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14. ABSTRACT
The Woods Hole Oceanographic Institution has developed, under ONR funding, a new UUV capability that provides the multi-use capabilities required to perform hull inspections and harbor surveys. Based on the proven, REMUS-100 core vehicle system, this vehicle has a new, modular tunnel thruster package, which includes four controlled through-hull thrusters. These individually controlled thrusters are integrated into the vehicle control system, allowing mission plans at any speed, including zero. The standard REMUS-100 thruster and fins remain present, and the vehicle control system automatically utilizes the systems as needed depending on the vehicle's speed through the water. At low speeds, the tunnel thrusters provide most of the control power, and at higher speeds the fins, which are more efficient, are used. The Oceanographic Systems Lab (OSL) at the Woods Hole Oceanographic Institution (WHOI) proposes to enhance the capabilities of the recently developed Hull and Harbor REMUS-100 vehicle by adding new sensors, navigation capabilities, and a higher degree of autonomy for hull inspection and harbor survey missions.

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A Single Vehicle Solution for Hull Inspection and Harbor Survey

N00014-08-1-0109 Final Technical Report

February 27, 2012

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LONG-TERM GOALS

Unmanned underwater vehicles have been identified as a potential tool in maintaining port security. Vehicle surveys may be used to establish a basic understanding of the port underwater environment and identify changes over time. In addition underwater vehicles are a potential tool for inspecting ship hulls both pier side and prior to entering port. Our goal in this project is to develop an Unmanned Underwater Vehicle (UUV) that can perform completed harbor surveys and ship hull inspections in support of port security operations.

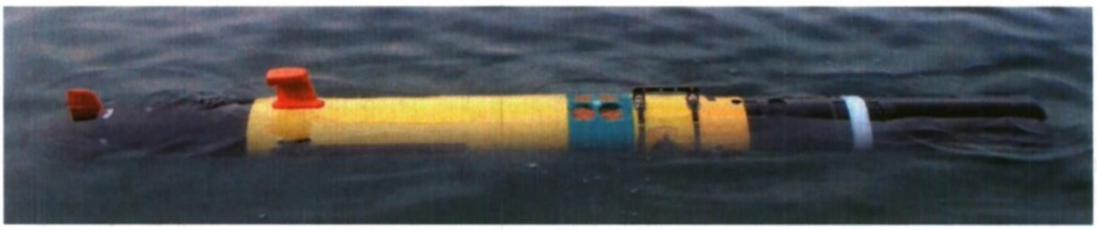


Figure 1. REMUS 100 Duct Thruster UUV with multibeam sonar

OBJECTIVES

This has been a multi-year project, which is based on the integration of four duct thrusters into a REMUS 100 vehicle. The modification allows the vehicle to hover, spin and operate at very low speeds in all directions. The overall objective of the project is establishing new performance capabilities for this vehicle in order to conduct high resolution acoustic surveys in harbors and on ships. This work was focused in five areas:

- Acoustic Sensors - This work involves integration, testing and demonstration of commercially available high resolution, short range sensors for inspecting ports and ship hulls.
- Optimal Sensor Positioning - Because of the complex and widely varying shapes of ships hulls, the REMUS 100 vehicle must be able to orient the sensors optimally. This effort will involve development of a rotator mechanism which serves as the interface between the forward sensor package and the vehicle.
- Control and Navigation - Both low speed operation and ship hull inspection have required new vehicle control software. The ship hull inspection requires that the processed data is accurately referenced to a ship-relative position. At the same time, it is important that the vehicle maintain its knowledge of its true position in world coordinates, so that it may transit, perform harbor surveys, and surface periodically in a known safe location for further instructions, data-offload, etc. WHOI proposed utilize the existing, standard REMUS inertial and acoustic navigation systems, combined with acoustic communication of ship position variations in order to provide a combined earth-referenced/ship-relative approach. Communications techniques will be developed which will allow the vehicle to stay aware of ship hull motion during its mission, and autonomously make mission planning adjustments as required.

- Thruster Efficiency - This project examines the original duct thruster propeller design and will investigate enhancements which may provide more thrust. Goals of this effort are reducing power requirements and increasing the level of current in which the vehicle can inspect ship hulls and piers.
- Real-Time Data Transfer – Establishing a link to transmit inspection data to the vehicle operator is critical in improving survey rates. In the harbor locale, the vehicle will generally not be far from potential acoustic tracking/communication positions. This allows high rate acoustic communication systems to be used for transferring data from the vehicle to the operator during the mission. Integration and testing of a high rate, short range acoustic modem provides an important new capability.

APPROACH

Acoustic Sensors – Our approach was to identify acoustic sensors, compatible with the REMUS 100 vehicle design, that are potentially capable of performing high resolution inspections of ship hulls and piers. Ideally the sensor will be able resolve the targets from a range of at least 3 meters, which allows the UUV to stand-off a reasonable distance. Selected acoustic sensors were integrated onto the vehicle and software was written to communicate with the sensor and log data. Vehicle tests with the sensors were conducted to evaluate acoustic performance.

Optimal Sensor Positioning – The changing profile of ship hulls requires that the primary inspection sonar be rotated to maintain proper alignment with the ship surface. Our goal was to be able to rotate the sensor up to 240°. This allows the vehicle to perform inspections on both sides of the UUV.

Control and Navigation – Control and navigation of the hovering UUV have been incrementally improved over the course of this project. However, a weakness has been obtaining good stand-off measurements necessary in ship hull inspection. As a result, WHOI decided to replace commercial sensor used initially with a sixteen- channel sensor that provides both vertical and along hull measurements of standoff.

Thruster efficiency – The original thruster design was capable of generating about 1.15 pounds of thrust at 4000 RPM. Increased understanding of the thruster design and performance suggested that improvements were achievable. As in the first design, WHOI developed the requirements and contracted a propeller design firm, Hydrocomp, to provide a design. Additionally, available power was increased to allow duct thruster RPM of up to 5000 RPM.

Acoustic communication – WHOI integrated FAU high data rate acoustic communication system onto the REMUS 100 AUV. A demonstration was completed alongside the dock at WHOI.

WORK COMPLETED

2008 – Work was focused on new sensor integrations, vehicle control work, operational demonstrations and data analysis software.

Acoustic sensors - The new sensors included a Marine Sonic Technology dual frequency (900/1800 kHz) side scan sonar and a Blueview forward looking multibeam sonar. The side scan integration required a new main housing design and electrical modifications for power and communication. Nose modules were built to accommodate a Blueview 900 kHz forward look multibeam. A second module was built for the Blueview dual frequency (900/2250 kHz) multibeam. Software for communicating with and logging data from the Blueview sensors was completed.

Control and Navigation - Improvements were made in the vehicle control software to improve low speed operation and control adjacent to ships. This work was demonstrated at AUVFEST 2008 in Newport, Rhode Island and at Harbor Protection Trials 2008 in Eckenforde, Germany.

Data Processing - New software was developed to improve analysis capabilities of the sonar data from the Imagenex Delta T imaging sonar. The new software allows generation of three-dimensional plots of ship hulls or seafloor, that make target detection much easier than viewing software provided by the sensor manufacturer.

2009 -

Acoustic Sensors – In 2009 a Blueview Technologies Dual Frequency Miniature Multibeam Imaging Sonar was integrated on the duct thruster vehicle as a forward look sonar. The system has sonar frequencies of 900 kHz and 2500 kHz with corresponding ranges of 5 meters and 50 meters. The different ranges result in different optimal vehicle altitudes and sensor angles. The sensor module allows adjustment to the preferred angle for each sensor. Integration work included mechanical design of the sensor module and software development to communicate with the sensor and log data. Figure 2 shows the sensor module on a standard REMUS 100 vehicle. The forward look sensor module was installed on the REMUS 100 duct thruster vehicle and tested in waters local to Woods Hole.

Figure 2. Forward look sonar sensor module on standard REMUS 100 UUV

Optimal Sensor Positioning – A design of the sensor rotating mechanism was completed. Figure 3 shows the Solidworks model of the design with the forward look sensor module. The rotating mechanism is incorporated in the forward duct thruster module forward end cap.

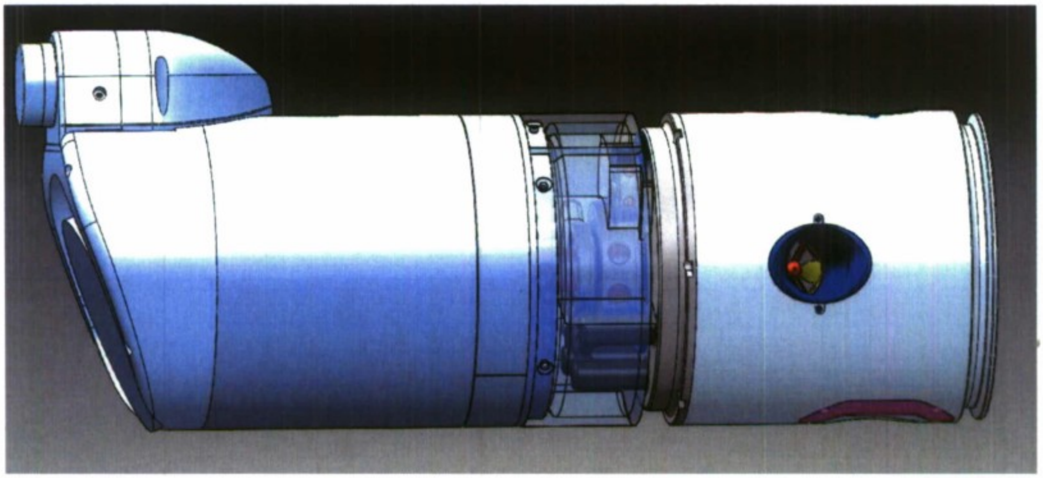


Figure 3. Sensor rotate mechanism

Thruster efficiency – A new duct propeller design was completed and fabrication was started. The new duct propeller had a slightly increased diameter and power to the each duct was increased from 30 to 38 watts. The maximum propeller RPM was increased from 4000 to 5000. Expected thrust increase was 40% to 1.6 pounds. In addition to improvements to increase thrust, the new ducts had other modifications that improved reliability and ease of maintenance. The new ducts were installed on an upgraded ONR REMUS 100 vehicle. Darter was outfitted with a Kearfott IMU, new chassis, modular end cap and new side scan electronics. Fabrication of the duct module components was initiated.

2010 -

Acoustic Sensors – A Blueview Technologies Dual Frequency Miniature Multibeam Imaging /3D Microbathymetry Sonar was integrated on the duct thruster vehicle. The multibeam sonar is forward looking and the operating frequencies are 900 kHz and 2500 kHz. The 3D Micro-bathymetry sonar has an operating frequency of 2250 kHz. The primary integration work was software development to communicate with the sensor and log data. Figure 1 shows the sensor module on a standard REMUS 100 vehicle. Testing was conducted at Woods Hole.

Optimal Sensor Positioning – The sensor rotating mechanism designed in FY 2009 was fabricated and assembled. This system was been tested at the component level. The rotating mechanism allows forward-mounted sensors to be rotated about the vehicle centerline and will be useful in surveys in areas of varying surface orientation relative to the vehicle. It has potential applications in areas of rough terrain, ship hulls and harbors. Figure 4 shows the rotate mechanism mounted between the Blueview Technologies sonar and duct thruster module.

Figure 4. Sensor rotate mechanism

Control and Navigation – A challenge to good REMUS 100 vehicle control adjacent to ship hulls and piers has been the ability to maintain adequate standoff for inspection. A commercially available scanning sonar has been used to measure standoff in a direction perpendicular to the vehicle centerline. WHOI determined that better control could be achieved with measurements at two different locations along the ship hull or pier. As a result, development of a new acoustic standoff sensor was started. The design consists of sixteen two-MHz transducers spaced circumferentially in a short housing section (a computer model is shown in figure 5). Eight are directed radially and eight look forward at a 45° angle. The housing unit is fabricated and assembly was started.

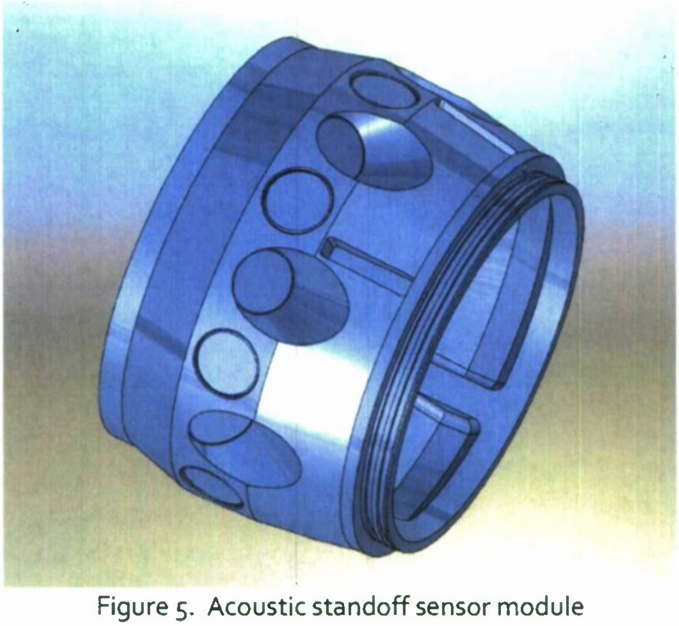


Figure 5. Acoustic standoff sensor module

Thruster efficiency – The new system was tested and generated about 25% greater thrust. This is primarily a result of an increase in maximum RPM from 4000 RPM to 5000 RPM. The new duct thruster modules were integrated in a REMUS 100.

Acoustic Communication – WHOI worked with Florida Atlantic University to integrate their high-rate, short range acoustic modem in the duct thruster vehicle. The integration was completed and tested in June.

2011 -

Acoustic Sensors – In the past year, software was improved to support the Blueview Technologies Dual Frequency Miniature Multibeam Imaging /3D Microbathymetry Sonar integration. The system was tested at WHOI and demonstrated at the MCM S &T demonstration in Panama City in June 2011.

Control and Navigation – Fabrication of the acoustic standoff sensor module was completed Figure 6 shows the module mounted on a forward duct thruster module. Bench and tank testing of the sensor were started.

Figure 6. Acoustic standoff sensor module attached to forward duct module

MAJOR RESULTS

2008

At AUVFEST 2008 the vehicle completed a hull survey of the USS Saratoga. The surveyed area was over 120 meters long and from the surface to a depth of 6 meters. Numerous targets and ship features were detected. Figure 7 depicts the vehicle path during the hull search and Figure 8 shows detected targets. At Eckenforde the vehicle conducted a harbor survey, which included legs between multiple piers, and conducted a hull survey of a submarine. Figure 9 shows the vehicle trackline for the harbor survey.

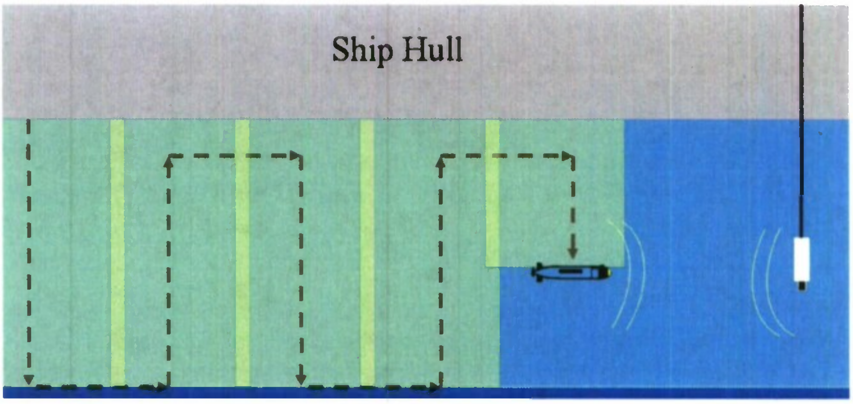


Figure 7. Vehicle path during hull survey

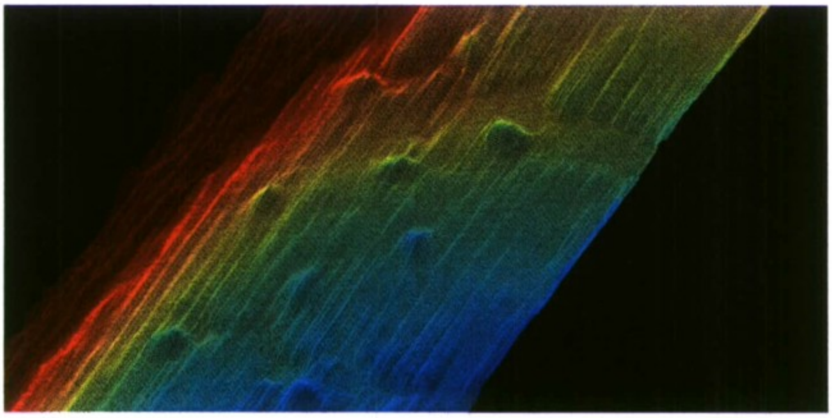


Figure 8. Close view of targets on USS Saratoga hull. Approximate size - 8" dia. x 8" height

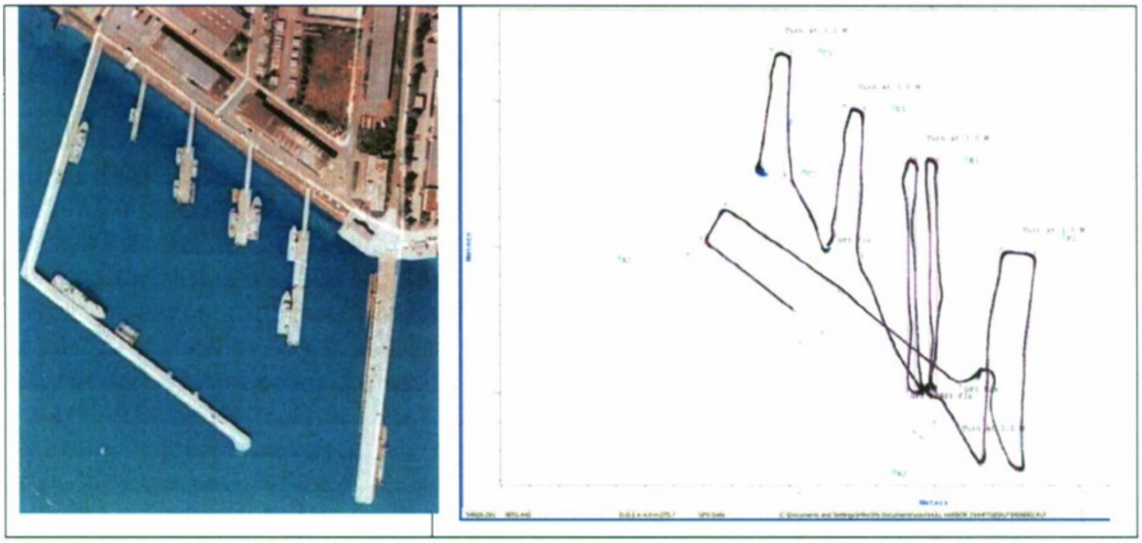


Figure 9. View of harbor and vehicle trackline. Pier spacing is approximately 50 meters

2009

Missions with the Blueview Technologies forward look sonar were conducted in Woods Hole. The sensor angle and vehicle mission (1-meter altitude) were optimized for the high frequency sonar. Figure 5 and 6 show high and low frequency sonar snapshots of a mine-like object on the seafloor. The high frequency image is with the target at a range of 2 meters. In the low frequency the object was evident at about 27 meters and is shown at about 21 meters. The test results indicate the dual frequency sonar may be effective for larger objects. Further testing is required to evaluate smaller objects on a ship hull.

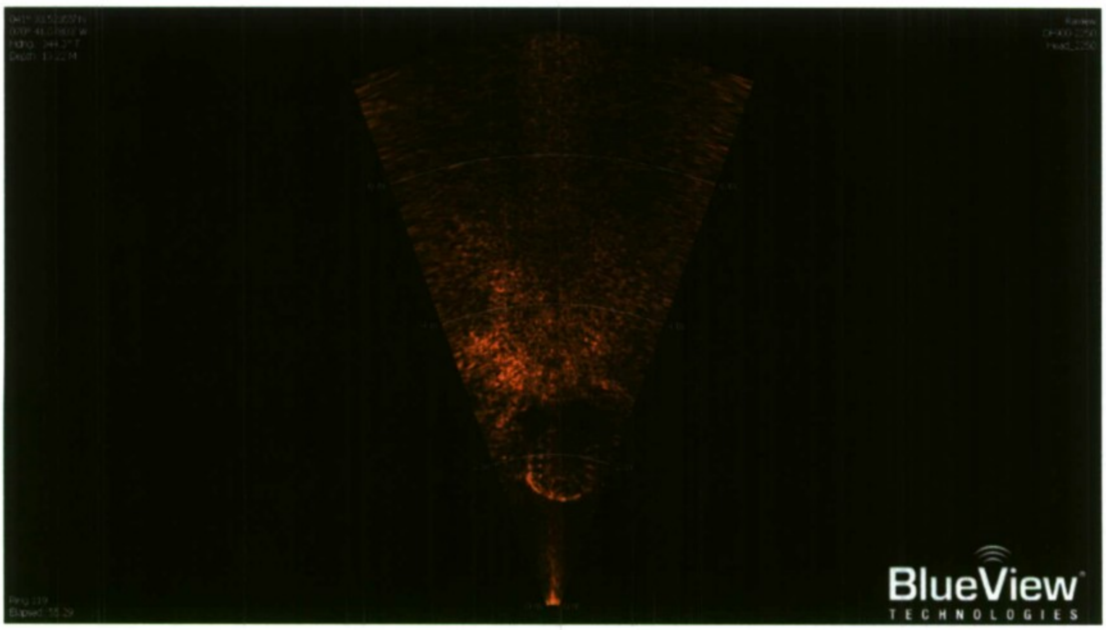


Figure 5. High frequency (2250 kHz) image of mine-like object

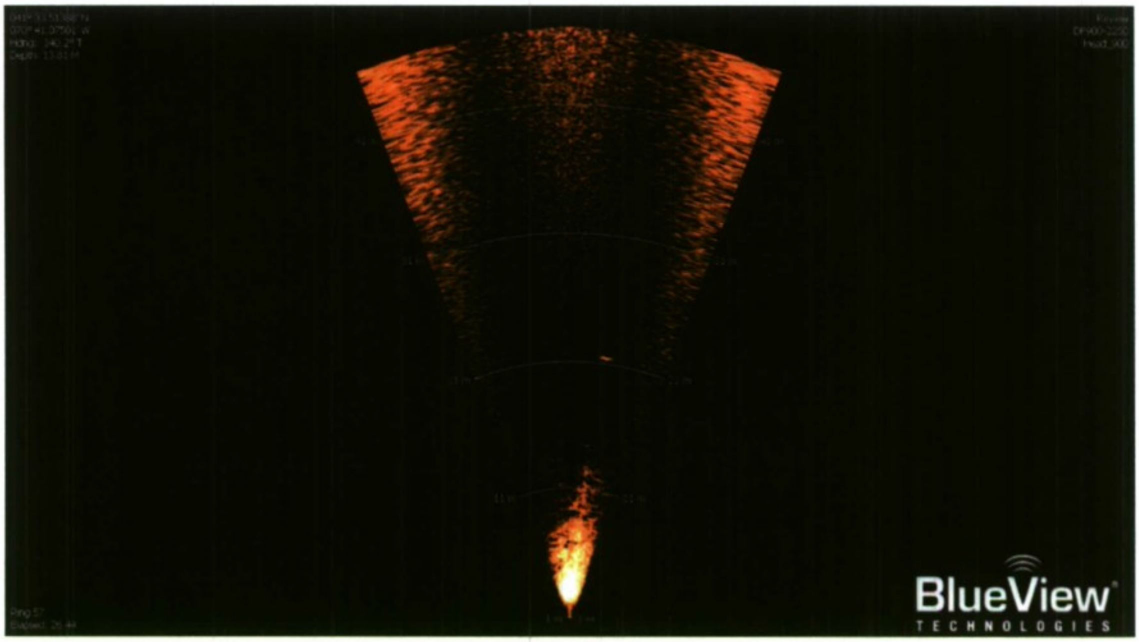


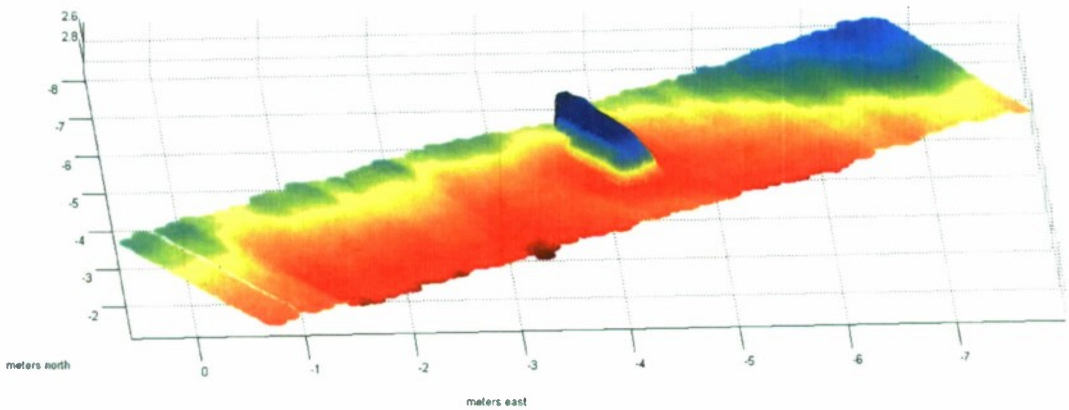
Figure 6. Low frequency image (900Khz) of mine-like object at over 20-meter range

2010

Vehicle testing in Woods Hole has demonstrated that the new duct thrusters were functional. During acoustic modem testing with FAU, Blueview Technologies 3D Microbathymetry files were transmitted from the vehicle to a shore station.

2011

The capabilities of the hovering AUV were displayed at the MCM S &T demonstration in Panama City in June 2011. The vehicle performed search and reacquire missions using side scan, CADCAC detection software and the Blueview FL/MB sonar. During the reacquire the vehicle would hover near the target to obtain forward look data and then swim over the target to obtain multibeam data. Figure 4 shows a multibeam plot of a target.



IMPACT/APPLICATIONS

The addition of duct thruster modules to a standard REMUS 100 vehicle allows the vehicle to hover and move at very low speeds in vertical, lateral and forward/aft directions with minimal impact on standard performance. REMUS 100 vehicles outfitted with the duct thrusters are dual use, with the capability to survey large areas at high speed and congested areas at low speed. This vehicle has many potential applications that include ship hull, pier and harbor inspections. The modular design allows straightforward integration of both acoustic and optical sensors. Equipment developed during this project continues to support ongoing vehicle and mission capabilities.

TRANSITIONS

WHOI established a licensing agreement with Hydroid, LLC. for commercial production of REMUS vehicles. The initial duct thruster designs were transferred to Hydroid in 2008 and two vehicles with duct thrusters have been delivered to EOD. Hydroid has also designed and installed duct thrusters in a REMUS 600 UUV.

PUBLICATIONS

Gwyneth E. Packard, Roger Stokey, Reed Christenson, Frederic Jaffre, Mike Purcell and Robin Littlefield, "Hull Inspection and Confined Area Search Capabilities of REMUS Autonomous Underwater Vehicle", Proceedings Oceans 2010, Seattle, September 22-25, 2010