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Temporally and Spatially Deconflicted Path Planning for Multiple Autonomous Marine Vehicles ⋆

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Abstract:
There is currently a surge of interest in the development of advanced systems for cooperative control of multiple autonomous marine vehicles. Central to the implementation of these systems is the availability of efficient algorithms for multiple vehicle path planning that can take explicitly into account the capabilities of each vehicle and existing environmental conditions. Multiple vehicle path planning methods build necessarily on key concepts and algorithms for single vehicle path following. However, they go one step further in that they must explicitly address inter-vehicle collision avoidance, together with a number of criteria that may include simultaneous times of arrival at the assigned target points and energy minimization, to name but a few. As such, they pose considerable challenges both from a theoretical and practical implementation standpoint. This paper is a short overview of multiple vehicle path planning techniques. The exposition is focused on specific algorithms developed in the scope of research work in which the authors have participated. Namely, algorithms that ensure that at no time will two vehicles get closer in space than a desired safety distance, that is, achieve trajectory *deconfliction*. The algorithms make ample use of *direct optimization methods* that lead to efficient and fast techniques for path generation using a polynomial-based approach. The paper affords the reader a fast paced presentation of key algorithms that had their genesis in the aircraft field, discusses the results of simulations, and suggests problems that warrant further consideration.

Keywords: Multiple Vehicle Missions, Path Planning, Spatial Deconfliction, Temporal Deconfliction, Autonomous Marine Vehicles.

1. INTRODUCTION

Space, land, and marine robots are becoming ubiquitous and hold promise to the development of networked systems to sample the environment at an unprecedented scale. This trend is clearly visible in the marine world, which harbors formidable challenges imposed by the extent of the areas to be surveyed, sea waves, currents, low visibility at depth, lack of global positioning systems underwater, and stringent acoustic communication constraints. Some of these difficulties can be partially overcome through the use of fleets of heterogeneous vehicles working in cooperation, under the supervision of advanced systems for cooperative control of multiple autonomous vehicles. Central to the implementation of these systems is the availability of efficient algorithms for multiple vehicle path planning that can take explicitly into account the capabilities of each vehicle and existing environmental conditions.

As an application example, consider the scenario where multiple autonomous marine vehicles (that have been launched from one or more support ships and are scattered in the ocean) are required to execute a cooperative mission underwater, adopting a desired geometrical formation pattern. To this effect, and while still at the surface, the vehicles must maneuver from their initial positions and reach formation at approximately the same speed, in a prescribed neighborhood of the diving site. Only then can the underwater mission segment start. Because the vehicles may be operating in a restricted area and in the vicinity of support ships, this initial Go-To-Formation maneuver must be executed in such a way as to avoid collisions. Furthermore, the vehicles must arrive at their target positions at approximately the same time. This scenario is depicted in Fig. 1, which shows the evolution of

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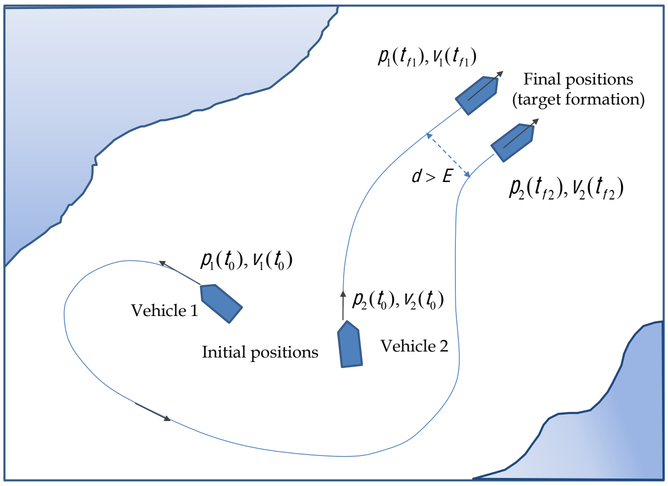

Fig. 1. Multiple Vehicle Path Planning: Go-To-Formation Maneuver with Spatial Deconfliction.

two vehicles that start from arbitrary positions and reach a simple side-by-side formation pattern prior to diving.

The example above can be further detailed to show how multiple vehicle path planning yields an optimization problem subject to a number of critical constraints. For example, in the case of an energy-related cost criterion the function to be minimized may be an weighted sum of the energies spent during a Go-To-Formation maneuver. However, other criteria may be envisioned such as average maneuvering time. Vehicle related constraints are the total energy available for vehicle maneuvering and vehicle dynamic restrictions such as maximum vehicle accelerations. Environmental constraints include external disturbances caused by ocean currents and sea waves. It is also required that collisions be avoided among vehicles as well as between vehicles and stationary and moving obstacles (e.g. support ships, the coastline, and harbor structures). In particular, it is crucial that path planning algorithms yield feasible paths and that any two vehicles never come to close vicinity of each other. This property is often referred to as *deconfliction* in the area of multiple air vehicle control, for it ensures that at no time will two vehicles get closer in space than a desired safety distance E, see Figure 1.

Stated in such generality, path planning is obviously a problem with far reaching implications not only in robotics but also in control theory, computer science, artificial intelligence, and other related engineering subjects (LaValle [2006]). Figure 2 illustrates the problem at hand and shows how a cost criterion, initial and final vehicle conditions, and internal and external constraints are used to produce (if it exists) a trajectory that meets the constraints and minimizes the cost. The spatial and temporal coordinates of this trajectory yield a spatial path and a corresponding vehicle profile. This simple observation is at the root of the methodologies for path planning that are briefly summarized in the paper.

In practice, deconfliction can be spatial or temporal. In the first category, shown in Fig. 1 for the case of two vehicles, non-intersecting spatial paths are generated without explicit temporal constraints. In the second case, temporally deconflicted paths will give rise to nominal trajectories (defined in space and time) for the vehicles to track. Clearly, temporal deconfliction introduces an extra degree of freedom (time) that is not available in the case of spatial deconfliction. As such, it leads to solutions whereby paths are allowed to come to close vicinity or intersect in space, but the temporal scheduling of the vehicles involved separates these occurrences well in time. In summary, temporal deconfliction allows for the solution of a larger class of problems than those that can be tackled with spatial deconfliction algorithms.

Motivated by the above considerations, this paper addresses the problem of deconflicted path planning with applications to multiple autonomous marine vehicles. For simplicity of exposition, the main focus is on vehicles moving in 2D space. The problem formulation and the solutions proposed have been strongly influenced by several mission scenarios studied in the scope of the two EU research projects described in $FREE_{\rm sub}NET$ [2006—2010] and GREX [2006—2009]. The key objective is to *obtain path planning methods that are effective, computationally easy to implement, and lend themselves to real-time applications.*

The techniques that are the focus of this survey paper build upon and extend the work first reported for unmanned air vehicles in Yakimenko [2000] and later in Kaminer et al. [2006] and Kaminer et al. [2007]. See also Ghabcheloo et al. [2009b] for recent work on the subject. Explained in intuitive terms, the key idea exploited is to separate spatial and temporal specifications, effectively decoupling the process of spatial path computation from that of computing the desired speed profiles for the vehicles along those paths. The first step yields the vehicles' spatial profiles and takes into consideration geometrical constraints; the second addresses time related requirements that include, among others, initial and final speeds, deconfliction in time, and simultaneous times of arrival. Decoupling the spatial and temporal constraints can be done by parameterizing each path as a set of polynomials in terms of a generic variable τ and introducing a polynomial function $\eta(\tau)$that specifies the rate of evolution of τ with time, that is, $d\tau/dt = \eta(\tau)$, see Kaminer et al. [2007]. By restricting the polynomials to be of low degree, the number of parameters used during the computation of the optimal paths is kept to a minimum, a fact that stands at the root of the success of the direct method for rapid prototyping of near-optimal aircraft trajectories proposed in Kaminer et al. [2006]. Once the order of the polynomial parameterizations has been decided, it becomes possible to solve the multiple vehicle optimization problem of interest (e.g., simultaneous time of arrival under specified deconfliction and energy expenditure constraints) by resorting to any proven direct search method Kolda et al. [2003].

The paper is organized as follows. Section 2 offers a general description of the methodology adopted for deconflicted path generation and details its application to the generation of the Go-To-Formation manoeuver with an energy cost criterion and a simultaneous time of arrival constraint. Section 3 contains simulation examples that illustrate the efficacy of the methods developed. Finally, Section 4 overviews the main results obtained and summarizes theoretical and practical issues that warrant further research. *Due to space limitations, some important details are necessarily omitted. The reader is referred to Häusler et al. [2009] for a thorough treatment of the topic.*

2. MULTIPLE VEHICLE PATH PLANNING WITH SPATIAL AND TEMPORAL DECONFLICTION

This section describes two algorithms for multiple vehicle path planning with spatial and temporal deconfliction. In