**FM²: A Real-time Sensor-based Feedback Controller for Mobile Robots**

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Abstract

The Fast Marching based algorithm proposed here solves the problem of finding Feedback Control Laws for mobile robots, including nonholonomic vehicles. It integrates in a single Real Time Controller the global motion planning tasks and the collision avoidance capabilities required to efficiently move a mobile robot in a dynamic environment. The solution proposed is fast enough to be used in real-time and to operate with a laser scanner system at the sensor rate frequency.

The method combines map-based and sensor-based planning operations to provide a smooth and reliable motion plan. The method works in two steps: In the first, it uses a Fast Marching technique to propagate a wave from the walls and obstacles to determine a potential of slowness for the robot. In the second step, this slowness map is used as refractive index, to calculate the potential of the propagation of a wave from the robot pose to the goal with time as the last axis. The generated trajectory corresponds to the path of the light ray through a medium with non-homogeneous refraction index. The robot trajectory is calculated on the vector field associated to the potential surface. The computational efficiency of the method allows the planner to operate at high rate sensor frequencies. For small and medium scale environments, the proposed method avoids the need for a collision avoidance algorithms plus a global motion planner.

Since the method works over a smooth vector field, it allows the simple introduction of nonholonomic constraints. This way, the method can be used directly to develop a control scheme for nonholonomic vehicles, for example for car like robots.

This enables simplification of the mobile robot architectures, while maintaining good time response, smooth and safe planned trajectories with continuous curvature. The trajectory generated by the planner is the fastest possible to reach the goal position, considering the best path according to the maximum acceptable velocity at each point in the trajectory (path plus velocity).
1 Introduction

Robot motion planning problems have received increasing attention over the last two decades. A significant number of researchers have been working on efficient methods to find motion plans and feedback control for global robot navigation. These subjects have been treated in two general ways: one approach has concentrated on solving motion planning problems using a previously known global environment, obstacle information and robot characteristics, while the other approach has focused on planning motion using local sensor information and the robot characteristics.

The first approach that is referred to in literature as "planned architectures" [?], only works under the assumption of a perfectly controlled and modeled environment, which does not exist in most real situations. Unexpected obstacles, people or moving elements make the method difficult to use except in tightly controlled environments such as industrial manipulation environments. The second approach produces local plans by using local sensor information to avoid obstacles. These reactive architectures [?] showed the advantages of using fast response methods based on a sensor-decision-action scheme to respond to environmental changes, but also showed the difficulty of extending reactivity to upper levels. This is obviously a solution to a local scale problem and needs to be integrated into a global planner or with some global information to guarantee a solution to the global problem. Ultimately, hybrid deliberative/reactive architectures [?, ?, ?, ?, ?, ?] have emerged as a result of recognition of the advantages provided by planning at high control levels, and the advantages of reactive architectures at lower control levels.

In order to navigate in complex environments, an autonomous mobile robot requires a negotiated compromise between the need to react to unexpected events and the need for efficient and optimized trajectories. Motion planning methods usually involve two steps: in the first, a global trajectory is calculated off line using an a priori known map of the environment, and in the second, the robot reads the sensor data and the local trajectory is modified reactively. This provides the path adaptation mechanism to cope with unexpected obstacles or dynamic environments. The reason for a two level planning approach is the high computational cost of most motion planning techniques required to achieve an updated environment model and to plan a smooth and dynamically adapted trajectory. The use of a two level planner strategy decreases the computational cost because the global planner is activated only occasionally (it can be done off line) and the local planner, which is much faster, runs on line. This two level approach also affects the control architecture of a mobile robot.

Other recent motion planning methods have demonstrated real-planning of entire trajectories with one level only. This is the case of Probabilistic Road Map[?] or the proposed method.

In order to calculate in a unified planner and in real time conditions trajectories that take into account the global map and the local sensor information, this paper presents a new Motion Feedback Controller method based on a two step application of the Fast Marching Method.

The Fast Marching Square method ($FM^2$) is based on a sensor-based global motion planning paradigm. This is a planning approach based on a fast sense-model-plan scheme able to integrate sensor information into a simple grid based environment.
model and to calculate a globally consistent, smooth and safe trajectory fast enough for use as a reactive navigation method. This approach has certain advantages: one is the ability of global planning methodologies to guarantee a path between a given point and the goal point, if a path exists. The others are the smoothness (the term smooth is used to denote $C^\infty$) and safety of the obtained solution. This solution eliminates the local minima trap problem and the oscillations in narrow places suffered in other methods. Besides, the methodology indirectly eliminates the need for a supervision system to detect local minima failures (obstructed paths) to determine a new, feasible global path from the current position to the goal point. Our algorithm builds a unique $C^\infty$ potential function $V(x)$ that can be used as a control law.

The first Fast Marching step generates a maximum admissible velocity map of the environment (a slowness field or refraction index field). This velocity map provides a grey scale image of the environment that is darker near the obstacles and walls and lighter further away. This slowness field works as the repulsive electric potential field from walls and obstacles, but with a limited maximum value. The slowness map is zero at obstacles and directs the robot to follow a trajectory sufficiently far from obstacles to maintain the maximum reference velocity in the trajectory. In this way, the trajectories tend to be close to the Voronoi Diagram\[3\]. In the second step, the application of the Fast Marching method to the slowness field obtained previously, provides the shortest time trajectory between the current robot position and the goal position in the medium with refraction index given by the repulsive potential ($FM^2$-1st step). The $FM^2$ second step creates a funnel potential function that represents a wave expansion with time as its last axis, and where the algorithm seeks a minimum time path over the refraction index field, using the gradient method, as explained later in section ???. The path obtained verifies the smoothness and safety considerations required for mobile robot motion. The advantages of this method are ease of implementation, its speed and the quality of the trajectories. The method can be used on a global or local scale; in this case operating only with sensor information instead of using an a priori map (sensor based planning).

The paper is organized as follows. After discussing related work in section 2, section 3 presents an introduction to the proposed method, an introduction to the Eikonal equation and an exposition of the optimal Motion Planning Problem. Section 4 explains the details of the proposed Fast Marching Square algorithm and the applications to the non-holonomic vehicles. Section 5 provides results of the method for holonomic and non-holonomic mobile robots. Section 6 discusses the contributions of the method with respect to others, and Section 7 concludes the paper.

## 2 Related work

From a theoretical point of view, the motion planning problem is well understood and formulated, and there is a set of classical solutions capable of computing a geometrical trajectory that avoids all known obstacles. Most of these general methods are not applicable if the environment is dynamic or there are no modelled obstacles. Thus, to avoid the problem of executing an unrealistic geometrical trajectory which can come into conflicts with obstacles, obstacle avoidance algorithms have been developed to
provide a robust way of coping with the problem.

The potential field is the most common approach to feedback motion planning in the presence of obstacles. Potential field methods, developed by O. Khatib [?], consider the robot as a point evolving under the influence of forces that attract it to the goal while pushing it away from obstacles. It is based on the creation of an artificial potential field in which the target is an attractive pole and the obstacles are repulsive surfaces. The robot follows the gradient of this potential toward its minimum. This technique can be used at either a global or local level, depending on the information used to generate the potentials. The major advantage of this method is its simplicity, and the possibility of using it dynamically because of the ease of treatment of fixed and mobile obstacles. Its major disadvantage is the possible existence of local minima and the oscillations for certain configurations of obstacles. In spite of this, this technique has been extensively used in reactive architectures because of its natural ability to encapsulate specific robot behaviors.

The mix between the attractive and the repulsive fields in a smooth field without local minima has been the biggest problem of these methods.

The majority of the potential methods have commutation difficulties between the local and the global parts, due to the fact that local avoidance algorithms provide modifications of global trajectories but do not offer solutions when the global trajectory is blocked or trapped in local minima. The traditional solution to this problem is to include a supervisor to analyze the global path execution. When a local trap or a blocked trajectory is detected, it starts a search for a new global path from the current location to the goal point.

Other approaches to motion planning based on potential fields nearest to our algorithm are: The navigation functions of Rimon-Koditscheck [?]. This method develops potential functions that have the advantage to present a unique minimum at the goal. The approach proposed by Conner et al. [?] is based on decomposing the free space into cells, and solving the navigation and control problem for specific cells, imposing a potential field over each individual cell. In this same line, Lindemann and LaValle [?] take a cell complex environment and define vector fields over the individual cells, which can be seen as component control policies.

Sethian [?], applies the fast marching method to find the shortest possible path from the initial state to the final state, but he uses only an attractive potential, which generates trajectories too close to the obstacles and more importantly, the trajectories may contain sharp angles that are not practicable for vehicles, as can be seen in fig. ??.

LaValle [?], utilizes on the feedback motion planning concept. To move in the physical world the actions must be planned depending on the information gathered during execution.

The motivation and objective of the present work is to unify the global motion planner and the obstacle avoidance planner, providing smooth and reliable global motion paths which avoid local obstacles from current position to goal destination. Although the objections to the design of this planning methodology have been dealt with in our previous work using Voronoi Diagram [?][?], the current work avoids the use of this diagram and consequently achieves smoother and faster solutions.