EXECUTIVE SUMMARY

Demonstration of Crawler-Towed Sensor Technologies in Challenging Nearshore Sites

ESTCP Project MR-201422

DECEMBER 2018

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1.0 OBJECTIVES OF THE DEMONSTRATION

Environmental remediation in nearshore environments is significantly complicated by the dynamics of the environment. Applications related directly to detection and characterization of Unexploded ordnance (UXO) in nearshore environments as well as those required to support UXO surveys are challenging due to the nature of the environment. There are a wide variety of problems presented:

- Limited mobility, traction and control,
- Poor visibility and overall situational awareness,
- Various physics-based challenges for sensing, such as acoustic backscatter and multi-path propagation, lack of radio frequency transmission, and moving free surface, and
- Accurate positioning and navigation.

Despite these challenges, there is a need for geophysical surveying in very nearshore areas. Underwater munitions are becoming increasingly problematic as ports & harbors, seashores, and other underwater environments are commercially developed or utilized for work or recreational activities. These environments vary significantly with respect to depth, morphology, geology, munitions density and human exposure scenarios.

Our focus was on relatively shallow-water areas such as surf zones, marshes, mudflats, swamps, intertidal/littoral zones, and other water bodies less than 5 m deep. Concentrated human activities and potential intrusive interactions occur in these areas due to fishing, shellfish gathering, swimming, surfing, bathing, jet-skiing, etc. Additionally, construction activity (i.e., dredging, infrastructure repair, pipeline installations) occur in these settings. These areas are also settings for munitions constituent pathways through direct consumption or via consumption of fish or shellfish.

The main goal of this demonstration project was to assess a combination of platform and sensing systems in order to deliver a UXO mapping survey and characterization technology in very challenging nearshore environments. Nearshore environments such as swash zones, surf zones with breaking waves, and shallow tidal areas provide hydrodynamic and bottom conditions that are particularly challenging from the standpoint of mobility and stability of sensing platforms in order to acquire high quality geophysical data. To overcome the limitations of current diver/man-portable or ship-towed configurations in these nearshore regimes, we evaluated both platform and sensor performance to demonstrate and characterize a tailored and integrated robotic bottom crawler-towed sensor solution in representative shoreline UXO sites. The tests and demonstrations reported on here are among the first of their kind in terms of quantification of UXO detection survey performance metrics for a system that can traverse back and forth between fully submerged and dry land environments.

We report here on the final demonstration in a series of graduated and systematic tests that progressed from basic system evaluations on land, to crawler mobility assessments in varying hydrodynamic conditions and on different bottom types, to engineering tests of initial integrated prototype systems, to full-scale demonstrations. Prior evaluations, system testing, and initial engineering trials and demonstrations are provided in interim project reports completed in 2015 and 2016. Validation is conducted through analysis of integrated electromagnetic induction
(EMI) array, position, and attitude data collected during execution of several dry (beach) and submerged survey profiles. We tracked the cost and time of using the demonstrated system to complete the various missions for comparison against the cost and time efficiency of currently used methods. The final objective of this demonstration was to identify shortcomings and areas of improvement in the hardware, software, and operation of the integrated system.
2.0 TECHNOLOGY DESCRIPTION

For this demonstration, we integrated and implemented a robotic amphibious crawler platform with a towed EMI sensor array designed to provide a stable and mobile geophysical sensing platform for seafloor investigations. Figure 1 shows the primary elements of the system. The crawler system is the SeaView SurfROVer, an amphibious robot with radio telemetry or integrated fiber optic tether system, track controller, lights and cameras, and Global Positioning System/Inertial Navigation System (GPS/INS) positioning system. The crawler is transported in the self-powered / self-contained operator control station (OCS) trailer system. The OCS contains the subunits for radio communication and data interface with the robotic crawler, GPS base station, helmsman navigation and control units and displays and sensor analyst computing facilities. The towed EMI sensor payload technology is the WRT FlexEM 3D system suitable for underwater UXO mapping, detection and dynamic target classification. It comprises two transmitters and six triaxial “cube” receivers across its 2-meter swath width. The integrated system contains subsea power supplies in the form of two 7.5 kWh smart battery pods in addition to an isolated and independent battery power supply for the EMI array, which enables 6-8 hours of continuous operations. Command and control of the crawler-EM unit is provided through a wireless radio link from the crawler antenna mast to the operator control station (located either on shore or on a vessel). Positioning of crawler and tow sled is provided through a mast-mounted real-time kinematic (RTK) GPS rover antenna on the crawler and a set of inertial measurements units combined with a tow-point optical encoder for translating yaw as well as roll and pitch motions from the GPS locations.

The crawler-EM platform contains 3 basic elements: i) the mobility platform with track motors for driving the tracks, camera and sonar sensors, and data interface backbone; ii) antenna mast system with RTK-GPS rover and wireless ethernet radios; and iii) the towed FlexEM 3D EMI sensor array sled. The operator control station is housed in a self-powered trailer unit and contains the helmsman navigation and control systems, communications, displays, and sensor analyst computing facilities.

Figure 1. Photographs of the Integrated Crawler-towed EM System (LEFT) and Display Units (RIGHT) in the Operator Control Station.
The crawler platform and integrated tow sled system were successfully deployed multiple times and proved to be a stable operating platform with adequate tractive control on all substrates on which it was tested (dry grass and gravel, soft sand, mud and silt, shelly sands, dry and saturated fine to coarse sand). Initial deployment testing exposed the need for improvements to the fiber optic tether system, the tow-point encoder and positioning system, and to the EM array sled. Analyses of EM data acquired during these preliminary tests were used to optimize system configuration and data acquisition parameters. Specifically, we made iterative modifications to the mechanical tow sled assemblies and EM system electronics to reduce the overall noise floor of the system by a factor of 6. Additionally, these tests yielded significant improvements for the mission operations and methods used to survey with the system. This included waypoint following and user interface navigation guidance software as well as assessments and planning tools for turn radius and traction/trafficability potential of the system.
3.0 DEMONSTRATION RESULTS

To support the preparation of the system, we began in 2015 with a series of instrumented sensor array sled tests and evaluations of amphibious vehicles to pull the sled. This progressed in 2016 to integration and shakedown testing with the SurfROVer crawler system including initial engineering trials in Lake Erie. These efforts culminated in a demonstration of the first prototype version of the integrated crawler-EM system at the USArmy Corps of Engineers (USACE) Field Research Facility (FRF) in Duck, North Carolina in November of 2016. These early demonstrations exercised the system in a variety of hydrodynamic conditions (from waves and surf to marsh and lake) and bottom types (from sandy beach to muddy marsh). The results of accumulated work in 2015 and 2016 were summarized in an interim report submitted to ESTCP.

We utilized many observations and lessons learned from those prior demonstrations to formulate a series of modifications and improvements toward the demonstrations reported on in this report. The primary modifications to the system included replacement of the fiber-optic tether system with a wireless radio link from the crawler to the topside control station in addition to topside user interface improvements and various additions or improvements to optimize the subsea platform and integration with EM sled. On the crawler, we implemented a greatly improved battery management system, a new tow point encoder unit, and completely self-sufficient and isolated power supply for the EM array. These improvements all benefited the overall operations of the system during our demonstrations.

In our 2017 demonstration, we also attempted to learn from and improve upon the installation of a target grid in the shallow nearshore areas at the USACE FRF surf zone site. An array of 20 targets were installed in a grid pattern over an area extending from the beach approximately 70 meters into the surf zone just south of the FRF pier in water up to approximately 2 meters deep. Figure 2 shows some photographs of the test set up. While it was somewhat challenging for particular targets to remain covered and in-place over more than a tidal cycle, we were able to perform a 100% coverage surveys over the entirety of the target grid area. These surveys resulted in data covering approximately 3500m$^2$ of coverage area at an approximate full coverage rate of 0.5 acres per hour.

![Figure 2. Photographs of the Targets Used in Our Demonstration.](image)

*Targets ranged from small ISO simulants and 60mm mortars to 105mm projectiles. Targets were buried approximately 25cm below the seafloor surface along shore-parallel lines in similar water depth. The deepest targets were submerged under 1.5-2.2 meters of water.*
To assess system stability, we analyzed and compared inertial data from the crawler and tow sled inertial measurement units (IMUs). Typical target area transects began on the beach and progressed directly into the surf perpendicular to the shoreline. Once in the surf, the crawler-EM system rate of forward advance would slow due to hydrodynamic resistance and possibly also due to softer sediments on the seafloor. Among the most dynamic and challenging regimes was deep swash and surf inside of the wave break where strong wave induced currents ebb and flow. This phenomena is illustrated in the data and photographs shown in Figure 3.

![Figure 3](image-url.png)

**Figure 3.** TOP: Histograms of the Roll, Pitch, and Yaw Deviations During Shore Perpendicular Transect Surveys into the Surf Zone. BOTTOM: Photographs Showing Various Viewpoints of the Crawler and Towed EM Sled During Operations in the Surf and Swash Zones.

Data from our full coverage surf zone surveys were analyzed using post-processing software to measure area coverage, target detection and localization, and classification performance. All targets were detected at signal-to-noise ratio > 20 dB for a 100% probability of detection. This far exceeded our detection metric of 100% detection using a 9-dB threshold. A map of the coverage data and detection localization results are shown Figure 4. The target localization accuracy was better than 30cm circular error probability (CEP) for all target encounters exceeding our performance metric of 100cm CEP. However, the variance in target positions were approximately 50cm, which was higher than our target metric of 35cm. This was found to be mainly due to wobble and sway of the GPS mast and motion of the GPS rover antenna atop of the mast. We also observed and analyzed data to assess the overall stability of the system in the relatively dynamic surf zone conditions during our operations. We found the crawler-towed system to be very stable in the face of crashing waves up to 1.8 meters tall and forceful currents in the swash and surf zones during ebb and flood cycles between wave breaking events. In some cases, the EM sled appeared to lift from the bottom (perhaps related to heavy cavitation) and sway before the motion of the crawler was enough to pull it back in track. This added to the uncertainty of the array position, although we were able to mitigate this through analysis of tow point encoder and relative differences between crawler- and sled-mounted IMU data.
Figure 4. LEFT: EM Signal Map from 100% Coverage Surveys Over the Target Grid. The Black Circles Indicate Ground Truth Locations. High Signal-to-noise Anomalies Are Shown Near Each Target Location with Only a Few Anomalies Not Associated with Emplaced Items Shown. Three of the Originally Installed Targets Washed Away Overnight Prior to Our Surveys. RIGHT: Summary Plot of Target Localization Deviations from Ground Truth. All Targets Were Localized to Within 1.0 m, and All But 3 (86%) Were Located Within 50 cm. Offset of the Aggregate Detection Localization Data Were Less Than 5 cm in Either Northing or Easting, Although the Standard Deviations Were Nearly 35 cm. This Was Likely Due to Motion of the GPS Antenna Mast, Which Was Especially Evident in Deeper Areas (As Designated as the Deepest Line of Surf Targets).

We also showed that the demonstrated configuration of the EM array was capable of target classification when multiple transects were aggregated together and inverted for magnetic polarizability curves. Inverted polarizability curves were matched to library curves for a subset of targets and analyzed. A few examples are shown in Figure 5. Although we were only able to compile a limited number of target encounters and even fewer clutter encounters, the consistency of the inverted polarizabilities yield promise for reducing the number of clutter by as much as 50-75%. Additional experiments with methods to switch the two side-by-side transmitter coils on the array indicate potential paths to improved classification that are less dependent on (or completely independent of) relative positioning between adjacent transect overpasses. This holds great promise for dynamic classification implementations in the marine environment.
Figure 5. Examples of Magnetic Polarizability Curve Matches to Library Curves for Target Encounters.

The inverted polarizability curves (red, blue, and green curves) match most closely to the library curves for most targets (gray curves). Good fits to the largest (105mm, as shown on LEFT) and the smallest (60mm, as shown in CENTER) were observed. Clutter objects did not exhibit the size and symmetry characteristics generally associated with UXO target classification.

In addition, we conducted assessments of the cost and logistical complexities for potential deployment and operation of the technology. Projected daily rates of approximately $8,500 for the integrated demonstration system (including a crawler helmsman operator) lead to considerable savings relative to deployment of an explosive ordnance disposal (EOD)-trained dive team searching the seafloor for UXO. Estimation of incurred labor and equipment costs estimated during survey mode operations yields a 100% real coverage costs of approximately $2,500/acre or $1,250/hour. We assessed potential cost savings using this technology for a particular UXO site study where 500 survey contacts required reacquisition and further investigation. In this case, the crawler-EM system reveals as much as a 50% cost savings relative to conventional diver-based methods. Previous assessments have identified as many as 420 underwater ranges at over 120 different military sites comprising approximately 10 million acres of marine or lacustrine environment potentially contaminated with UXO. Of these 420 sites, it projected that 100 or more contain water depths that prohibit the use of towed geophysical survey systems or EOD divers. In many highly dynamic or otherwise challenging nearshore sites, it is likely not cost effective or just plain impossible to use dive teams for geophysical surveying.
4.0 IMPLEMENTATION ISSUES

In general, we experienced relatively smooth operations from the set-up stage through to completing surveys to demobilization at the end of the day. Very little calibration of the system is required. A functional test of power and communications of all systems was conducted without any issues. The crawler platform was mobilized and positioned initially through a small handheld controller that attaches directly to the crawler platform. The demonstration surveys were conducted without any particular issues; however, we noted some observations toward future implementation and optimization for potential cost-effective production operations. These include: (i) added perception and control for obstacle avoidance and navigational awareness; (ii) automation of the grid surveys to reduce operator demands and potential fatigue; and (iii) stability of the antenna mast and sensor sled to maximize positioning accuracy and tracking.

After completion of our full grid coverage surveys, we performed a couple of additional surveys to test the system in water deeper than that in our grid surveys. During one of these “deep water” surveys, the system halted its forward advance and stopped moving. Subsequent investigations revealed that one of the crawler track axles had become entangled in a 2.5-inch treated manila docking line rope (the type usually used for deck, docking, and anchoring lines on a vessel). The system was pulled back to shore and it was obvious that the rope entanglement was the unfortunate cause of the survey stoppage. This resulted in a bent axle and some minor damage to the crawler track assembly. Repairs have been made so that the system is fully functional again and ready for follow-on surveys. It was determined that this type of entanglement is unlikely to be a common occurrence during operations and was an unfortunate event rather than more likely event that requires mitigation. A possible mitigation strategy for such an entanglement event may be to add flooded cowling covers around the sprocket and axle.

While the demonstrations of this crawler-based EM technology showed effective surveying over moderately sized (1-2 acres) areas, larger areas may prove more challenging. Implementation effectiveness will depend highly on the hydrodynamic and bottom conditions at a site as well as the overall shape and size of the survey area. In general, we might anticipate a need to clear areas from a beach or shoreline to a prescribed closure depth. This is generally the depth of water along a shoreline profile at which sediment transport is very small or essentially non-existent and coincides with the foreshore region including swash, surf, and longshore current dominated nearshore. In this case, it would likely be more effective to plan surveys along shore-parallel transects and, thus, stability to shore-normal hydrodynamics such as currents from impinging waves and ebb/flow in swash areas is critical to maintaining high quality towed EM data.

Overall, the demonstrations reported on here illustrated the degree to which the crawler-towed EM system can fill gaps in current nearshore geophysical mapping, detection, and UXO classification. Specifically, we proved that the system could: (i) be mobilized and deployed in a cost-effective manner for shore-based operations; (ii) effectively cover surf zone target areas with 100% coverage transects; (iii) detect and localize UXO targets from 60mm to 105mm in size buried beneath the seafloor to within 50cm radius; and (iv) reduce clutter through analyses of inverted polarizabilities with moderate levels of confidence and effectiveness.