Demonstration of the Real-Time Tracking Gradiometer for Buried Mine Hunting While Operating From a Small Unmanned Underwater Vehicle

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***Abstract*-In many undersea conditions, optical sensors and sonar can be used to discriminate against sea mines. However, there are many conditions where these sensors are insufficient. For example, when a mine is fully buried these sensors are of little help. Under these conditions, additional sensor technologies are required. Since it is not affected by the medium, a technology of choice is magnetics.**

In the late 1990's a "T-shaped" gradiometer with a 12-inch baseline was developed. It became known as the RTG. Measurements performed in the nonmagnetic facility at the Naval Surface Warfare Center Panama City (NSWC-PC) demonstrated good localization capabilities and it was selected to become part of an ONR initiative to replace the human diver with Unmanned Underwater Vehicles (UUVs) using custom designed payload modules in high-risk mission areas. In the early 2000's the land-based RTG was refitted for underwater applications and integrated with the Florida Atlantic University's Buried Object Scanning Sonar (BOSS). Both were operated from a towed nonmagnetic sled where they demonstrated the ability to localize on buried undersea magnetic targets. The collection of simultaneous magnetic and acoustic data provided the opportunity to apply sensor fusion.

While the towed nonmagnetic sled was an ideal magnetic platform, it was unsuited for the shallow water operations required by the Navy. In response to those requirements, both RTG and BOSS were redesigned to fit on newly developed UUVs, such as the 12.75"-diameter Bluefin 12. As expected the UUVs magnetic platform noise level was considerably higher due to the increased number of magnetic noise sources on an active autonomous vehicle and the closer placement of the RTG to these noise sources. To mitigate this increased noise, a magnetic noise cancellation system using magnetometers and current sensors, strategically placed within the control section of the UUV, was implemented.

The initial underwater shake down of this entirely new system occurred in August 2005. This demonstrated, for the first time, autonomous control of the RTG by the Bluefin 12. Sea tests continued during 2006, collecting simultaneous data from the RTG, BOSS and a simple optical camera. These co-registered data have been used to demonstrate the common detection and localization of buried targets.

This paper focuses on the 2006 sea testing of the system and the initial analysis of the data from the fluxgate-based RTG.

I. Introduction

The Office of Naval Research (ONR) is currently funding two magnetic sensor systems for the Buried Mine Hunting (BMH)program – the Real-time Tracking Gradiometer (RTG) from GE Infrastructure, Security (formerly know as Quantum Magnetics) [1], and Polatomic's Laser Scalar Gradiometer (LSG) which can be referenced in earlier papers [2-4]. As its name suggests, the purpose of this program is to develop the capability to detect mines buried in the sea bottom. This paper will focus on the at-sea capabilities of the RTG.

The RTG was originally designed for land-based operation and was built to demonstrate its tracking capabilities. This system then was then fitted for underwater use and placed in a tow body, along with the Bottom Object Scanning Sonar (BOSS), a sensor created by Florida Atlantic University (FAU). The hope was that the fusing of information from these sensors would result in more reliable detection, classification and localization of buried targets. Many problems arose and were overcome, as is typical when working with any new concept. Ultimately, it was demonstrated that the same targets could be detected and localized from data that were collected simultaneously. Based on these encouraging results, the program was continued. However, changes would be required in the next generation of the sensors.

ONR has embraced the use of Unmanned Underwater Vehicles (UUVs) as a replacement for divers in high-risk

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mission areas. The precise navigation and good coverage rate of a UUV make it well suited to the tasks of finding or reacquiring isolated mines. In addition, the ability to closely follow the bottom is an advantage (compared with surface-based tows) when searching for buried targets with short detection ranges. In light of this initiative, ONR wanted to reduce the physical sizes of the RTG and BOSS and placed together on a UUV. The Bluefin 12, also funded by ONR, was selected as the host as shown in Figure 1 [5].

In 2006, the improved RTG/BOSS/Bluefin 12 system participated in multiple sea tests. This paper details the improvements that were made to both the RTG and its signal processing algorithms along with data from sea testing. While past papers have emphasized hardware issues, the focus of this paper is shifted toward data collection and analysis.

II. Description of Subsystems

As described, above the BMH system can be split into several subsystems. The major components of this system are the Bluefin 12, the FAU BOSS, and the RTG. Additionally, there is a bottom-looking video camera.

Produced by Bluefin Robotics, the basic production Bluefin 12 is five feet long with a cylindrical cross section of 324 mm in diameter. The vehicle can be divided into a payload section and a tail-cone section. Each section is free flooded and every system is encased in waterproof housings. Both sections have foam and weights added to properly ballast the vehicle. Almost all materials used in fabrication have minimal magnetic properties, consistent with good performance. All systems are controlled or monitored by the Bluefin's Main Electronics Housing (MEH). The MEH also records mission information, except data from sensors in the payload section, for subsequent analysis. Communications with the MEH is by one of three methods: Ethernet when on shore power, RF when it is on the surface and away from the boat, and acoustically while under water. In the future, the payloads will inform the MEH that a target has been detected, and the MEH will make mission modifications on the fly [6].

The BOSS, developed and fabricated by FAU, is specifically designed to penetrate the sea bottom. It is the primary sensor and is able to detect most materials, whether buried or proud. It consists of a single hemispherical projector, located on the centerline, and numerous receiving transducers.

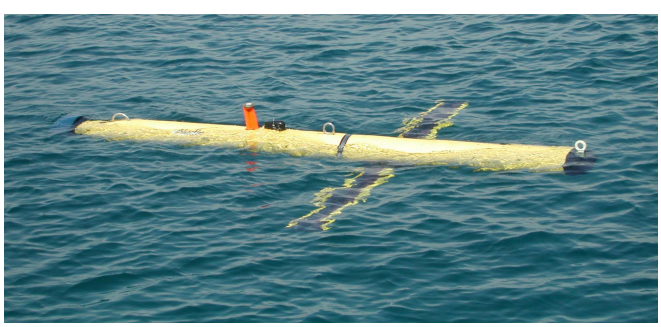


Figure 1. RTG/BOSS Configuration of Bluefin 12 at sea just prior to beginning of mission.

The receivers are positioned in a line array along specially designed wings that are located on the payload section. All required electronics are located within the payload section that is also shared with the RTG and the camera [7].

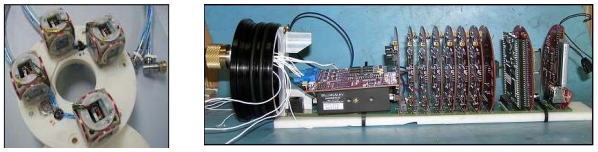
Figure 2 depicts the RTG system which consists of a sensor head and an aluminum electronics bottle. The RTG's ability to operate on a moving platform is the result of a three-sensor gradiometer concept developed by Dr. Roger Koch of IBM. The sensor head consists of four 3-axis fluxgate magnetometers, each located within a 3-axis Helmholtz coil.

Three of these sensors are located at the vertices of an equilateral triangle, whose sides are 165 mm long. These three magnetometers are used to form six gradients, only five of which are independent. A fourth 3-axis sensor is centrally located on the same base plate, and is used as a reference sensor to provide feedback to the three gradient-generating sensors. Note that although this reference sensor has the three-axis Helmholtz coils, they are not connected. This allows the reference sensor to respond to the ambient magnetic variations, and to produce the "nulling corrections" that are applied, through their Helmholtz coils, to the sensors that generate the gradients. This feedback greatly reduces the motion response in the compensated sensors and allows them to operate in a nominal low-field environment.

III. Redesign of the RTG

The current RTG was delivered to NSWC PC in 2005. Using data obtained during the 2005 sea tests, several improvements were made before the 2006 testing. These include the re-engineering of several major parts. First, there was a major redesign of the sensor head. The old sensor head was made of ABS plastic which flexed and leaked under pressure. A MACOR base plate with a Delrin cover replaced this old head. The reason for using the MACOR plate is that it does not flex under pressure, so the distances between the fluxgates remain constant. Use of the Delrin cover eliminated the need to fill the sense head with oil, allowing the use of a vacuum. The A/D boards were repeatedly failing, which resulted in excessive noise throughout the RTG electronics. Teams from NSWC PC and GE Infrastructure joined to solve this problem. A key step was the development of a real-time display, permitting a quick examination and diagnosis of the cause. Subsequent design modifications were deemed successful.

IV. Physical Integration of the RTG



RTG Sensor Head **RTG System Electronics**

Figure 2. Displayed are the two major components of the RTG electronics.

The RTG sensor head is tightly coupled to an inflexible base plate, which is attached to the nose of the Bluefin 12 payload section as seen in Figure 3. The electronics bottle is located 483 mm away and mounted above the BOSS III bottle. The RTG electronics bottle is connected to the sensor head by two oil-filled cables. It is also connected to the Bluefin's MEH bottle through a third underwater connector and host cable. This host connection from the Bluefin 12 supplies both a 32-volt power connection and Ethernet communication. Two additional connectors on the RTG electronics bottle are for auxiliary sensors. More extensive details about integration is given in an earlier paper [8]. The auxiliary sensors were not used in the 2006 sea trials because there was no room for them in the production Bluefin 12. It was also found, late in the redesign, that the auxiliary sensors created additional noise in the RTG electronics. Improvements to the auxiliary sensors' size, mounting, and electronic noise will be explored following the 2006 sea trials.

V. Data Collection

In May of 2006 a sea test, hosted by NSWC PC, was hampered by the weather and by electrical and mechanical problems associated with several of the subsystems. Limited RTG data were collected, and were considered inadequate for the fusion effort. Only a few targets were observed and the lines over these targets were too short for successful processing. In June 2006 a continuation of the May 2006 test took place. Part of the test was conducted in St. Andrew Bay, over a mud bottom with buried targets, and over a sand bottom with both buried and proud targets. Most of the test took place in the Gulf of Mexico, at sand and mud sites with buried targets. A number of sets of co-registered RTG/BOSS data were collected at these sites in support of the fusion studies.

VI. Results

The target positions and moments were found using an algorithm that was developed at NSWC PC and previously described [8]. Briefly, the algorithm uses overlapping segments of magnetic gradient data to estimate the positions and moments of stationary dipole targets. The dipole parameters are estimated with a combination of linear (to find the moments) and nonlinear (to find the positions) least-squares fits. Effects of platform motion are removed by including a linear fit to measurements from a vector magnetometer reference. It is assumed that the output of the reference magnetometer is dominated by the time-varying signal that results from platform rotations in the fixed external field. Multiple targets are handled with an iterative scheme, with new targets being successively added until there is no improvement in the fit. The targets were assumed to be on the bottom and the known altitude, measured by the Bluefin vehicle, was used to constrain the solution.

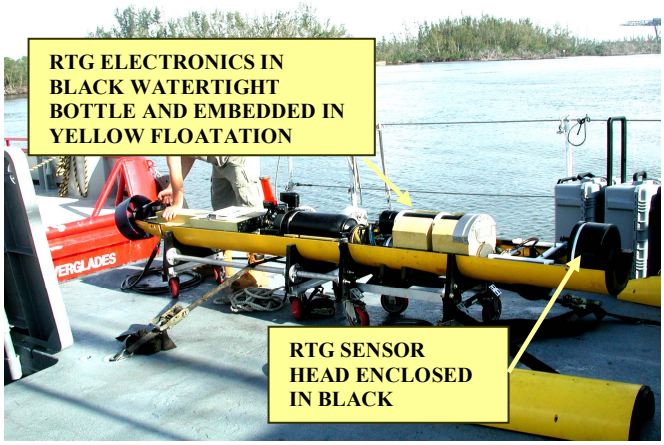


Figure 3. Integration of RTG/BOSS in Bluefin 12

As an example of our results, Figure 4 shows the estimated target positions from independent runs over a field in St. Andrew Bay. Results from earlier tests at this same site were reported in [9].

In general, the results are good. Most of the estimated positions are within a few meters of the ground truth positions. Several factors must be kept in mind when assessing the quality of the estimates. First, although we use the term "ground truth," the process of determining true position is notoriously difficult and subject to its own errors. Second, each estimated position is found from navigation information supplied by the vehicle during the line on which it was found. Although the vehicle position was usually disciplined by a GPS fix before each line was run, there was a variable accumulated error from line to line. Finally, although the position estimates from those lines passing close to a target will generally be more reliable than those made from a greater distance (simply because the target's signal will be larger and the SNR will be higher), we sometimes see a negative effect when passing very near a strong target, which we believe is a by-product of our motion-compensation procedure. A very large target signal will also appear in the reference magnetometer, and the compensation will have the effect of removing some of the target signal from the gradient channels. This will result in a distortion of the gradient signal and will lead to an erroneous position estimate. Based on an analysis of the distribution of the localizations, we estimate a 95% confidence bound of approximately 10m.

Figures 5a and 5b are BOSS images, from two different runs, of a target in one of the Gulf fields. Markers have been placed on these images to indicate RTG localizations that resulted from data taken simultaneously with the BOSS data. Since the position estimates from each sensor use the same vehicle navigation information, such comparisons will eliminate the first two uncertainties described in the previous paragraph, and will give a better idea of the intrinsic spread in the RTG position estimates. Additional results from this data-fusion study can be found in a companion paper [10].

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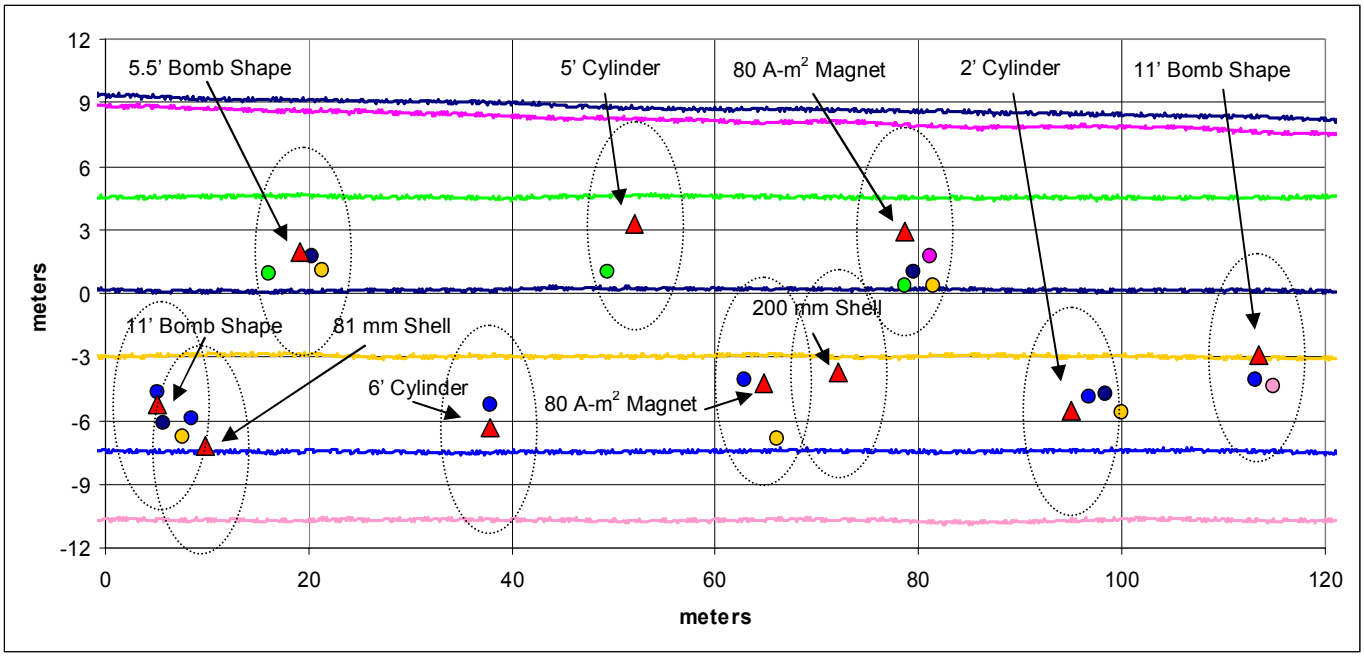

Figure 4. Estimated positions from RTG data, color-coded by run. The triangles represent known positions. The error circle radius is 10 m.

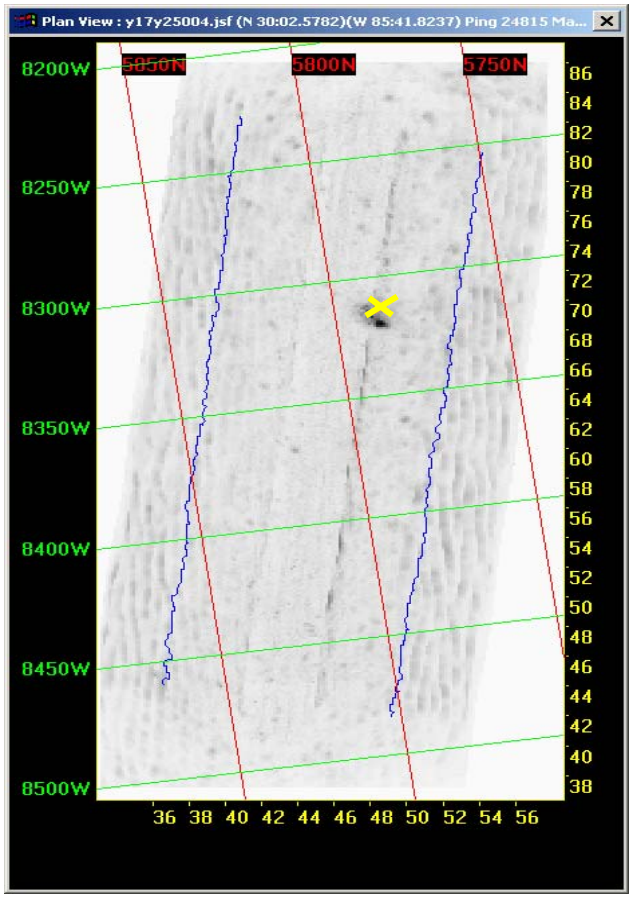

Figure 5a. BOSS and RTG localizations.

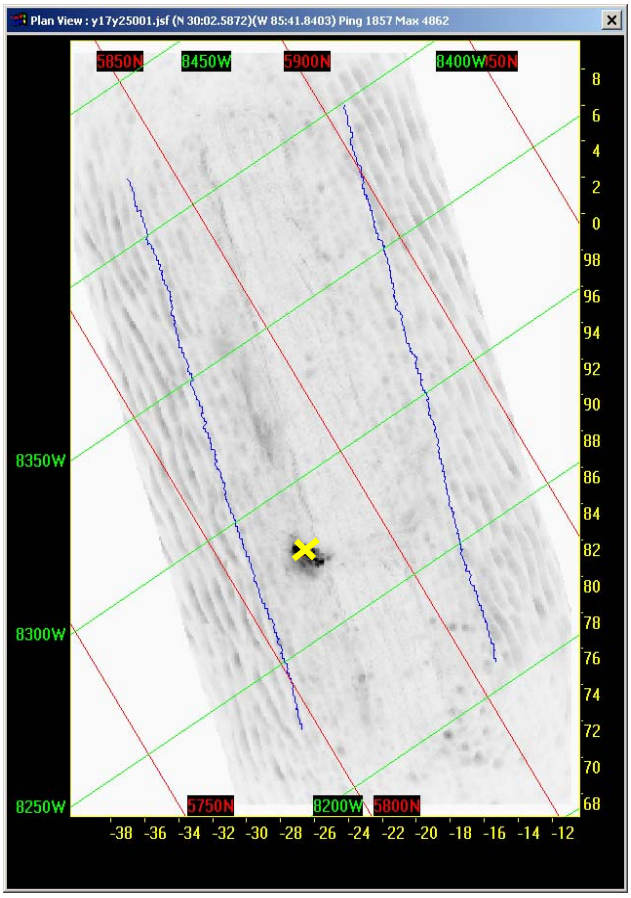

Figure 5b. BOSS and RTG localizations.

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