks.

Keywords—autonomous navigation, mobile robot, obstacle avoidance, path planning.

I. INTRODUCTION

Obstacle avoidance is the process of directing a robot's path to overcome expected or unexpected obstacles. The resulting motion depends on the robot's actual location and on the sensor readings. Given a map and a goal location, path planning involves finding a geometric path from the robot's actual location to the goal [1].

This is a global procedure whose execution performance is strongly dependent on a set of assumptions. However, in mobile robots operating in unstructured environments, a prior knowledge of the environment is usually absent or partial, the environment is not static and execution is often associated with uncertainty [2].

Therefore, for a collision free motion to the goal, the global path planning has to be associated with a local obstacle handling that involves obstacle detection and obstacle avoidance.

II. OBSTACLE AVOIDANCE/PATH PLANNING TECHNIQUES

Three techniques will be reviewed.

A. The Bug algorithms

The Bug algorithms are simple algorithms or ways used to overcome unexpected obstacles in the robot motion from a start point s, to a goal point g [3]. Bug algorithms assume only local knowledge of the environment and a global goal. The goal of the algorithms is to generate a collision free path from s to g with the underlying principle based on contouring the detected obstacles. Bug behaviors are simple e.g. follow a wall (right or left), move in a straight line toward goal.

There are two versions of the algorithm and they differ on the conditions under which the border-following behavior is switched to the go-to-goal behavior [4].

Consider that the robot is a point operating in a plane, moving from s to g, and that it has a contact sensor or a zero range sensor to detect obstacles.

In the Bug 1 algorithm, as soon as an obstacle i is detected, the robot does a full contour around it, starting at the hit point H_i. This full contour aims at evaluating the point of minimum distance to the target, L_i. The robot then continues the contouring motion until reaching that point again, from where it leaves along a straight path to the target. L_i is named as the leave point. This technique is very inefficient but guarantees that the robot will reach any reachable goal. Figure (1) represents a situation with two obstacles where $H1$ and $H2$ are the hit points and $L1$ and $L2$ the leave points [3].

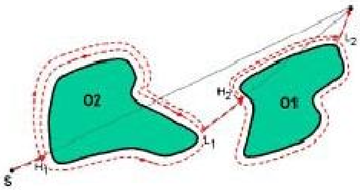

Fig. 1. Obstacle avoidance with Bug 1 algorithm.

In the Bug 2 algorithm, the obstacle contour starts at the hit point H_i but ends whenever the robot crosses the line to the target. This defines the leave point L_i of the obstacle boundary-following behavior. From L_i the robot moves directly to the target. The procedure repeats if more obstacles are detected. Figure (2) represents the path generated by Bug 2 for two obstacles [3].

The Bug algorithms have several merits and demerits.

Merits of the Bug algorithms

- They are simple to implement [4].
- Bug 2 algorithm has a shorter travel time than Bug 1 algorithm and is more efficient especially in open spaces [4].

Drawbacks of the Bug algorithms

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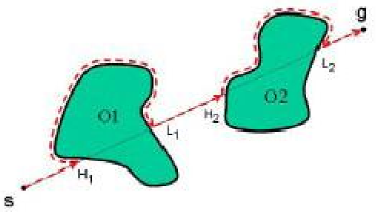

Fig. 2. Obstacle avoidance with Bug 2 algorithm.

- There are situations where the Bug 2 algorithm may become non-optimal. In particular, the robot may be trapped in maze structures [3].
- None of these algorithms take robot kinematics into account which is a severe limitation, especially in the case of non-holonomic robots [3].
- Since only the most recent sensorial data is taken into account, sensor-noise has a large impact in the robot performance [3].

B. Potential Field Methods

Path planning using artificial potential fields is based on a simple and powerful principle, proposed in [5]. The robot is considered as a particle that moves immersed in a potential field generated by the goal and by the obstacles present in the environment. The goal generates an attractive potential while each obstacle generates a repulsive potential.

A potential field can be viewed as an energy field and so its gradient, at each point, is a force. The robot immersed in the potential filed is subject to the action of a force that drives it to the goal (due to the action of the attractive force that results from the gradient of the attractive potential generated by the goal) while keeping it away from the obstacles (due to the action of a repulsive force that is the gradient of the repulsive potential generated by the obstacles) [5].

The robot motion in potential field based methods can be interpreted as the motion of a particle in a gradient vector field generated by positive and negative electric particles [5].

In this analogy, the robot is a positive charge, the goal is a negative charge and the obstacles are sets of positive charges. Gradients in this context can be interpreted as forces that attract the positively charged robot particle to a negative particle that acts as the goal. The obstacles act as positive charges that generate repulsive forces that force the particle robot away from the obstacles. The combination of the attractive force to the goal and the repulsive forces away from the obstacles drive the robot in a safe path to the goal.

Let q represent the position of the robot, considered as a particle moving in an n-dimensional space R^n. For presentation simplicity consider the problem applied to a point robot moving in a plane, i.e., $n = 2$ and that the robot's pose is defined by the tuple $q = (x, y)$.

The artificial potential field where the robot moves is a scalar function $U(q) : R^2 \longrightarrow R$ generated by the superposition of attractive and repulsive potentials

$$U(q) = U_{att}(q) + U_{rep}(q). \qquad (1)$$

The attractive potential

According to the work of [5], the attractive force considered in the Potential Field based approach is the negative gradient of the attractive potential herein calculated as

$$F_{att}(q) = -\nabla U_{att}(q) = -k_{att}(q - q_{goal}) \qquad (2)$$

where $(q - q_{goal})$ is the Euclidean distance of the robot (considered at q), to the goal, at q_{goal} and k_{att} is a scaling factor.

Setting the robot velocity vector proportional to the vector field force, the force (2) drives the robot to the goal with a velocity that decreases when the robot approaches the goal. The force (2) represents a linear dependence towards the goal, which means that it grows with no bound as q moves away from the goal which may determine a fast robot velocity whenever far from the q_{goal}.

When the robot is far away from the goal, this force imposes that it quickly approaches the goal, i.e., that it moves directly to the goal with a high velocity.

On the contrary, the force tends to zero, and so does the robot velocity, when the robot approaches the goal. Therefore the robot approaches the goal slowly which is a useful feature to reduce the overshoot at the goal [6].

Figure (3) represents the attractive potential and the negative gradient force field for a situation where the goal at (10, 10) is represented by a mark.

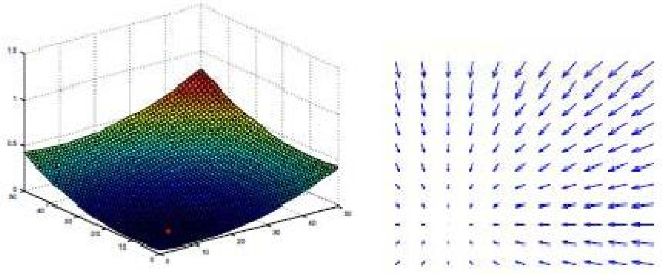

Fig. 3. a) Attractive Potential, b) Attractive Force to the goal.

The Repulsive potential

The repulsive potential keeps the robot away from the obstacles, both those priorly known or those detected by the robot's on-board sensors. This repulsive potential is stronger when the robot is closer to the obstacle and has a decreasing influence when the robot is far away.

Given the linear nature of the problem, the repulsive potential results from the sum of the repulsive effect of all the obstacles, i.e.,

$$U_{rep}(q) = \sum_i U_{rep_i}(q) \qquad (3)$$

The negative of the gradient of the repulsive potential, given by the equation

$$F_{rep_i}(q) = -\nabla U_{rep_i}(q) \tag{4}$$

, is given by,

$$F_{rep_i}(q) = \begin{cases} k_{obst_i}\left(\frac{1}{d_{obst_i}(q)} - \frac{1}{d_0}\right)\frac{1}{d^2_{obst_i}(q)}\frac{q-q_{obst}}{d_{obst_i}} & \text{if } d_{obst_i}(q) \leq d_0 \\ 0 & \text{if } d_{obst_i}(q) \geq d_0 \end{cases} \tag{5}$$

where $d_{obst_i}(q)$ is the minimal distance from q to the obstacle i, k_{obst_i} is a scaling constant and d_0 is the obstacle influence threshold.

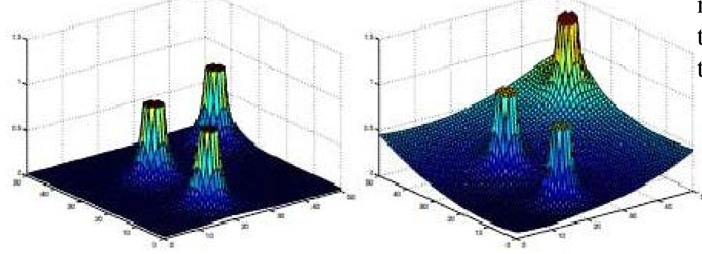

Fig. 4. a) Repulsive Potential, b) Attractive + Respulsive Potential.

For the environment where the goal leads to the attractive potential represented in Figure (3), the repulsive potential for three obstacles and the sum of the attractive and repulsive potentials is plotted in Figure (4).

Taking this example, it is clear that the motion of a point robot to the goal, starting in an arbitrary position, can be viewed as the motion of a frictionless ball that is left at the robot starting point. The ball path is along the largest negative slope to the goal.

The potential field approach is a simple path planning technique based on energy type fields and has several advantages and disadvatages in application [5].

Merits of the potential field methods approach

- For a static and completely known environment, the potential can be evaluated off-line providing the velocity profile to be applied to a point robot moving in the energy field from a starting point to a goal.
- The technique can be applied in an on-line version that accommodates an obstacle avoidance component.

Drawbacks of the potential field approoach

In its simplest version the potential field based methods exhibit many shortcomings, namely [7]:

- The sensitivity to local minima, that usually arises due to the symmetry of the environment and to concave obstacles, and robot oscillatory behavior when traversing narrow spaces.

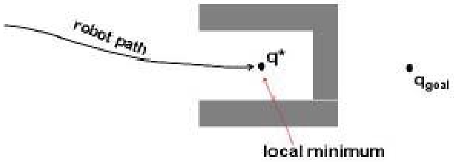

Fig. 5. Local minimum of the total potential due to a concave obstacle.

Figure (5) presents a situation where the robot is attracted by the goal while approaching a concave obstacle. When inside the concave obstacle, it happens that in a particular position, q^*, the attractive force to the goal is symmetric to the repulsive force due to the obstacle surfaces, this leading to a local minimum of $U(q^*)$, i.e.,$\nabla U(q^*) = 0$.

Attraction to local minimum of the potential also arises with non-concave obstacles as represented in Figure (6) where the total repulsive force due to the two obstacles is symmetric to the attractive force due to the goal.

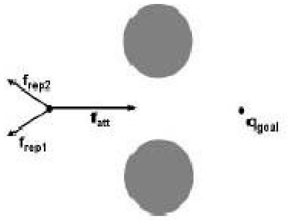

Fig. 6. Local minimum of the total potential due to environment symmetry.

C. The Vector Field Histogram

The Vector Field Histogram (VFH) method is a real-time obstacle avoidance method that permits the detection of unknown obstacles and avoids collisions while simultaneously steering the mobile robot towards the target [2].

The VFH method uses a two-dimensional Cartesian histogram grid as a world model. This world model is updated continuously with range data sampled by on-board range sensors.

The VFH method subsequently employs a two-stage data-reduction process in order to compute the desired control commands for the vehicle.

In the first stage, a constant size subset of the 2D histogram grid considered around the robot's momentary location, is reduced to a one-dimensional polar histogram. Each sector in the polar histogram contains a value representing the polar obstacle density in that direction.

In the second stage, the algorithm selects the most suitable sector from among all polar histogram sectors with a low polar obstacle density, and the steering of the robot is aligned with that direction.

The three main steps of implementation of the VFH method are summarized as [2]:

Step 1 Builds a 2D Cartesian histogram grid of obstacle representation.

Step 2 From the previous 2D histogram grid, considers an active window around the robot, and filters that 2D active grid onto a 1D polar histogram.

Step 3 Calculates the steering angle and the velocity controls from the 1D polar histogram, as a result of an optimization procedure.

Figure(7) [8]illustrates the cells certainty value update along the movement of a robot equipped with ultrasonic sensors. It is clear that, for each range reading, only one cell is updated.

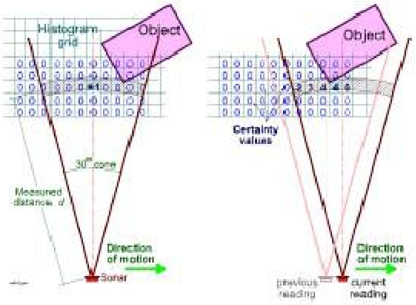

Fig. 7. Construction of the 2D Histogram grid map.Reproduced from [2]

The active grid C^* is mapped onto a $1D$ structure known as a polar histogram, H, that comprises n angular sections each with width α. Figure (8) illustrates the cell occupancy of C^*, the active window around the robot, and represents the angular sectors considered for the evaluation of the $1D$ polar histogram [9]. Figure (9a) represents the 1D polar histogram with obstacle density for a situation where the robot has three obstacles, A, B and C in its close vicinity. In Figure (9b) the previously obtained $1D$ histogram is shown in polar form overlapped with the referred obstacles.

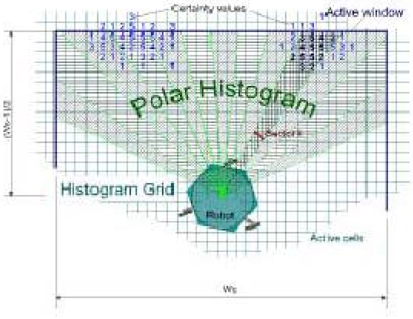

Fig. 8. Mapping of active cells onto the polar histogram. Reproduced from [2].

The Vector Field Histogram overcomes some of the limitations exhibited by the potential field methods [10].

Merits of VFH method

- The influence of bad sensor measurements is minimized because sensorial data is averaged out onto a histogram grid that is further processed.
- Instability in travelling down a corridor, present when using the potential field method, is eliminated because the polar histogram varies only slightly between sonar readings.

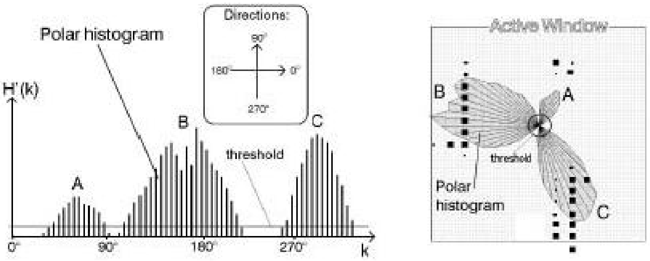

Fig. 9. a) $1D$ polar histogram of obstacle occupancy around the robot. b) Polar histogram shown in polar form overlapped with C^*. Both Reproduced from [2] .

- In the VFH there are no repulsive nor attractive forces and thus the robot cannot be trapped in a local minima, because VFH only tries to drive the robot through the best possible valley, regardless if it leads away from the target.

Drawback of VFH

- The method may lead to the robot being led far away from its target location.

III. CONCLUSION

Obstacle avoidance and path planning play an important role in achieving autonomous navigation of a mobile robot, whether it is in a static or a dynamic environment. There are many different approaches deployed to achieve succesful navigation, the choice of which depends on the application area or task of the robot. The schemes reviewed in this paper have different advantages and drawbacks, but all are based on purely using sensor data for obstacle avoidance and path planning.

By borrowing elements of the different systems e.g. the simplicity of the Bug algorithms and the advanced map nature of the Vector Field Histogram, and fusing with other technologies, an advanced algorithm can be developed to solve the autonomous navigation problem.

Development of a hybrid system that uses both sensor data and a visual system can provide much better performance in achieving autonomous navigation, as the merits of the separate systems are utilised to create a more robust system.

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