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Fast Marching Square Method for UAVs Mission Planning with consideration of Dubins Model Constraints

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Abstract: In this work we present an approach for mission planning carried out by Unmanned Aerial Vehicles (UAVs) in a three-dimensional urban environment. The approach is based on the Fast Marching Square (FM^2) algorithm. The FM^2 algorithm is used as the planner, which generates the optimal-time path from an initial point to a final point, avoiding static obstacles in a three-dimensional building environment. The Dubins airplane model is used to check if the path resulting from the FM^2 is feasible, considering constraints in flight such as turning rate, climb rate and velocity. All these constraints are considered for a fixed-wing aircraft. Thanks to this approach, the trajectory generated by the FM^2 will be perfectly feasible for an UAV, always considering its constraints and the static obstacles of the environment. Two examples of application will be shown to demonstrate the good performance of the approach, introducing different altitude constraints.

Keywords: Mission planning, Fast Marching Square, Dubins model, 3D building environment, Unmanned Aerial Vehicle.

1. INTRODUCTION

Path planning with Unmanned Aerial Vehicles (UAVs) has taken a great importance in recent years. There is a wide variety of applications where the UAVs have become an indispensable tool. Many researchers have focused on different subjects related to human security and environmental protection. Due to this fact, the Federation Aviation Administrator (FAA) has facilitated the introduction of Unmanned Aerial Systems (UAS) in the medium to carry out these different operations.

All types of missions to be performed by the UAV require a proper path planning to reach an adequate autonomous flight (Barrientos et al. (2009)). The planning needs to be adapted to any environment respecting its geometry. The minimisation of the collision risk and safety distance with the obstacles are two key elements to consider. Different techniques are utilized to plan trajectories for UAVs, for example, Rapidly exploring Random Tree (RRT) (Lin and Saripalli (2014)), A* Search algorithms (Bo-Bo and Xiaoguang (2010)) and Probabilistic Roadmap Method (PRM) (Yan et al. (2014)). Besides, in previous works (Arismendi et al. (2015), Garrido et al. (2009)) the Fast Marching Square (FM^2) algorithm has been used to plan optimal trajectories in bidimensional scenarios for mobile robots. We have also used FM^2 as a planner to create formations of vehicles in 2D (Gómez et al. (2013)) and 3D (Alvarez et al. (2014)) environments. All these works have obtained successful results. However, when the problem includes kinematic constraints, a simple path planning may not be sufficient to describe a solution path. Any method used for the path planning has to find an adequate solution respecting the kinematic model of the vehicle (Arismendi et al. (2015)), in this case an UAV.

The novelty of this approach lies in the fact that it is the first time that the FM^2 algorithm is implemented for path planning with UAVs in a 3D environment, where the kinematic constraints are more demanding than in mobile robots. Therefore, it is important to compare it with a kinematic model of a UAV, which in our case, we have been chosen the Dubins model (Hanson et al. (2011), Beard and McLain (2013), Chitsaz and LaValle (2007)), since this model is the most widespread.

In this paper, we focus on path planning in a 3D urban environment consisting of a set of buildings. The FM^2 method is used as a planner, which provides smooth and safe trajectories avoiding static obstacles. The Dubins airplane model is used to verify if the FM^2 path is feasible according the constraints of the UAV, these being the velocity resulting from the first potential of the FM^2 method, the turn rate and the climb rate. Unlike other works (Lin and Saripalli (2014)), here, this model is used only for the sake of the verification of the planned path feasibility, and not as a second step in the approach to correct the planned path, since it would be computationally undesirable.

The approach proposed is conceptually and mathematically very simple, since the FM^2 algorithm is based on natural movements and the kinematic model is composed of simple movement equations. The advantages of this approach are listed below:

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- *Optimal solution.* It ensures a global minimum, and not local minimum, at the source point of the wave. One single wave is employed, providing the optimal solution.
- *Feasible and realistic trajectories.* Due to the fact that it is a continuous method, it gives very smooth and totally feasible trajectories to be carried out by the UAV without the need to be refined. The planned path is later verified with that from the Dubins model taking the physical constraints of the UAV into account.
- *Fast response.* It is a very fast and efficient method giving good results in shorts periods of time, always depending on the size of the environment.

The paper is organized as follows. Section 2 summarizes Fast Marching (FM) and FM^2 algorithms. Section 3 introduces the Dubins model and the kinematic equations utilized. Section 4 describes the implementation of the FM^2 algorithm in a 3D urban environment and the control model for the UAV. Section 5 presents the simulation results obtained from the application of the approach. Conclusions and future works are pointed out in Section 6.

2. FAST MARCHING AND FAST MARCHING SQUARE METHODS

2.1 Fast Marching Method

The FM method is an efficient numerical algorithm introduced by Sethian (1996) and it explains how a wave front is expanded in a media. As explained in Valero-Gómez et al. (2013), to better understand the FM method, we can think about what happens when a stone hits the water. A set of concentric waves are generated from the exact point where the stone has fallen. The waves expand with a forward movement with a certain velocity. In this case, the waves are circular, since the media is water. If the media changes, it is possible that the waves do not have a concentric movement, since the velocity also changes.

Assuming a bidimensional map, the FM method calculates the time that the wave front takes to reach each point of the space. The movement of the wave front is described by the Eikonal equation (1) (Osher and Sethian (1988)), where x is a point of space, *W(x)* is the expansion speed and *D(x)* is the arrival time of the wave front to each point of the space.

$$1 = W(x)|\nabla D(x)| \tag{1}$$

To solve (1) at each point of the space it is necessary to discretize the gradient conforming to Osher and Sethian (1988):

$$\begin{aligned} D_1 &= min(D_{i-1,j}, D_{i+1,j}) \\ D_2 &= min(D_{i,j-1}, D_{i,j+1}) \end{aligned} \tag{2}$$

$$\left(\frac{D_{i,j} - D_1}{\triangle x}\right)^2 + \left(\frac{D_{i,j} - D_2}{\triangle y}\right)^2 = \frac{1}{W_{i,j}^2}. \tag{3}$$

The wave front starts in a point x_0 where $D_0 = 0$. The FM method works by interactions and solves $D_{i,j}$ for each point of space, as it is explained in Osher and Sethian (1988) and Valero-Gómez et al. (2013). This process gives rise to a distance map (see Fig. 1), where the distance is equivalent to the time of arrival of the wave front. The gradient descent will be applied over any point of the time of arrival map until the point where the wave has been originated. In this way we can obtain the path between a start point and the goal point. It is noteworthy that this method is applicable for n dimensions.

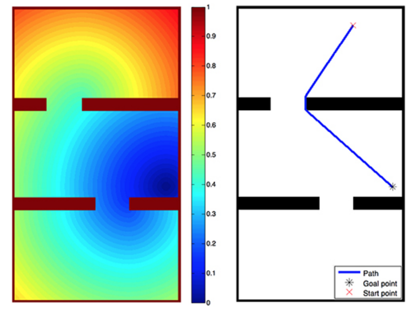

Fig. 1. FM method. The map of distance computed by the FM method (left) and the resulting path (right).

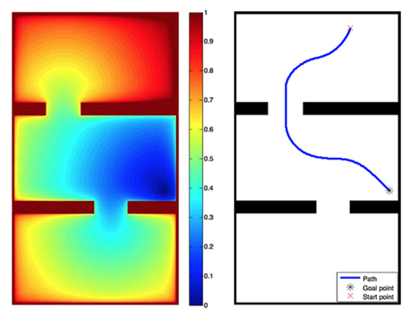

Fig. 2. FM^2 method. The map of distance computed by the FM^2 (left) and the resulting path (right).

2.2 Fast Marching Square Method

The FM^2 method was introduced by Garrido et al. (2009), whose operation is based on applying the FM method twice. It solves certain problems caused and not resolved by the FM method: the distance to elements of the environment is not suitable in terms of security; and the curves arising from the method are very abrupt, making it impossible to follow the path in some cases.

The procedure described below summarizes how the FM^2 method works:

- *Input*: the input of the method is an environment map where the simulation is carried out. This map is converted into a binary map where the cells belonging to obstacles are labeled with value 0 (black), whereas the cells representing free space are labeled with value 1 (white). The initial and final points are also given.
- *Velocities map*: when the FM method is applied, each cell of the resulting map has a value between 0 and 1. This map is considered as a velocities map, since the value of each cell is proportional to the distance from obstacles. This means that the wave speed is reduced or increased depending on if it is close to or away from the obstacles, respectively.