Autonomous Underwater Inspection
Using a 3D Laser

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Lockheed Martin

Ultra-Deepwater Drilling, Completions, and Interventions TAC Meeting
June 4, 2014
Greater Fort Bend Economic Development Center
Sugarland, Texas
Meeting Agenda

- Project Overview

- Overview of Phase III Activities & Results
  - Simulation Lab Test Results
  - 3D Laser Factory Acceptance Results

- Forward Plans for Phase IV
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
Benefits of AUV-based 3D Laser Inspection

- **Benefits of geo-registered 3D models:**
  - CAD Modeling for structural and thermal analysis
  - Precise Measurement/Metrology

- **Benefits of AUVs over ROVs/Divers:**
  - Smaller vessel (or no vessel)
  - Fewer people offshore
  - No umbilical management
  - Highly mobile platform for efficient IRM operations

- **Benefits of AUV-based 3D Laser Inspection:**
  - 3D model generated “on the fly”
  - Autonomous change detection without Operator Intervention
  - Rapid Condition Assessment

AUV-Based 3D Laser Imaging Holds the Potential to Become a Key Tool for Structural Integrity Management
## Scope of Work

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

- **CONOPS Requirements / Interface Definition (Completed)**
- **Design / Build (Completed)**
- **Onshore Integration / Test (Completed)**
- **Local Offshore Integration / Test (In-Progress)**
No-Cost Baseline Change Request Approved to Shift Phase IV Start to Jan 2014 and Increase Contract Period of Performance by 3 months
Stage Gate Milestones Summary

☑ Phase I (SOW Task 5.0)
  ✓ Successful Completion of SW/HW System Requirements Review
  ✓ Authorization to Proceed to Phase II

☑ Phase II (SOW Task 6.0)
  ✓ Successful Completion of Software / Hardware Design Review
  ✓ Authorization to Proceed to Phase III

☑ Phase III (SOW Task 7.0)
  ✓ Successful Completion of Lab Simulation Demonstration
  ✓ Successful Completion of 3D Laser Factory Acceptance Testing
  ✓ Authorization to Proceed to Phase IV

☐ Phase IV (SOW Task 8.0, Final Phase)
  ☐ Successful Completion of Dockside Integration / Offshore Prototype Testing
Depth Perception™ 2 (DP2)
Factory Acceptance Test (FAT) Overview
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
Test Configuration – System Level

- Test Configuration:
  - Laptop & Test GUI Simulated the AUV Sending Commands
    - Utilizes editable configuration files for packet definitions to send to the sensor
  - Laptop & Serial NAV Software Simulated the INS Sending RS422 NAV Packets
  - Processing Tool Used to Analyze Laser Data
  - Remote Desktop Capability to Sensor
Test Configuration Components – Processing Tool

- Processing Tool:
  - Used to Process Raw Binary Data From the DP2 Sensor to Provide Time Stamped Range & Position Output Files
  - Included in the DP2 System Delivery
  - Graphical Interface to Interactively View and Analyze Processed Data
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

<table>
<thead>
<tr>
<th>Test ID</th>
<th>Test Name</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Sensor Startup &amp; Connection</td>
<td>Pass</td>
</tr>
<tr>
<td>2</td>
<td>Sensor Ethernet Communications Reconnect</td>
<td>Pass</td>
</tr>
<tr>
<td>3A - 3C</td>
<td>Environmental Packets</td>
<td>Revisit 3A, 3C</td>
</tr>
<tr>
<td>4A - 4I</td>
<td>Laser Control Packets</td>
<td>Revisit 4B</td>
</tr>
<tr>
<td>5A - 5E</td>
<td>Scan Configuration Packets</td>
<td>Revisit 5A</td>
</tr>
<tr>
<td>6</td>
<td>Gain Control Packet</td>
<td>Pass</td>
</tr>
<tr>
<td>7A - 7G</td>
<td>Mode Control Packet Tests/Scan Packets</td>
<td>Revisit 7D</td>
</tr>
<tr>
<td>8A - 8B</td>
<td>Power Down Packet Control Tests</td>
<td>Pass</td>
</tr>
<tr>
<td>9</td>
<td>Continuous Scanning in Water</td>
<td>Revisit 9</td>
</tr>
<tr>
<td>10</td>
<td>Bowtie Scanning in Water</td>
<td>Pass</td>
</tr>
<tr>
<td>11</td>
<td>Full Scanning in Water</td>
<td>Pass</td>
</tr>
<tr>
<td>12A - 12C</td>
<td>Scanning Demonstration in Air</td>
<td>Pass</td>
</tr>
<tr>
<td>13</td>
<td>Sensor Navigation Data Integration</td>
<td>Pass</td>
</tr>
<tr>
<td>14A - 14C</td>
<td>Mechanical Inspection(s)</td>
<td>Pass</td>
</tr>
<tr>
<td>15A - 15C</td>
<td>Scan Mode Parameter Validity</td>
<td>Pass</td>
</tr>
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</table>

100% of 3D Laser Sensor FAT Tests Achieved Pass Criteria
Simulation Lab Demonstration
Simulation Lab Demonstration Overview

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
A High Fidelity Simulation Lab is Configured for 3D Laser Mission Planning
Mathematical Models of Errors/Noise Are Added To Simulated LADAR Data
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

<table>
<thead>
<tr>
<th>Vehicle Parameter</th>
<th>Value</th>
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</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>
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</table>

<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>
Overview of 3D LADAR Simulation Test Cases

- Test Case #1: Wellhead Verticality
- Test Case #2: Jumper Metrology
- Test Case #3: Anode Volumes on a Manifold
- Test Case #4: Pipeline Bracelet Anode Depletion
- Test Case #5: Pipeline Bar Anode Depletion
- Test Case #6A: Pipeline Dent Detection
- Test Case #6B: Pipeline Pit Detection
- Test Case #7: Pipeline Concrete Coating Damage Detection
- Test Case #8: Spoils Volume
- Test Case #9: Platform Inspection (SONAR vs. LADAR)
- Test Case #10A: Mooring Chain Pit Detection
- Test Case #10B: Mooring Chain Link Wear
Jumper Metrology

- Simulation Images:

<table>
<thead>
<tr>
<th>Vehicle Parameter</th>
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<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:

<table>
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<th>Value</th>
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<tbody>
<tr>
<td>AUV Speed</td>
<td>1 m/s</td>
</tr>
<tr>
<td>Target Scan Range</td>
<td>5m</td>
</tr>
</tbody>
</table>
Pipeline Concrete Coating Damage

- Simulation Images:

<table>
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<th>Value</th>
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<tr>
<td>AUV Speed</td>
<td>1 m/s</td>
</tr>
<tr>
<td>Target Scan Range</td>
<td>5m</td>
</tr>
</tbody>
</table>

Dent Dimensions
8.2 – 12.6 cm wide
3.0 – 5.6 cm deep
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 4: Offshore Prototype Testing

- **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 adjacent to Palm Beach, FL
  - Water depths 60 – 80 ft.
  - Currents 0.5 – 2 kt
Test Cases and Fixtures

Test Cases:

- **Sandy Bottom Area:**
  - 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 - Progress To Date

- Dockside Integration Completed
- Test Fixtures Placed Offshore
- Testing in Progress
- Results Pending
Project Status and Next Steps

- Working Group Review and Concurrence Obtained
  - Successful Completion of Simulation Laboratory Demonstration
  - Successful Completion of 3D Laser FAT
  - Implemented Sensor-to-INS Calibration Approach
  - Completed Perception SW Integration
  - Developed & Delivered Offshore Prototype Testing Procedure (Final)
  - Developed & Delivered Simulation Lab Demo Report (Final)
  - Developed & Delivered 3D Laser FAT Document
  - Authorization to Proceed to Phase IV from RPSEA

- Next Steps:
  - Execution of Phase IV Offshore Technology Prototype Testing
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