RPSEA

Phase I Final Test Report

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Autonomous Inspection of Subsea Facilities

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November 7, 2011

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for Dan McLeod

Dan McLeod, Senior Program Manager

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ABSTRACT

The work performed under this contract developed, integrated and tested technology for autonomously conducting a pre/post hurricane inspection of a subsea facility. This report documents the results of the integration and testing phase that was conducted both onshore and in local waters off the coast of Palm Beach, Florida, resulting in a successful demonstration of an autonomous inspection capability of an underwater facility using an Autonomous Underwater Vehicle (AUV).

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1.0 OVERVIEW

This report documents the results of the integration and testing phase that was conducted in local waters off the coast of Palm Beach, Florida to demonstrate an autonomous inspection capability of an underwater facility using and Autonomous Underwater Vehicle (AUV). This integration & test phase started on January 4, 2011 and concluded on June 22, 2011, resulting in a successful demonstration of an AUV facility inspection capability. Demonstration of this capability was accomplished by conducting several autonomous missions around a wreck (barge) resting on the bottom of the ocean in approximately 60 feet of water using Lockheed Martin's Marlin™ Autonomous Underwater Vehicle (AUV) equipped with an Offshore Platform Inspection System (OPIS) mission package as shown in Figure 1.

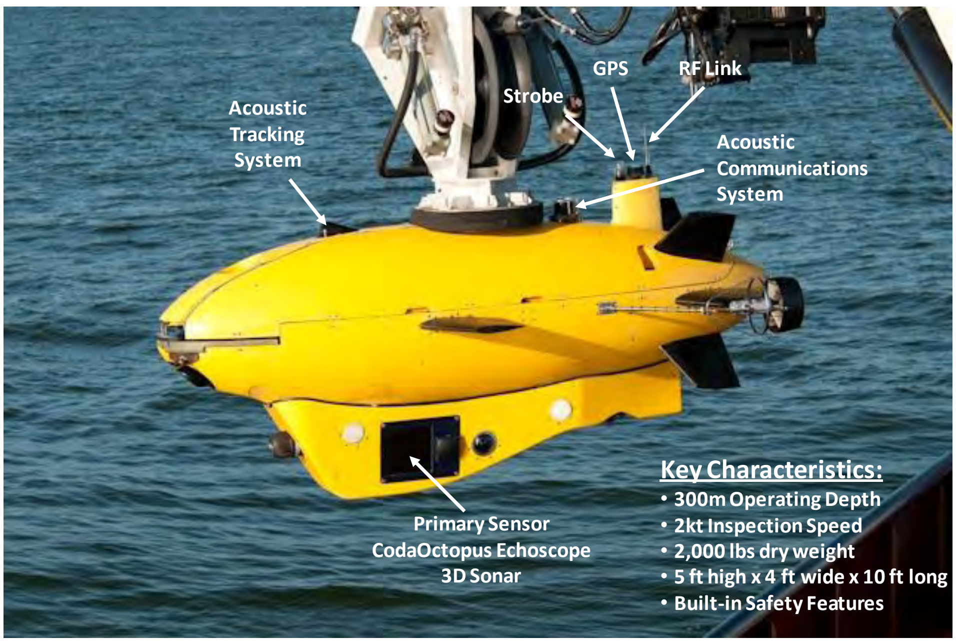

Figure 1 - Lockheed Martin's Marlin™ AUV (with OPIS mission package)

With little information known about the condition of the wreck, the Marlin AUV was able to scan the barge utilizing its onboard 3D sonar, and, with its patented onboard autonomy technology, was then able to re-construct an accurate 3D representation of the barge and detect large scale structural changes from a previous model or scan in real-time. During this integration and test phase, the Technology Readiness Level (TRL) was advanced from TRL 2 to TRL 4, as shown in Figure 2, which should help increase operator confidence of AUV facility inspection capabilities for use in deepwater field environments.

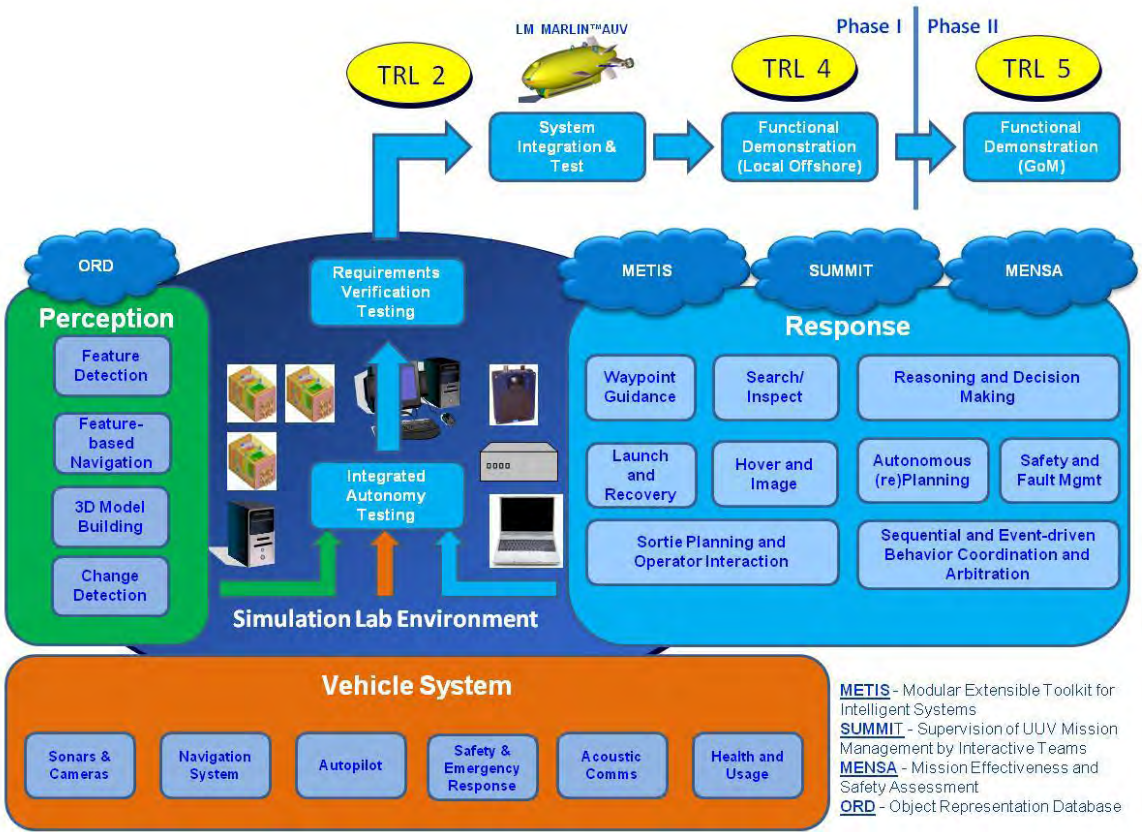

Figure 2 - Autonomy Development, Integration and Test, TRL Progression

2.0 INTEGRATION AND TEST APPROACH AND RESULTS

Integration and testing of the system was conducted in a logical, phased approach in order to mitigate risk as early as possible and was executed in three phases.

2.1 Integration Facility Phase

During this phase, the Marlin™ AUV (constructed in 2010) was integrated with the autonomy software for the first time and checked out in a dry environment. First time power-up of the vehicle was conducted along with functional checkout of various vehicle components and sensors that could be operated safely in a dry environment. This phase started on January 6, 2011 and completed on February 17, 2011 with a simulated facility inspection mission run that readied the system for in-water operations. The configuration used for this testing phase is shown in Figure 3.

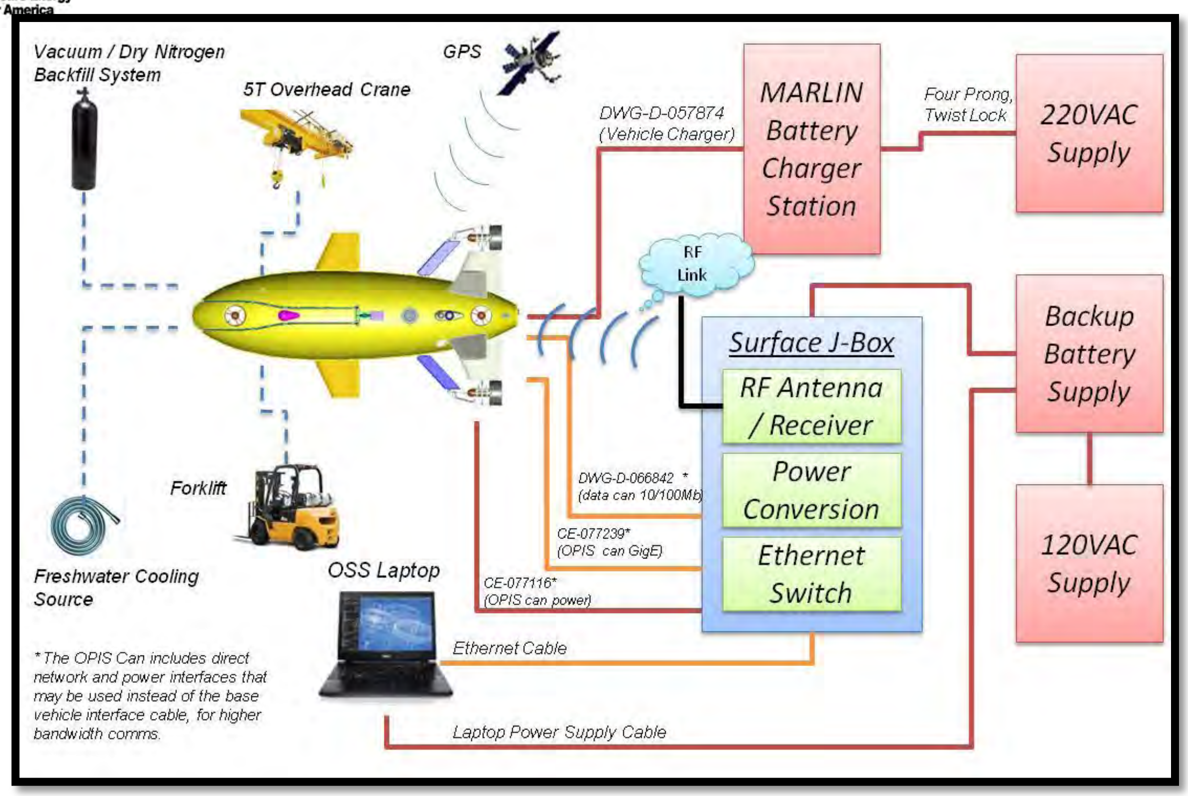

Figure 3 - Integration Facility Test Configuration

Specific integration facility tests that were successfully completed during this phase include:

- First Time Vehicle Power-up
- Battery Checkout
- Vehicle Communications Checkout (AComms, RF, E-Net Tether)
- Sensor Functional Checkout (INS/DVL/GPS, HD Camera/Lights, Strobe, CTD, Position Switches)
- Control, Data and OPIS Can Electrical Checkout
- Sonar Functional Checkout (3D Sonar, Forward Looking Sonar)
- Vehicle Actuator Checkout (Fins, Cable Guides, Vehicle Release)
- Homing & Docking System (HDS) Checkout
- Fault Checkout (loss of communications, thruster faults, sensor faults, etc.)

2.2 Dockside Phase

During this phase, the vehicle was placed in the water dockside for the first time. Vehicle weight and trim were measured and adjusted, and sensors that could not be checked completely during the integration facility phase were checked with the vehicle submerged in the water dockside. This phase started on Feb 23, 2011 and completed on May 28, 2011 with a three hour simulated inspection mission run with the vehicle in the water while it was secured to the dock. Specific dockside tests that were successfully completed during this phase include:

- Vehicle Weight and Trim Measurement/Adjustment (Pitch, Roll, BG Separation, Roll Natural Frequency))
- Vehicle Communications Checkout (AComms, RF, E-Net Tether)
- Sonar Functional Checkout (3D Sonar, Forward Looking Sonar)

- Sensor Functional Checkout (INS/DVL/GPS, HD Camera/Lights, Strobe, CTD, HDS)
- Vehicle Propulsion System Functional Checkout (Thrusters)
- Vehicle Actuator Checkout (Fins, Cable Guides, Vehicle Release)
- Acoustic Tracking System (ATS) Functional Checkout (Topside to Vehicle)
- Emergency Stop Functionality
- Acoustic Sensor Interoperability Evaluation
- GPS Accuracy Measurement
- INS Boresight Measurement (Offsets between INS and Vehicle Axes)
- 3D Sonar Calibration
- Initial Sonar Scan and Model Building (Dock Pilings)
- Endurance Testing

2.3 Local Offshore Phase

During this phase, the vehicle was tested for the first time in the offshore environment off the coast of Palm Beach, Florida. For this phase of testing, the vehicle was towed between the Lockheed Martin facility and the offshore operational area (OPAREA) each day, approximately one hour each way. Figure 4 shows the relative locations between the Lockheed Martin Facility and local offshore OPAREA.

Figure 4 – Lockheed Martin Facility and Local Offshore OPAREA

Offshore testing started with basic maneuvering and initial shakedown of the Marlin vehicle, followed by a series of open loop (speed, pitch, roll, yaw, and heave) control runs to evaluate and adjust the control gains. Although this Lockheed Martin vehicle is a proven/tested design, the large mission package added to the bottom of the vehicle for facility inspection impacted the vehicle's drag, requiring a re-characterization of the vehicle dynamics and subsequent control gain adjustments. After the vehicle control gains were set, the next portion of testing focused on evaluating the new autonomy that was developed for conducting an inspection of a subsea facility. The local offshore phase started on Feb 18, 2011 and completed on June 22, 2011 with a successful demonstration of the capability to autonomously scan a subsea structure, re-construct a 3D model of the structure using the sonar imagery from the onboard 3D sonar, and detect changes to the structure in real-time. Since an oil and gas platform was not available in the local OPAREA, a wreck (sunken barge) was utilized for this demonstration. Specific local offshore tests that were successfully completed during this phase include:

Base Marlin Vehicle Testing:

- Vehicle Tow Test (evaluate INS/DVL/GPS performance)
- Initial Shakedown Testing (basic vehicle maneuvering & functionality)
- Vehicle Dynamics and Control Characterization Testing (speed, pitch, roll, yaw, heave)
- Control Gains Validation Testing (final adjustments)
- Communications Range Testing (AComms, ATS, RF)

Local Autonomy Testing:

- Waypoint Planning and Following
- Initial Data Collection Runs (30m offset around sunken barge)
- Model Building Runs (15m offset around sunken barge)
- Inspection Runs (15m offset around sunken barge) (FBN open loop)
- Inspection Runs (15m offset around sunken barge) (FBN open closed loop)

Although integration and testing of the base Marlin vehicle was a necessary and essential first step, the real core of the technology that was developed over the past several months and matured from TRL 2 to TRL 4 was evaluated during the Local Autonomy Testing portion. This testing occurred between April 7, 2011 and June 22, 2011 in incremental steps that not only reduced risk but allowed for early evaluation and adjustments of the core autonomy algorithms (Perception, Response, and Vehicle System) in an incremental fashion.

The first step of the local autonomy testing phase was to scan the sunken barge at an offset distance of 30 meters (several passes) using the vehicle's autonomy software and onboard 3D sonar. With only approximate ground truth known of the barge's bottom location, the 30 meter offset provided a safe distance away from the structure to avoid a potential collision with the barge. Once the scan was completed, a 3D coarse model was generated offline (post mission) using a Lockheed Martin developed model building application. The coarse 3D model that was generated for the sunken barge is shown in Figure 5.

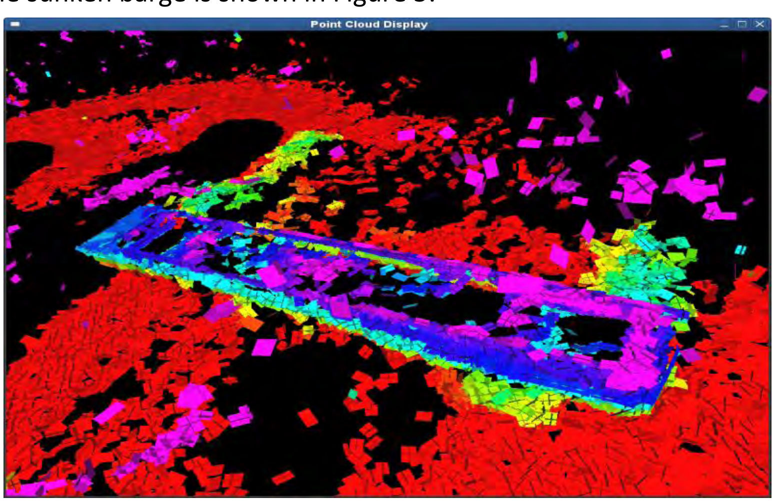

Figure 5 - Coarse Model (from 30-meter Offset Autonomous Scan)

Once the coarse model was constructed, its ground truth location was known within one to three (1-3) meters. The next step was to conduct closer runs at a 15 meter offset around the barge so that a more detailed model can be generated. The closer the scans are to the structure, the higher the resolution of the model, which is a function of the limitations of the 3D sonar itself. After several passes around the barge at 15 meter offset, a higher resolution 3D model was generated in a similar fashion as the coarse model and is shown in Figure 6.

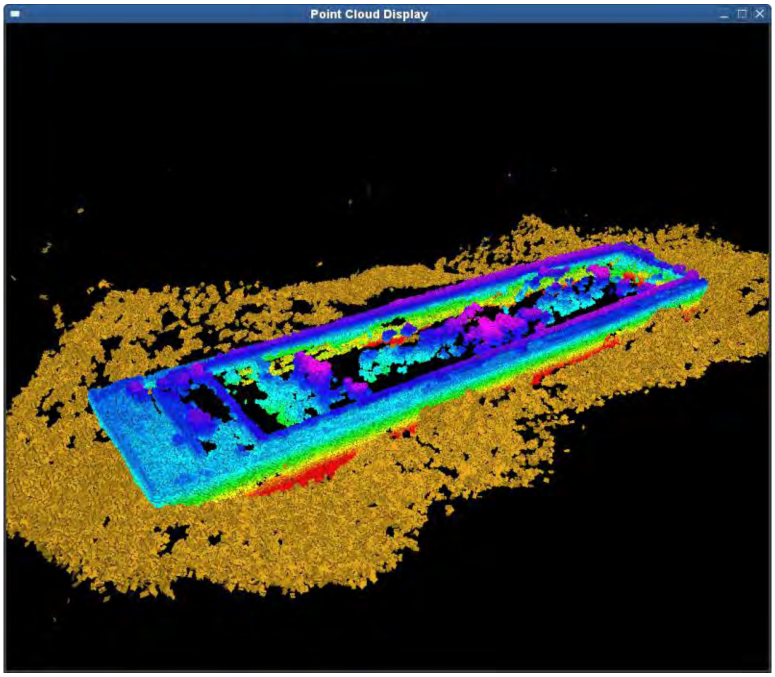

Figure 6 – Higher Resolution Model (from 15-meter Offset Autonomous Scan)

The higher resolution model now becomes the baseline (prior) model for the next set of inspection runs, also conducted at an offset of 15 meters. The purpose of the inspection runs was to demonstrate the ability of the system to autonomously re-scan the platform, accurately navigate relative to the features of the structure, and detect and localize changes from the baseline scan. This process is representative of what would be done during a level 2 post-hurricane autonomous inspection of an offshore oil and gas platform in order to determine the damage that may have occurred as a result of the hurricane.

The baseline (prior) model can either be generated from a 3D CAD model of the structure (if available) or, as in this case, generated from an actual scan of the structure because no initial geometric information was available for the barge. In order to detect changes from the baseline model, the structure must be modified before it is re-scanned. Since it was not feasible to make changes to the barge itself, a change was instead made to the baseline (prior) model by peeling away a portion of the barge and placing other changes on the order of 1 cubic meter in encumbered space (within the barge structure) and 1 cubic foot changes in unencumbered space (outside of the barge structure). The 15-meter inspection runs were then conducted, and not only did the vehicle successfully navigate around the structure (based on its features), it also detected and localized 100 percent of the cubic meter and cubic foot changes. Figure 7 (left) shows the baseline model that was modified to add a change (peeled away portion of the barge), and the right side shows the re-constructed model that was generated in situ during the inspection run along with the detected changes. A negative change (something that should be there but is missing) was detected for the bent away portion of the barge hull, and a positive change (something that shouldn't be there but is) was detected at the hole that was left in the side of the barge.

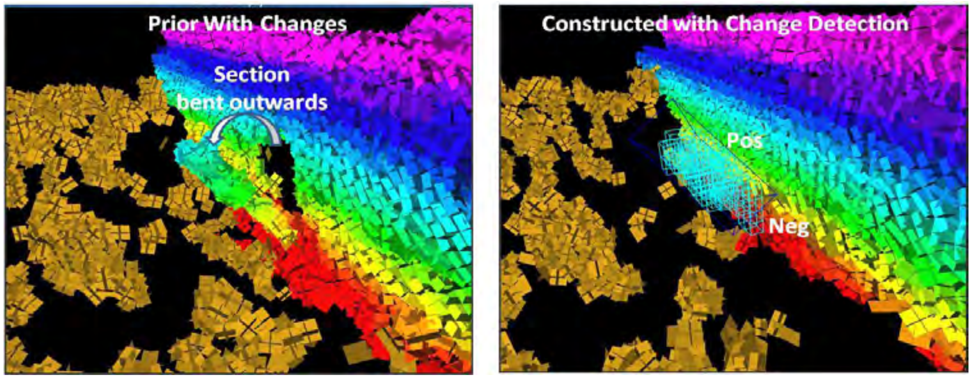

Figure 7 – Model Re-construction and Change Detection (Peeled Away Hull)

Another type of change was made to the base model by removing a small section of the barge and placing it in another location, as shown in Figure 8 (left). This change was again successfully detected during the 15-meter inspection run, as shown in Figure 8 (right).

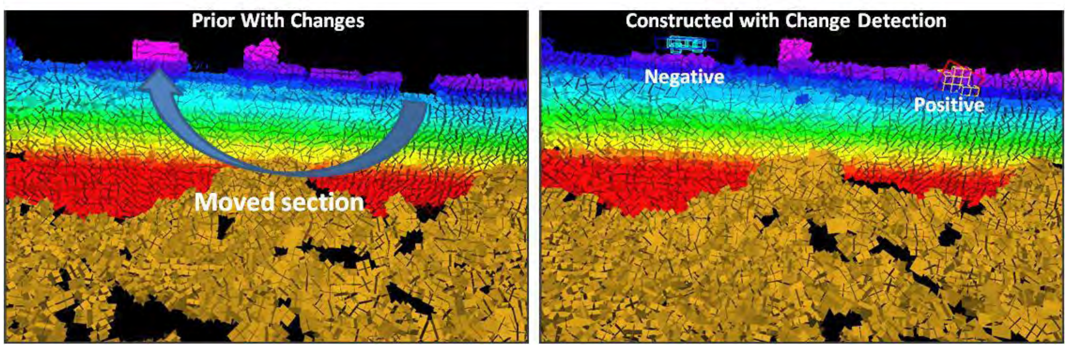

Figure 8 - Model Re-construction and Change Detection (Portion of Hull Re-located)

High accuracy navigation around the barge was accomplished using a combination of Doppler aided inertial navigation and feature based navigation. Feature based navigation is achieved by matching 3D sonar data in real time to an *a priori* 3D model of the barge to compute a very accurate (< 10 cm) estimate of the position of the vehicle in 3 dimensions relative to the platform.

The local offshore testing phase completed on June 22, 2011 and achieved all of the planned objectives for RPSEA Phase I. It reduced all of the technical risk to an acceptable level for starting RPSEA Phase II, which will demonstrate a similar capability in the Gulf of Mexico using an actual oil and gas platform in shallow (<200 ft) water.

In conclusion, the RPSEA 09121-3300-05 Phase I primary project objective was to develop, integrate, and test the autonomy technologies needed to conduct pre/post hurricane Inspection of an offshore subsea facility. This objective was fully achieved, and included the demonstration of the following capabilities in local offshore waters adjacent to Lockheed Martin's facility in Riviera Beach, Florida:

- Autonomous imaging and real-time 3D re-construction of a subsea facility
- Detection and highlighting of changes to a subsea facility
- High accuracy navigation in the vicinity of the subsea structure