Autonomous Underwater Inspection Using a 3D Laser

10121-4903-02
John Jacobson
Lockheed Martin

Final Project Presentation
November 18, 2014
Meeting Agenda

- Background
- Project Overview
- Recap of Phases I, II, and III
- Phase IV Offshore Prototype Testing
  - Test Objectives
  - Test Preparation and Logistics
  - Test Results and Data Analysis
- Conclusions
- Summary
Vision for AUVs in Deepwater Fields

- AUVs will offer significant improvements in safety and operating efficiencies as well as substantial reductions in cost over current methods.
- AUVs will leverage a wide range of inspection sensors and technologies, including video, photographic, sonar, laser, ultrasonic, magnetic, and others.

AUVs Will Become an Increasingly Important Tool for IRM in Deepwater Fields
Prior Work: RPSEA 09121-3300-05
“Autonomous Inspection of Subsea Facilities”

Project Objective:
• Develop and demonstrate 3D Modeling and Change Detection using an AUV-based 3D Sonar including:
  ✓ Close-in, high resolution 3D sonar imaging
  ✓ High resolution, geo-registered 3D models
  ✓ Detection of changes against a priori models

The Marlin® AUV Builds Geo-Registered 3D Models “On the Fly” At Speeds of ~ 2 Knots
Prior Work: RPSEA 09121-3300-06
“High Resolution 3D Laser Imaging for IRM Operations”

**Project Objectives:**

- Develop subsea 3D laser imaging and measurement capability from TRL 2 to TRL 5:
  - Pool test on tripod
  - ROV Test Tank
  - Offshore testing on tripod
  - Offshore testing on ROV

Underwater 3D Laser Prototype Testing Has Produced Spectacular Results with Millimeter Accuracies
Project Overview

**Project Objective**

- Develop and demonstrate 3D Modeling and Change Detection using an AUV-based 3D Laser, including:
  - Close-in, high resolution 3D laser imaging
  - Generation of high resolution, geo-registered 3D models of subsea structures
  - Detection of changes against a priori models

**4 Phase Project Plan:**

- Requirements / Interface Definition
- Hardware / Software Design & Build
- Onshore Integration & Testing
  - 3D Laser FAT
  - Simulation Laboratory Integration & Testing
- Offshore Prototype Testing

Potentially dramatic cost reductions and improved operating efficiencies can be achieved if high-accuracy inspections can be performed with an AUV
## Scope of Work

<table>
<thead>
<tr>
<th>Phase</th>
<th>Duration</th>
<th>Scope of Work</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>3 Months <em>(Aug-Oct 2012)</em></td>
<td><strong>AUV 3D Laser Inspection Requirements</strong>&lt;br&gt;• Concept of Operations (CONOPS)&lt;br&gt;• System / Sensor Requirements Analysis &amp; Modeling&lt;br&gt;• 3D Laser Hardware / Software Interface Definition&lt;br&gt;• Marlin AUV Interface Definition &amp; Layout</td>
</tr>
<tr>
<td>II</td>
<td>11 Months <em>(Nov 2012-Sep 2013)</em></td>
<td><strong>AUV Software / Hardware Development</strong>&lt;br&gt;• LADAR Sensor SIM&lt;br&gt;• Perception (LM-MFC) SW Development&lt;br&gt;• Laser Sensor HW / SW Interface&lt;br&gt;• Design / Packaging for AUV-based 3D Laser&lt;br&gt;• AUV Mod Kit Design/Procurement</td>
</tr>
<tr>
<td>III</td>
<td>6 Months <em>(May 2013-Oct 2013)</em></td>
<td><strong>Laboratory Integration and Test / Hardware Integration</strong>&lt;br&gt;• Fabrication &amp; Test of AUV-based 3D Laser&lt;br&gt;• Factory Integration and Testing of 3D Laser with AUV&lt;br&gt;• AUV Simulation Lab Integration and Test&lt;br&gt;• AUV Simulation Lab Test and Demonstration&lt;br&gt;• Offshore Test Plans and Procedures</td>
</tr>
<tr>
<td>IV</td>
<td>11 Months* <em>(Jan 2014-Nov 2014)</em></td>
<td><strong>AUV Integration and Test</strong>&lt;br&gt;• AUV Mod Kit Install&lt;br&gt;• 3D Laser Installation and Checkout&lt;br&gt;• Dockside Testing&lt;br&gt;• Local Offshore Testing&lt;br&gt;• Final Report</td>
</tr>
</tbody>
</table>
### Phase IV Offshore Prototype Testing Was Completed on 30 October 2014
Phase I Summary

✓ Conducted Project Kickoff on 24 Jul, 2012
✓ Developed Laser Sensor Requirements Document
✓ Developed Interface Control Document (ICD)
✓ Developed Parametric Analysis to study variation of AUV speed, target distance, and scanner control to predict laser spot resolution and target coverage
✓ Delivered Operational Concept and Requirements Document
✓ Conducted successful System Requirements Review (SRR)
✓ Received Approval for Phase 2 on 22 Oct, 2012

Received RPSEA Approval to Proceed with Phase 2 in October 2012
Phase II Summary

- Developed Sensor Simulation Tools
- Simulated Proposed Collection Geometries in Various Environments
- Determined Mathematical Approach for Laser Calibration
- Selected Optimal Scan Pattern for Phase 4 R&D Trial
- Developed Sensor to Navigation Alignment Approach
- Developed Laser Safety Plan for Operating the 3D Laser
- Completed Open Water Data Collection of 3D Laser Imagery Data to Support Software Development
- Completed HW / SW Design Review on 3 Apr, 2013
- Procured / Received 3D Laser Sensor Long Lead Materials

Received RPSEA Approval to Proceed with Phase 3 in May 2013
Phase III
3D Laser Factory Acceptance Test (FAT)

- **Objective:**
  - Perform validation testing of the DP2 3D Laser system hardware and software components in a lab setting. FAT will include in-air and in-water tank testing for scanning operations.

- **Test Agenda:**
  - Test Overview / Safety Brief
  - Sensor Packet Control Testing
  - Scanning Operations in Water
  - In-Water Range Demonstration
  - Scanning Operations in Air
  - Mechanical / Mounting Validation
  - Navigation / Serial Data Validation
Factory Acceptance Test Results

- **Summary of Results:**
  - 2 ½ Days of Sensor Testing Scheduled
  - 2 Days of Sensor Testing Utilized
  - 42 Unique Tests Conducted
  - 42 Unique Tests **PASSED**
  - 6 Tests Revisited on Day 2 with All Bugs/Errors Resolved
  - Factory Acceptance and Signoff by Lockheed Martin
  - Final Delivery of:
    - DP2 Sensor Test GUI Simulator
    - DP2 Sensor Software Users Manual
    - DP2 Sensor ICD Final Version

100% of 3D Laser Sensor FAT Tests Achieved Pass Criteria
Objectives:

- Integrate the 3D laser interfaces into the system
- Maximize the use of actual hardware interfaces such as processors and sensors
- Use simulators and emulators in place of actual hardware
- Simulate AUV-based underwater 3D laser imaging
- Assess and optimize performance prior to offshore testing
AUV Scanning Methods

- Three methods for scanning
  - Continuous Line Scan Mode
    - Scans back and forth to achieve cross track coverage
    - Along-track coverage achieved with AUV forward motion
    - Provides continuous coverage of Area of Interest
  - Full Scan Mode
    - Provides high resolution or wide Field of View (FOV) over predetermined target of interest for limited period of time
    - Utilizes both scanning axes for operation
  - Bow Tie Scan Mode
    - Provides fast scanning in both cross and forward look angles
    - Similar to continuous line scan mode, utilizes AUV forward motion to complete a full area scan
    - Provides solid single scan “look-ahead” capability within a single scan motion
- All scan modes are fully programmable and reconfigurable at any time.
Assumed Vehicle Parameters & Noise Sources

Objective(s):
- Simulate typical vehicle characteristics and adjust parameters based on the specific test case(s):
  - Ex. Decrease vehicle speed for measuring pits on pipeline
  - Ex. Adjust range based on subsea structure type

### Vehicle Parameter

<table>
<thead>
<tr>
<th>Vehicle Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Typical AUV Speed</td>
<td>1.0 m/s</td>
</tr>
<tr>
<td>Alternative AUV Speed</td>
<td>0.2 m/s</td>
</tr>
<tr>
<td>Cross Track Angle</td>
<td>+/- 15°</td>
</tr>
<tr>
<td>Cross Track Scan Rate</td>
<td>50 Hz</td>
</tr>
<tr>
<td>Target Scan Range</td>
<td>3m – 15m</td>
</tr>
<tr>
<td>Scan Type</td>
<td>Bow Tie</td>
</tr>
<tr>
<td>Scan Pulses</td>
<td>504</td>
</tr>
<tr>
<td>Scan Frame Time</td>
<td>33msec</td>
</tr>
<tr>
<td>Scan Dead Time</td>
<td>9msec</td>
</tr>
</tbody>
</table>

### Noise Source(s)

<table>
<thead>
<tr>
<th>Noise Source(s)</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Navigation Error</td>
<td>Standard</td>
</tr>
<tr>
<td>Timing Error</td>
<td>1.8 msec std dev</td>
</tr>
<tr>
<td>Sensor Calibration – Offset</td>
<td>1mm about all axes</td>
</tr>
<tr>
<td>Sensor Calibration – Rotation</td>
<td>.25° about all axes</td>
</tr>
<tr>
<td>Sensor Noise – Range</td>
<td>1 cm std dev</td>
</tr>
<tr>
<td>Sensor Noise – Pointing Angle</td>
<td>.02° std dev</td>
</tr>
</tbody>
</table>

Shows the vehicle pose, path, and bowtie scan for a single frame of the mooring chain scan simulation.
Jumper Metrology

- Simulation Images:

<table>
<thead>
<tr>
<th>Vehicle Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>AUV Speed</td>
<td>1 m/s</td>
</tr>
<tr>
<td>Target Scan Range</td>
<td>8m above wellhead flange</td>
</tr>
<tr>
<td></td>
<td>5.5m above manifold</td>
</tr>
</tbody>
</table>
Pipeline Bar Anode Depletion

- Simulation Images:
  - Uncorroded Bar Anode
  - Corroded Bar Anode

<table>
<thead>
<tr>
<th>Vehicle Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>AUV Speed</td>
<td>1 m/s</td>
</tr>
<tr>
<td>Target Scan Range</td>
<td>5m</td>
</tr>
</tbody>
</table>
LiDAR Scans at 2 Knots Simulation

- Other Notable Test Cases:
  - Wellhead Verticality
  - Manifold Anode Depletion
  - Pipeline Bracelet Depletion
  - Pipeline Dent / Pit Detection
  - Mooring Chain Pit / Wear Damage Detection and Measurement
  - Platform Inspection
  - Spoils Volume
Laboratory Simulation
Conclusions

- Excellent Results for Some Test Cases:
  - Wellhead Verticality: < 0.08 degrees angular error
  - Jumper Metrology: < 0.5% length / elevation error
  - Anode Depletion: < 2% to 10% dimensional errors
  - Spoils Volume: < 2% volumetric error

- Additional Work Required to Assess / Optimize Other Test Cases:
  - Pipeline Dent / Pit / Concrete Coating Damage Detection and Measurement
  - Mooring Chain Pit / Wear Damage Detection and Measurement
Phase III – Hardware Integration

- Finalized 3D Laser Mechanical, Electrical, & Software Designs
- Finalized AUV Mod Kit Hardware Designs & Started Fabrication Process

**Optics Canister:**
- 6.9” OD
- 13.5” Canister Length
- 3.35” Mirror Aperture Length
- ≈ 32 Pounds in Air

**Electronics Canister:**
- 7.8” OD
- 14” Canister Length
- ≈ 32 Pounds in Air

**AUV Mechanical Interface with Marlin AUV Mission Package**
(Top Represents Baseline Configuration)

**Optics & Electronics Canister Bracketry**
Phase IV: Offshore Prototype Testing

- **Primary Test Objectives:**
  - Image test targets using an AUV-based 3D laser
  - Generate geo-registered 3D models
  - Evaluate 3D model resolution and dimensional accuracy
  - Evaluate viability of AUV-based 3D inspection for use in deepwater fields

- **Test Venue:**
  - Local offshore waters (Palm Beach, FL)
  - Water depths 60 – 80 ft.
  - Currents 0.5 – 2 kt
Test Cases and Fixtures

Test Cases:

- Test Targets:
  - Pipeline Test Fixtures
  - PRCI Pipeline Sample (6” ID, 6’ L)
  - Anode Volumes on Manifold
  - Mooring Chain
  - Jumper Metrology
  - Wellhead Verticality

- Downed Barge
  - Structural Inspection of the Barge
  - Spoils Volume
Offshore Prototype Testing – Test Execution

- Dockside Testing Completed in Feb 2014
- Test Fixtures Deployed in Early March
- 12 Offshore Test Days Completed from March to October 2014
- Many Challenges!
Testing Challenges and Implications

- **Challenges:**
  - **Environmental:**
    - Many Weather Days and/or Early Test Terminations Due to Weather
    - High currents on some test days
    - Dragged Anchors Through Test Area
  - **Equipment Problems:**
    - AUV Inertial Navigation System (INS) Performance; 3 months to resolve vendor issues
    - Unable to Get Automated Calibration Algorithm to function leading to manual calibration

- **Implications:**
  - Weather Days and Equipment Problems ➔ Schedule Delays and Cost Impacts
  - High Currents ➔ Higher AUV speeds / altitudes than desired during Test Operations
  - Dragged Anchors ➔ Pipeline Test Fixture Lost
  - INS Performance ➔ Limited to Single Pass 3D Point Cloud Images (so far)
  - Manual Calibration ➔ Time-Consuming Data Analysis; Lower Accuracy Results
Test Results: Downed Barge

- Single pass scan by AUV at approximately 1 knot and 5.25 meter standoff range
- Scanned barge structure is approximately 72 ft. in length; scan completed in ~ 45 seconds
- Consistent with Simulation Lab results for a single pass at a 5 meter standoff
Test Results: Downed Barge

- Image of a cleat with rope hanging from side of the Downed Barge
- Cleat / Rope Dimensions:  A: 48.43”  B: 37.4”
- Consistent with expectations from Simulation Lab testing
SONAR vs. LADAR Comparison
The SONAR data has a higher point density and field of view, but a lower angular and range resolution. This means that smaller features can be identified more easily and accurately in the LADAR data. The laser data also has less of a problem with multipath, and no side lobe noise.

The “tie down point” is a good example of a feature that is easily seen in the laser data which cannot be readily found in the sonar data. We believe this is mainly due to the large beam width of the SONAR, which makes it difficult to resolve depressions, and other negative features.
SONAR vs. LADAR Comparison

The SONAR data has a higher point density and field of view, but a lower angular and range resolution. This means that smaller features can be identified more easily and accurately in the LADAR data. The laser data also has less of a problem with multipath, and no side lobe noise.
Downed Barge: 3D Laser vs. 3D Sonar

LIDAR Point Cloud

3D Sonar Images
Verticality / Jumper Metrology Test Results

Verticality / Jumper Metrology Test Target, raw point cloud, single pass of the AUV at 1 knot and 6.5 meter standoff range

Multiple Imaging Passes by the AUV and/or Slower Survey Speeds at Closer Standoff Ranges will Result in Denser Point Clouds and Higher Accuracy Measurements for All Cases
Cylinders were fit to the raw point clouds within Leica Cyclone (3D Point Cloud Analysis Tool) to aid in recreating the PVC pipes which make up the test target. These cylinders were used in subsequent measurements for the pipe positions, angles, and diameters.
Jumper Metrology Measurement Results

Preliminary Results: Jumper Metrology Test Case

<table>
<thead>
<tr>
<th>Segment</th>
<th>Measured Length (in)</th>
<th>Actual Length (in)</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>13.5</td>
<td>17.6</td>
<td>23.3%</td>
</tr>
<tr>
<td>B</td>
<td>48.5</td>
<td>52</td>
<td>6.7%</td>
</tr>
<tr>
<td>C</td>
<td>17.6</td>
<td>16</td>
<td>10%</td>
</tr>
<tr>
<td>D</td>
<td>269.9</td>
<td>274.75</td>
<td>1.77%</td>
</tr>
</tbody>
</table>

Results are Consistent with Expectations for a Single Pass at 1 knot and at a 6.5 m Standoff from the Target
Verticality Measurement Results

Pipe Diameter Measurements

<table>
<thead>
<tr>
<th>Location</th>
<th>Measured</th>
<th>Actual</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>8.8”</td>
<td>8.625”</td>
<td>2%</td>
</tr>
<tr>
<td>B</td>
<td>9.4”</td>
<td>8.625”</td>
<td>8.9%</td>
</tr>
</tbody>
</table>

Results consistent with expectations from Simulation Lab Testing

Verticality Measurement

The angle measured between the two large pipes as part of the verticality test was measured to 3.823°. This angle will be verified upon recovery of the test targets.
PRCI Sample Pipe

- **PRCI Sample Pipe:**
  - Obtained on loan from PRCI
  - 6" OD pipe (6.625")
  - Nominally 72" (~6 ft.) Long

- **Best Fit Measurement:**
  - Used Leica Cyclone tool
  - Best fit of cylinder to point cloud scan of PRCI sample Pipe
  - Measured Diameter 7.3"
  - Measured Length 81.5"

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Measured Diameter (in.)</th>
<th>Actual (Ground Truth) Diameter (in.)</th>
<th>Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pipe O.D.</td>
<td>7.3</td>
<td>6.625</td>
<td>10.2%</td>
</tr>
<tr>
<td>Pipe Length</td>
<td>81.5</td>
<td>72</td>
<td>13.1%</td>
</tr>
</tbody>
</table>

Results are Consistent with Simulation Lab Results for a Single Pass at 1 knot and at a 7.5 m Standoff from the Target
Mooring Chain Measurement

Mooring Chain Test Target and point cloud imaged with single pass of the AUV at 1 knot and 7.5 meter standoff range

26.93 in

15.27 in
Automated calibration algorithm development was abandoned due to late resolution of INS issues

Manual calibration was applied and achieved acceptable results, but not as accurate as expected using automated calibration
Conclusions

- **Primary Offshore Test Objectives Were Achieved**
  - Imaged test targets using an 3D laser from a moving AUV
  - Generated high resolution geo-registered point clouds
  - Evaluated 3D model resolution and dimensional accuracy vs. simulation
  - Demonstrated viability of AUV-based 3D inspection for use in deepwater fields

- **Further Work is Required to Demonstrate the Full Potential of AUV-Based 3D Laser Imaging:**
  - More Rigorous Testing Is Required to Get Better Ground Truth Measurements
  - Additional Testing at Closer Ranges, Slower Speeds, Different Geometries
  - Development of Automated Calibration Process To Support Multi-Pass Point Cloud Alignment
  - More Rigorous INS Calibration Procedures Must be Developed
Vision for the Future

- **AUV-Based 3D Laser Imaging Offers Powerful Capabilities for Structural Integrity Management:**
  - Imaging from Moving AUV is faster and more efficient than other means
  - Provides geo-registered 3D models with millimeter resolution
  - Provides autonomous change detection against a baseline model
  - Eliminates Human Fatigue and Inspection Data Overload
  - Leverages 3rd Party Software Tools from Terrestrial Survey Industry
  - More Accurate, Efficient Inspections ➔ Lower Overall Life-of-Field Costs

- **Potential Applications Include:**
  - Pipeline Inspection
  - Subsea Facility Inspection
  - Riser / Mooring Line Inspection
  - Jumper Metrology / Wellhead Verticality

AUV-Based 3D Laser Imaging Holds the Potential to Become a Powerful Tool for Structural Integrity Management
Lockheed Martin gratefully acknowledges the key contributions and inputs received from the following organizations and individuals:

- Project Sponsorship by the Research Partnership to Secure Energy for America (RPSEA) with direct oversight and inputs from RPSEA Project Managers, Mr. Donald Richardson and Mr. James Pappas.

- Participation and Support from underwater laser technology developer 3D at Depth LLC, including key contributions by Carl Embry, Brett Nickerson, and Mark Hardy.
Questions?
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