2021

Performance Impacts on Unmanned Vehicle and Sensor Capabilities for Standoff Mine Detection in the Very Shallow Water, Surf Zone, and Beach Zone

Klamo, Joseph; Kragelund, Sean P.; Gozzi, Benjamin; Loberg, Ronan

Monterey, California: Naval Postgraduate School

http://hdl.handle.net/10945/69879

NAVAL RESEARCH PROGRAM
NAVAL POSTGRADUATE SCHOOL

MONTEREY, CALIFORNIA

PERFORMANCE IMPACTS ON UNMANNED VEHICLE AND SENSOR CAPABILITIES FOR STANDOFF MINE DETECTION IN THE VERY SHALLOW WATER, SURF ZONE, AND BEACH ZONE

EXECUTIVE SUMMARY

Principal Investigator (PI): Dr. Joseph Klamo, Graduate School of Engineering & Applied Science (GSEAS), Systems Engineering
Co-Investigator (Co-I): Dr. Sean Kragelund, GSEAS, Mechanical and Aerospace Engineering
Additional Researcher(s): Mr. Benjamin Gozzi, CIV, INT; Mr. Ronan Loberg, CIV, INT

Student Participation: LT Alexander Fedorovich USN, Mechanical and Aerospace Engineering

Prepared for:
Topic Sponsor Lead Organization: Marine Corps Forces Command (COMMARFORCOM)
Topic Sponsor Name(s): Science Advisor, Fleet Marine Force, Atlantic, Mr. Jeremy Hoff
Topic Sponsor Contact Information: jeremy.hoff@usmc.mil,
Topic Sponsor Name(s): Science Advisor, Navy Expeditionary Combat Command, Mr. Phillippe Reed
Topic Sponsor Contact Information: phillippe.l.reed.civ@us.navy.mil, 757-462-4316 x238
Topic Sponsor Name(s): Science Advisor, Fleet Marine Force, Atlantic, Mr. John Phillips
Topic Sponsor Contact Information: John.T.Phillips2@usmc.mil, 757-836-2127

This research is supported by funding from the
Naval Postgraduate School, Naval Research Program (PE 0605853N/2098).

Project Summary
The Navy and Marine Corps have a need to detect underwater mines and explosive ordnance from safe standoff distances in very shallow water (VSW), surf zone (SZ), and beach zone (BZ) environments. This study investigated the relationship between unmanned vehicle motion and the object detection performance of imaging sensors used for mine countermeasures. Several computer vision algorithms for automatic object detection were investigated, and the well-known Region-based Convolutional Neural Network (R-CNN) was selected. A pre-trained network was modified to detect spherical targets with an underwater camera. Prior research on the wave-induced motion for different vehicle hull forms was used to design an apparatus for subjecting the camera to roll, pitch, and yaw motions expected in typical VSW/SZ settings. Camera motion was recorded by an inertial measurement unit, and the resulting videos were processed by the modified R-CNN algorithm to analyze the impact of platform motion on the algorithm's object detection performance.

The R-CNN detection algorithm performed remarkably well on video imagery captured in clear water, correctly detecting a glass sphere with greater than 99% confidence whenever this object was fully visible in an image frame. The algorithm maintained this robust detection performance in every motion profile tested, even those which exceeded the wave-induced pitch angles and rates predicted for typical VSW and SZ environments. Although angular rates above the camera's frame rate produce blurred images that reduced detection performance, these rates are much greater than underwater vehicles experience in actual maritime environments. We, therefore, conclude that in clear water, wave-induced platform motion has no effect on the object detection performance of a well-trained deep learning algorithm processing video imagery from a camera with sufficiently high frame rate (i.e., an order of magnitude higher than vehicle pitch rates).

Keywords: *mine, very shallow water, VSW, surf zone, SZ, beach zone, BZ, detection, sensing, standoff, unmanned, mine countermeasures, MCM, explosive ordnance disposal, EOD*

Background
The Navy and Marine Corps conduct expeditionary warfare in very shallow water (VSW), surf zone (SZ), and beach zone (BZ) environments. Both services have a need to detect underwater hazards, mines, and explosive ordnance from safe standoff distances, but VSW/SZ/BZ environments pose severe challenges for unmanned underwater vehicles (UUVs). Breaking waves, currents, and uneven seafloor topography can produce large disturbances and unwanted vehicle motion. The goal of this study is to investigate the relationship between a vehicle's motion and the object detection performance of imaging sensors commonly used for mine countermeasures (MCM). This study will contribute to the sponsors' goals of understanding the capabilities and limitations of existing systems, inform future technology investment, and better define the role of each service for MCM in VSW/SZ/BZ environments.

Prior Naval Postgraduate School (NPS) research by Turner et al. (2018) and Klamo et al. (2021) examined wave-induced motion for a circular cylinder with hemispheric end caps. This canonical shape approximates the hull form of torpedo-shaped vehicles like NPS's Hydroid REMUS 100 and the Navy's Mk 18 UUVs used for MCM missions. Additional research by Marks (2020) analyzed the dynamic response of a remotely operated vehicle (ROV) from BlueRobotics. This platform resembles boxy, tethered vehicles like the Seabotix vLBV300 or SRS Fusion ROVs used by explosive ordnance disposal teams. These experimental results determined the range of wave-induced motions and experimental parameters used for this study.

We investigated several object detection algorithms for this project. MATLAB's Computer Vision Toolbox was used to calibrate the underwater camera, implement well-known object detection algorithms, and assess their utility for detecting underwater mines. First, we tested an April Tag detector for finding a set of predefined fiducial markers typically used for robot localization. While not practical for MCM missions, this method provided a baseline for detecting known objects. Next, we tested the Speeded Up Robust Features (SURF) detection algorithm normally used for three-dimensional object recognition and reconstruction. This algorithm produced numerous false positives, yet failed to reliably detect the spherical target, despite benign test conditions. Finally, we used MATLAB's Deep Learning toolbox to implement a Region-based Convolutional Neural Network (R-CNN). We replaced the last three layers of the ResNet-18 pre-trained network with new fully connected, softmax, and classification layers, and used MATLAB's tools to train the network to detect a spherical "mine" (glass sphere) in our training image dataset.

Two interns with the Naval Research Enterprise Internship Program and the Science & Engineering Apprentice Program worked with an NPS student to design the experimental apparatus. This test fixture was used to constrain the underwater sensor to one angular degree of freedom and subject it to different motion profiles. An inertial measurement unit recorded the sensor's angular position, rate, and acceleration as it captured images of the spherical target in a water tank. After moving the sensor through a series of roll, pitch, and yaw motions, the resulting videos were processed by the R-CNN to assess the impact of platform motion on automatic object detection performance.

Findings and Conclusions

The R-CNN detection algorithm performed remarkably well on video imagery captured with an underwater camera in clear water. We had anticipated that large amplitude or high frequency motion would adversely impact detection performance. However, our testing found that the R-CNN algorithm correctly detected a glass sphere with greater than 99% confidence whenever this object was fully visible in an image frame. Surprisingly, the algorithm maintained this robust detection performance in every motion profile we tested, even those which exceeded the wave-induced pitch angles and pitch rates predicted for typical VSW and SZ environments. We note that angular rates above the camera's frame rate produce blurred images that reduce detection performance, but these rates are much greater than underwater vehicles experience in actual maritime environments. We, therefore, conclude that in clear water, wave-induced platform motion has no effect on the object detection performance of a well-trained deep learning algorithm processing video imagery from a camera with sufficiently high frame rate (i.e., an order of magnitude higher than vehicle pitch rates). However, these results should be verified for different types of objects in operationally relevant environments.

The latter is particularly important, as MCM vehicles and sensors are unlikely to encounter benign water conditions in VSW/SZ/BZ environments. Suspended sediment, air bubbles, vegetation, and variable light conditions reduce visibility and pose significant challenges for underwater cameras. Imaging sonar provides an alternative sensing modality to potentially overcome the poor visibility of these environments, but forward-looking sonars (FLS) produce very different images—at lower frame rates—than underwater cameras do. Moreover, sonar imagery can vary greatly as a function of the target's aspect angle relative to the sensor. It remains to be seen whether an R-CNN algorithm can be trained to reliably detect a mine-like object in FLS images generated under platform motion. We have begun analyzing this aspect dependence by generating synthetic FLS images from a simulated sonar in a three-dimensional model of our water tank and spherical target. Meanwhile, an NPS student has started to collect actual FLS imagery to train a new R-CNN detection algorithm and analyze its performance for comparison with our camera results. This project's topic sponsors will be included on the distribution list for the completed master's thesis.

Recommendations for Further Research

This study investigated the relationship between an unmanned vehicle's motion and the object detection performance of imaging sensors typically used for mine countermeasures. A deep learning algorithm trained to detect a spherical target in underwater camera imagery was capable of successful target detection under a variety of motion profiles expected in very shallow water (VSW), surf zone (SZ), and beach zone (BZ) environments. Platform motion was found to have no effect on detection performance, but these experiments were conducted in clear water. It is important to verify these results in the desired operational settings, where decreased visibility will be a significant factor for optical cameras.

This project modified an existing convolutional neural network used for computer vision, trained it to identify a spherical target, and employed it for real-time object detection. Ongoing thesis research is applying this process to forward-looking imaging sonar. Future research should investigate whether these deep learning algorithms, trained for one vehicle's sensor, can be adapted to other vehicles' sensors.

Deep learning algorithms have greatly improved automatic target recognition algorithms used on Navy unmanned underwater vehicles. These algorithms have been trained using historical datasets collected by side-looking sonar systems on free-swimming vehicles operating primarily in VSW environments. Additional research should assess whether these algorithms can be adapted to use imagery from forward-looking sensors in SZ/BZ environments. Similarly, a future study can research ways to implement these algorithms on tethered remotely operated vehicles, bottom-crawlers, or unmanned aerial vehicles equipped with different sensors.

References

Klamo, J. T., Turner, T. M., Cool, C. Y., Yeager, K. I., & Kwon, Y. W. (2021). On the accuracy of an analytical solution to model wave-induced loads on an underwater vehicle in real-time. *Journal of Offshore Mechanics and Arctic Engineering, 143*(3), 031202. https://doi.org/10.1115/1.4049119

Marks, J. D. (2020). *The effects of wave-induced loads on ROV performance while operating at near-surface depths* [Master's thesis, Naval Postgraduate School]. NPS Archive: Calhoun. https://calhoun.nps.edu/handle/10945/65400

Turner, T. M., Klamo, J. T., & Kwon, Y. W. (2018). Comparison of wave-induced loads on a near surface slender body from inviscid flow linear solution and an experimental model test. *ASME 2018 37th International Conference on Ocean, Offshore and Arctic Engineering, Volume 7A: Ocean Engineering*, V07AT06A015. https://doi.org/10.1115/OMAE2018-77760

Acronyms

BZ	beach zone
FLS	forward-looking sonar
MCM	mine countermeasures
NPS	Naval Postgraduate School
R-CNN	Region-based Convolutional Neural Network
ROV	remotely operated vehicle
SURF	Speeded Up Robust Features
SZ	surf zone
UUV	unmanned underwater vehicle
VSW	very shallow water