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Stochastic Time-Optimal Path-Planning in Uncertain, Strong, and Dynamic Flows

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Abstract

Accounting for uncertainty in optimal path planning is essential for many applications. We present and apply stochastic level-set partial differential equations that govern the stochastic time-optimal reachability fronts and time-optimal paths for vehicles navigating in uncertain, strong, and dynamic flow fields. To solve these equations efficiently, we obtain and employ their dynamically orthogonal reduced-order projections, maintaining accuracy while achieving several orders of magnitude in computational speed-up when compared to classic Monte Carlo methods. We utilize the new equations to complete stochastic reachability and time-optimal path planning in three test cases: *(i)* a canonical stochastic steady-front with uncertain flow strength, *(ii)* a stochastic barotropic quasi-geostrophic double-gyre circulation, and *(iii)* a stochastic flow past a circular island. For all the three test cases, we analyze the results with a focus on studying the effect of flow uncertainty on the reachability fronts and time-optimal paths, and their probabilistic properties. With the first test case, we demonstrate the approach and verify the accuracy of our solutions by comparing them with the Monte Carlo solutions. With the second, we show that different flow field realizations can result in paths with high spatial dissimilarity but with similar arrival times. With the third, we provide an example where time-optimal path variability can be very high and sensitive to uncertainty in eddy shedding direction downstream of the island.

Keywords:
Stochastic Path Planning, Level Set Equations, Dynamically Orthogonal, Ocean Modeling, AUV, Uncertainty Quantification

1. Introduction

Planning optimal paths of autonomous platforms in dynamic environments such as the ocean and atmosphere is important for maximally utilizing the platforms' capabilities. In the ocean, commonly used autonomous vehicles–underwater gliders, propelled underwater vehicles and surface crafts–often undertake complex missions such as oceanographic data collection, search and rescue operations, oil and gas discovery, and acoustic surveillance and security tasks (Bellingham and Rajan, 2007; Curtin and Bellingham, 2009; Schofield et al., 2010). Path planning is the task of predicting paths for these vehicles to navigate between any two points while optimizing some or all operational parameters such as time, energy, data collected, and safety. A related concept is dynamic reachability forecasts, the task of predicting the dynamic set of all the locations that can be reached by these vehicles.