2019-12

In-stride Optimal Motion Planning/re-planning for MCM Missions using Optimization

Kaminer, Isaac I.; Kragelund, Sean

Monterey, California: Naval Postgraduate School

http://hdl.handle.net/10945/69977

NPS NRP Executive Summary
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Report Date: 10/14/2019 Project Number (IREF ID): NPS-19-N257-A
Naval Postgraduate School / School: Graduate School of Engineering and Applied Sciences

NAVAL RESEARCH PROGRAM
NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

IN-STRIDE OPTIMAL MOTION PLANNING/RE-PLANNING FOR MCM MISSIONS

Executive Summary Type: Final Report
Period of Performance: 10/15/2018–10/14/2019

Researchers:

Principal Investigator (PI):	Dr. Isaac Kaminer, GSEAS, Department of Mechanical and Aerospace Engineering (MAE)
Additional Researcher(s):	Dr. Sean Kragelund, GSEAS, MAE Dr. Claire Walton, GSEAS, MAE
Student Participation:	LT Joshua Sale USN LT Christofer Price USN LT Richard McClane USN LT Justin Laddusaw USN

Prepared for:
Topic Sponsor Lead Organization: N8 - Integration of Capabilities & Resources
Topic Sponsor Organization: Naval Surface and Mine Warfighting Development Center Mine Warfare Division (SMWDC-MIW)
Topic Sponsor Name: N8/9 Deputy, Mr. Rich Kimmel
Topic Sponsor Contact Information: richard.kimmel@navy.mil (619) 524-4488

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EXECUTIVE SUMMARY

Project Summary

Unmanned vehicles have become increasingly important for naval mine countermeasures (MCM), but they have not yet realized their full potential to reduce mine clearance timelines while providing sufficient risk level guarantees. Mine hunting operations typically employ multiple search, identification/classification, and neutralization sorties. These tasks are often conducted as sequential phases, each employing different vehicles and sonar sensors. This approach requires laborious post-mission analysis and planning cycles between each phase. Our research seeks to overcome the limitations of this sequential search paradigm by enabling simultaneous deployment of dissimilar vehicles with complementary capabilities.

Specifically, we investigated new algorithms and computational tools for generating optimal search trajectories for heterogeneous, multi-vehicle teams in a real-time, event-based framework. Simulations verified that these new techniques are orders of magnitude faster than previous algorithms, yet still achieve equivalent search performance. Significantly, these techniques do not require specialized computing equipment. Therefore, these algorithms are suitable for implementation on unmanned vehicle autopilots, a key capability for in-stride optimal mission planning and re-planning by collaborative vehicle teams. The ability to conduct simultaneous mine hunting sorties with multiple autonomous vehicles promises to improve the speed and effectiveness of MCM missions.

Keywords: *optimal search, mine countermeasures, MCM, mine hunting, sonar, mission planning, autonomous vehicles, unmanned vehicles, unmanned surface vessel, USV, unmanned underwater vehicle, UUV*

Background

Mine countermeasures (MCM) is an extremely challenging and complex Navy mission set. A number of different capabilities and techniques are required to confront the wide variety of potential threats and operational environments encountered (U.S. Navy, 2004). Unmanned vehicles and advanced sensor systems now play an integral role in these operations, so it is imperative that MCM commanders and vehicle operators have the ability to maximize the efficiency and utility of these resources.

The objective of this research is to develop in-stride MCM planning algorithms that allow a team of heterogeneous vehicles to conduct mine detection and identification/classification missions in tandem instead of sequentially. Recent theoretical work by Phelps, Gong, Royset, Walton, and Kaminer (2014) produced a mathematical and computational framework called Generalized Optimal Control (GenOC). Leveraging a numerical toolbox developed by Walton (2015), GenOC has been used to solve optimal search problems with realistic mine hunting vehicle and sonar models (Kragelund, 2017; Kragelund, Walton, Kaminer, & Dobrokhodov, 2018). Although GenOC trajectories outperformed conventional area coverage patterns under the same time or resource constraints, initial trajectory optimization routines were so computationally expensive that solutions had to be computed off-line, which precluded in-stride planning.

To achieve a true in-stride planning capability for MCM, motion planning algorithms must 1) update target distributions, 2) address false targets, and 3) re-compute new search trajectories in near real-time. The first two issues have been analyzed by Walton, Kragelund, and Kaminer (2017), and additional methods for dealing with false targets were reviewed during this study. The majority of our research effort, therefore, investigated computationally efficient planning algorithms based on Bezier curves to achieve near real-time optimal motion planning (Cichella, Kaminer, Walton, & Hovakimyan, 2018).

Findings and Conclusions

The Naval Surface and Mine Warfighting Development Center supports research and development needed to better understand and optimize the sensor and vehicle performance of next-generation MCM systems. The results of this study support the topic sponsor's ultimate goal of providing a faster and more effective search, identification/classification, and neutralization timeline for the MCM commander. The ability to conduct these missions simultaneously with multiple autonomous vehicles has great potential for future MCM operations.

In general, the presence of false targets in the search area requires a two-stage search strategy: 1) broad search to detect contacts, and 2) contact investigation to distinguish actual targets from false targets. Therefore, our study examined different ways for cooperating vehicles to plan contact investigation trajectories on demand. The literature describes several methods for dealing with false targets during a search operation. Many utilize a Poisson probability distribution to model the number, location, and detection of false targets (Stone, 1989; Kalbaugh, 1992; Decker, Jacques, & Pachter, 2007). We conclude, therefore, that the GenOC model-based solution framework can accommodate false-target searches with slight modifications to the objective function being minimized. Other potential objective functions include the risk due to undetected mines after MCM (Washburn, 2006; Monach & Baker, 2006), or the risk of incorrectly estimating the number of targets present in an area (McMahon, Yetkin, Wolek, Waters, & Stilwell, 2017).

Our research also examined the computational barriers to in-stride planning posed by initial GenOC implementations. Significant complexity stems from the methods used to approximate vehicle trajectories and discretize the search problem for numerical solution (Phelps et al., 2014). Since vehicle dynamics place constraints on vehicle state and control trajectories that much be satisfied at discrete times, solutions are also sensitive to the number of time nodes chosen (Kragelund, 2017). This study analyzed GenOC performance improvements achieved by modifying the problem formulation in three ways. Specifically, we adopted the methods described by Cichella et al. (2018) to 1) exploit the differential flatness of search vehicle dynamics and 2) approximate vehicle trajectories with Bernstein polynomials. These two improvements reduced the number of constraints on the optimization, and produced smooth numerically-stable Bézier curves as output trajectories, respectively.

The degree elevation property of Bézier curves (Cichella et al.,2018) enabled our third modification, a continuation algorithm based on homotopy methods similar to one described by Dobrokhodov, Walton, Kaminer, & Jones (2020). This approach iteratively solves a sequence of simple problems to arrive at an optimal solution in fewer iterations; beginning with a trivial problem, each solution supplies the initial guess for the next problem. Our continuation algorithm first computes the best low-order Bézier curve trajectory, then uses degree elevation to successively find higher-order Bézier curve trajectories from lower-order initial guesses. These modifications drastically improved solution times. A desktop computer running standard optimization software can now solve MCM search problems about 50 times faster than prior GenOC implementations using specialized software on the NPS Hamming supercomputing cluster (Kragelund, 2017). We conclude, therefore, that these algorithms are suitable for implementation on unmanned vehicle autopilots, a key capability for in-stride optimal mission planning by collaborative vehicle teams.

Recommendations for Further Research

McCray describes a promising approach for planning optimal, semi-adaptive searches that uses interim search results to update probability densities for both real and false targets, based upon prior intelligence about their relative spatial distribution (2017). Future research should investigate whether this technique can be applied to learn the parameters of a minefield's laydown pattern to inform future search plans. In addition, since GenOC offers a centralized method for planning MCM missions, we recommend that future research investigate distributed, event-driven planning and information sharing methods.

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Acronyms

Mine Countermeasures	MCM
Generalized Optimal Control	GenOC