Three-Dimensional Time-Optimal Path Planning in the Ocean

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Abstract

Autonomous underwater vehicles (AUVs) operate in the three-dimensional and time-dependent marine environment with strong and dynamic currents. Our goal is to predict the time history of the optimal three-dimensional headings of these vehicles such that they reach the given destination location in the least amount of time, starting from a known initial position. We employ the exact differential equations for time-optimal path planning and develop theory and numerical schemes to accurately predict three-dimensional optimal paths for several classes of marine vehicles, respecting their specific propulsion constraints. We further show that the three-dimensional path planning problem can be reduced to a two-dimensional one if the motion of the vehicle is partially known, e.g. if the vertical component of the motion is forced. This reduces the computational cost. We then apply the developed theory in three-dimensional analytically known flow fields to verify the schemes, benchmark the accuracy, and demonstrate capabilities. Finally, we showcase time-optimal path planning in realistic data-assimilative ocean simulations for the Middle Atlantic Bight region, integrating the primitive-equation of the Multidisciplinary Simulation Estimation and Assimilation System (MSEAS) with the three-dimensional path planning equations for three common marine vehicles, namely propelled AUVs (with unrestricted motion), floats (that only propel vertically), and gliders (that often perform sinusoidal yo-yo motions in vertical planes). These results highlight the effects of dynamic three-dimensional multiscale ocean currents on the optimal paths, including the Gulf Stream, shelfbreak front jet, upper-layer jets, eddies, and wind-driven and tidal currents. They also showcase the need to utilize data-assimilative ocean forecasts for planning efficient autonomous missions, from optimal deployment and pick-up, to monitoring and adaptive data collection.

Keywords: path planning, three-dimensional, level set, data-assimilation, ocean forecasting, AUVs, gliders, floats

1. Introduction

The problem of planning feasible, safe, and optimal paths in complex and dynamic environments has received much attention from many branches of science and engineering. In the most general sense, "optimal path planning" refers to a set of rules provided to an autonomous robot such that the robot can navigate from some initial configuration to the desired configuration in an optimal fashion. Typically, such optimality is governed by some objective function. Autonomous robotic platforms are becoming ubiquitous day by day, and are used to perform a variety of tasks with different levels of complexity. This leads to a wide range of objective functions. Principled path planning theories that apply to several situations are thus not common.

Optimal navigation of autonomous underwater vehicles (AUVs) is crucial for many applications, including security, search and rescue, monitoring, and data collection. Underwater gliders and floats are ideal for ocean sampling due to their long-range endurance and significant autonomy. However, these vehicles typically travel at relatively slow speeds, in many cases comparable to that of the local ocean currents \cite{74; 12; 101}. Hence, the effect of currents on their net motion cannot be neglected and should be modeled accurately.

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