

Littoral Seafloor Sensing and Characterization Using Marine Electromagnetics, Optical Imagery, and Remotely and Autonomously Operated Platforms

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Abstract— Seafloor sensing in littoral environments is challenged by a combination of technical requirements related to the detection, georegistration, and confirmation or characterization of natural and man-made items on, or beneath the seafloor. Specifically, EM sensing from unmanned systems enables the positioning of array-based sensors directly over targets of interest in a wide range of littoral environments: from surf zone to benthic areas in 100's of meters of water. Targets include both anthropogenic objects such as marine archeology and salvage, infrastructure associated with undersea cables, seabed foundations for windfarms, and unexploded ordnance (UXO) and other munitions hazards as well as shallow natural and geologic objects such as freshwater lens, gas hydrates, mineral ore, and heterogeneous sediment deposits.

In this paper, we present aspects of the design, development and testing of array configurations from testing and evaluations in littoral environments. This includes integration and testing with multiple remotely and autonomously operated swimming platforms (ROVs, AUVs, and hybrids). In particular, we demonstrate the deployment of an integrated system based on a hybrid autonomous underwater vehicle and comprising bottom following, station keeping, and waypoint mapping control, a multi-channel frequency-domain EM array, and multiple high resolution imaging sensors. Results from initial testing and pilot studies for UXO surveying, marine archeology, and seabed classification are summarized.

Keywords—marine electromagnetics, remotely operated vehicles, unexploded ordnance, littoral sensing

I. INTRODUCTION AND BACKGROUND

Various subsea applications, including unexploded ordnance (UXO) surveys and underwater pipeline and cable tracking, require the detection, geo-registration, and characterization of man-made targets on, or below, the seafloor. Investigations in littoral environments can be time-consuming and expensive due to the challenges of accurately tracking underwater assets, the difficulty of quick or effective

site reconnaissance activities, high levels of clutter in nearshore areas, and lack of situational awareness and real-time feedback to operators. Consequently, a high payoff exists for effective methods using sensor and data fusion, feature extraction, and effective payload integration and deployment for improved assessments of littoral infrastructure. Over the past 3 years, we have developed and demonstrated integrated sensing technologies for multiple DOD-funded projects that focus on advancing seafloor target detection, tracking, and classification for specific seabed investigation/recovery missions. This includes integration and testing with remotely and autonomously operated sensing platforms (ROVs, AUVs and bottom crawling systems). In particular, we have designed, developed, and tested array configurations of optical seafloor imaging and marine multi-sensor electromagnetic (EM) arrays.

Testing from nearshore deployments in coastal North Carolina and South Florida demonstrate the potential to fuse these methods and enable rapid discrimination of various metallic and other man-made targets as well as characterization, localization, depth of burial estimation, and condition assessment. Current work highlights the technological challenges for both individual sensing modalities and integration of sensors onto various unmanned platforms, with underwater positioning systems, and operated through topside control and interface systems. Targets include both anthropogenic objects such as marine archeology and salvage, infrastructure associated with undersea cables, seabed foundations for windfarms, and unexploded ordnance and other munitions hazards as well as shallow natural and geologic objects such as freshwater lens, gas hydrates, mineral ore, and heterogeneous sediment deposits. In this paper, we present aspects of the design, development and testing of array configurations from littoral site testing and evaluations. This includes integration and testing with multiple remotely and autonomously operated swimming platforms (ROVs, AUVs, and hybrids) as well as bottom crawling systems.

II. INTEGRATED ROV AND AUV GEOPHYSICAL SENSING

A. ROV and AUV Platforms

Remotely operated vehicles (ROVs) can serve many applications in littoral surveys including assisted awareness in support of dive teams, quality control, and target contact reacquisition and digital recording of video or still photos. Previous work [1] presented assessments of the utility of different size and types of ROVs for various UXO remediation support missions. ROV form factors range from man-portable (~15 kg) mini-class systems to large worker-class (1000+ kg) ROVs. Deep submergence worker-class systems (e.g., ROUMRS or Remotely Operated Underwater Munitions Recovery System) are significantly more expensive and complex to deploy and operate than smaller inspection-class (mini-to-midsized) systems. The most common class of ROVs in terms of availability and application to UXO work are the man-portable inspection-class ROVs such as the Seabotix vLBV, the Teledyne Stingray, and the Saab Seaeye Falcon among others.

The Seabotix vectored-thrust ROV (vLBV) is an up-sized version of the previously configured Seabotix fixed-thruster LBV mini-ROV. For our initial engineering trials, we integrated the Seabotix vLBV-300 system with an inertial core navigation system (the Greensea Balefire) and a small marine controlled-source electromagnetic (EM) sensor array. The vLBV-300 we used was originally configured for the U.S. Naval Expeditionary Combat Command (NECC, Little Creek, Virginia) and includes six powerful brushless direct current (DC) thruster motors. Four of them are actuated for vectored thrust and two are fixed for vertical thrust control. The adjustable vectored thrusters provide equal horizontal thrust in all directions, or extreme unidirectional pulling power for maneuvering and payload positioning in high currents. The total forward bollard thrust (22.5 kgf) of the vLBV is more than 3 times that of the smaller LBV mini-ROVs (7 kgf) commonly used for visual inspections. Although these ROVs are 75% larger and heavier than the LBV mini-ROVs, they are still portable enough for single-person dockside or boatside deployment. Their remote control systems are straightforward to operate, precisely controllable, and very powerful for their size. Because they are man-portable, no special launch and recovery systems are required. They are also representative of a large portion of the available commercial rental pool and thus have large and immediate applicability for UXO operations.

These ROVs can be outfitted with high resolution cameras (HD1080i, zoom), scanning/sector sonars, multibeam imaging sonars, and use a low-drag tether. The vLBV system also supports additional payloads through several available sensor pass-through ports on the vehicle. The system used for our



Figure 1. The integrated VLBV-EM system is based on the Seabotix LBV inspection class ROV system. The MFDA sensor array is mounted below and forward of the vehicle platform with a counterbalancing deflector below the stern to provide stability in turn and dive maneuvers.

demonstration is depth rated to 300 m in saltwater, though depth ratings to 950 m are possible on a slightly larger version of the system. Our demonstration system was equipped with a Tritech MicronNav Ultra-Short Baseline (USBL) positioning system as well as a high resolution inertial navigation and positioning system.

We have also integrated EM and optical sensors onto larger and more capable autonomous platforms such as the the Cobalt Marine "Dolores" Hybrid AUV (HAUV-1000). This AUV system, "Dolores", is permanently installed on an operations vessel and is equipped with forward-looking sonar, side-scan sonar, a low-grade inertial navigation system, and is powered by two 5.35 kW-hour lithium-iron (LiFePO₄) rechargeable batteries.

The Dolores HAUV vehicle body (Figure 2) is primarily constructed of non-ferrous materials and was specifically designed for metallic object detection operations. As a hybrid system, it provides remote control typical of traditional ROVs using a fiber-optic tether as well as a fully autonomous mission execution without a tether. Similar to most other ROVs, when deployed with a tether, Dolores allows for direct operator-in-the-loop control and provides full bandwidth data to and from the HAUV including video, sonar data, payload data, and systems monitoring. A full autopilot suite provides for higher performance control than is typical with traditional inspection class ROVs by augmenting the remote control operation with waypoint navigation, station keeping, attitude control, precision bottom following, and fly-by-wire joystick features. When deployed as an AUV with or without the tether, Dolores is capable of conducting pre-planned missions, large scale surveys, search patterns, and high-resolution interrogation surveys via station keeping.

The hydrodynamically stable body is propelled by two fixed forward thrusters, one lateral thruster, and one vertical thruster. The thrusters are fixed but provide powerful bollard thrusts of over 35 kgf each. They are composed of brushless DC motors actuated by the HAUV control system. This allows the 300 kg (in air) HAUV system to remain stable in moderate currents (2.5 knots). This means that the system can hold station in terms of attitude, depth, and lateral position even with the forward mounted EM array platform (discussed in the following sections). A significant advantage that this HAUV system configuration has over traditional tethered ROVs for operating UXO detection technologies is that it is battery powered, eliminating noisy umbilical and power distribution systems. The on-board power management system provides up to 14 continuous hours of operation in ROV mode and over 18 hours in AUV mode.



Figure 2 The Hybrid Autonomous Underwater Vehicle HAUV-1000 or "Dolores" is a hybrid AUV-ROV with highly accurate positioning and control realized through 1 fixed lateral thruster, 1 fixed vertical thruster, and 2 aft forward thrusters. The MFDA EM sensor array is shown here mounted from the bow and extending down and in front of the platform.

B. Marine Electromagnetic Array

The multi-frequency digital array (MFDA) was based on a multi-frequency technology originally incorporated in US Army handheld metal detectors. This system utilizes a differential receiver design similar to that in the vehicle-mounted Single-Transmit Multiple-Receive (STMR; originally developed Minelab Ltd.) system. In contrast to similar frequency-domain EM (FDEM) instrumentation (e.g., Geophex GEM-3), the MFDA employs a single transmitter and three single-axis (z-oriented) differential receivers. This multi-static configuration provides multiple measurements of the sampled scattered magnetic field that in turn yields information about the spatial distribution of the scattered field from targets of interest.

The sensor head is constructed of very lightweight (1.4 kg) high density foam and comprises a 65 cm-wide transmitter and three figure-8 shaped (quadrupole) receiver coils (Figure 3). The three quadrupole receivers form oppositely wound coils (monoloops) that create an equal and opposite electromagnetic field from the transmitter on each monoloop coil. When the signals from each coil are added in series, the primary field



Figure 3. The Multi-Frequency Digital Array (MFDA) is a frequency-domain multi-sensor array capable of detecting and characterizing both ferrous and non-ferrous conductors on or below the seafloor. Originally developed for finding buried explosive hazards, this system was modified and retrofitted for marine EM deployment from ROV's by our team in 2011.

disappears leaving only the secondary field response. This arrangement has the advantage of canceling the net primary field from the transmitter and vehicle noise as well as providing accurate 3-dimensional target localization. The digital data acquisition and processing electronics are housed in a small pressure vessel and weigh about 0.24 kg. The system currently transmits 4 frequencies simultaneously, but can transmit and receive up to 8 frequencies over a range of 400 Hz to 70 kHz. Communication with the host at a rate of 10 Hz provides in-phase and quadrature-phase signals for each frequency and for each coil. As well as the raw in- and quadrature readings, the sensor supplies a set of ground-compensated data based on a simple normalization method [2]. The digital demodulation procedures utilized in this array are unique among frequency-domain detectors in that they do not require sequential (or stepped) detection of each frequency component, but utilizes a continuous wave demodulation such that higher frequency harmonics are nearly eliminated [3]. This is achieved through the application of an optimally designed 3-level waveform through two half-bridge amplifier circuits.

This frequency-domain sensor has the advantage of superior control of selection and power in the frequency content of received signals. In marine applications where conduction currents influence the quadrature-phase signal, the FDEM approach provides additional in-phase information that may be important for characterizing targets of interest [4]. The quadrupole (figure-8 shaped) receiver coil configuration is well-suited for canceling plane wave fields that may be induced in the water column from conduction currents. Additionally, this system is less band-limited than similar pulsed induction arrays and, thus offers a greater equivalent time range of response, particularly at very early times (or equivalently high frequencies) and at sufficiently late times where information on the asymptotic limits of scattering may reveal important discriminating information.

In 2011, the system was encased in a ruggedized pressure vessel, integrated with a Seabotix mini-ROV (LBV-300-5), and tested in the underwater environment as part of a pilot study at the Port of Seattle. During exercises and tests, the integrated ROV-EM system logged hundreds of hours of operation and was deployed from docks, a large pier, and from

rigid-hulled inflatable boats (RHIBs). ROV-EM data were primarily acquired along dive lines to provide quality assurance of visual dive inspections.

C. Optical Imagery

Optical imagery was utilized at a few sites to assess the potential of supervised classification to support the detection and characterization of underwater infrastructure such as UXO and benthic habitat. The main strength of underwater images of the seabed is their high spatial resolution relative to other acoustic wave or magnetic/electromagnetic field methods. Underwater images provide significant enhancement for situational awareness of the seabed and can be georegistered and correlated with anomalies identified in EM or sonar maps. Well established methods developed by the University of Miami ([5],[6]) have yielded new automated seabed and UXO image segmentation and classification algorithms that accurately classify benthic biota and UXO.

Optical images were generated at multiple sites in south Florida and Hawaii using two GoPro Hero 3+ cameras, generally set to record high definition (1080 x 1920 pixels), progressive scan video. The CMOS (complementary metal oxide semiconductor) image sensors can be integrated into a single stereoscopic housing configuration and synchronized full-resolution video or imager can be acquired for three-dimensional scene generation. For ROV-based image acquisition, we mounted the cameras on the aft tail stabilizer focused downward toward the seafloor at an approximately nadir view angle.

III. SEAFLOOR SENSING APPLICATIONS & DEMONSTRATIONS

Integrated multi-modal sensing for seafloor characterization applications has been demonstrated through a handful of pilot studies at littoral sites along the coast of the continental U.S. These pilot studies have ranged in application from demonstration of ROV- and AUV-based sensing for UXO, to mapping for marine salvage and treasure to, pipe and cable characterization. Examples of the results of applying integrated EM, imagery, and ROV or UAV systems are described in the sections below. :

A. Unexploded Ordnance Mapping and Characterization

We have conducted multiple demonstrations and pilot studies using the MFDA EM sensor array integrated with both inspection-class ROV's and the HAUV platform. Here we highlight and summarize results from recent demonstrations (2013-2015) of technology that has been tailored for underwater UXO detection. In 2013, we demonstrated the vLBV platform for deploying the MFDA for detecting UXO on the seafloor. The ROV's inertial navigation and control system was tightly integrated with EM array data acquisition system allowing for the robust detection of small munitions (60 mm diameter and smaller) under varied conditions by providing accurate sensor positioning.

We demonstrated operations including executing bottom following, station keeping, and autonomous search modes in water depths of up to 20 m at an open water site approximately 10 miles offshore of the Bogue Banks in southeastern North Carolina. The test site was prepared and simulant UXO installed on a flat sandy seabed by divers. Data were acquired to assess the baseline performance of the system with emphasis on validating the precise system positioning and control required for execution of underwater UXO detection and characterization missions. We successfully performed a number of functions of the integrated ROV-EM sensor system including: (i) bottom seabed following to within ± 10 cm at a commanded 35 cm standoff, (ii) system station keeping to within ± 25 cm of a commanded target location, (iii) UXO target detection with signal-to-noise ratios >9 dB and localization accuracy within 60 cm, and (iv) stable and controllable manual and automated waypoint navigation and re-positioning of the system. Figure 4 shows some examples of integrated ROV-based EM signals over a myriad of UXO and pipe targets set of on the seafloor for testing.

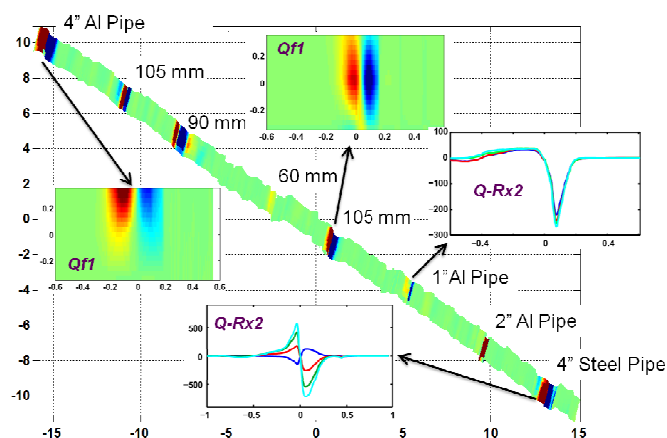


Figure 4. Example map response map from ROV-based EM data collection over multiple UXO test targets and small pipe sections. MFDA EM sensor array detection data show the response of each target (blue/red) is well above the sensor noise floor (green). Zoom-ins of four of the target responses are shown.

In a subsequent demonstration, we utilized the larger and more capable HAUV platform for deployment of the MFDA EM sensor array. This demonstration progressed to more challenging objectives for detection, mapping, and reacquisition and characterization of UXO test items. This system was demonstrated at a test site in approximately 16 meters of water a few kilometers south of Boca Chica Key in the lower Florida Keys. The seabed varied over the site with predominantly flat and sandy bottom as well as areas of sea grass and patch reef as are common in this part of the Hawk Channel and spur-and-groove bank reef on the southern flank of the lower Florida Keys.

After a 40m by 20 m grid was established and surveyed in, we installed 21 test objects on the seafloor including UXO, common clutter objects, archeological artifacts, and pipe sections. The HAUV system was then deployed from a 120-foot aluminum hull vessel. Key mission objectives such as bottom following, waypoint navigation and station keeping for UXO surveys were assessed. Table 1 summarizes the results of the integrated system control and sensor detection performance for our seafloor UXO tests.

TABLE I. SUMMARY OF INTEGRATED HAUV-EM PERFORMANCE

Table Column Head		
Objective	Metric	Performance
Bottom Following ^a	$\Delta Z = \text{cmd_Alt} - \text{obs_Alt} $	$\Delta Z = 10\text{cm}$ $\Delta \text{roll} = 0.15 \text{ deg}$
Station Keeping ^b	$\Delta XYZ = \text{cmd_XYZ} - \text{obs_XYZ} $	$\Delta X, Y, Z < 12 \text{ cm}$ $\sigma X, Y, Z < 13 \text{ cm}$
Waypoint Navigation	$\Delta R = (\Delta N^2 + \Delta E^2)^{1/2}$	$\Delta R = 26 \text{ cm}$
UXO Detection	Detection Probability, False Alarm Rate	100% Detection 5 False Alarms
Detection Accuracy	$\Delta R = (\Delta N^2 + \Delta E^2)^{1/2}$	$\Delta R = 66 \text{ cm}$ $\sigma R < 56 \text{ cm}$

^a. Sampled over 4km of seafloor survey transects

^b. Sampled over 14 stations.

Full coverage over the entire grid was not possible due to limitations for time on site. Figure 5 shows the MFDA EM sensor map over the test grid with groundtruth locations (circles) and target detection locations (crosshair) overlain.

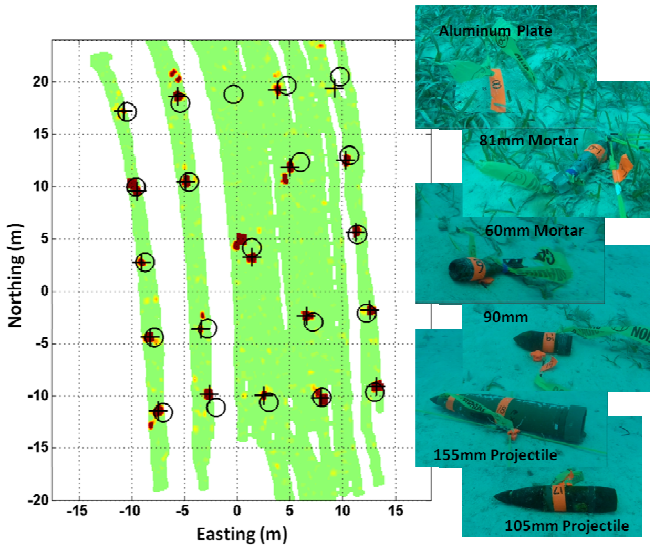


Figure 5. Example response map from ROV-based EM data collection over multiple UXO test targets and small pipe sections. MFDA EM sensor array detection data show the response of each target (blue/red) is well above the sensor noise floor (green). Zoom-ins of four of the target responses are shown.

Related work to distinguish surface features such as benthic biota from man-made artifacts or targets of interest by University of Miami incorporates imagery and structure from motion processing to produce 2 and 2.5 dimensional features. We call the digital elevation model (DEM) approach used here

a “two and a half dimensional” (2.5-D) method because it only

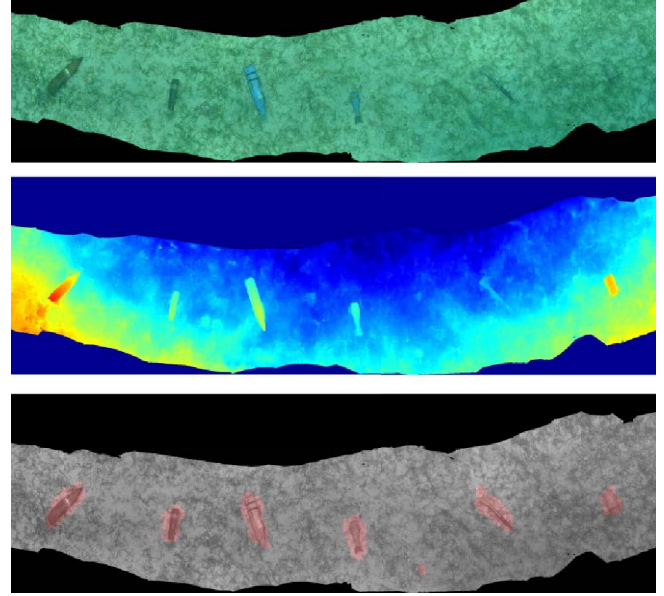


Figure 6. Top: Color image over test UXO items among littoral reef vegetation and sea grass. Middle: Computed digital elevation model based on stereo image pair and structure from motion processing. Bottom: Grayscale image with transparent red pixel classification of UXO objects.

captures information that can be seen from the overhead viewpoint of the camera. In contrast, a true three-dimensional (3-D) method would require data from all viewpoints around an object and would therefore capture information from vertical or overhanging surfaces that can't be seen from overhead.

Features based on image color and texture were used in an image classifier to learn and discriminate the features of UXO such as shape, size, symmetry, and contextual cues. This is exemplified in Figure 6, where seafloor-emplaced UXO are clearly segmented and discriminated against vegetation and other non-UXO items.

B. Seabed, Pipeline, and Marine Salvage Characterization

During production operations over marine archeological salvage sites off the lower Florida keys, we also emplaced artifacts on the seafloor for testing the sensitivity and clutter rejection capability of the integrated system. The data shown in Figure 7 illustrate the sensitivity of the EM array to both precious metal artifacts as well as changes in the seabed. Here we show the in-phase and quadrature-phase responses over a silver bar and moderately sized hole. The silver bar relic was reportedly from the Nuestra Senora de Atocha Spanish galleon shipwreck of 1622. Each bar weighs approximately 28-31 kg and is 37 x 12 x 8 cm in size. The adjacent whole reveals the sensitivity of the MFDA to seafloor bathymetry and objects. We have generated signals with adequate signal-to-noise (>9 dB) for reliable detection of these artifacts at ranges over 200 cm from the sensor array.

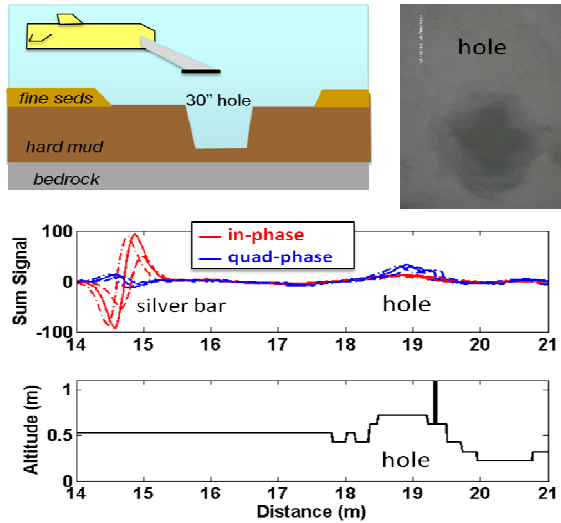


Figure 7. MFDA EM profile as the HAUV traverses a silver bar artifact emplaced on the seafloor and moderately sized hole. The silver bar has a distinct spatial and spectral signature owing to its size, material composition, and position; whereas the hole has a relatively flat spectral signature and broad profile related to the reduced contrast between the conductive water column and the somewhat more resistive seafloor.

Proud seabed objects can also be rapidly classified and corroborated with EM anomalies using high resolution underwater imagery. The University of Miami has demonstrated this at the Ordnance Reef site Hawaii where man-made objects of interest are scattered amongst similar sized coral heads. Figure 8 shows a 2.5-dimensional reconstruction where image data are transformed into a textured surface to allow analysts a rich perspective from which object classification can be derived. The coral head is clear to visible eye in this view with cylindrical-shaped man-made objects very nearby.

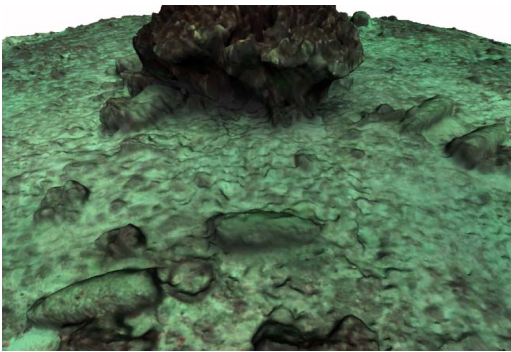


Figure 8. Textured surface derived from seafloor imagery covering a ~ 2 m area of the seabed at the Ordnance Reef, Hawaii site. A moderately sized coral head is evident in the center top portion surrounded by cylindrical man-made objects of interest.

We have also utilized similar sensing methods to map and characterize linear seafloor features such as pipes and cables. In order to better characterize the three-dimensional location of seafloor utilities we have implemented dipole inversion and tracking methods such as those used for the advanced classification of munitions. This method has proven especially useful when multi-axis EM receivers are used in conjunction

high powered marine EM transmitters [7]. We have also experimented with methods to aid in the determination of the composition of seabed objects. For example, we emplaced small pipe sections of ferrous (e.g., steel, iron) and non-ferrous (aluminum, brass) materials on the seafloor and characterized their spectral EM response. At low frequencies, ferrous and non-ferrous objects will have distinct correlations of in-phase and quadrature-phase signals. This is shown in Figure 9 where a 3-inch diameter steel pipe section was buried flush with the seafloor and then surveyed with the ROV-based MFDA EM sensor array. The ferrous pipe exhibits opposite polarity of the low frequency in-phase and quad-phase signals. The spatial distribution of this correlation was found to be robust within a reasonable radius around the pipe (for our array and this size pipe, that radius was ~ 85 cm).

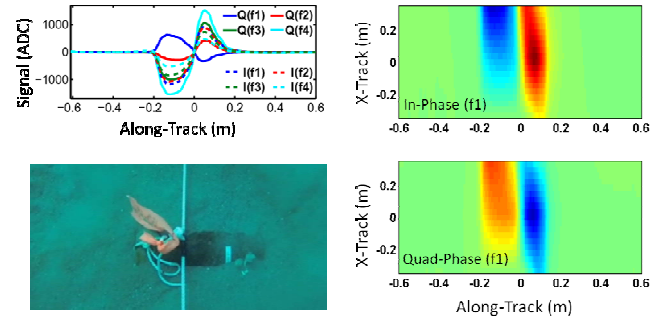


Figure 9. HAUV-based MFDA sensor responses over a steel pipe segment emplaced on the seafloor. Top Left: Signal profile showing the multiple frequency response for both in-phase (I) and quadrature-phase (Q) data acquired at 37cm above the pipe. Bottom Left: Photograph of the pipe segment buried flush with seafloor. Right: Map view signal response for the lowest frequency in-phase (top) and quadrature-phase (bottom) data. Note the opposing polarity indicating a ferrous target.

IV. SUMMARY AND CONCLUSIONS

Results from initial testing and pilot studies of application-specific integrated sensing platforms show promise for improving littoral sensing for UXO survey, marine archeology, and seabed classification applications. Our results are from assessments of platform navigation and control data (bottom following, station keeping, and waypoint control) integrated with data from an EM array and high resolution imaging sensors. Investigations of EM sensor responses to natural variability (varying porosity, benthic habitats, and bottom sediment type) are compared to those from specific man-made artifacts (sunken ship salvage) and military munitions (UXO and mines). We show that frequency domain (in-phase and quadrature-phase) features are described to classify the material composition of individual anomalies. Optical imagery that utilizes stereographic imaging, structure-from-motion, and advanced seabed classification significantly augment and support both areal mapping and detailed surveying and target tracking. Extensions of existing seabed classification algorithms that use seafloor micro-bathymetric height data derived from stereo reconstruction illuminate the utility of so-called 2.5D data in identifying and classifying proud infrastructure.

The ROV-based EMI and imaging technology has particular advantages over instrument-equipped divers or arrays towed from surface vessels. Divers are highly constrained in terms of the mobility, depth and duration during dives due to strict health and safety regulations as well as physics. In addition to being difficult to maneuver, surface towed systems place sensors >2 m above the sea floor, and thus restrict detection capabilities to large UXO only. The ROV-based EM and imaging technology we have demonstrated can be leveraged for specific littoral investigation and recovery operations:

- *Tightly integrated vehicle position and control with high resolution marine EM data and underwater optical imagery.* This has the potential for improved detection and false alarm reduction through multi-sensor anomaly classification using high resolution EM and imaging sensor data collected synchronously with high resolution position data. The image classifier by itself was shown to distinguish munitions from non-munitions (background) with generally high (> 80%) accuracy. This was accomplished at multiple sites in shallow water over seagrass, reef, and sand, and at depths greater than 500 m in sand. Discrimination of environments was high for the major seabed types. For example, sand and mixed sand-seagrass were classified with 80-100% accuracy in both shallow and deep water. Examples of EM-based discrimination were shown through analysis of I/Q data from a multi-frequency digital array.

- *Maneuverable ROVs integrated with accurate navigation and control systems enables precise navigation and positioning of the sensor array in close proximity to the seafloor.* This provides accurate positioning, tracking, and bottom following, which leads to improved survey efficacy and a dynamic repositioning capability for interrogation of individual anomalies. It is critical to accurately and precisely position the sensor in varying conditions while conducting EM and imaging surveys because signal levels drop off quickly with range from a target. Additionally, this affords the operator both a dynamic mapping mode and a detailed reacquisition or static characterization mode with data collection over suspected targets.

- *Tele-operation removes the operator from the water column and allows for accurate operations in both shallow (<3m) and deep water (>20 m).* The endurance of an ROV system is only limited by the tether length and not power supply (UUVs) or safety (divers). This enables extended time on the seafloor as well as significant cost savings relative to deployment of dive teams.

Current and future work is focused on extensions of the technology to more complete characterization of the 3D structure of the seafloor, shallow sediments, and embedded compact targets (such as UXO). Specifically, EM sensing from unmanned systems is positioning our array-based sensors directly over targets of interest in a wide range of littoral environments: from surf zone to benthic areas in 100's of meters of water. The goal of future algorithm development will be on multi-sensor data fusion to exploit texture features from seabed imagery and anomaly-specific EM features to improve discrimination and classification of proud and subsurface anomalies (UXO, pipes, seabed features).

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