Cooperative Navigation for Autonomous Underwater Vehicles

Navigare 2011, 4 May 2011, Bern

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Why go under water?

• Land, atmosphere and sea surface maps:
  • Many parameters obtainable through remote sensing
  • High-resolution
  • (Almost) complete coverage
  • Up to date
  • Cheap to obtain

• Subsurface maps:
  • **In situ** measurements required!
  • Low resolution
  • Sparse
  • Out-of-date (often by decades)
  • Expensive to obtain
Outline

• What is an AUV?
• Types of AUVs
• Payloads (sensing/scientific and navigation)
• Challenges in underwater robotics (Communication, Navigation)
• Cooperative Navigation
• Applications
What is an AUV? – and what not

• **Vehicle**
  • Mobile
  • Resource-constrained

• **Underwater**
  • Hostile environment
    • Pressure
    • Corrosion
    • Fouling
  • Potential loss of vehicle

• **Autonomous**
  • Not remote controlled
  • On board decision making
  • Limited intervention capabilities
## Types of AUVs – active propulsion

<table>
<thead>
<tr>
<th></th>
<th>Low end AUV</th>
<th>Top end AUV</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Dimensions</strong></td>
<td>0.7 m length * 0.1 m diameter</td>
<td>5 m length * 0.7 m diameter</td>
</tr>
<tr>
<td><strong>Price</strong></td>
<td>$15’000</td>
<td>$2’000’000</td>
</tr>
<tr>
<td><strong>Top speed</strong></td>
<td>1 m/s</td>
<td>3 m/s (15 m/s ?)</td>
</tr>
<tr>
<td><strong>Max depth</strong></td>
<td>100 m</td>
<td>11’000m</td>
</tr>
<tr>
<td><strong>Endurance</strong></td>
<td>2h</td>
<td>24h (72h)</td>
</tr>
</tbody>
</table>

*Pictures courtesy of University of Hydroid, Ocean Server*
Types of AUVs – active propulsion

- Cetus (Lockheed Martin, USA)
- Gavia (Hafmynd, Iceland)
- Flapping foil AUV (MIT)
- SAPPHIRES (Saab, Sweden)
- Hovering AUV (MIT/Bluefin)
- Solar AUV (AUVSI, USA)
- SeaBed (WHOI, USA)
- Nereus, hybrid AUV/ROV (WHOI)

http://auvac.org/resources/browse/configuration/
Types of AUVs – buoyancy driven

- Vehicle changes buoyancy from positive to negative and back
- Attached wings cause forward motion
  - Maximum depth (2000 m)
  - Forward speed (0.3 m/s)
  - Range: 5000 km (and more)
- Very long endurance vehicle (6 months – many years)
  - Very low power consumption
  - Limited sensing capabilities
  - Limited navigation sensors
  - Limited controllability
  - Bio fouling becomes relevant
- Price: $100’000

Pictures courtesy of University of Washington/APL, Webb Research
Types of AUVs – buoyancy driven

Pictures courtesy of University of Washington/APL, Webb Research
External sensing payloads

- Video Camera
- Sophisticated sonar (multi-beam, SAS)
- Active acoustics (sub-bottom profiler)
- Sampler
- Manipulator
- Large chemical sensors (CO₂)
- Computationally expensive sensors

- Camera (still)
- Simple sonar (side-scan, pencil beam)
- Magnetometer
- Small chemical sensors (O₂, chlorophyll)

- Passive acoustics

- Conductivity, Temperature, Depth
- Fluorescence
- Backscatter
External sensing payloads

- Side-scan sonar

- Photos

- Imaging sonar

- Multi-beam sonar:

*Pictures courtesy of Dana Yoerger, Hanu Singh, Hafmynd, Bluefin, IMOS Australia*
Navigation payloads

- Fiber-optic north seeking gyro
- Sophisticated INS

- Doppler Velocity Logger (DVL)
- Simple Inertial Navigation System (INS)
- Long / Ultra-short Base Line

- GPS
- Depth
- Simple accelerometer (orientation)
- 3 axis magnetic compass

Pictures courtesy of University of Hydroid, Ocean Server, Webb Research
Challenges - communication

• What does not work
  • Very High Frequency, Ultra High Frequency radio (MHz) (Wifi, Bluetooth, etc.)
  • Extremely High Frequency radio (GHz) (GSM, Satellite)
  • Infrared

• What “sort-of” works (short range)
  • Very Low Frequency radio (kHz)
  • Green/blue LEDs
  • Directed laser
  • Return current

• What works
  • Extremely Low Frequency (Hz)
  • **Acoustic**

*Pictures courtesy of WHOI, MIT, Grumman, ANU, US Navy*
Acoustic communication

- Acoustic modem (WHOI, Benthos, MIT, …)
- Range: $O(100 \text{ m}) - O(1-10 \text{ km})$
- Data rate: $O(\text{bytes/s}) - O(\text{kbytes/s})$
- Energy expensive $O(1 \text{ Joule/byte})$
- Small channel capacity (one modem at a time)
- Strong temporal and local variations of channel
- Interference with navigation equipment (LBL, DVL)
- Strong acoustic signature
- Multipath
  - Direct (1)
  - Surface bounce (2)
  - Thermocline Bounce (3)
  - Bottom bounce (4)

32 bytes every 10s!
Underwater navigation

• Absolute positioning
  • GPS (only when surfacing)
  • LBL:
    1. AUV send query ping to all beacons
    2. Beacon 1 responds
    3. Beacon 2 responds
    4. Vehicle computes position
  • Beacon field needs to be predeployed
  • Operating area is limited by to a few km²

• Vision-aided navigation

*Picture courtesy of Ryan Eustice*
Underwater navigation

• Relative positioning:
  • Depth sensor → underwater navigation is a 2D problem
  • Magnetic compass ($1k; accuracy: 1-3 degrees)
  • Fiber Optical Gyro (FOG) ($40k; accuracy: 0.1 degree)
  • Inertial Navigation System
  • Doppler Velocity Logger (DVL)
    – Provides 2D speed over ground
    – Maximum distance to seafloor: 30 m – 200 m

Best case AUV navigation accuracies
  • Surface: GPS
  • Near seafloor: 0.1% distance traveled
  • Mid-water column: 1.5 km/h drift

Pictures courtesy of RDI, IXSEA
Cooperative navigation

Different vehicles have different navigation sensors with different accuracies

- **Glider**
  - (compass + speed estimate)

- **AUV**
  - (DVL/compass based navigation)

- **AUV deluxe**
  - (INS with fiber-optic gyro)

- **Surface vehicle**
  - (GPS)

*Pictures courtesy of University of Washington/APL, Hydroid, Kongsberg*
Cooperative navigation

In heterogeneous teams:

“Use other vehicles’ position estimate to update my own”

- Each vehicle is outfitted with an acoustic modem
- Vehicle broadcast
  - Position estimate \( x(x,y, \text{depth}, \text{course}, \text{speed}) \)
  - Certainty estimate \( P \)
  - (additional information)
- Inter-vehicle measurement (range \( r \) is available)
Cooperative navigation

• Ad-hoc:
  – Heterogeneous group of vehicles
  – Broadcast when position uncertainty low

• Hierarchical:
  – Task specific AUVs
  – Dedicated communication and navigation aids (CNA) (expensive navigation sensors, frequent surfacings, few vehicles) → master
  – Mission specific AUVs (cheap navigation sensors, no surfacing, many vehicles) → slave

Illustration courtesy of Bluefin Robotics
Cooperative Navigation experiment

- Panama City, FL, December 2006
- Mine Counter Measure (MCM)
- 2 Autonomous Surface Crafts
- 1 AUV:
  - Bluefin 12”
  - Navigation: depth gauge, DVL, INS, compass
  - Acoustic modem
- ASCs followed AUV
- ASCs broadcast GPS position, AUV got range to ASC
Cooperative Navigation experiment

- GPS
- Dead-reckoned
- "Ground-Truth"
- CN algorithm

30 m!
Applications

- **Static missions**
  - Pre-programmed
  - List of waypoints
  - Non-adaptive

- **Adaptive missions**
  - Partially pre-programmed
  - List of behaviors
  - Vehicle adapts depending on sensor reading

- **Multi-vehicle missions**
  - Pre-programmed or adaptive

*Pictures courtesy of Ocean Server*
Conclusions

• AUVs face difficulties not encountered in other environments
• Expensive hardware, but cheaper alternatives are underway
• Experiments require careful planning and execution

• Most difficult terrain to navigate in
• Drift will always get you
• Absolute position update requires extensive infrastructure OR
• Cooperative navigation
Thank you!