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Optimal routing strategies for autonomous underwater vehicles in time-varying environment

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HIGHLIGHTS

- Practice-oriented considerations in path planning for AUVs are discussed.
- The algorithms find a time optimal path in a time-varying ocean flow.
- The path planning algorithms are based on graph methods.
- It is important to define a large number of edges with different directions.
- Zermelo's formula leads to a pre-selection of promising successor vertices.

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ABSTRACT

This paper presents a mission system and the therein implemented algorithms for path planning in a time-varying environment based on graph methods. The basic task of the introduced path planning algorithms is to find a time-optimal path from a defined start position to a goal position with consideration of the time-varying ocean current for an autonomous underwater vehicle (AUV). Building on this, additional practice-oriented considerations in planning are discussed in this paper. Such points are the discussion of possible methods to accelerate the algorithms and the determination of the optimal departure time. The solutions and algorithms presented in this paper are focused on path planning requirements for the AUV "SLOCUM Glider". These algorithms are equally applicable to other AUVs or aerial mobile autonomous systems.

1. Introduction

This paper is an abridgement of a research fellowship and has been previously published in parts in [1–4]. The following sections review the important results of the study for path planning in a time-varying environment for the autonomous underwater vehicle (AUV) "SLOCUM Glider".

Path planning represents an important characteristic of autonomous systems. It reflects the possibility for a planned behaviour during a mission using all current and future information about the area of operation. This planning task will be complicated because of the unknown, inaccurate and varying information. The path planning algorithms presented in this paper are designed considering the mission requirements for the AUV "SLOCUM Glider". These gliders have a low cruising speed (0.2–0.4 m s^{-1}) in a time-varying ocean flow over a long operation range for periods up to 30 days.

There exists a variety of solutions for the path planning in a time-varying environment, especially for mobile autonomous systems. A generic algorithm was used for an AUV in [5] to find the path with minimum energy cost in a strong, time-varying and space-varying ocean current field. This approach finds a robust solution which will not necessarily correspond with the optimal solution. In [6], an adaptive genetic algorithm is presented for determining routes for a large-scale sea area under real-time requirements. The defined fitness function allows the generation of a time-optimal, obstacle-free route with few waypoints. The mixed integer linear programming (MILP) will be used for handling multiple AUVs [7] or UAVs (Unmanned Aerial Vehicles) [8]. As the computing time of MILP increases exponentially with the problem size, this approach has limitations in real-sized applications. A solution with a non-linear least squares optimization technique for a path planning of an AUV mission through the Hudson River was presented in [9]. The optimization parameters are a series of changeable nodes $(x_i, y_i, z_i, \Delta t_i)$, which characterize the route. The inclusion of the time intervals Δt_i allows a variation of the vehicle speed during the mission and thus the integration of energy considerations in the optimization. This approach runs the risk of finding only a local minimum. In [10] a solution with optimal control to find the optimal trajectory for a glider in a time-varying ocean flow was presented. This approach applied the Nonlinear Trajectory Generation (NTG) algorithm including an ocean current flow B-spline model, a dynamic glider model as well as a defined cost

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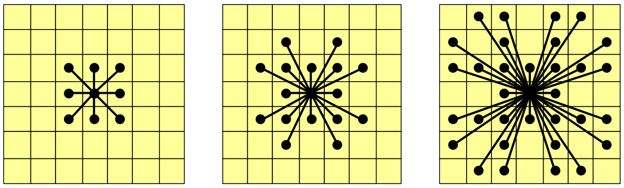

(a) 8 edges. (b) 16 edges. (c) 32 edges.

Fig. 1. Rectangular grid structure (a) 1-sector, (b) 2 sector, (c) 3 sector.

function which is a weighted sum of a temporal and an energy cost. The inclusion of energy requirements using priori known wind information in a graph based path planning for UAVs was discussed in [11]. In [12], the level set method for time-optimal path planning in a time-varying flow field is used. In this case, a wave front, starting from the start position is generated. It consists of particles, which describe the most distant position from the vehicle, which can be achieved at a defined time. When the wave front reaches the target position the optimal route will be determined by backtracking the particles. The accuracy of the numerical solution found and the computing time correlate with the defined points to describe the individual wave front lines at certain discrete times. In [13] a modified A*-algorithm was used to find a time optimal path using Regional Ocean Model (ROM) data. This algorithm, called Constant-Time Surfacing A*(CTS-A*), considered the specific glider dynamics under the influence of ocean currents. An A*-algorithm was used in [14] to find a minimum risk path for gliders using historical data from the Automated Information System (AIS) for automatically identifying and locating vehicles.

The chosen pre-defined mesh structure to define the connectivity relations of the several vertices in a geometrical graph has an important influence to find the optimal path in a current field using graph algorithms. This is confirmed in [15] which is a continuing work of [16]. Both works use an A* algorithm to find an optimal path in a spatial variability and time-invariant ocean current field. The influence of the mesh structure on the determined path is discussed in Section 2.1.

The planning algorithms presented in Sections 2.2.1–2.2.3 are based on a modified Dijkstra Algorithm (see [17]), including the time-variant cost function in the algorithm which will be calculated during the search to determine the travel times (cost values) for the examined edges. This modification allows the determination of a time-optimal path in a time-varying environment. In [18] this principle was used to find the optimal link combination to send a message via a computer communication network with the shortest transport delay.

The presented methods to accelerate the path planning algorithms result from trying to determine real mission plans for the AUV "SLOCUM Glider" to collect oceanographic data along the Newfoundland and Labrador Shelf [3]. The number of edges in the geometrical graph ranges from one hundred thousand to one million for a real mission of duration of 10 days, whereby the sum of the cost function calculations is very time-intensive. This cost function calculations to detect the travel time for an edge are described in Section 3 in detail.

Because the required geometrical graph is not complete as not all vertices are connected by an edge within the graph, the found path has to be smoothed for a real glider mission. This path post processing is a necessary step in real applications (see [19,20]). The path smoothing for time varying conditions will be discussed in Section 4.

A fast working algorithm is also a precondition for the detection of an optimal departure time, which is described in Section 5. A symbolic wavefront expansion (SWE) technique for a UAV in time-varying winds was introduced in [21] to find the time optimal path and additionally the optimal departure time. The path planning algorithms in this paper use a similar principle as is used in the SWE to calculate the time-varying cost function for the several vertices. This includes the arrival time at the several vertices in the cost function calculation during the search. To find the optimal departure time, the SWE and the approach described in this paper use separate solution methods. The reasons are the accurate and fast determination of the optimal departure time, as well as the possible inclusion of uncertainties in the path planning as a result of forecast error variance, accuracy of calculation in the cost functions and a possible use of a different vehicle speed in the real mission than planned [22].

Section 6 shows the results of the presented algorithms using a simple mathematical model of the Gulf Stream and real netCDF files for a 10-day forecast. Conclusion and future research topics are in Section 7.

2. Graph algorithm

2.1. Generation of the geometrical graph

The geometrical graph is a mathematical model for the description of the area of operation with all its characteristics. Therefore defined points (vertices) within the operational area are those passable by the vehicle. In this paper these points define positions in the 2D Euclidean space whereby the geometrical graph is planar. The passable connections between these points are recorded as edges in the graph. Every edge has a rating (cost, weight) which can be the length of the connection, the evolving costs for passing the connection or the time required for traversing the connection. There exist many approaches to describe an obstacle scenario with as few of the vertices and edges as possible, and, to decrease the computing time (visibility and quadtree graph [23]). In the case of the inclusion of an ocean current, the mesh structure of the graph will be a determining factor associated with its special change in gradient. In other words, the defined mesh structure should describe the trend of the ocean current flow in the operation area as effectively as possible. A uniform rectangular grid structure is the easiest way to define such a mesh. In the simplest case the edges are the connections between neighbouring obstacle-free sectors; see Fig. 1(a). To achieve a shorter and smoother path for mobile robots additional edges to other sectors are implemented in [24]; see Fig. 1(b). The analyses of the found paths in a current field show (see also [1,2]) that is it important to define a great number of edges with different slopes; see Fig. 1(c). A further increase of the number of radiated edges leads to increasing lengths which is not practical to describe the change in gradient of the current flow.

2.2. Graph-based search-algorithm

The developed search algorithms are all based on the Dijkstra Algorithm [17] which solves the single-source shortest paths problem on a weighted directed graph. The exact solution by using a Dijkstra algorithm in a time-varying environment requires the inclusion of the time information as an additional dimension in the