Underwater Robotics Research

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Underwater Robotics

• Ocean Exploration: Challenges
• Ocean Exploration: Methods
  – Traditional Oceanographic Methods
  – Submarines
  – Robotics: Teleoperated and Autonomous
• Research Laboratories in the US
• Research Accomplishments in the US
• Research Goals
• Research Accomplishments beyond the US
• Opportunities for International Research
# The World’s Oceans

<table>
<thead>
<tr>
<th>Depth</th>
<th>What</th>
</tr>
</thead>
<tbody>
<tr>
<td>~100m</td>
<td>Professional diver (mixed gas)</td>
</tr>
<tr>
<td>~300m</td>
<td>Professional diver (saturation)</td>
</tr>
<tr>
<td>~1,000m</td>
<td>Nuclear submarine</td>
</tr>
<tr>
<td>3,730m</td>
<td>Average ocean depth</td>
</tr>
<tr>
<td>4,500m</td>
<td>Deepest US Submarine - <em>DSV Alvin</em></td>
</tr>
<tr>
<td>6,000m</td>
<td>97% of ocean floor shallower than this</td>
</tr>
<tr>
<td>6,500m</td>
<td>Deepest submarine, Deepest robot</td>
</tr>
<tr>
<td>11,000m</td>
<td>Deepest ocean depth</td>
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**Pressure at 11,000m:**

\[
P = \rho g h
\]

\[
P = 1000 \frac{kg}{m^3} \times 9.8 \frac{m}{s^2} \times 11,000m \times \frac{1 \text{ bar}}{1.01 \times 10^5 N}
\]

\[
P = 1,064 \text{ bar}
\]

\[
P = 15,640 \frac{lb}{in^2}
\]
Global Ocean Depth
Traditional Research Methods for Deep Sea Oceanography

Mid-Water trawl for fish and invertebrate studies aboard the *R.V. Ronald H. Brown* in Astoria Canyon, Pacific Ocean.

Image Credit: NOAA Ocean Exploration Program.

CTD and cast aboard the *R.V. Ronald H. Brown* in the Strait of Juan de Fuca, Pacific Ocean.

Image Credit: NOAA Ocean Exploration Program.
Applications
Tethered Remotely Operated Vehicles (ROVs)

Dynamically Positioned Mother Ship

Main Steel Cable 6000 m x 17mm 400 Hz 3Φ at 20kVa 3 single mode fibers

MEDEA 500 kg depressor weight

50m Kevlar Cable Power & Fiber-Optics

JASON ROV robot vehicle

The JHU ROV Experimental Vehicle
Tethered Remotely Operated Vehicles (ROVs)

6500m Jason 2 (USA)

6500m the DSL-120A (USA)

5000m the DSL-120A (USA)

6500m ISIS ROV (UK)

4000m MARUM Quest ROV (Germany)

6500m Hercules (USA)
Untethered Autonomous Underwater Vehicles

REMUS 100m AUV, WHOI and Hydroid, Inc
Image credits: © Hydroid Inc

ABE 6000m AUV, WHOI
Image credits: © Rod Catencah WHOI

SAUVIM AUV 6,000m, University of Hawaii
Image credits: © Honolulu Star-Bulletin Hawaii News

HUGIN 3000m AUV, Kongsberg Simrad
Image credit: © Kongsberg Simrad.
Autonomous Underwater Vehicles (AUVs)
Underwater Robotics Research Laboratories in the U.S.

- Woods Hole Oceanographic Institution (WHOI)
  - Dana Yoerger: Control; Hanumant Singh: Sensing; Mark Grosenbaugh: Fish Propulsion; Chris von Alt: REMUS
  - Develop and Operate all U.S. deep submergence oceanographic vehicles: *Alvin, Jason 1 & 2, DSL120, Sea Bed, Remus*

- University of Hawaii
  - Developed *ODIN* AUV and *SAUVIM* AUV
  - Junku Yuh and Song Choi

- Monterey Bay Aquarium Research Institution (MBARI)
  - Developed *Tiburon* ROV, *Altex* AUV, novel instrumentation.
  - Jim Bellingham, Bill Kirkwood

- Johns Hopkins University
  - Whitcomb’s navigation and control systems are employed worldwide.
Underwater Robotics Research Laboratories in the U.S.

- Virginia Polytechnic Institute
  - Dan Stilwell: swarm vehicles; Craig Woolsey: internal actuation.

- Naval Postgraduate School
  - Tony Healey: Control; Don Brutzman: Visualization.

- Stanford:
  - Steve Rock: vision based vehicle control.

- MIT:
  - John Leonard: SLAM.
  - Mike Triantafyllou: Fish propulsion.

- Florida Atlantic University:
  - Edgar An: High level AUV simulation and control architecture.

- University of Washington: Underwater Gliders
- AUSI: Autonomous Underwater Systems Institute
- RPI: Rivernet
Links to Some Underwater Robotics Research Web Sites

- Sias Patterson, Inc. http://www.spiauv.com/
- Naval Command Control and Ocean Surveillance Center http://www.nosc.mil/robots/
- Naval Undersea Warfare Center http://www.nuwc.navy.mil/
- Florida Atlantic University http://www.oe.fau.edu/AMS/
- Massachusetts Institute Technology http://auvserv.mit.edu/
- Monterey Bay Aquarium Research Institute http://www.mbari.org/
- Pennsylvania State University http://www.arl.psu.edu/areas/autosys/autosys.html
- Standford University http://sun-valley.stanford.edu/projects/underwater_robots/
- University of Hawaii http://www.eng.hawaii.edu/~asl/
- University of South Florida http://www.marine.usf.edu/COT/cothome1.html
- Princeton U. http://www.princeton.edu/%7edcsl/aosn/
- Johns Hopkins U. http://robotics.me.jhu.edu/dscl/
- Caltech. http://robotics.caltech.edu/~kristi/
- RPI http://www.ausi.org/research/research.html
- Woods Hole Oceanographic Institute http://www.marine.whoi.edu/
- Autonomous Undersea Systems Institute http://www.ausi.org/
- Draper Laboratory USA http://www.draper.com/tuna_web/vcuuv.htm
Research Accomplishments: Theory

• Vehicle Dynamics and Control
  – Neural Network Control: Yuh
  – Model Free Adaptive (DOB) Control: Yuh, Choi
  – Model-Based Adaptive Control: Healey; Smallwood

• Thruster Dynamics
  – Yoerger and Slotine
  – Healey
  – Bachmayer

• Navigation and Sensing
  – Combined Optical and Acoustic Mapping: Singh
  – SLAM: Leonard and others.

• Underwater Robotic Manipulation
  – Marani, Yuh

• Biomimetic Fish Propulsion
  – Triantafyllou, Grosenbaugh.
Research Accomplishments: Systems

• Jason 1&2 ROV, DSL120: Ballard, Yoerger, Whitcomb, Bowen.
  – U.S. National 6,500 m Oceanographic Vehicles
  – Over 500 oceanographic dives, 10,000 hours bottom time.
• Autonomous Benthic Explorer (ABE) AUV: Yoerger & Bradley.
  – 6,000m Autonomous Survey Vehicle, 120+ dives, 1000+ hours.
• REMUS AUV: von Alt
  – Small 300m survey AUV. Commercialized. Comm. and mil. versions.
• Odyssey and Altex AUVs: Bellingham et al.
  – 6,000m AUVs for long-range survey. Commercialized.
• SLOCUM Gliders: Doug Webb
  – Buoyancy driven AUV for mid-water survey. Commercialized.
• Solar AUV: AUVSI Blidberg
• SAUVIM: Yuh, Marani, Choi
  – Semi-AUV with a robotic arm
• Underwater Robot ROV and AUV Companies: Oceaneering, ISE, Bluefin, Hydroid, Deep Ocean Eng., Schilling, DSSI, Simrad, Slingsby, more…
Influential Papers: 1 of 2

• Autonomous Vehicles (AUVs)

• Remotely Operated Vehicles (ROVs)

• Dynamics and Control:

• Thruster Dynamics:
Influential Papers: 2 of 2

• Acoustic Communication:

• Vehicle Navigation and Sensing

• Autonomous Ocean Sampling Networks

• Underwater Archaeology

• Biomimetic Propulsion
Research Goals: 1 of 2

• Focus on Specific Missions:
  – Science: Oceanography, Archaeology
    • Hadal: Deep trenches below 6,500m, Arctic/Antarctic.
    • Abyssal: Oceanic basins, Mid-Ocean Ridges.
    • Littoral and Estuarian – coastal, continental shelf, rivers and lakes.
    • Rapid event response with global reach.
  – Commercial
    • Survey and inspection in denied areas
    • Intervention
  – Military
    • Forward surveillance
    • Mine countermeasure

• Autonomous Operation
  – Adapting to a Changing Environment
  – Cooperative Behavior of Multi-vehicles
  – Adaptive Sampling
  – Autonomous Mission Planning/Operation
  – Semi-Autonomous Control (fleets)
  – Robotic Manipulation
Research Goals: 2 of 2

• Endurance
  – Missions of Days, Weeks, Years.

• Navigation
  – Higher Precision, Higher Accuracy
  – Environment Referenced
  – Obstacle Avoidance

• Communications
  – Higher Bandwidth, Network Protocols, Information Content
  – User Interface, System / User Interconnectivity

• Sensors and Sensor Processing
  – Smaller, Lower Power, High Reliability, Self Calibrating
  – Distributed Networks of Sampling Platforms
  – Quantitative spatial imaging:
    • acoustic and optical
    • relation to navigation problem
11,000m Hybrid ROV
Bowen, Yoerger, Whitcomb
Woods Hole Oceanographic Institution
Fletcher, Young
SPAWAR – U.S. Navy

LxWxH 3m x 2m x 2m
Air Weight 2100 kg
Payload 25 kg

Battery Rechargeable Lithium ion. 6 kWh in main pressure housing, 6kWH in tool package housing

Speed 3 knots (1.5 m/s), 2 knots (1.0 m/s) with work package

Arm Electric, 5 DOF, 20kg lift at 1m

Thrusters 2 aft, 2 vertical, 1 lateral

Lights Variable output LED array, strobes.

Sonars Scanning sonar, multibeam

Sensors Magnetometer, CTD
NSF Polar Program – Lake Vostok
We would like to know if there's life on Jupiter's frozen moon Europa. We'd also like to know if there's life in Antarctica's ice-covered Lake Vostok.

- Lake Vostok about the size of Lake Ontario, which lies buried under thousands of meters of ice high on the Antarctic Plateau, is thought to be home to unique habitats and microorganisms. Confirming the existence of life forms and unique biological niches without contaminating the pristine lake waters, however, is a difficult scientific and technical challenge with international ramifications.

- An ice core -- one of the world's longest -- was drilled by a joint U.S., Russian, and French team at Russia's Vostok Station on the lake's western shore. But coring was stopped roughly 100 meters (328 feet) above what is thought to be the surface of the water to prevent contamination of the lake. The ice layers reveal a 400,000-year environmental record with microorganisms present throughout most of the core.
Adapt to changing situations expected and unexpected
Same or better performance at a lower cost with no single point of failure
Use mix of unmanned vehicles (air, surface, and underwater) for different tasks and group coordination optimizes coverage of the multi-dimensional space
Each type of platform has significant potential for synergistic performance improvements through coordinated operation
Group Behavior Technical Issues

- Coordination of autonomous vehicles will require some level of **communication**. Efforts are being made to define a common language for autonomous agents to direct, receive direction and perform adaptive tasking.

- **Path-planning** algorithms for military operations may require planning to intercept single or multiple moving target and possibly hostile moving target(s). This is not a common concern in most commercial applications and thus may not be addressed in various research facilities. It may prove to be a critical capability for homeland defense and harbor protection.

- **Operator-to-Machine interface** issues are also open-ended for both single and multiple vehicles. The operator is receiving and processing information from the group while commanding the group. The challenge is to remove the burden of group coordination from the operator.

- Coordination and **data fusion** from multiple sensing vehicles both real-time (e.g. target tracking and pursuit) and post-run is required.
Major Accomplishments Outside the U.S.

- NDRE’s *Hugin* series AUV (Norway).
- Univ. of Southampton’s *Autosub* AUV and *ISIS* ROV (UK).
- JAMSTEC’s *KAIKO* ROV (Japan).
- Heriot-Watt University’s *ALIVE* AUV (UK).
- IFREMER’s *Victor* ROV (France)
- Instituto de Sistemas e Robótica *Marius* AUV (Portugal).
- CNR-ISSIA’s *Romeo* ROV (Italy).
- Technical University of Denmark’s *Martin* AUV.
• Heriot-Watt University UK http://www.cee.hw.ac.uk/oceans
• Simon Fraser University Canada http://www.ensc.sfu.ca/research/url/
• Tokai University Japan http://mdesign.os.u-tokai.ac.jp/katolab/katolabe.html
• University of Tokyo Japan http://underwater.iis.u-tokyo.ac.jp/Welcome-e.html
• JAMSTEC Japan http://www.jamstec.go.jp/
• IFREMER France http://www.ifremer.fr/anglais/
• Southampton Oceanography Centre UK http://www.soc.soton.ac.uk/OTD/asub/
• Sydney University Australia http://www.acfr.usyd.edu.au/
Opportunities for International Cooperation

• New underwater robotics research development programs in Korea, Taiwan, Australia, Germany, and other countries can benefit from U.S. experience.

• Major international programs for permanent oceanographic observatories present new opportunities for ROVs and AUVs in complementary roles.

• Nascent field of deep-water archaeology requires new sensing and manipulation technology and collaboration of site host country.

• Oceanographic sensor and propulsor development.
Acknowledgements

The authors are grateful for the thoughtful input from a variety of researchers in the field, in particular:

– Professor Daniel Stilwell Ph.D., Virginia Polytechnic University, Blacksburg, VA.
– Professor Anthony Healey Ph.D., Naval Postgraduate School, Monterey, CA.