Hunting Sea Mines with UUV-Based Magnetic and Electro-Optic Sensors

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***Abstract*--The US Navy (USN) has recognized the need for effective buried-mine hunting as one of its Organic Mine Countermeasures (MCM) Future Naval Capabilities. Current thinking envisions a two-step process for identifying buried mines. First, an initial survey, or Search-Classify-Map (SCM) mission, will be performed using low-frequency synthetic aperture sonar (SAS). Second, a Reacquire-and-Identify (RI) mission will provide confirmatory final classification by reacquiring the target, at close range, with magnetic, acoustic, and electro-optic sensors, and evaluating properties such as geometric details and magnetic moment that can be fused to identify or definitively classify the object.**

The goal is to demonstrate a robust capability to identify buried sea mines through sensor fusion. Specifically, the classification results of a passive magnetic sensor and an electro-optic sensor will be generated for fusion with the results from a short-range bottom-looking sonar, with all three sensors co-residing and operating simultaneously on an Unmanned Underwater Vehicle (UUV).

The Bluefin12 Buried Mine Identification (BMI) System will be used as the platform to develop a capability for the identification of buried mines. This system houses the bottom looking sonar, the Real-time Tracking Gradiometer (RTG), and an Electro-Optic Imager (EOI). This paper will address the applications of the RTG, EOI, and data fusion results with bottom looking sonar.

The objective for the RTG is the enhancement of the processing that extracts target locations and magnetic moments from the raw RTG data. In particular, we are adding a capability to conduct real-time processing capability to provide autonomous target classification and localization results soon after the UUV passes the target, while the system is still performing the mission. These results will be shared with the vehicle or other sensors for transmission back to a base station when the vehicle surfaces.

The objectives for the EOI include additions to the control software and the development of a set of versatile image processing techniques. A significant goal is to develop the ability to make images viewable remotely over the vehicle's RF link. This allows for a quick review of contacts and improved flexibility in mission planning and execution. Image processing goals included the development of image enhancement algorithms that could be applied to all EOI data. The intent of the enhancement algorithms is to enhance image contrast and sharpness to better differentiate targets from background and increase target detail. The software will be used to batch process large amounts of raw EOI images and save them in a format so that the user can scroll through the images using a standard image viewer.

In 2008, the Bluefin12 BMI system participated in multiple sea tests. The data collected from these missions proved that sensor fusion aboard an UUV was possible. Post Mission Analysis (PMA) also concluded that data fusion was successful. Both the RTG and the EOI participated in sea tests of the Bluefin12 BMI System to evaluate, optimize and demonstrate a BMI capability. Specifically in 2008, this system was demonstrated at Panama City, FL and at AUVfest 2008 in Newport, RI.

This paper focuses on the 2008 sea testing using the modified RTG and the EOI sensors and the ability to use near real-time detection.

I. Introduction

The Office of Naval Research (ONR) currently has programs to develop, test, and demonstrate sensors to detect, classify, and localize (DCL) buried targets in the underwater marine environment while operating onboard autonomous underwater vehicles (AUVs) [1], [2]. Under the current concept of operations, AUV-based systems hosting low-frequency sonars are first used to search-classify-map (SCM) relatively large areas at a high search rate. Based on results from the SCM mission, contacts of interest are then reacquired at close range by AUV-based systems with appropriate sensor suites to identify SCM contacts.

Under the ONR Program, two prototype Buried Mine Identification (BMI) Systems have been integrated with suites of magnetic, acoustic and electro-optic sensors, one onboard a Bluefin12 UUV and a second onboard a REMUS 600 UUV. Both systems have participated in multiple tests, including ONR-sponsored AUV-Fest demonstrations in 2007 and 2008. This paper will concentrate solely on the magnetic and electro-optic sensors onboard the Bluefin12.

Magnetic sensors have been proven to work aboard in UUVs in the past and now included in the Bluefin12 sensor payload is an optical sensor. Optical sensors are typically used to identify proud targets. The identification of buried targets using optical sensors is problematic. The merit of acoustic and magnetic sensor fusion for buried target detection and classification has been reported [3]. In this investigation,

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we are extending the fundamental fusion concept. We select a set of sensors capable to collect information about buried objects. In many cases, the information from any one of the sensors may be limited. If the sensors are selected to have sufficiently distinct modalities, the data fused from their full complement may significantly increase the confidence whether a SCM detection was properly classified or not. The ultimate goal for our data fusion is to establish statistical confidence high enough that we can reliably distinguish between a target of interest and clutter; i.e., we can reacquire and identify (RI) buried contacts for cases in which optical imaging is not sufficient.

The Bluefin12 BMI System features the Real-time Tracking Gradiometer (RTG), which is a multi-channel tensor gradiometer using conventional fluxgate technology. Also in this sensor package the Electro-Optic Imager (EOI), this employs a high resolution digital camera and LED illuminator. Both systems are accompanied by electronics which control the sensor and data collection.

In this paper, a discussion of the RTG and EOI sensors and data products co-registered with a bottom-looking sonar aboard the Bluefin12 BMI UUV will be presented.

II. Description of the RTG Sensor

The Bluefin12 BMI system is displayed in Figure 1(a). It hosts a multi-sensor suite including the RTG [3-4] along with a bottom looking sonar, and an Underwater Electro-Optic Imager (EOI) integrated together into a Bluefin12 AUV [5].

A. *RTG Sensor Technology*

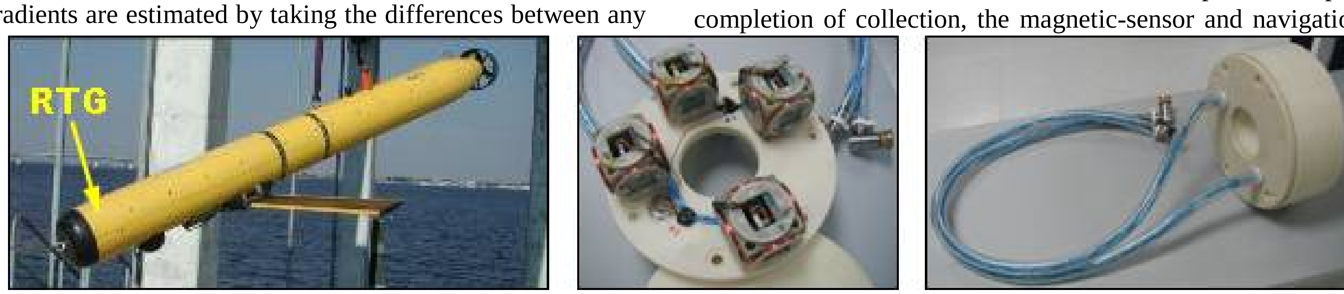
The RTG is a multi-channel tensor gradiometer using conventional fluxgate technology [6], which employs a novel electronic feedback system to increase sensitivity for mobile operations. It is a passive instrument that does not transmit any magnetic or electrical signal to probe a target. Rather it measures the distortion of the earth's magnetic field because of the target's presence. The basic sensing unit of the RTG is a three-axis fluxgate magnetic-sensor, which measures three orthogonal components of the local magnetic field. The RTG incorporates three sets of primary sensing three-axis sensors in a triangle formation depicted in Figure 1(b), with a separation of 6.5 inches. These sensors are used to construct six rank-2 tensor gradient components of which five are independent. Gradients are estimated by taking the differences between any one magnetic-field vector component at the three locations. The magnetic-field components measured by a fourth three-axis sensor is used in the feedback system to drive the three axis bucking coils that null the magnetic fields around the primary sensors, thereby significantly relaxing the requirements for sensor dynamic range and linearity. In addition, the fourth sensor is used as a reference sensor to further cancel noise through software correction. The RTG provides a nominal performance of 200 pT/m (rms) in a typical frequency bandpass for targets of interest when operated in an isolated, magnetically quiet environment. This level of performance is maintained under operational conditions onboard the Blufin12 BMI System, without bottom-looking sonar operating; however, there is currently a significant increase in the RTG's noise floor when bottom-looking sonar is activated. For a target modeled as a point magnetic dipole, the noise-cancelled time series from any five independent channels obtained as the sensor passes nominally in a straight line by the target can be used to estimate the three position coordinates and three magnetic moment components, which provides a full characterization of the dipole.

The RTG has been integrated into a single composite-material payload section along with the bottom looking sonar. This section is free flooded during underwater operations. The four three-axis sensors are very tightly coupled to an inflexible ceramic base and are encased with a cylindrical, watertight, air-filled delrin housing as shown in Figure 1(c). This sensor subassembly is mounted in the nose section of the free-flooded AUV. The electronics are housed in a watertight aluminum cylinder partially vacuumed to 10 psi, rigidly mounted above the bottom-looking sonar bottle 19" away from the sensor head.

B. *RTG Recent Enhancements*

A PC/104 computer and a network switch were added to the existing RTG electronics. Everything was installed in a new, slightly larger electronics bottle. These additions required minimal modifications (mostly to the power supply) since the new computer is self-contained and independent of the existing computer. Communications between the computers is done over Ethernet through the switch.

The existing software was modified to perform data transfer and communications between the computers. Upon completion of collection, the magnetic-sensor and navigation



(a) (b) (c)

Figure 1. The Bluefin12 BMI System Configured with a multi-sensor suite including the RTG: (a) system ready for deployment, (b) assembly of four 3-axis fluxgate magnetometers and (c) magnetometer package for underwater deployment in flooded body section.

data are automatically transferred to the new computer. The original computer can continue data collection or other tasks while the second computer processes the transferred data. The processed results can be viewed with any web browser, via RF link, when the vehicle surfaces. It should be emphasized that the existing computer continues to perform the same functions it did before the modifications, and all operations continue in the absence of the new computer.

III. Description of the EOI Sensor

A. *EOI Sensor Technology*

The EOI sensor combines a high-dynamic-range (12 bit), commercially-available camera with a PC/104-based high-speed Pentium processor for camera/illuminator control and data handling/storage. The camera itself has a pixel resolution of 1392 x 1040 with a pixel size of 6.45 microns square. The shutter control ranges from 0.063 ms to 98 ms and the field of view in air is 59.3 x 45.8 degrees. The camera itself in encased in an aluminum air filled housing. Data transfer between the computer and camera is accomplished over a FireWire interface. Software and electrical interfaces were designed to work with the existing Bluefin-12 interfaces, and a pass-through capability is included to facilitate joint function with other sensors operating on the platform. The AUV-deployable system was designed to function as a passive imager or to use active LED strobe illumination. Three different illuminator packages were constructed so that, depending on water conditions, the system to be configured to operate at either 532 nm, 590 nm, or 630 nm. The software architecture permits the camera and illuminators to be turned on and off, on command, from the main vehicle computer, allowing a reasonable approach to managing data volume and power use during a mission. Recording and illumination, along with exposure time, frame rate, and camera gain, can also be controlled remotely via the vehicle's radio-frequency (RF) link. Also, a process was developed to enable data from the camera to be co-registered with data collected by the other short range sensors to facilitate the classification of targets via data fusion efforts or other classification methods.

The approach to image processing is to correct images for camera system irregularities, such as CCD voltage bias offset, CCD sensitivity variations, and vignetting, as well as sensitivity response of the entire optical system. After the initial corrections, enhancements made to the images using techniques such as intensity transformations, special filtering, frequency filtering, and de-convolution. These processing steps combined in a script file for automated batch processing of multiple images files.

B. *EOI Recent Enhancements*

A remote viewing capability was added to the EOI system. Using a web browser, any of the recorded images can be retrieved through a series of drop-down select boxes. A selected image is returned as a small JPEG, along with information about the image (time, position, exposure, etc.).

JPEG images can also be requested by another application that is used to review sonar contacts. When a user selects a sonar contact of interest the coordinates are sent to the EOI system. The image whose center is closest to the desired coordinates is returned.

The first step in the image enhancement of the raw EOI images is the removal of bias voltage from the CCD chip. Steps for generating a bias frame were developed, but for the initial processing an average bias value was found and subtracted form both the flat field image and the raw image. The flat field image is a measure of the sensitivity response of the entire optical system. This includes the electronics, the electro-optics, and the optical system including the housing window. It was determined that due to the changing location and amount of contaminants on the optical system for different runs of the system, a flat field image needed to be built using multiple featureless images of the bottom. This flat field image would be used on the images collected during that run. The subtraction of the flat field image from the raw image, dramatically reduces the effect of vignetting, and spots on the image due to contaminants on the optical system. The unfocused image of a piece of sand on the outer window of the system, can be mistaken for a target, and also interfere with correct image restoration.

Several different types of image enhancement algorithms were tried on multiple EOI images. These types of enhancements included special filtering, frequency filtering, pixel intensity adjustments, and deconvolutions. The most successful were found to be the Contrast-Limited Adaptive Histogram Equalization algorithm for pixel intensity adjustment, and the Wiener algorithm for deblurring. These algorithms, along with the removal of the bias voltage and the flat field correction were incorporated into a script file that can automatically process all raw EOI images located in a file. These processed images are saved in a lossless format Tiff file, and can be viewed using a standard image viewer.

Both the RTG and the EOI imager were used during two sea tests in FY 2008. These tests were noteworthy for routine operations. Testing during previous years was focused more on each sensor as a standalone device, verifying that the sensors were functioning properly, successfully collecting data, communicating with the vehicle, and inter-senor data co registration. In contrast, in FY 2008, the sensors operated harmoniously as subsystems in a well integrated system. More emphasis was placed on sharing information between the sensors and using the combined outputs for more effective decision making.

IV. Results

The March test, in Panama City, FL, was a continuation of a series of tests that focus on system testing and development by collecting data from well-defined, known targets. These targets included mine simulants, artillery and mortar shells, man-made clutter, and calibration targets such as magnets and sonar reflectors. The targets were in various states of burial

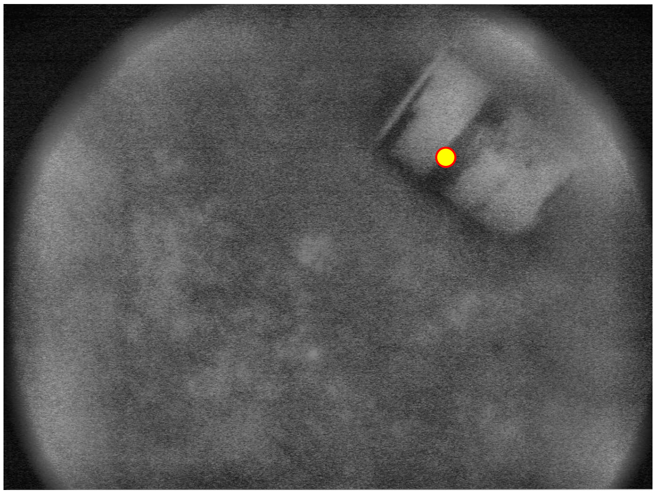


Figure 2. EOI sensor image of an oil drum. The yellow dot indicates the RTG contact position.

(proud, partially-buried, flush-buried, and fully-buried), in different bottom types (muddy or sandy), and were distributed among several sites in St. Andrew Bay and in the Gulf of Mexico. Water depths ranged from approximately 5 m to 20 m.

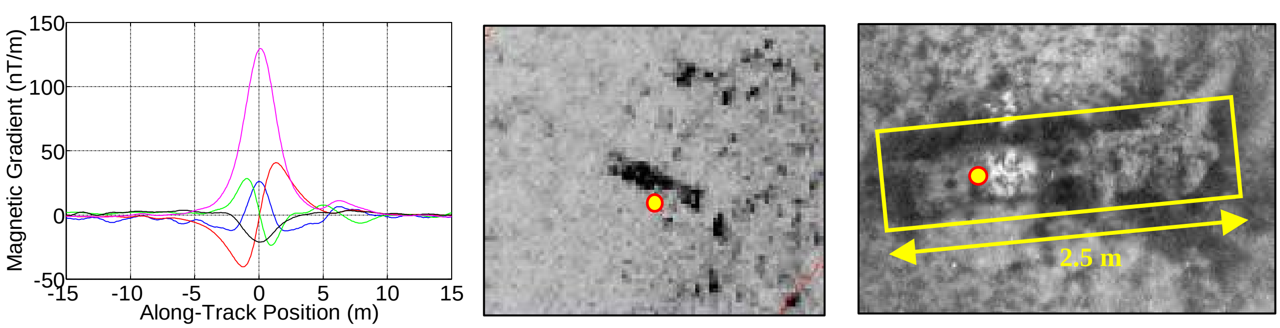
Two new target sets were notable. Two groups of oil drums were put in place for a study of the effects of target orientation. This was of particular interest to sonar systems. Finally, a sunken ship (USS Strength) was surveyed as a practice mission for upcoming tests at AUVfest.

Figure 2 is an EOI image of an oil drum. The somewhat grainy appearance is a consequence of the large amount of contrast enhancement used on this image as the result of the poor optical quality of the water, which was caused by a storm that had recently passed through the test area. The yellow dot is the position of the RTG contact. As is often the case, the target location estimated by the RTG is coincident with the acoustic and optical images. In a few cases the exact position is not meaningful, since the magnetic signals resulting from a close passage of the sensor to an extended object are not well fit by the point-dipole model (i.e., a multi-pole model fit is required under these circumstances). The estimated position will usually fall within the region of a compact target, as in this case. The estimated magnetic-dipole moment is a useful target classification parameter.

AUVfest 2008 was held at Newport, RI, in June. Once again, missions were conducted against mine-like objects, but the event focused on surveys over archaeological sites. Missions were conducted over a wooden barge with steel machinery, a steel ship, both from the early twentieth century, and over two British frigates from the Revolutionary War. The twentieth-century wrecks were ill-suited to study by the RTG, EOI and bottom-looking sonar systems, as these had to be surveyed from high in the water column because vehicle safety required a large stand-off distance from the wrecks. On the other hand, the surveys over the British frigates were a good match for the capabilities of these sensors and their fusion.

HMS Cerberus and HMS Lark were set alight and scuttled after they were trapped in port by a French fleet. Both ships sank near the shore. The location of the Cerberus debris field is known, and many artifacts have been identified by divers. However, because the Cerberus drifted as it burned, and items were lost all along the path, the full extent of its debris field is yet to be determined. In contrast, little is known about the Lark. There is only a general idea about its location, and only one small artifact concretion has been identified. These wrecks provided an excellent opportunity to demonstrate the capabilities of the RTG and EOI sensors. The burial states of the artifacts ranged from proud to fully-buried, and there were a number of cast iron objects (large cannon, in particular) that were detectable by the RTG. A challenging aspect of these sites is that they contain a great deal of man-made clutter resulting from the long history of settlement and maritime commerce in the area.

Weather and scheduling conflicts limited the amount of time that was spent on these sites. Additional constraints arose



(a) (b) (c)

Figure 3. Results are shown for a survey conducted by the Bluefin12 BMI System over the archeological site for the British frigate HMS Cerberus. This frigate was scuttled by the British in Narragansett Bay, Rhode Island in a 1778 battle between the British and French navies during the American Revolutionary War. During the survey, the Bluefin12 BMI System successfully imaged several artifacts previously identified by archeologists. In this figure, we display data collected over one of the frigate's cannons: (a) the noise-cancelled RTG time series as the system passes by the cannon, (b) a sonar image, and (c) an optical image. The location of the target as classified by the RTG is displayed by a yellow circle overlaid on the sonar and optical images. The cannon as measured from these images were approximately 2.5 meters in length with its axis oriented approximately 120 degrees with respect to North. The cannon's magnetic moment was estimated to be 100 A-m^2.

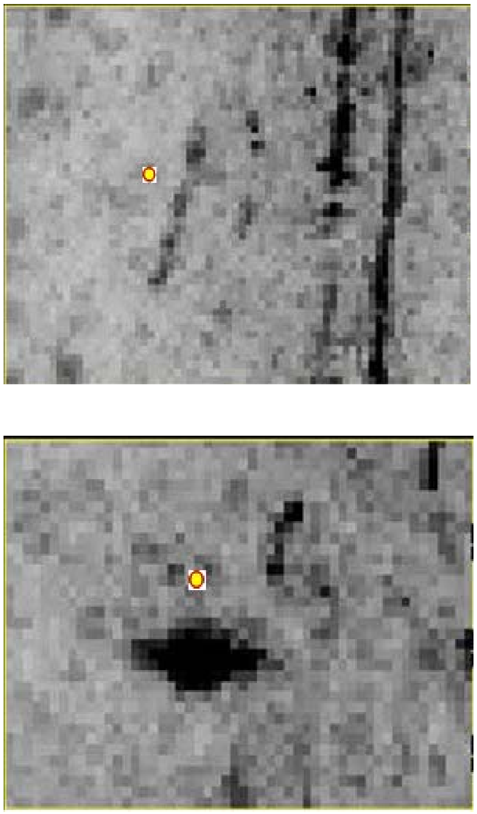


Figure 4. Bottom-looking sonar image of buried object with the RTG contact positions, at the HMS Lark site

from the shallowness of the water and an uncertainty about the height of projections from the bottom. Concerns about vehicle safety and a desire for greater sonar coverage during the limited time on site, especially in the case of HMS Lark, combined to limit the operating depth. This reduced the quality of the data from the RTG and EOI sensors. The latter also suffered from poor water quality caused by the bad weather. In spite of these difficulties, the RTG and EOI combination produced some excellent results.

Figure 3 depicts magnetic data, sonar image, and an optical image of a cannon from the Cerberus. Figure 3(a) shows magnetic data form the RTG, Figure 3(b) depicts sonar data, and Figure 3(c) is a closer look by the EOI sensor. As before, the yellow dot indicates the position of the RTG contact. This case clearly demonstrates the value of the RTG and EOI sensors, and the insufficiency of using only sonar systems. There is little doubt that the object in the EOI image is a cannon, and the RTG confirms that it is a large iron object. Previously, this was a known object that had been identified during diver surveys.

The next example, Figure 4, is from the Lark site. Several contacts of interest were found during the analysis of the RTG data. Among these were the two contacts shown. Depth estimates of these RTG contacts suggested that these were buried. A subsequent review of the bottom-looking sonar data showed large objects within ~ 1m of the RTG contacts. The RTG and sonar results are consistent; in particular, both sensors indicate that the target is buried. No EOI images were available in these cases due to the very poor optical quality of the water and the relatively high altitude at which the survey was conducted. The presence of these objects was unknown.

ACKNOWLEDGMENT

The authors gratefully acknowledge the Office of Naval Research, Code 321, which contributed the major support for these developments and demonstrations. In particular, we would like to recognize Dr. Kerry Commander, Mr. Robert Manning, and Dr. Thomas Swean as the principal sponsors. The authors would also like to acknowledge the technical contributions to these efforts from our colleagues at NSWC PCD too numerous to single out all of the significant participants. We will recognize the following principal contributors: Mr. George Allen, Dr. John Hyland, Dr. Jeff Rish, Dr. Dan Sternlicht, and Dr. Cheryl Smith. In addition, we would like to recognize our partners (identifying only the Organization's Principal Investigator): Applied Signal Technology (Dr. Kent Harbaugh), Bluefin Robotics (Mr. Rich McMahon), Florida Atlantic University (Dr. Steven Schock), Quantum Magnetics (Dr. Sankuran Kumar).

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