REMUS 600 Autonomous Undersea Vehicle Planning, Acquisition, and Processing Workflow

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Charts and bathymetry provided courtesy of the Canadian Hydrographic Service

The views expressed in this presentation are those of the author and do not necessarily reflect the official policy or position of the Department of the Navy, Department of Defense, nor the U.S. Government.
• **Littoral Battlespace Sensing – Autonomous Underwater Vehicle (LBS-AUV)**
  
  Acquisition delayed approximately two years from original schedule
  
  - Schedule opportunity used to procure COTS REMUS 600 AUV system in CY 2009
  - This talk focuses on the COTS REMUS 600 AUV, and the data it acquires

• **NAVOCEANO goals and objectives**
  
  - Expand existing AUV capabilities to support littoral requirements (less than 500 meters)
  - Force multiplier, increase rate of effort for mapping coverage
  - Operationalize COTS multibeam and side-scan sonar technology on AUV platform
  - Integrate AUV collected data into NAVOCEANO’s processing and production scheme
  - Develop concept of operations to support:
    - Mine warfare: detect contacts (0.5 m long by 0.1 m high) within 15 m horizontal uncertainty
    - Bathymetry/hydro surveys: International Hydrographic Organization (IHO) “1A” bathymetry, coverage, feature detection

COTS = Commercial Off The Shelf, REMUS = Remote Environmental Monitoring UnitS, CY = Calendar Year
Technology Improvements

• REMUS 600 with Kongsberg NavP and NavLab capabilities
  – Leveraged FFI and Kongsberg development for HUGIN systems
  – NavP and NavLab integration completed in July 2011

• NavP provides a rigorous, subsea, real-time navigation solution
  – Robust time synchronization of distributed onboard computer architecture
  – Integration of onboard navigation and environmental sensors
  – Remote monitoring and control via modem for mission initialization and completion

• NavLab provides a toolset for post-mission navigation reconstruction
  – Position and orientation uncertainty is reduced from forward/backward processing
  – Robust integration of position, speed, and acceleration measurements
  – Offsets, calibration alignments can be corrected post-mission

REMUS = Remote Environmental Monitoring UnitS, FFI = Norwegian Defense Research Institute, HUGIN = High Precision Untethered Geosurvey and Inspection System
REMUS 600 Overview
Hydrographic and Mine Warfare Mapping AUV

**Navigation Sensors**
- NavP
- Paroscientific Pressure
- \( P(y) \) Code GPS
- Kearfott SeaNav T24 INS
- TRDI 600 kHz DVL
- Imagenex 852 Pencil Beam
- Acoustic: USBL, LBL, UTP

**Environmental Sensors**
- Kongsberg EM3002 MBS
- EdgeTech 230/850 kHz SSS
- Neil Brown C,T Sensor
- Wet Labs Inc.’s ECO Optical
- Comms: Acoustic, Iridium, RF


Approximately 2,000 nautical miles to date
AUV Data Flow

Standard file formats:
1. MBS: raw.all, GSF
2. SSS: UNISIPS
3. CTD: ASCII
4. Bathy grids: PFM, BAG

Typical Mission Workflow Sequence

• Pre-mission planning
  – Requirements: hydrography and MIW
  – Environmental characteristics, traffic, notice to mariners
  – Navigation fixing, route and line sequencing, etc.
  – Power planning and maintenance
  – Revisit/monitor schedule

• Deploy, conduct mission, recover
  – INS initialization, prelaunch checklist
  – Launch, communications checks, sensor checks
  – Complete pre-dive checklist
  – Initial navigation solution

• Post-mission processing, analysis, feedback
  – Data offload, navigation post-processing and merge
  – Apply correctors, TPU, gridding, contact detection, quality assurance/quality control, correlate contacts
  – Post-mission checklist and feedback to next mission plan

MIW = Mine Warfare, TPU = Total Propagated Uncertainty
AUV Uncertainty Budget Plan

- **Navigation dominates horizontal TPU**
  - GPS and/or acoustic provides initial position
  - DVL constrains inertial drift between fixes
    - Approximation: 0.1% of distance traveled (as $\sigma$)
  - DVL uncertainty is directional, some canceling occurs on reciprocal azimuth
  - Modeling suggests AUV can run 40 - 45 minutes between fixes for IHO 1A in 75 meter depth regime

- **Vertical TPU**
  - Sounding uncertainty: sonar measurements, roll, pitch, heading, alignments, integration, SVP, etc.
  - Water levels remain a dominant issue in shallow water
  - Vehicle depth added to MBS measurements
  - Factors influencing AUV depth solution
    - Salinity, temperature, atmospheric pressure, surface waves, latitude, pressure sensor, gravity
    - NavP/NavLab mitigate influence of surface waves

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**Example V TPU budget for AUV, 75 m depth**

<table>
<thead>
<tr>
<th>Component</th>
<th>Uncertainty (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sonar, integration, SVP, varies across swath</td>
<td>0.15</td>
</tr>
<tr>
<td>Tide measurement</td>
<td>0.05</td>
</tr>
<tr>
<td>Tide zoning</td>
<td>0.3</td>
</tr>
<tr>
<td>Surface waves</td>
<td>0.05</td>
</tr>
<tr>
<td>Pressure measurement</td>
<td>0.07</td>
</tr>
<tr>
<td>Pressure conversion to depth</td>
<td>0.1</td>
</tr>
<tr>
<td>Atmospheric pressure</td>
<td>0.05</td>
</tr>
<tr>
<td>Gravity anomaly</td>
<td>0.05</td>
</tr>
</tbody>
</table>

**Vertical TPU estimate (m, 95% CL)**: 0.37

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TPU = Total Propagated Uncertainty, GPS = Global Positioning System, DVL = Doppler Velocity Log, IHO = International Hydrographic Organization, CL = Confidence Level, MBS = MultiBeam Sonar, SVP = Sound Velocity Profiler

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Concurrent Multibeam and AUV Testing

- NAVOCEANO and CHS collaboration
  - CHS/IOS provided facilities, water levels, and reference data
  - NAVOCEANO provided exposure to system technologies

- Canadian Coast Guard vessel *Otter Bay* outfitted with
  - Kongsberg EM2040 (0.5° fore/aft x 1.0° athwart ships)
  - NavCom GPS, POS/MV, CTD, MVP-30, ISS-60

- NAVOCEANO’s MHS 1 outfitted with
  - AUV launch and recovery system (LARS)
  - AUV vehicle interface program (VIP)
  - NavCom GPS, POS/MV, CTD, HiPAP, ISS-60, Reson 7125

- CHS personnel provided invaluable local-area knowledge

CHS = Canadian Hydrographic Service, IOS = Institute of Oceanographic Science, GPS = Global Positioning System, MHS-1 = Mine Hunter SWATH (Small Waterplane Area Twin Hull) 1, POS/MV = Positioning and Orientation System, Marine Vessels, AUV = autonomous undersea vehicle, CTD = Conductivity, Temperature, Depth, HiPAP = High Accuracy Acoustic Positioning, ISS = Integrated Survey System (for T-AGS 60 class ship)
AUV Test Objectives

- **Assess depth accuracy**
  - Pressure sensor performance

- **Assess navigation accuracy**
  - Straight line performance
  - Reciprocal azimuth performance
  - Position fix/aiding needs

- **Environmental sensitivity**
  - Temperature and salinity
  - Barometric pressure
  - Effect of surface waves
  - Water levels

- **Try out new launch and recovery system**

- **Process AUV navigation, MB, SSS data**

- **Train NAVOCEANO field personnel**

- **Wide range of depths and seabed conditions in close proximity to CHS/IOS**

- **Targets for feature detection testing**

- **Test areas protected from weather**

- **Really BIG tidal range!**

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MB = multibeam, SSS = side-scan sonar, AUV = autonomous undersea vehicle, CHS/IOS = Canadian Hydrographic Service/Institute of Ocean Sciences

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Sidney Test Overview

• Look at three specific areas
  – (1) Saanich Inlet, deep area
  – (2) Victoria, mid-depth area
  – (3) Sidney, shallow area

• Look at vertical uncertainty
  – EM2040 data
  – CHS reference bathymetry data

• Look at horizontal uncertainty
  – MHS-1 HiPAP reference position
  – Contact/feature alignment from overlapping coverage

CHS = Canadian Hydrographic Service, MHS-1 HiPAP = MHS-1 = Mine Hunter SWATH (Small Waterplane Area Twin Hull) 1 High Precision Acoustic Positioning
Deep Water Test Area Results

- Depth range: 200 – 225 meters
- AUV position aided with HiPAP
- Seabird CTD casts taken pre-mission and post mission
- CTD data also extracted from AUV
  - Good agreement with Seabird profile
- Pressure to depth conversion includes
  - Latitude
  - Salinity profile, temperature profile
  - Atmospheric pressure

HiPAP = High Precision Acoustic Positioning, CTD = Conductivity, Temperature and Depth
Deep Water Test Area Results

- Look at temperature, salinity impact on AUV depth
- AUV lines run at 75, 50, 30, and 10 meter altitudes
- Compare EM2040 bathymetry to:
  - AUV bathymetry, where AUV depth => Pressure (T, S)
  - AUV bathymetry, where AUV depth => Pressure (0, 35)

<table>
<thead>
<tr>
<th>AUV Altitude</th>
<th>Using (0 °C, 35 PPT)</th>
<th>Using measured (T, S)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Difference @ 95% CL</td>
<td>Difference @ 95% CL</td>
</tr>
<tr>
<td>75 m</td>
<td>+1.26 m</td>
<td>+0.64 m</td>
</tr>
<tr>
<td>50 m</td>
<td>+1.39 m</td>
<td>+0.60 m</td>
</tr>
<tr>
<td>30 m</td>
<td>+1.50 m</td>
<td>+0.62 m</td>
</tr>
<tr>
<td>10 m</td>
<td>+1.61 m</td>
<td>+0.61 m</td>
</tr>
</tbody>
</table>

REMUS track lines superimposed on EM2040 bathymetry data

T = Temperature, S = salinity, CL = Confidence Level
Mid-Range Depth Area, Depth Difference

- Depth ranges from 70 meters to 90 meters
  - Area surveyed with EM2040 system Aug 26
  - Area surveyed with REMUS Aug 20 and Aug 21
- AUV operated with 30 meter altitude goal
- NavLab navigation using full HiPAP
  - Use best navigation to focus on depth
- Results of bathymetry surface differencing
  - Subtracting EM2040 bathy from 2008 CHS bathy shows 95% CL difference of 0.31 m, 86% positive
  - Subtracting EM3002 bathy from EM2040 shows 95% CL difference of 0.39 m, 98% positive

Difference obtained by subtracting EM3002 CUBE depth surface from EM2040 CUBE depth surface. Both grids at 1.0 meter node spacing.

REMUS = Remote Environmental Monitoring UnitS, HiPAP = High Precision Acoustic Positioning, CL = Confidence Level, bathy = bathymetry
Mid-Range Depth Area, Horizontal

- **Mission statistics**
  - 10 transects, 6 kilometers in length
  - Approximately 9 hours long
  - AUV aided with HiPAP at mission start
  - AUV aided with HiPAP at mission end
  - DVL, inertial navigation between mission start and mission completion

- **Post-mission (KM NavLab) forward backward processing** to generate new time series of AUV position and orientation
  - #1) HiPAP at start/end DR in between
  - #2) HiPAP at start/end, UTP in between
  - #3) HiPAP throughout, no UTP

HiPAP = High Precision Acoustic Positioning, DVL = Doppler Velocity Log, DR = Dead Reckoning, KM = Kongsberg Maritime, UTP = Underwater transponder positioning

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Mid-Range Depth Area, Horizontal

- **Dead reckoning, DVL bounded inertial**
  - HiPAP aided at mission start and mission end
  - Horizontal uncertainty ramp consistent with modeling
  - Partial horizontal uncertainty cancelling as expected
  - Demonstrates value of forward, backward processing

- **UTP, using single transponder**
  - 80% of area covered meets order 1 horizontal criteria
  - Peaks in error correlate with range to transponder

- **NavLab uncertainty estimate is reasonable**

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HiPAP = High Precision Acoustic Positioning, DVL = Doppler Velocity Log, UTP = Underwater transponder positioning, GPS = Global Positioning System, IHO = International Hydrographic Organization
Mid-Range Depth Area, Bathymetry

- Image on left is based on full HiPAP aiding from NavLab
- Image on right is based on UTP aiding from NavLab
  - Alignment of bed form features suggests offset in range of 5 – 10 meters

HiPAP = High Precision Acoustic Positioning, UTP = Underwater transponder positioning,
Mid-Range Depth Area, Bathymetry

- Image on left is based on full HiPAP aiding from NavLab
- Image on right is based on DVL bounded inertial (HiPAP only at start/end) from NavLab
  - Alignment of bed form features suggests offset in range of 30 – 35 meters

HiPAP = High Precision Acoustic Positioning, UTP = Underwater transponder positioning, DVL = Doppler Velocity Log
Shallow Depth Area, Depth Difference

- Depth ranges from 18 meters to 20 meters
  - Area surveyed with EM2040 system Aug 27
  - Area surveyed with REMUS Aug 18 and Aug 19
- AUV operated with 10 meter altitude goal
- NavLab navigation using full HiPAP
  - Use best navigation to focus on depth
- Results of bathymetry surface differencing
  - Subtracting EM2040 bathy from 2003 CHS bathy shows 95% CL difference of 0.17 m, 80% negative
  - Subtracting EM3002 bathy from EM2040 shows 95% CL difference of 0.46 m, 100% positive

Difference obtained by subtracting EM3002 CUBE depth surface from EM2040 CUBE depth surface. Both grids at 0.5 meter node spacing.

REMUS = Remote Environmental Monitoring UnitS, HiPAP = High Precision Acoustic Positioning, CL = Confidence Level, bathy = bathymetry
Shallow Depth Area, Horizontal

- 1.0 km long transects, 15 m spacing
- AUV aided with HiPAP at mission start and end
  - DVL, bounded inertial throughout mission
  - No UTP for this mission
- NavLab post-processed navigation compared with HiPAP tracking
- NavLab estimate of position uncertainty is conservative
- Majority of this mission completed with navigation error below IHO order 1 guideline

HiPAP = High Precision Acoustic Positioning, DVL = Doppler Velocity Log, UTP = Underwater Transponder Positioning
Summary

• Data from the AUV can meet IHO Order 1A guidelines, and MIW requirements
  – When horizontal uncertainty is managed via UTP positioning, or HiPAP positioning
  – Should also be possible via surfacing for GPS fixes though not demonstrated here
  – Line length factors into horizontal uncertainty management and mission planning
  – Management of vertical uncertainty requires salinity and temperature profile
  – Management of vertical uncertainty requires correction for atmospheric pressure

• AUV launch and recovery system on SWATH boat provides great platform for future work

• Future Directions
  – More work required to better understand influence of heading changes on horizontal uncertainty
  – Define parameters for optimal placement of seafloor transponders
  – Navigation solutions that allow AUV to remain submerged (USVs, feature matching, etc.)

Thank You

Questions?