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Optimal path planning for autonomous underwater gliders in time-varying flow fields

by

James Ju Heon Lee

A thesis submitted in partial fulfilment of the requirements for the degree of Doctor of Philosophy

at the
School of Mechanical and Mechatronic Engineering
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Certificate of Original Authorship

I certify that the work in this thesis has not previously been submitted for a degree nor has it been submitted as part of requirements for a degree except as fully acknowledged within the text.

I also certify that the thesis has been written by me. Any help that I have received in my research work and the preparation of the thesis itself has been acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

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Abstract

Marine robots perform various oceanic missions for commercial, scientific and military purposes. Some of these tasks include resource tracking, environmental surveying and coastal surveillance. Underwater gliders are a special class of marine robots that do not use active propulsions to move forward. This property makes the gliders more energy-efficient compared to other marine robots, and thus well-suited for long-duration missions. These missions benefit from autonomous operations that are either energy-optimal or time-optimal to maximising glider operation time and minimise human interactions. Such a level of automation is difficult to achieve, however. The underwater glider operates under a high-dimensional dynamic model with non-linear control, making it difficult to model mathematically. Optimal navigation in a flow field environment, known as Zermelo's Problem, is also a century-old open problem. This research introduces a trim-based model that reduces the glider control problem to a simpler 6D kinodynamic problem. We address this simpler problem using a state-of-the-art sampling-based algorithm to demonstrate full 3D underwater glider motion planning over various static flow fields and obstacles.

For real-world applications, it is also essential to consider the dynamics of the environment. Therefore it is natural to expect planning algorithms for underwater gliders to handle variations in flow fields. As the glider's performance heavily depends on the surrounding flow field, planning involves the time-dependent shortest path (TDSP) problem, which has been open since the original work on graph search problem in the 1960s. This research introduces a new special case of the TDSP problem for vehicles in dynamic ocean currents. An optimal policy is solved for a time-dependent discrete graph over a dynamic flow field in polynomial time. Integrating both the trim-based and TDSP work addresses the path planning problem for underwater gliders by synthesising a continuous path from the optimal policy using the trim-based model.

The significance of this research is that it introduces an increased level of autonomy in underwater robots. The theoretical work allows for more accurate glider navigation, and considering dynamic ocean currents allows the glider to exploit the environment for practical advantages. These results also improve autonomous operation so that it requires less manual intervention from humans. This thesis shows examples of these ideas, and we are currently planning a long-duration field deployment to demonstrate these results in practice.

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Acronyms & Abbreviations

1D One-Dimensional

2D Two-Dimensional

3D Three-Dimensional

6D Six-Dimensional

12D Twelve-Dimensional

AO Asymptotically optimal

ASV Autonomous Surface Vessel

AUV Autonomous Underwater Vehicle

Dec-MCTS Decentralised monte carlo tree search

Dec-POMDP Decentralised partially observable markov decision process

dRRT Discrete rapidly-exploring random tree

DSLX Discrete search leading continuous exploration

DSTG Defence Science and Technology Group

EAC East Australian Current

FIFO First–in–First–Out

FMT Fast marching tree

KPIECE Kinodynamic motion planning by interior-exterior cell exploration

MCTS Monte carlo tree search

PF Piecewise-constant function

PRM Probabilistic roadmap

RRT Rapidly-exploring random tree

SBL Single-query, bi-directional, lazy in checking collision

TDSP Time-dependent shortest path

UCB Upper confidence bound

UTS University of Technology, Sydney