Long-endurance AUV capabilities

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Goals of this talk

• Describe what drives the energy budget
• Describe consequences of design for long range
Background

- Multi-vehicle control to maximize detection, classification performance
- Autonomy for long-range missions: e.g., guidance for large, poorly mapped riverine systems, energy minimizing control.
- Search and search
High-Speed AUV

Engineering highlights
• No passive roll stability requires active roll control
• 50% heavier than displacement sinks fast when not moving
• Nose-down hover when not in flight

Virginia Tech activities
• Propulsion
• Hydrodynamics
• Guidance/control
• Electronics/software
• Flight testing

Speed: 10 knots
Endurance: 8 minutes

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value (units)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>~39 (inches)</td>
</tr>
<tr>
<td>Diameter</td>
<td>3 (inches)</td>
</tr>
<tr>
<td>Displacement</td>
<td>7.84 (lbs)</td>
</tr>
</tbody>
</table>

Summer 2006 contact:
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Animation of data from AUVfest June 7, 2007
~675 ft. run at 10 Knots (40 sec)
Features

- Acoustic communication and acoustic navigation
- Client/server software architecture
- Removable mast

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>SPECIFICATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>34 inches</td>
</tr>
<tr>
<td>Diameter</td>
<td>4.75 inches</td>
</tr>
<tr>
<td>Mass</td>
<td>18.3 lbs.</td>
</tr>
<tr>
<td>Propulsion/Control</td>
<td>brushless DC motor with encoder feedback; 4 independently servoed flaps</td>
</tr>
<tr>
<td>CPU/Software</td>
<td>x86 compatible; LINUX OS; database server architecture utilizing TCP/IP client/server connections</td>
</tr>
<tr>
<td>Endurance</td>
<td>&gt;8 hours at 3 knots</td>
</tr>
<tr>
<td>Communications</td>
<td>900MHz RF modem; Wi-Fi with external antenna; WHOI micromodem for acoustic communication</td>
</tr>
<tr>
<td>Navigation</td>
<td>GPS, transponder-based acoustic navigation; time-synchronized acoustic navigation for AUV to AUV ranging, and AUV to chase boat ranging; gyro-stabilized dead reckoning.</td>
</tr>
<tr>
<td>Moving mass</td>
<td>9.9 lbs; electronics carriage with battery stack moves 0.5 inches longitudinally</td>
</tr>
</tbody>
</table>
Self-Mooring AUV

Capabilities

• Self-mooring; long-term deployment of ocean sensors
• 100 nm round trip to mooring location
• Subsea acoustic communication, even while moored

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>SPECIFICATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>89 “ (with anchor), 74” (without anchor)</td>
</tr>
<tr>
<td>Diameter</td>
<td>6.9 inches</td>
</tr>
<tr>
<td>Endurance</td>
<td>100 nautical miles at 4 knots</td>
</tr>
<tr>
<td>Depth</td>
<td>500 meters</td>
</tr>
<tr>
<td>Communications</td>
<td>900MHz RF modem; Wi-Fi, acoustic communication, satellite communication</td>
</tr>
</tbody>
</table>
Ingress system

- Trawl-resistant
- low-cost (not recovered)
- Miniature Self-Mooring AUV payload provides brains and sensors

Egress system

- Miniature Self Mooring AUV (fewer batteries, no mooring hardware)
Survey AUV

Concept

- Bathymetric surveys up to 500m depth
- Re-use of Self-Mooring AUV technology
- Pressure-compensated tail section

<table>
<thead>
<tr>
<th>PARAMETER</th>
<th>SPECIFICATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>80.1“</td>
</tr>
<tr>
<td>Displacement</td>
<td>94.7 lbs</td>
</tr>
<tr>
<td>Diameter</td>
<td>6.9 inches</td>
</tr>
<tr>
<td>Endurance</td>
<td>35 hrs @ 4 knots (non-rechargable)</td>
</tr>
<tr>
<td></td>
<td>25 hrs @ 4 knots (rechargable)</td>
</tr>
<tr>
<td>Depth</td>
<td>500 meters</td>
</tr>
<tr>
<td>Communications</td>
<td>900MHz RF modem; Wi-Fi , acoustic communication, satellite communication</td>
</tr>
<tr>
<td>Navigation</td>
<td>DVL + IMU</td>
</tr>
</tbody>
</table>
The energy budget
Typical range versus velocity

![Graph showing the relationship between range (km) and velocity (m/s). The graph peaks at a velocity of approximately 1.5 m/s.]
Energy budget

Drag

\[ F = \rho C_d A \, v^2 \]

- Coefficient of drag
- Cross-sectional area
- Velocity
Energy budget

Drag

Propulsive power (mechanical)

\[ F = \rho C_d A \nu^2 \]

\[ p_m = F \nu \]

Propulsive power is velocity cubed
Energy budget

Drag

\[ F = \rho C_d A \nu^2 \]

Propulsive power (mechanical)

\[ p_m = F \nu \]

Propulsive power (electrical)

\[ p_e = p_m / \eta \]

Efficiency of propulsion system
Energy budget

Drag

Propulsive power (mechanical)

Propulsive power (electrical)

Endurance

\[ F = \rho C_d A v^2 \]

\[ p_m = Fv \]

\[ p_e = \frac{p_m}{\eta} \]

\[ B / (p_e + p_h) \]

Battery capacity

Hotel load
Selected approaches to increase range

• Be large
• Propulsive efficiency
• hotel
US Navy Large-Diameter UUV

- 70 days
- Nominal speed + sprint

\[ F = \rho C_d A \nu^2 \]
Propulsive power (electrical) \[ p_e = \frac{Fv}{\eta} \]
DC motor efficiency

Our selected operating point

Challenges
• No sprint
• Difficulty leaving surface

NeuMotor 1925 3Y
Propeller and seals

Propeller

- $\eta = 73.7\%$
- Required Torque = 16.98 in-oz
- Diameter = 12 cm

OpenProp 3D Propeller Image

Shaft seal

>15 in-oz at pressure and speed
### Energy budget

<table>
<thead>
<tr>
<th>Parameter</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_d$</td>
<td>0.2</td>
</tr>
<tr>
<td>$A$</td>
<td>0.0241</td>
</tr>
<tr>
<td>$\eta$</td>
<td>0.6</td>
</tr>
<tr>
<td>$B$</td>
<td>2500 watt-hour</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Parameter</th>
<th>value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Velocity</td>
<td>2 m/s</td>
</tr>
<tr>
<td>Hotel</td>
<td>25 watts</td>
</tr>
<tr>
<td>Endurance</td>
<td>1.15 (days)</td>
</tr>
<tr>
<td>Range</td>
<td>197 km</td>
</tr>
<tr>
<td>Percent hotel</td>
<td>27%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>value</th>
<th></th>
<th>value</th>
<th></th>
<th>value</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0.75 m/s</td>
<td>25 watts</td>
<td>3.36 (days)</td>
<td>7.73 (days)</td>
<td>500 km</td>
<td>74%</td>
</tr>
</tbody>
</table>
Modern processors allow dynamic voltage and frequency scaling

\[ P \propto V^2 f \]

Performance vs. prob of missing control update

Stochastically unstable for $p_o \geq 0.218$
Other systems
MBARI long range AUV

- 8 W sensor, 1000 km at 1 m/s
- 120Kg displacement
- 300 m max depth

Hybrid Glider

# Self-Mooring AUV

<table>
<thead>
<tr>
<th></th>
<th>Ingress</th>
<th>Egress</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Length</strong></td>
<td>95.7 in</td>
<td>81.3 in</td>
</tr>
<tr>
<td><strong>Weight</strong></td>
<td>111.5 lb</td>
<td>92.5 lb</td>
</tr>
<tr>
<td><strong>Diameter</strong></td>
<td>6.9 in</td>
<td></td>
</tr>
<tr>
<td><strong>Cruise Speed</strong></td>
<td>4 knots</td>
<td></td>
</tr>
<tr>
<td><strong>Range</strong></td>
<td>100 nmi (with 0.5 knot current)</td>
<td></td>
</tr>
<tr>
<td><strong>Deployment</strong></td>
<td>Up to 1 year</td>
<td></td>
</tr>
<tr>
<td><strong>Max depth</strong></td>
<td>1640 ft (500 m)</td>
<td></td>
</tr>
<tr>
<td><strong>Payload Capacity</strong></td>
<td>160 in³, 1.5 lb</td>
<td></td>
</tr>
<tr>
<td><strong>Payload Energy</strong></td>
<td>1000 Wh</td>
<td></td>
</tr>
</tbody>
</table>
Mission Overview

- Mission phases:
  1. Ingress: Proceed from Deployment to Target Surface Location.
Mission Overview

• Mission phases:
  1. Ingress: Proceed from Deployment to Target Surface Location.

![Diagram showing mission phases with nodes D, S, T, and labeling for Deployment, Ingress, Target Surface Location, and Actual Surface Location.](image-url)
Mission Overview

- Mission phases:
  1. Ingress: Proceed from Deployment to Target Surface Location.
  2. Descent: Deploy anchor from the surface and quickly descend.
Mission Overview

- Mission phases:
  1. **Ingress**: Proceed from Deployment to Target Surface Location.
  2. **Descent**: Deploy anchor from the surface and quickly descend.
Mission Overview

- Mission phases:
  1. Ingress: Proceed from Deployment to Target Surface Location.
  2. Descent: Deploy anchor from the surface and quickly descend.
  3. Mooring: Remain in a low power state near the seafloor.
Mission Overview

• Mission phases:
  1. Ingress: Proceed from Deployment to Target Surface Location.
  2. Descent: Deploy anchor from the surface and quickly descend.
  3. Mooring: Remain in a low power state near the seafloor.
Mission Overview

- **Mission phases:**
  1. **Ingress:** Proceed from Deployment to Target Surface Location.
  2. **Descent:** Deploy anchor from the surface and quickly descend.
  3. **Mooring:** Remain in a low power state near the seafloor.
  4. **Egress:** Release anchor and return to Recovery point.
Mission Overview

• Mission phases:
  1. Ingress: Proceed from Deployment to Target Surface Location.
  2. Descent: Deploy anchor from the surface and quickly descend.
  3. Mooring: Remain in a low power state near the seafloor.
Vehicle Layout

- Anchor: Attached by vacuum.
- Nose: Anchor release mechanism and mission payload.
- Tube: Battery and mast.
- Tail: Navigation and propulsion.