Three-Dimensional Time-Optimal Path Planning in Dynamic and Realistic Environments

by

Chinmay Sameer Kulkarni


Submitted to the Department of Mechanical Engineering in partial fulfillment of the requirements for the degree of Master of Science in Mechanical Engineering at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

June 2017

© Massachusetts Institute of Technology 2017. All rights reserved.

Signature redacted

Author .....................

Department of Mechanical Engineering

May 12, 2017

Signature redacted

Certified by ..................

Pierre F.J. Lermusiaux
Professor
Thesis Supervisor

Signature redacted

Accepted by .................

Rohan Abeyratne
Chairman, Department Committee on Graduate Theses
Three-Dimensional Time-Optimal Path Planning in Dynamic 
and Realistic Environments

by

Chinmay Sameer Kulkarni

Submitted to the Department of Mechanical Engineering 
on May 12, 2017, in partial fulfillment of the 
requirements for the degree of 
Master of Science in Mechanical Engineering

Abstract

Autonomous underwater vehicles (AUVs) are a valuable resource in several oceanic applications such as security, surveillance and data collection for ocean prediction. These vehicles typically travel at speeds comparable to ocean currents, and their movement is significantly affected by these dynamic currents. Further, the speed of currents may vary greatly with depth. Hence, path planning to generate safe and fast vehicle trajectories in such a three-dimensional environment becomes crucial for the successful operation of these vehicles. In addition, many marine vehicles can only move in specific directions and with a speed that is dependent on the direction of travel. Such constraints must be respected in order to plan safe and optimal paths.

Thus, our motivation in this thesis is to study path planning for vehicles with and without motion constraints in three-dimensional dynamic flow-fields. We utilize the time-optimal path planning methodology given by Lolla et al. (2012) for this purpose.

In this thesis, we first review some existing path planning methods (both in two and three-dimensional settings). Then, we discuss the theoretical basis of the rigorous partial differential equation based methodology that is utilized in order to plan safe and optimal paths. This is followed by an elaborate discussion about the application of this methodology to the various types of marine vehicles. We then look at the robust and accurate numerical methods developed in order to solve the governing equations for the path planning methodology with high accuracy in real ocean domains. We illustrate the working and capabilities of our path planning algorithm by means of a number of applications. First we study some benchmark examples with known analytical solutions. Second, we look at more complex flow-fields that analytically model different oceanic flows. Finally, we look at the path planning for different types of marine vehicles in a realistic ocean domain to illustrate the capabilities of the path planning methodology and the developed numerical framework.
Acknowledgments

I would like to thank my advisor Prof. Pierre Lermusiaux for his guidance, support and for allowing me to work on research problems of my interest. His motivation, words of encouragement and constructive criticism have gone a long way in helping me develop a wide research perspective.

I thank Dr. Pat Haley for helping the realistic ocean examples studied in this work. I am also grateful to Dr. Chris Mirabito, Dr. Sudip Jana and Dr. Yulin Pan as well as Marcia and Leslie for their help.

I am grateful to the Office of Naval Research for support under Grants N00014-15-1-2616 (DRI-NASCAR) and N00014-14-1-0476 (Science of Autonomy LEARNS) to the Massachusetts Institute of Technology (MIT).

Thanks to my MSEAS family for being a home away from home! Thank you Deepak for always being around and for helping me whenever needed. I will always cherish our numerous late night discussions. Thanks Johnathan for being a great friend and for sharing my enthusiasm for good food. I can never forget our sailing adventures! Thanks to Corbin, Abhinav, Florian and Yukino for being the best lab-mates anyone could ask for. Thank you Arkopal, Jing and Wael for your support, friendship and the many fun-filled conversations. Special thanks to Tapovan, Sydney, John, Matt and the other senior students for helping me settle into the group.

Life at MIT has been an amazing experience. I would like to thank all my friends at MIT and at IIT Bombay for always being there, looking out for me and being a great company over all these years! Finally, I would like to thank my family, both back home and here in the United States. None of this would have been possible without their constant encouragement and support.