SERDP/ESTCP MUNITIONS RESPONSE PROGRAM: AN UPDATE ON DEVELOPMENT AND DEMONSTRATION OF TECHNOLOGIES FOR UNDERWATER REMEDIATION OF UNEXPLODED ORDNANCE (UXO)

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Abstract: *The U.S. Department of Defense Strategic Environmental Research and Development Program (SERDP) and Environmental Security Technology Certification Program's (ESTCP) Munitions Response program supports the development and demonstration of innovative technologies that characterize, remediate, and scientifically manage sites affected by military munitions, including unexploded ordnance (UXO) and discarded military munitions (DMM) (https://serdp-estcp.org). The Munitions Response Program is focused on reducing the costs and improving effectiveness of UXO remediation in underwater environments. The first stage of the program includes the development and evaluation of underwater sensors (acoustic, magnetic, electromagnetic, and optical) and platforms (ROV, AUV, towed, bottom crawling, and airborne) required to detect, classify, and locate (DCL) UXO found in a variety of underwater environments (lakes, rivers, ponds, estuaries, and coastal regions). These systems are currently being evaluated at standardized underwater demonstration sites (Sequim Bay, WA; Kaneohe Bay, HI; Panama City FL; and La Spezia, Italy). Field and laboratory studies of UXO behavior are being used to develop models to predict burial, migration, and re-emergence of UXO in coastal, estuarine, freshwater, and riverine environments. Development of new technologies for physical removal or in situ remediation of UXO are also investigated. In this paper, we will summarize progress and provide a vision for the way ahead for cost effective and efficient remediation of underwater UXO. A comparison of UXO problems and remediation solutions between US and European waters will also be provided.*

Keywords: *munitions remediation, target classification, burial and migration*

1. INTRODUCTION

The Strategic Environmental Research and Development Program (SERDP) and the Environmental Security Technology Certification Program (ESTCP) are the U.S. Department of Defense's (DoD) environmental research programs, harnessing the latest science and technology to improve environmental performance, reduce costs, and enhance and sustain mission capabilities at DoD facilities. Five program areas (https://serdp-estcp.org/Program-Areas) support technologies to 1) improve energy efficiency, increase the use of renewable energy, and enhance water conservation on DoD installations; 2) characterize, perform risk assessments, remediate, and manage contaminants in soil, sediments, and water; 3) advance the DoD's management of its natural and cultural resources; 4) reduce, control, and understand the sources of waste and emissions in the manufacturing, maintenance, and use of weapon systems and platforms; and 5) characterize, remediate, and scientifically manage sites affected by military munitions on U.S. lands and underwater.

SERDP-ESTCP program support for unexploded ordnance (UXO) remediation (item 5) at terrestrial sites has been completed and advanced geophysical systems and signal-processing/machine-learning methodologies proven to detect, classify, and locate buried UXO have transitioned to commercial contractors. This approach allows for separation of harmless subsurface scrap from dangerous, buried UXO, which should reduce the number of costly UXO removal actions and improve the effectiveness of UXO remediation found on the wide variety of contaminated sites. The SERDP-ESTCP Munitions Response (MR) program has turned its support to improving remediation of underwater UXO found in ponds, lakes, rivers, estuaries, and coastal areas out to depths of 30 meters. The main areas of research include development of systems to detect, classify, and localize UXO during wide-area assessment and detailed surveys; munitions burial and mobility; UXO recovery and disposal; and phenomenology associated with characteristics of munitions and site environmental conditions. Standardized underwater UXO demonstration sites (test beds) for testing and evaluation of sensors and platforms designed to detect, classify, and localize UXO in this environment have been established. These technologies are intended to support Defense Environmental Restoration Program remediation of sites contaminated by munitions which is conducted following the Comprehensive Environmental Response, Compensation, and Liability Act. The U.S. Army Corps of Engineers and the U.S. Navy Naval Facilities Command have identified over 450 formerly used and active underwater defense sites, totalling more than 10 million acres in U.S. coastal and territorial waters potentially contaminated with munitions. The basic remediation issues center upon the assumption of the military's liability for ordnance contamination on active and previously DoD-controlled sites in U.S. and territorial waters; most of which were weapons development, testing, and training sites.

Although the research and development objectives of the SERDP-ESTCP MR Program are often similar to those of European nations, the threat from underwater UXO, environmental and societal impacts, legal liabilities, stakeholder roles and responsibilities, and funding for UXO remediation include significant differences. These differences were evident in presentations at the recent Munitions Clearance Workshop held in Kiel, Germany, 6–10 September 2021 (https://munitionclearanceweek.org), and may account for the differences in the respective approaches to development of remediation technologies. Many of the largest remediation sites in European waters (e.g., Baltic and North Sea) are open-water dump sites developed to dispose of stockpiles of munitions and munitions constituents (MC) after World War II. Dumping of munitions (projectiles, bombs, mines, and barrels of MC) is the major contributor to munitions contaminants in the Baltic and North Seas. The large quantities, age, and concentrated nature of these dump sites result in the release of measurable quantities of toxic munitions contaminants into the environment. These contaminates have gotten into the food chain and caused harm to individual species and the ecosystem. In contrast, a compilation and examination of available data revealed that MC concentrations in water, sediment, and biota at U.S. remediation sites were largely below detection [1]. The nature and even definition of underwater UXO may account for these differences. UXO found at U.S. remediation sites mostly include thick-walled projectiles and mortars whereas UXO in the Baltic and North Seas include thinner-walled bombs, mines, and barrels of MC, which are more susceptible to corrosion and leakage. These factors account for the manage-in-place strategies for U.S. remediation sites and the emphasis on investigations of UXO burial, migration, and re-emergence since the thick-walled UXO predominant in U.S. waters are not likely to leak and pose threats to the surrounding environment. Europeans invest more research effort on UXO corrosion and leakage of the energetics into the water column and pathways of energetic constituents to sediment eventually entering the food chain. Environmental and toxicological impact assessments emphasize the state of corrosion of UXO; concentrations, types, and rates of release of munition compounds near dump sites; and the impact of MC on the ecosystem. Furthermore, the legal and financial responsibility for remediating European dump sites include a number of competing local, national, and international (North Atlantic Treaty Organization (NATO) and European Union (EU) committees and commissions) organizations charged with planning and coordination of UXO remediation efforts. UXO remediation in U.S. waters is the prime responsibility of the U.S. military. Large-scale UXO remediation is neither the primary mission nor responsibility of the EU nations' military. It is apparent that large-scale remediation efforts will be conducted by private industry contractors in both European and U.S. waters.

2. SENSORS AND PLATFORMS

Given the wide variety of environments (coastal, estuarine, freshwater, and riverine), water depths, bottom types, munitions types, and hydrodynamic conditions, a single sensor modality or platform type is probably inadequate to accommodate requirements at all possible underwater remediation sites. A wide range of options for systems (sensors and platforms) to detect, classify, and localize (DCL) UXO is therefore being investigated. Sensor modalities include high- and low-frequency acoustic sensors, various magnetometer sensors, optical systems including light detecting and ranging (LiDAR) and traditional still and video camera systems, and cued and single-pass electromagnetic (EMI) sensors. Platforms include autonomous underwater vehicles (AUVs), remotely operated vehicles (ROVs), towed systems, surface systems, bottom crawlers, and airborne (drone) platforms. Optical systems are limited to targets proud on the sediment surface in clear waters. High-frequency acoustic sensors (side-scan and multibeam sonars) are primarily limited to proud targets without water clarity restrictions. Active electromagnetic induction (EMI), passive magnetometer/gradiometer sensors, and low-frequency acoustic sensors can detect buried targets but with different standoff distances, coverage rates, and classification ability. Towed or AUV platforms may be optimal for waters deeper than about 5 meters; bottom crawlers and surface and airborne (drone) platforms including LiDAR and magnetic sensors are most appropriate for shallow-water sites. Platform orientation (roll, pitch and yaw) and geolocation (latitude, longitude, and depth) often require 6-axis sensor orientation for detection and classification algorithms and for reacquiring targets for subsequent remediation.

2.1. Magnetometer/Gradiometer and EMI Sensors and Platforms

The SERDP-ESTCP MR program is supporting the development and demonstration of magnetometer/gradiometer and EMI systems for underwater environments. Potential magnetic and electromagnetic technologies include modified advanced systems proven for terrestrial UXO remediation; systems developed for mine countermeasures operations; and purpose-built systems specific for underwater UXO remediation. Magnetometers and gradiometers generally lack classification ability, other than to provide a magnetic moment measurement related to the size of the object, but have greater standoff detection ranges (up to 5 meters) and are better suited for larger scale surveys. The shorter detection ranges (1–3 meters) for EMI systems restrict use to smaller areas (smaller coverage rates) and for cued classification but can provide excellent classification ability, as demonstrated by their widespread success for terrestrial DCL and clearance applications [2].

Some of the magnetic systems developed or demonstrated under the MR program include towed magnetometer arrays such as the Marine Towed Array (MR-2003421) [3], and the Marine Gradient Array (MR-200808); hand-held diver-operated systems (MR-2104); AUV-based laser scalar gradiometers (MR-201612); drone-based wide-area survey for hard-to-access very shallow underwater sites (MR19-5212); and commercially available AUV-based systems such as the Geometrics G-880 total field magnetometer (MR-2730, MR-201002). Recent advances in magnetometer sensors include miniaturization, improved sensitivity, lower power requirements, and lower cost. Platform magnetic interference and precise navigation and positioning continue to be technology issues.

The advanced EMI sensors, signal processing (dipole inversions), and machine-learning methodologies developed for land-based UXO detection and classification dominate the development of underwater EMI systems. While cued EMI systems have been widely employed on land remediation efforts, the recent focus in that regime has been a transition to one-pass data collection for detection and classification. It is clear that cued data collection will be very difficult to implement underwater, so recent MR program-funded research efforts have focused on dynamic data collection systems and accompanying DCL software for underwater operation. The main logistical difficulties in using EMI technology in the marine environment include waterproofing all receiver and transmitter loops and electronics for a conductive environment; designing the optimal transmitter coils and receiver cube configurations for one-pass data collection; and providing appropriate platform support including accurate navigation and positioning for operation in a dynamic (e.g., wave and currents) and GPS-denied environment. Most importantly for towed EMI systems, the capability to safely and accurately fly the sensor within ~1 meter of the bottom is critical for optimum performance. The geophysical inversions (dipolar polarizations) of UXO electromagnetic responses seem unaffected by biofouling or corrosion (MR-2500). Numerical (MR-2412, MR-2728, and MR-2409) and field studies (MR-201313, MR201233, MR-2321, MR-2409, MR21-5066, MR19-5073, and MR-2228) have demonstrated that the inversion classification techniques (library matching, relevance vector machines) developed in the terrestrial setting are adaptable to the underwater setting. The influence of eddy current response due to currents generated in the target and the galvanic coupling of currents through the target's body (the current channeling response) may affect the scattered field from a metallic target, but typically only at very early times and for large receiver-to-object offsets (MR19-1261). Determining the effects of background subtraction from a highly variable seafloor (e.g., vertical gradients and horizontal variability) and accounting for point-to-point position uncertainties in data processing are still ongoing research issues. Recent performance by the UltraTEM system (MR19-5073) in blind demonstration at Sequim Bay, Washington, showed promising performance but pointed toward additional research and engineering efforts required to reach desired DCL goals, including improved data acquisition and analysis systems and improved detection and classification software.

2.2. Acoustic Sensors and Platforms

Acoustics offer increased standoff distances relative to magnetic and EMI detection and classification systems. This in turn offers both increased area coverage rates and deployment-system safety advantages (by maintaining a larger altitude relative to the seafloor), thus making acoustics an attractive technology. For munitions that are proud or at least partly proud of the sediment, commercially available high-frequency systems such as multibeam and side-scan sonars (e.g., EdgeTech Model 6205 Combined Bathymetry & Side Scan Sonar; MR19-5079) have the resolutions needed to detect, classify, and localize these munitions. Issues associated with sonar calibration, resolution, and range; target burial, orientation, biofouling, and corrosion; and natural seafloor scattering all still need to be addressed.

Detecting and classifying buried munitions, however, offers a larger challenge. The frequency dependence of the attenuation of sound in sediments motivates use of low frequencies while the resolutions important for classification drive the solution to high frequencies or large apertures. The solution being pursued by multiple SERDP research groups (MR-201714, MR-2545, MR18-5004, MR-2752, and MR21-1279) is to combine broadband, low-frequency acoustic systems with real cross-track and synthetic along-track processing. The along-track processing requires motion compensation to meet synthetic aperture sonar positioning requirements. Recent developments in motion compensation [4,5] have proven successful under these challenging conditions. Data from low-frequency, broadband systems allow examination of munition response in a variety of two-dimensional (2D) spaces, for example, time-angle, wavenumber, frequency-angle (acoustic color), and *x–y* (i.e., image) (MR18-1051), as well as in 3D voxel formats. Recent efforts have made great strides in co-registering and mosaicking data from multiple data collection passes on different headings, greatly enriching the products available for DCL processing (MR18-1051).

Different feature spaces offer easy access to different types of unique munitions information. From a classification standpoint, the ability to operate in a variety of feature spaces allows development of more discriminating feature sets. The maturity of these low-frequency sensors is to the point that ESTCP efforts to quantify their capabilities using ground-truthed demonstration sites are now underway using three different deployment platforms. One effort (MR-201714) is fielding an AUV with down- and side-looking synthetic aperture sonars; the second (MR-2545) is a shallow-water surface-vessel-mounted sediment volume search sonar; and the third (MR18-5005) is a multi-sensor towbody sensor suite including an EdgeTech eBOSS synthetic aperture sonar and an EdgeTech 2205 side-scan sonar with all sonars mounted on a MacArtney FOCUS-3 towbody.

UXO classification algorithms are required to separate UXO from non-UXO based on the aforementioned processed sonar data. Many of the classification algorithms require considerable training data which are difficult and costly to collect during field operations. To supplement this training data, simulation techniques are being developed including finite element methods (MR21-1275, MR20-1359, MR20-1443, and MR-2649); Fourier-domain facet diffraction models using computer graphics methods (MR21-1339); and Target-in-the-Environment Response (TIER) simulations (MR-2505 and MR-2231). Classification algorithms being investigated include convolutional neural networks (MR21-3543, MR18-1444, and MR21-1330); adaptive multichannel broadband coherence detection algorithms including incremental learning (MR-2416); and a two-factor relevance vector machine using correlation and symmetry features (MR-201714). These classification algorithms trained with simulated data, sonar data from calibration facilities, and sonar data collected during system development and demonstrations, have shown significate success at detection, classification, and geolocation of UXO and clutter (MR-201714, MR-2545, and MR18-5005).

Regardless of the acoustic system, an essential component is the ability to geolocate any object classified as a munition to a resolution sufficient for scoring system performance [6] and for relocating UXO for subsequent remediation. SERDP and ESTCP investigators have previously used a variety of navigation and positioning methodologies, including high-quality inertial navigation modules onboard AUVs, real-time kinematic (RTK) GPS systems in concert with ultra-short-baseline and long-baseline acoustic systems for towed sensors, and RTK GPS-only strategies for surface-vessel deployments. These commercially available navigation sensors, in concert with the current generation of geographic information system mapping technologies, should allow the geolocation requirements to be fulfilled.

2.3. Optical Sensors and Platforms

Optical seafloor characterization, including the use of still and video imaging, is a well-developed science for habitat mapping (MR-2414), and therefore has received limited SERDP-ESTCP MR program support in the past. Recent program support includes the use of LiDAR-based unmanned airborne drones (LiteWave's EDGE) to detect, classify, and locate UXO (via target morphometry) in waters shallower than 5 meters (MR18-1459, MR22-3257, and MR22-7371). Issues associated with AUV motion, water depth, water turbidity, and surface wave action can degrade accuracy, uncertainty, and resolution of LiDAR 3D point clouds. Those effects may degrade resolution beyond the cm-scale resolution required for UXO DCL and are being investigated and modeled.. Methods to improve target geolocation and improvements in post-processing and 3D point cloud manipulation are also being addressed. The LiteWave technology is currently being demonstrated at the Northeastern Gulf of Mexico demonstration site. An Optical Munitions Detector (OMD) is being developed and evaluated that can be used on surface ships or deployed from an AUV (MR19-1423). The OMD uses 3D optical imaging techniques (structure from motion and structured light imaging) to survey the seafloor, extracting information useful for munition DCL. Initial results from these optical approaches are encouraging. Work has recently begun on the use of active fluorometric imaging to detect proud UXO (MR20-1472). This imaging technique is similar to fluorescence lights used by scuba divers to view coral habitats at night.

3. BURIAL AND MOBILITY MODELING OF MUNITIONS

Underwater environments represent areas where munitions are much more susceptible to mobility, burial, and re-exposure than terrestrial environments. A wide range of contaminated underwater environments exists, including rivers, lakes, estuaries, and coastal beaches. Each location has different wave action and water circulation patterns that drive sediment erosion and deposition, which are directly linked to burial, mobility, and re-exposure processes. Likewise, the bottom type can include soft clays or muds, sandy sediments, large cobbles, or coral reefs. Heterogeneous bottom types (or mixtures) are also prevalent, complicating models for burial and mobility. The wide range of boundary and forcing conditions that exist across underwater environments adds complexity to the problem. The need to assess and manage risk associated with each underwater site necessitates the development of robust predictive models. These models will be housed in the Munitions Response Library (MRL) together with sediment databases and relevant hydrodynamic models required to run these models (MR21-5207). This should allow remediation site managers easy access to the research, databases, and model predictions developed by the Munitions Response Program which are relevant for site management. Sediment data bases and hydrodynamic models of waves and currents are especially important for modeling UXO behavior (MR-2733). Predictive models require detailed observations for verification and validation. One of the goals of the burial and mobility modeling aspect of the SERDP-ESTCP MR program is to develop predictive models to quantify the behavior of UXO and predict the distribution of munitions contamination present at an underwater site (MR-2645, MR19-1073, and MR21-1081). It is generally believed that these predictive models must be probabilistic in nature such that they not only make predictions, but also simultaneously estimate the uncertainty of the predictions.

Burial and mobility modeling of munitions in underwater environments will play an essential role in the management of contaminated sites from the initial wide-area assessment phase through any eventual remediation phase that may be required. Consequently, the critical inputs for burial and mobility modeling must be determined. The inputs must be well characterized at each site; due to the ephemeral nature of the environments, some inputs will require continuous monitoring such as hydrodynamic and atmospheric forcing and subsequent changes in seafloor morphology. We anticipate that site management will always begin by characterizing the necessary environmental inputs for burial and mobility modeling, which in turn also overlap with the necessary inputs to assess sensor performance before deploying assets for DCL. The initial environmental characterization would be followed by site surveys to detect, classify, and localize munitions (i.e., quantify contamination). After initial mapping of munitions contamination is performed and any UXO deemed hazards remediated, models for the hydrodynamic and atmospheric forcing and probabilistic prediction of burial and mobility can be employed to determine if UXO not initially remediated could become a hazard to the public because of re-emergence or mobility. If UXO are deeply buried and predicted to remain in place, a manage-in-place strategy would appear to be the safest and least costly option. The chosen sequence of events will constitute a concept for operations focused on making predictions over the relatively short term, such as storm events and seasonal changes (intra-annual variability), as opposed to making predictions over multi-annual to multi-decadal time scales. The focus on predictions of intra-annual variability, starting with individual storm events, will provide a practical method for long-term site management.

The portfolio of projects funded by the SERDP-ESTCP MR program focused on burial and mobility modeling of munitions in the underwater environment ranges from the theoretical to the experimental. Both field and laboratory data have been collected to provide an empirical and physics-based understanding of UXO burial, migration, and re-emergence along sandy coastlines. The field studies include the shoaling zone (MR-2320, MR18-1453, and MR19-1317), energetic surf zone (MR-2319, MR-2729, MR21-1341, and MR22-3303), and the swash zone (MR-2503 and MR20-1094). More recent experiments have been conducted on cohesive estuarine muddy sediment (MR-2730 and MR20-1480) and are underway for riverine environments (MR21-1227). Laboratory flume studies have addressed issues associated with the initial motion of UXO under a variety of hydrodynamic conditions (MR-2410) and provided measurements of the effects of sediment type on burial and migration (MR21-1333, MR21-1291and MR21-1251). A synthesis of published observations on object burial on sandy sediment was compiled by Friedrichs [7]. Laboratory and field studies have investigated the importance of liquefaction on extreme UXO burial and enhancing scour burial (MR20-3058 and MR-2731). Results from the laboratory and field data are used to develop process-specific empirical and physics-based models which expand the physical process included in the Underwater Munitions Expert System (UnMES) and populate existing nodes of the Bayesian belief network (MR19-1128). The experimental data are also used to validate computational fluid dynamics model simulations of sediment transport (scour, liquefaction, sheet flow, and bedform migration) and their effects on scour burial, extreme burial due to liquefaction, UXO migration, and re-emergence during bedform migration (MR20-1478 and MR-2732).

Results from field experiments are necessary for verification and validation of the modeling systems for predicting munitions burial and mobility in underwater environments (MR19-1317). Several ongoing and previous projects under the MR program portfolio have focused on gathering time-series observations of burial and mobility processes (MR-2320) through the development of technologies for determining the location and state of burial of munitions (MR-2319). In addition, high spatial and temporal resolution measurements of the relevant boundary layer processes (e.g., wave height and direction, current profiles, suspended sediment concentrations, and sediment erosion and deposition) have been recorded simultaneously while monitoring the burial and mobility of surrogate munitions. Unlike previous investigations that have provided before-and-after snapshots of munitions mobility (MR-200417, MR-201033), more recent experiments have provided long time-series observations of munitions phenomenology.

The development of so-called smart surrogate munitions has provided a valuable tool to improve our understanding of munitions phenomenology. Smart surrogates contain embedded, self-logging sensors that allow monitoring of the state of munitions with high temporal resolution. A wide range of internal sensors has been placed inside of surrogate munitions, including miniature inertial motion units, Wi-Fi tags, shock sensors, photocells, pressure sensors, and data loggers (MR-2730, MR20-1480, MR-2503, MR20-1094, MR19-1317, MR-2729, MR21-1227). While embedding sensors, care was taken to maintain the properties of size, shape, density, center of gravity, and moments of inertia of the munitions that the smart surrogates represent. The capability provided by smart surrogates becomes particularly significant in the harsh, shallow-water environment of the inner surf zone and swash zones of the beach. In these areas, foam on the water surface, along with intermittently high concentrations of bubbles and sediment in the water column, make it exceedingly difficult to remotely sense the behavior of munitions using traditional optic and acoustic techniques.

4. REMEDIATION AND NEUTRALIZATION TECHNOLOGIES

Underwater munitions may require cost-effective, safe, and environmentally acceptable remediation technologies if leave-in-place options are unacceptable. Current practices employ divers for manual retrieval of targets, a dangerous and costly practice, or blow-in-place procedures, which produce shock-wave pressures and acoustic noise from bubble formation/collapse detrimental to marine life, vessels, and underwater infrastructure. The SERDP-ESTCP MR program has supported a variety of alternate neutralization procedures designed to be less dangerous and more environmentally acceptable. These include the use of bubble curtains to reduce the shock-wave and acoustic pressures generated from blow-in-place practices (MR-200736); covering UXO with geotextile bags to eliminate contact with the public and reduce the effects of potential detonations (MR-1641); robust underwater caisson-like structures to contain explosive impacts (MR-2648); development of blast-barge technology where munitions are brought to the surface and exploded in blast-restricting containers (MR18-1663 and MR-201613); dredging equipment modifications that detect and remove munitions from the dredged material (MR-200321); development of electromagnets to remove large, deeply buried UXO (MR-200606); and designing robotic techniques to remove munitions from the seafloor, eliminating the need for divers (MR-2323, MR-2734, and MR19-1369).

More recent development of in situ methods to neutralize energetics contained in munitions include using a high-pressure water jet to cut access holes into the body of the munition casing and wash out the internal explosive, which is then captured in bags for later analysis and disposal (MR18-5116); development of an explosively generated plasma tool to cut holes in munitions via a plasma ablation process and generate high-temperature chemical decomposition that results in rapid deflagration of energetics without detonation (MR-201611); and evaluation of an underwater electrochemical remediation system that uses an ablative chemical drilling method to drill access holes in munitions and electrochemical processes to transform nitro-containing explosives into stable compounds that can easily be removed (MR18-1466). Another recent remediation technology includes demonstration of cofferdams with water-filled geotextile bags (MR22-7345). These cofferdams are used to drain nearshore beach areas allowing the use of cart-deployed terrestrial EMI systems for DCL of buried UXO and subsequent removal.

The long-term goal of these systems is to develop safe, cost-effective methods to remove or render inert the energetics from underwater UXO without leakage or detonation. But it has been shown that working in a dynamic underwater environment, especially using tethered ROV or independent AUV robotic platforms, is more difficult than operating in easily controlled laboratory settings.

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5. STANDARDIZED UNDERWATER UXO DEMONSTRATION SITES

A workshop on the development of standardized underwater UXO demonstration sites ("test beds") was held during the SERDP and ESTCP 2018 Symposium (https://serdp-estcp.org/News-and-Events/Conferences-Workshops/Past-MR-Workshops/Underwater-UXO-Test-Bed-Workshop-Nov-2018). The objectives of this workshop were to establish the requirements, framework, protocols, responsibilities, and timelines for development of a series of sites that can be used to test, evaluate, and demonstrate acoustic, magnetic, EMI, and optical systems designed to detect, classify, and localize underwater UXO. Test-bed site locations were selected based on a combination of environments representative of sites and munitions slated for near-term remediation (surrogate environments) and based on test-bed conditions appropriate for systems and sensors that are ready for demonstration. Based on these criteria, a rather benign (easy) area (5–20-meter depths) free of native UXO with both sandy and muddy sediments provided an ideal location for the development of the initial test bed (Sequim Bay, Washington; MR-2735 and MR21-7564). Sequim Bay contains large 100-meter-sized areas with little spatial and temporal variation in sediment properties and is protected from storms providing benign operating conditions. Successful demonstrations of two towed systems: the UltraTEM-4 electromagnetic (EMI) array and the Multi-Sensor Towbody (MuST) with a synthetic aperture sonar have been conducted. A second demonstration site was established along a shallow-water sandy beach site (0-5m) in the northeastern Gulf of Mexico (MR20-5116). This site allows evaluation of systems designed for DCL in dynamic sandy coastal regions. Two unmanned airborne drones flying LiteWave's EDGE LiDAR (MR22-3257) and a miniature magnetic sensor (MR19-5212) have been demonstrated at this site. Additional demonstration sites in carbonate sediments near Coconut Island, Kaneohe Bay, Hawaii, (MR20-5292) and in European waters near La Spezia, Italy, (MR21-3146) have been developed and can be considered operational. The development, operation, and recent use of these demonstration sites are described in another paper in this conference (David Bradley, this issue). Specific issues include adequate measurement of environmental properties (e.g., currents, waves, water column, bathymetry, meteorological, and sediment type, properties, and layering); selection of the types, numbers, and deployment methodology of munitions and clutter; geo-positioning and orientation requirements for buried and proud targets of interest; environmental permitting associated with demonstration site operations and permits for the use of sensors and platforms used at the demonstration sites; and development of scoring requirements and methodology for remediation system evaluation.

6. THE WAY FORWARD

The success of the terrestrial SERDP-ESTCP programs in reducing cost and improving the safety of UXO remediation via development of electromagnetic classification of UXO provides lofty goals for a similarly structured underwater program. Three technology improvements can greatly reduce costs and improve safety of underwater UXO remediation: a) improved UXO DCL technologies, especially for buried UXO; b) development of probabilistic models to predict the behavior (burial, migration and re-emergence) of UXO in dynamic environments; and c) development of in situ methods to neutralize UXO without explosion or contaminating the environment with energetics or energetic residues. Significant developments in all three areas have been realized with ongoing SERDP-ESTCP–supported programs.

In addition to these three areas of technological advancement, technologies to measure and model environmental factors are being supported by the SERDP-ESTCP MR program. The behavior of UXO depends on sediment type, water depth, and the dynamics of the overlying water column. Along with a knowledge of the types and spatial distribution of munitions, these environmental conditions provide the necessary inputs to predict UXO behavior. Sediment and water column properties also provide important inputs to determine remediation system performance and thus, determine what types of platforms and sensors are most appropriate for UXO DCL technologies in the wide range of contaminated underwater environments.

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