2022

Clandestine Mine Countermeasures Optimization for Autonomy and Risk Assessment

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https://hdl.handle.net/10945/71832

NAVAL RESEARCH PROGRAM
NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

CLANDESTINE MINE COUNTERMEASURES OPTIMIZATION FOR AUTONOMY AND RISK ASSESSMENT

EXECUTIVE SUMMARY

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Prepared for:
Topic Sponsor Lead Organization: N8 - Integration of Capabilities & Resources
Topic Sponsor Organization(s): Surface and Mine Warfighting Development Center (SMWDC), Mine Warfare (MIW)
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This research is supported by funding from the
Naval Postgraduate School, Naval Research Program (PE 0605853N/2098).
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Project Summary
Mines are inexpensive, easily deployed, and put distributed maritime operations (DMO) at high-risk, particularly as Great Power Competition (GPC) requires naval forces to operate in contested environments. Autonomous underwater vehicles (AUVs) will play an increasingly important role in mine countermeasures (MCM), but research is required to optimize their performance when support from surface or airborne assets is denied or severely limited by the constraints of GPC. This project investigated methods for AUVs to conduct entirely clandestine MCM. It examined whether a conventional MCM search problem could be inverted: instead of conducting sequential operations to find and neutralize mines in a predefined transit lane, an AUV can find a navigable mine-free route that maximizes its probability of survival, potentially decreasing MCM mission timelines. Preliminary results suggest that this framework can also be used to prioritize mines for neutralization to achieve acceptable risk levels. Additional student thesis research examined methods for object detection and size determination with forward-looking sonar (FLS) to enable more efficient AUV path planning.

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

Background
Today's MCM systems still rely on surface and airborne assets for vehicle support, data analysis, and mission planning. In the contested battlespace of the future, it may not be possible to establish and maintain the permissive environment that current systems require. While AUVs are capable of clandestine operations, research is required to identify and assess new methods for conducting entirely clandestine MCM—without support from vulnerable surface assets.

Many MCM missions are search problems, and recent advances in computational optimal control have made it possible to optimize search functions performed by AUVs. Examples include area search to determine optimal track line geometry and collaborative search to detect, localize, identify, and (when necessary) neutralize mines. Past research by Kragelund et al. (2020a, 2020b) has shown that these capabilities can improve upon conventional MCM methods that rely on sequential "lawnmower" search missions to clear a designated transit lane. By using targeted rather than exhaustive search, clandestine MCM has potential to reduce MCM timelines even further. Based on prior Naval Research Program research conducted for the topic sponsor, this study topic was developed in consultation with Navy stakeholders at the sponsor's organization, the Naval Surface and Mine Warfighting Development Center Mine Warfare Division (SMWDC-MIW).

For this study, Naval Postgraduate School (NPS) researchers contacted subject matter experts to develop realistic assumptions about MCM vehicles, sensors, and operations. Contacts included topic sponsors at SMWDC-MIW, AUV operators in the expeditionary MCM and explosive ordnance disposal communities, and engineers at Naval Information Warfare Center-Pacific responsible for fielding automated target recognition algorithms on MCM AUVs. A brief literature review of search theory, optimal trajectory generation, and coordinated path following algorithms was also conducted. Finally, NPS reviewed papers by MCM planning experts at the Naval Surface Warfare Center-Panama City covering new methods for calculating and assessing MCM risk.

This study's initial focus on AUV sensing capabilities led to a thesis by Fedorovich (2022) that explored the potential to classify underwater objects using only FLS. Experiments with two different target shapes were conducted in a controlled environment to determine relationships between a target's actual size/shape and its apparent size/shape in head-on FLS imagery. Fedorovich et al. (2022) presents a potential obstacle avoidance strategy for AUVs conducting MCM in these environments.

Finally, we developed an optimal control formulation for an AUV to find a safe route through a minefield by computing a feasible trajectory which maximizes the AUV's probability of survival. This optimal control framework can be generalized to accommodate probabilistic models for mine damage, vehicle navigation, etc.; performance; and mission objectives for numeric optimization.

Findings and Conclusions

While preliminary in nature, this study found qualitatively that an optimal control framework can find a safe, navigable route through a minefield. This result relied on assumptions about an AUV's ability to detect and localize mines in the environment. These assumptions were informed by our literature review and by our thesis student's experiments with a sensor used on some actual MCM AUVs. However, additional modeling and simulation is required to assess the capabilities of actual MCM vehicle/sensor systems for clandestine MCM.

One benefit of optimal control is that it is a model-based framework. This method can generate a wealth of data for parametric studies (e.g., Kragelund et al., 2020b) by incorporating different models of the mine threat, vehicle dynamics, sensor capabilities, and mission objectives. Monte Carlo simulation can be employed to generate results for analysis. Another benefit of optimal trajectory generation is that vehicle trajectories found in this manner are feasible by definition (i.e., they can be followed by vehicle autopilots). NPS has demonstrated this on several of its autonomous vehicle systems, but rigorous experimentation with fleet MCM vehicles is needed to test this capability in the field.

In this study, we defined risk in terms of the AUV's probability of survival along its trajectory. Additional analysis is required to assess the risk to other vehicles following the first AUV's path. This risk is a function of each vehicle's navigation accuracy, acoustic/magnetic signature, etc., and was considered outside the scope of our study. However, the proposed trajectory generation framework can be modified to account for the risk to other vehicles. Alternatively, the objective function could also be modified to identify/prioritize individual mines that must be neutralized to guarantee a specified risk threshold.

In conclusion, our initial findings represent a promising approach to MCM that can be explored for future operational concepts.

Recommendations for Further Research

The preliminary results can be improved and expanded in several ways. First and foremost, a complete definition and rigorous assessment of risk is needed for clandestine mine countermeasures (MCM) operations. Methods have been developed to calculate the risk to vessels transiting through a mined area, both before and after MCM operations have been performed. Whereas these methods compute the risk to follow-on vessels transiting through a relatively large area, clandestine MCM concentrates search effort in a much smaller area to find a specific route with a much lower level of risk, provided other vessels can accurately follow it. Additional research should focus on adapting existing risk models to fit this paradigm, including the risk due to navigation errors—especially in contested environments where GPS may not be available. One way to create a common risk assessment baseline for future research is to utilize the same minefield simulation software developed by Naval Surface Warfare Center-Panama City for both concepts of operation.

Another area to explore in future research are tradeoffs associated with multiple, cooperating vehicles in contested environments. Additional simulation and analysis could help determine optimal AUV team compositions, assess tradeoffs associated with information sharing versus its attendant motion constraints, and compare mission performance metrics, among other factors.

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Acronyms

AUV	autonomous underwater vehicle
DMO	distributed maritime operations
FLS	forward-looking sonar
GPC	great power competition
MCM	mine countermeasures
SMWDC	Naval Surface and Mine Warfighting Development Center
NSWC-PC	Naval Surface Warfare Center—Panama City