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

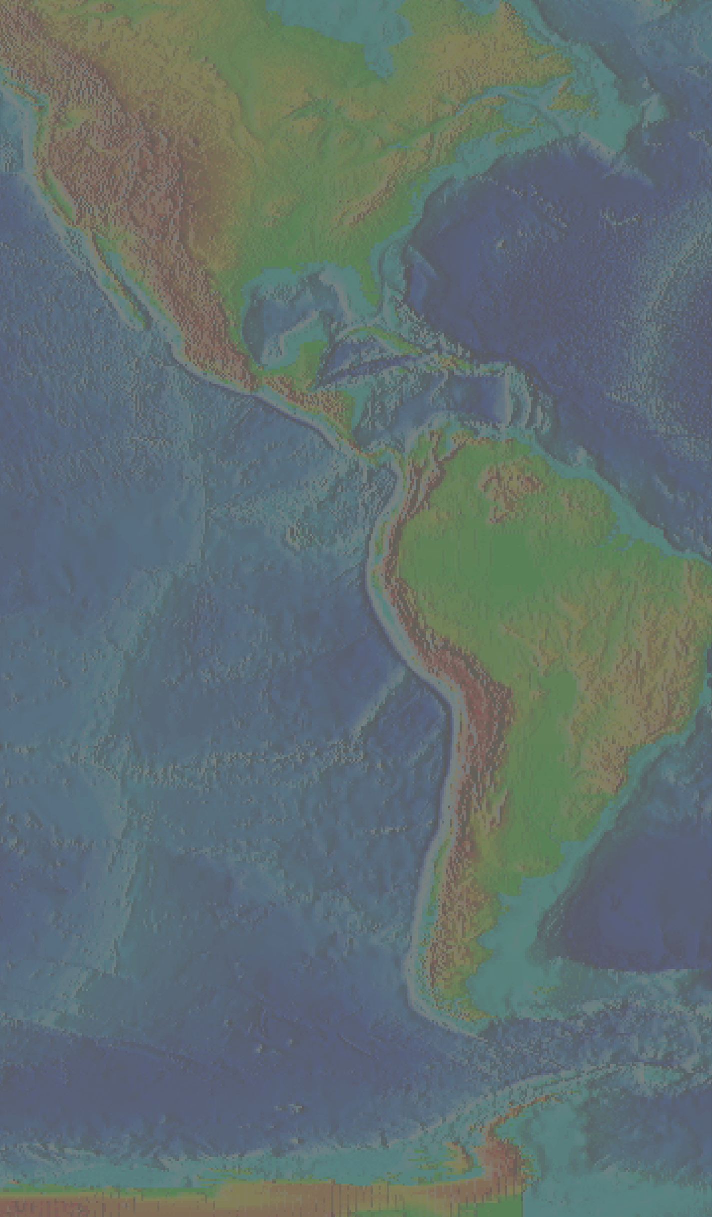


Image Source: NOAA National Geophysical Data Center, Boulder, CO

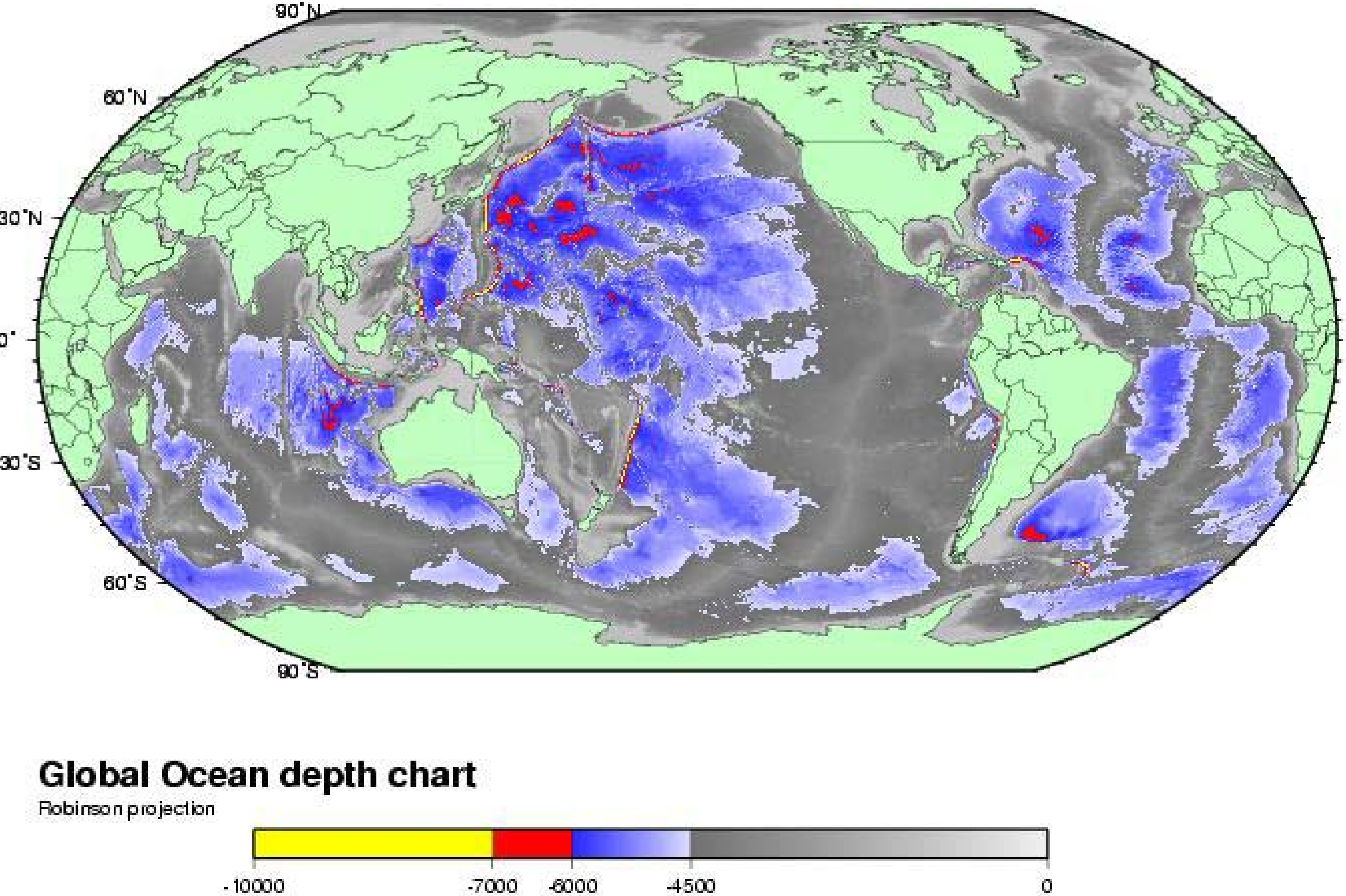
Area: **361,000,000 km^2 (71% of earth surface)**

Depth	What
~100m	Professional diver (mixed gas)
~300m	Professional diver (saturation)
~1,000m	Nuclear submarine
3,730m	Average ocean depth
4,500m	Deepest US Submarine - *DSV Alvin*
6,000m	97% of ocean floor shallower than this
6,500m	Deepest submarine, Deepest robot
11,000m	Deepest ocean depth

Pressure at 11,000m:

$$\begin{aligned} P &= \rho\, g\, h \\ &= 1000\frac{kg}{m^3}\ 9.8\frac{m}{s^2}\ 11,000m\frac{1\ bar}{1.01 * 10^5 N} \\ &= 1,064\ bar \\ &= 15,640\ \frac{lb}{in^2} \end{aligned}$$

Global Ocean Depth



Traditional Research Methods for Deep Sea Oceanography

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

Image Credit: NOAA Ocean Exploration Program.

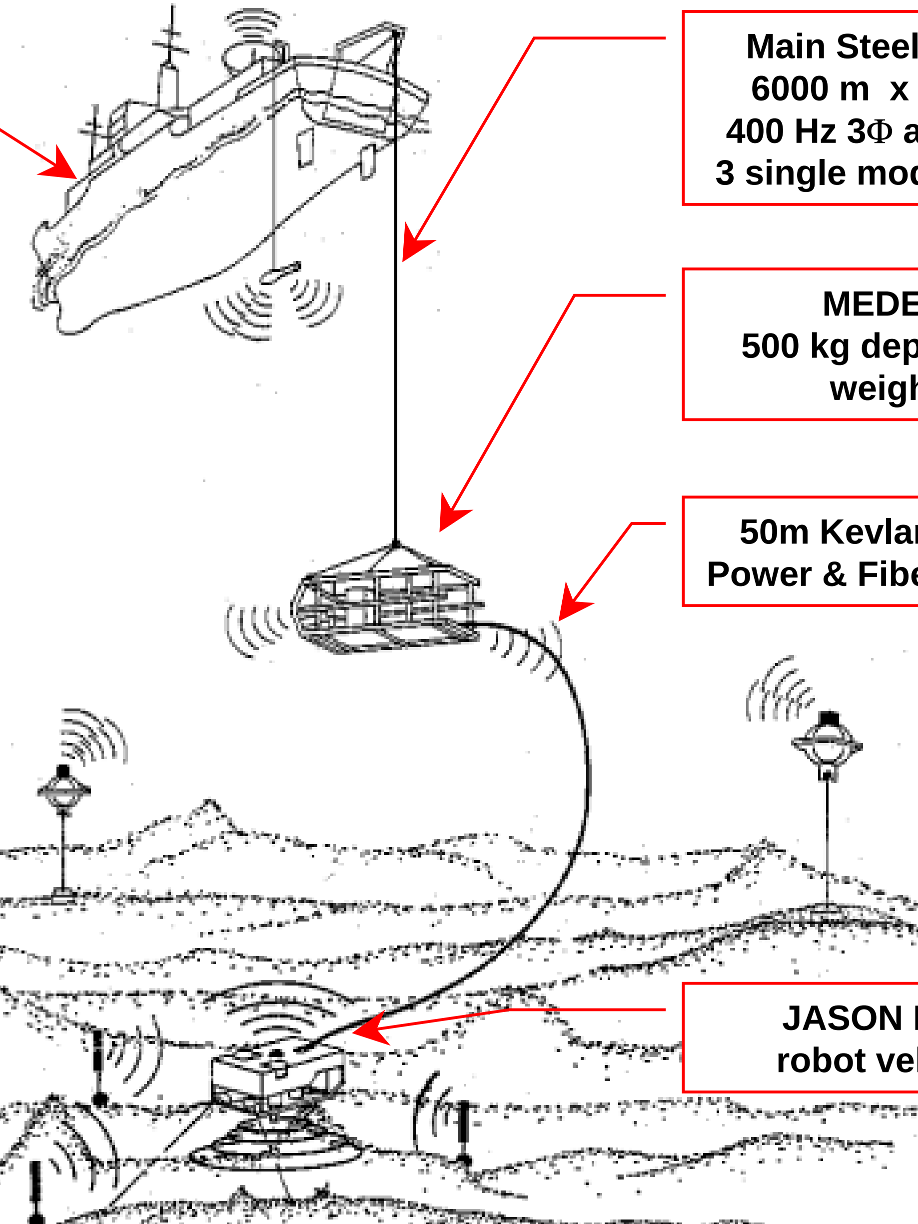
CTD and cast aboard the *R.V. Ronald H. Broawn* in the Strait of Juan de Fuca, Pacific Ocean.

Image Credit: NOAA Ocean Exploration Program.

Applications

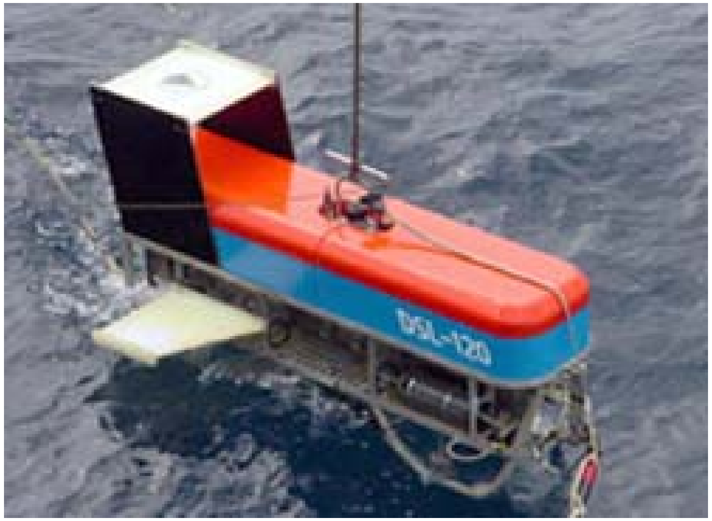
Tethered Remotely Operated Vehicles (ROVs)

The JHU ROV Experimental Vehicle



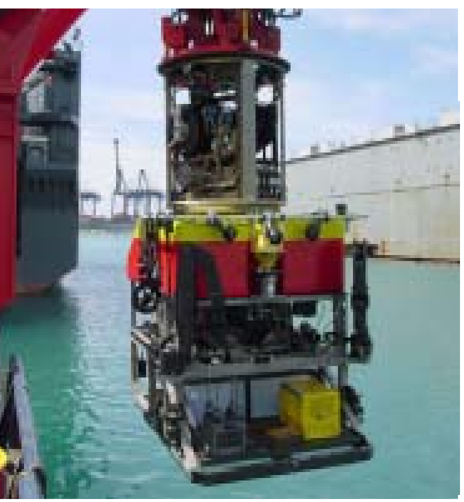
Tethered **R**emotely **O**perated **V**ehicles (**ROV**s)

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 **A**utonomous **U**nderwater **V**ehicles
AUV

REMUS **100m AUV, WHOI and Hydroid, Inc**

Image credits: © Hydroid Inc

ABE **6000m AUV, WHOI**

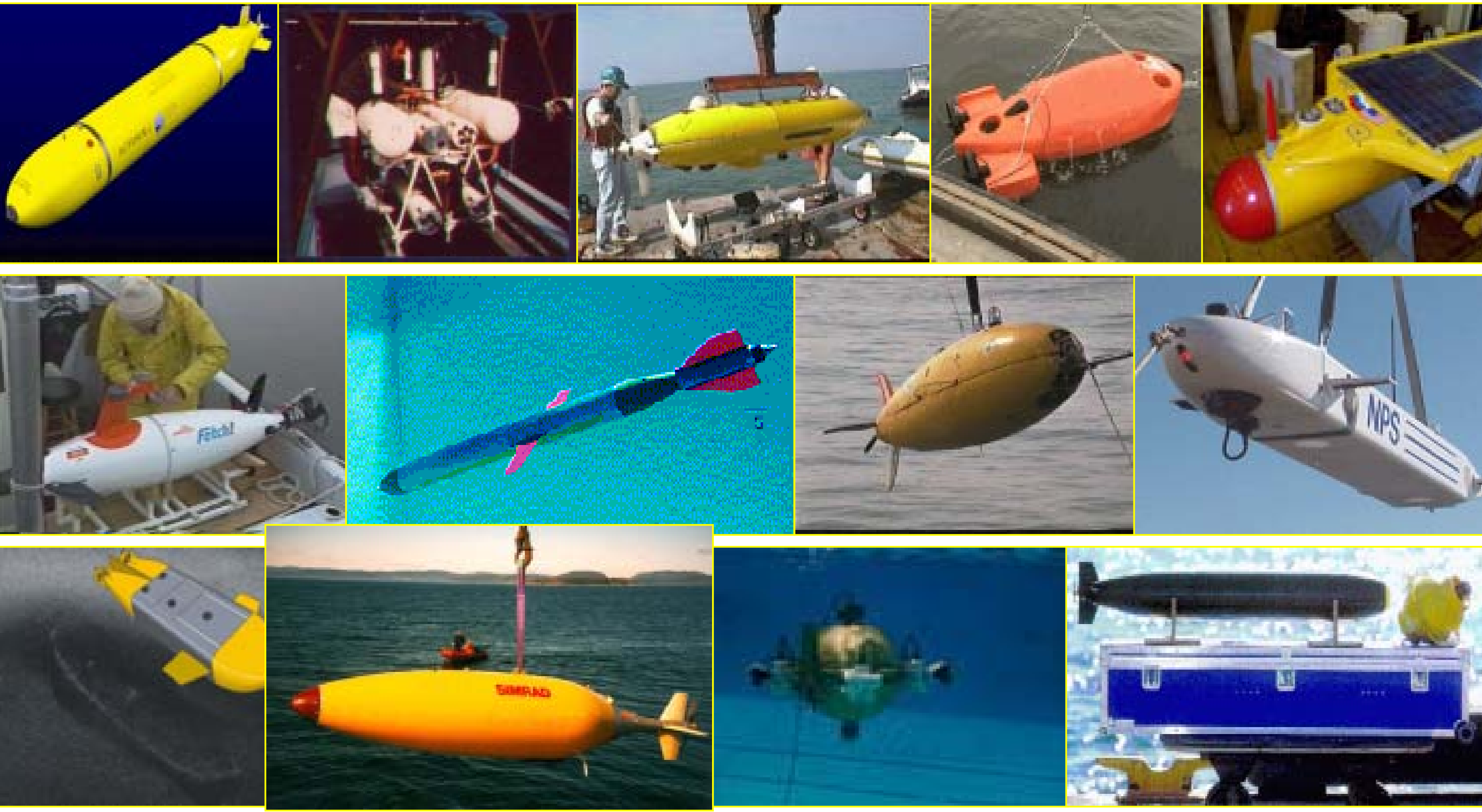
Image credits: © Rod Catencah WHOI

SAUVIM AUV 6,000m, University of Hawaii

Image credits: © Honolulu Star-Bulletin Hawaii News

HUGIN **3000m AUV, Kongsberg Simrad**

Autonomous Underwater Vehicles (AUVs)



Underwater Robotics Research Laborotories 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 Laborotories 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

- Sippican, Inc. http://www.sippican.com/
- Sias Patterson, Inc. http://www.spiauv.com/
- Bluefin, Inc. http://www.bluefinrobotics.com/
- Naval Command Control and Ocean Surveillance Center http:// www.nosc.mil/robots/
- Naval Postgraduate School http://www.cs.nps.navy.mil/research/auv/
- 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
- Virginia Tech. http://www.ascl.ece.vt.edu/
- 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)
  - Yuh, Ura, and Bekey (Eds), *Autonomous Underwater Robots*. Kluwer, 1996.
  - Yuh. Design and Control of Autonomous Underwater Robots: A Survey. In *Int'l J. of Autonomous Robots*, 2000.
  - Yoerger at al. Surveying a subsea lava flow using the Autonomous Benthic Explorer (ABE) *International Journal of Systems Science*, (29)10:1031-1044, 1998.
  - Michel at al. Epaulard: Deep Bottom Surveys Now with Acoustic Remote Controlled Vehicle - First Operational Experience. *Proc. IEEE Oceans'81, (13)99-103.*
- Remotely Operated Vehicles (ROVs)
  - Ballard at al. A Remotely Operated Survey and Sampling System for Full-ocean Depth. *IEEE Oceans '91*, Vol 1, Pages 71-75.
- Dynamanics and Control:
  - *DTNSRDC Standard Submarine Equations of Motion*, Feldman 1979.
  - Fossen, *Guidance and Control of Ocean Vehicles*, Wiley, 1994.
  - Smallwood et al. Model Based Dynamic Positioning of Underwater Robotic Vehicles: Theory and Experiment. *IEEE J. Oceanic Eng.* 29(1):169-186, January 2004.
- Thruster Dynamics:
  - Yoerger et al The influence of thruster dynamics on underwater vehicle behavior and their incorporation into control system design," *IEEE J. Oceanic Eng.*, (15)3:167–178, June 1990.
  - Healey et al. "Toward and improved understanding of thruster dyamics for underwater vehicles," *IEEE J. Oceanic Eng.*, (20):354–361, Oct. 1995.
  - Bachmayer et al. An Accurate Four-Quadrant Nonlinear Dynamical Model for Marine Thrusters: Theory and Experimental Validation. *IEEE J. Oceanic Eng.* (25)1:146-159, Jan. 2000.

Influential Papers: 2 of 2

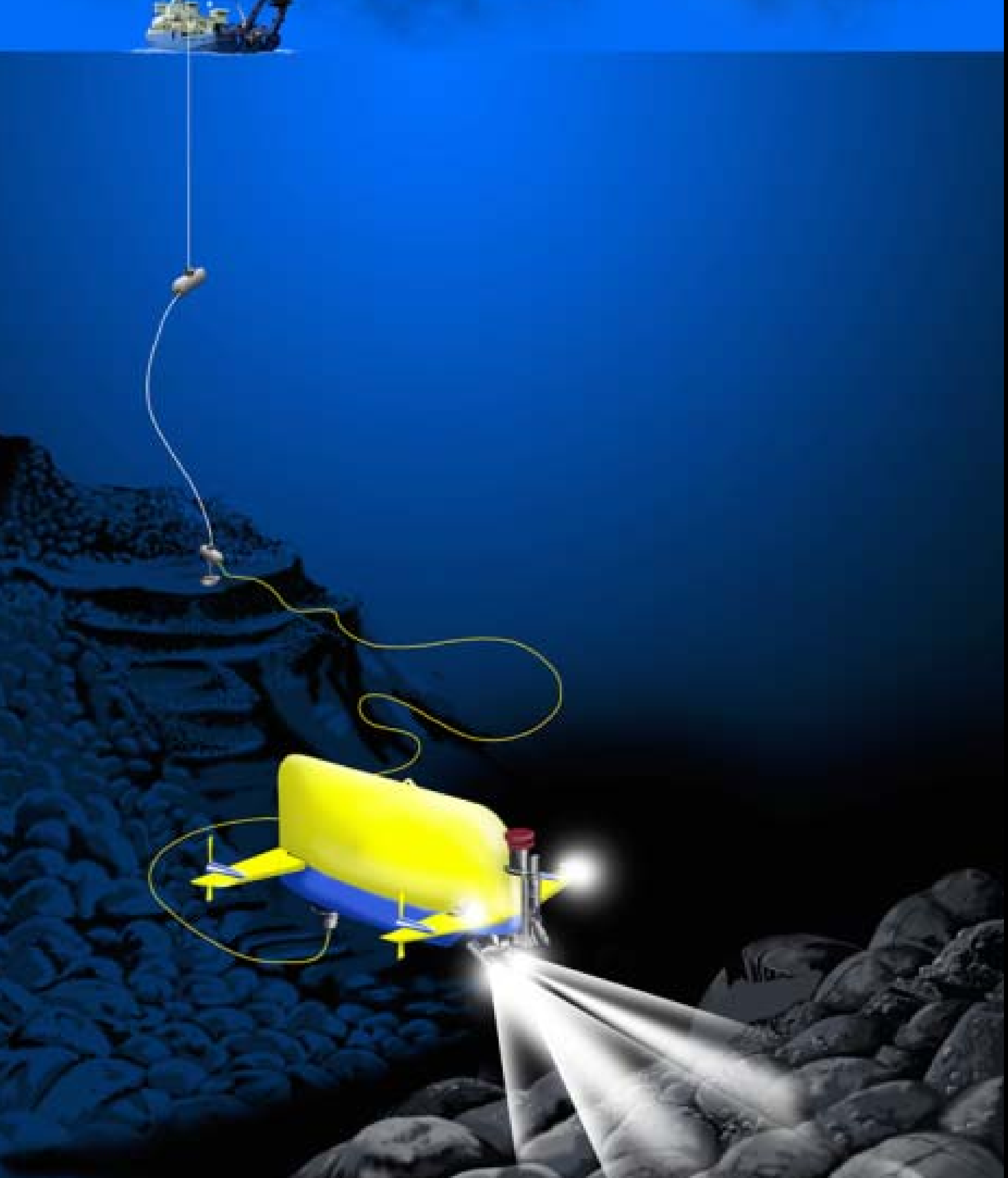
- Acoustic Communication:
  - Stojanovic at al. Adaptive Multichannel Combining and Equalization for Underwater Acoustic Communications, *JASA.* (94)3:1621-1631, 1993.
  - Baggeroer et al. State of the art in underwater acoustic telemetry *IEEE J. Oceanic Eng. (*25)1:4-27 Jan. 2000.
- Vehicle Navigation and Sensing
  - Acoustic Long-Baseline Navigation: Huntet al. An acoustic navigation system.Technical Report WHOI-74-6. WHOI (1974).
  - Acoustic Doppler Navigation: Brokloff. Matrix algorithm for Doppler sonar navigation. In: *Proceedings of IEEE/MTS OCEANS'94* Vol.2. pp.378 –83. 1994.
  - IEEE J. of Oceanic Eng. Special Issue on Underwater Image and Video Processing, Vol 28, no. 4, October 1993: Papers by Rock, Lane, Negadaripour, Singh.
- Autonomous Ocean Sampling Networks
  - IEEE J. Oceanic Eng. Special Issue on Autonomous Ocean Sampling Networks Vol 26, no. 4, October, 2001.
- Underwater Archaeology
  - Ballard et al.The Discovery of Ancient History in the Deep Sea Using Advanced Deep Submergence Technology. *Deep Sea Research Part 1*, 47(9):1591-1620, Sept. 2000.
- Biomimetic Propulsion
  - Triantafyllou et al. An Efficient Swimming Machine, *Scientific American*, (272):64-70, 1995.

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

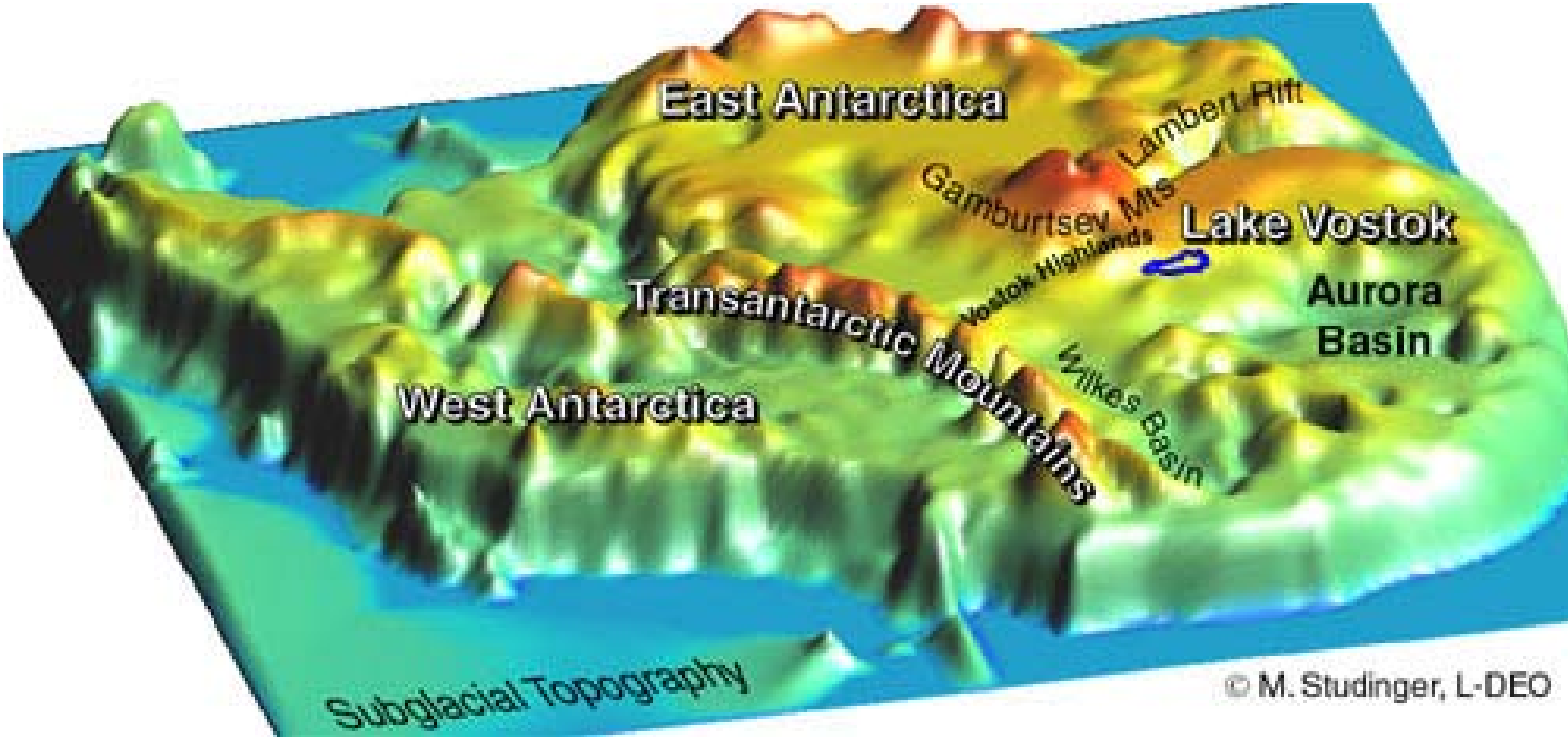


11,000m Hybrid ROV

Bowen, Yoerger, Whitcomb
Woods Hole Oceanographic Institutio
Fletcher, Young
SPAWAR – U.S. Navy

L×W×H	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 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

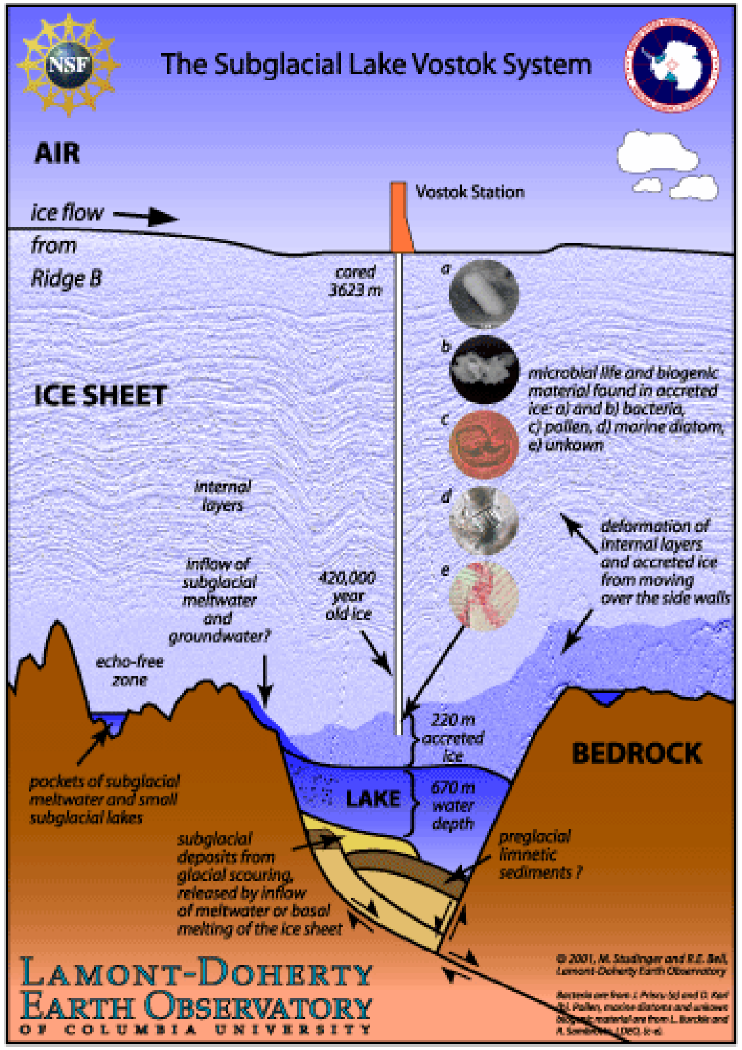
NSF Polar Program – Lake Vostok



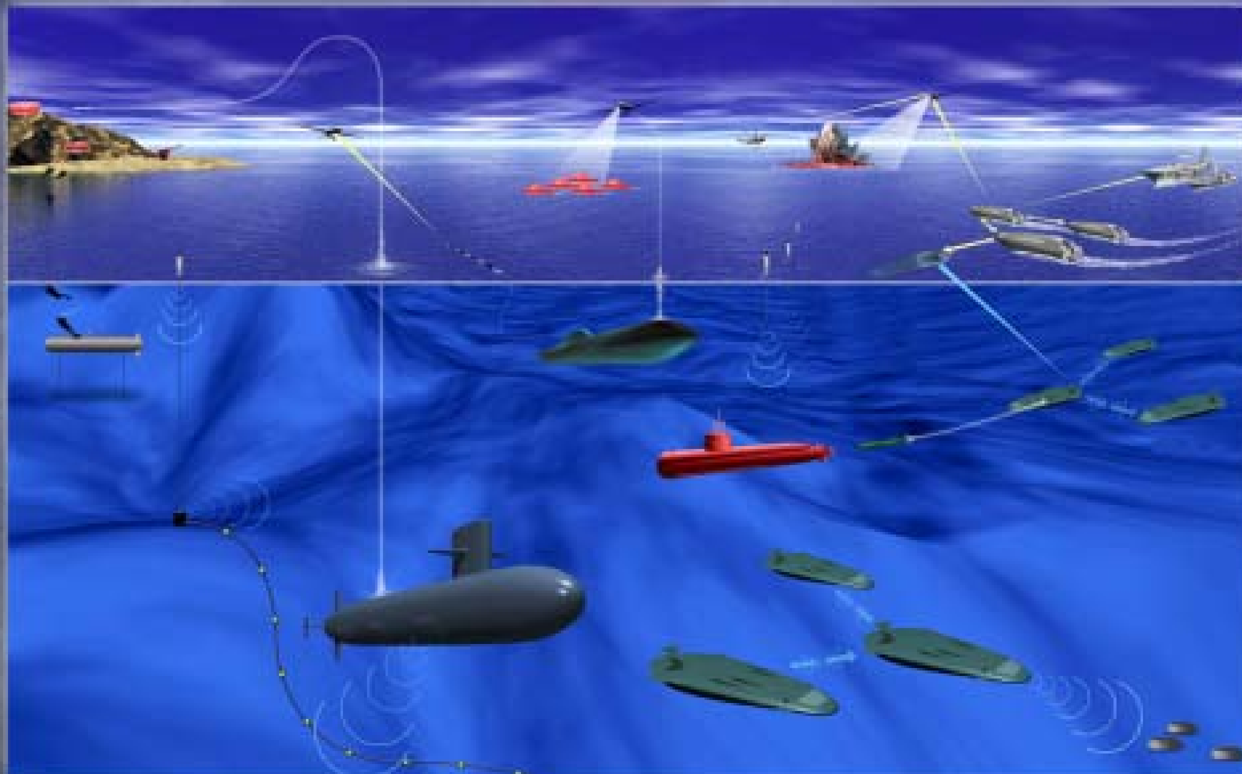
We would like to know if there's life on Jupiter's frozen moon Europa. We'd also like to know if there's life in Antarctica's ice-covered Lake Vostok.

- **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.**



Group Coordination Payoffs



- 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 grou The challenge is to remove the burden of group coordination from he 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.

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