Development of a Remotely Operated Underwater Vehicle for Oceanographic Access Under Ice

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Photo courtesy S. McPhail, NOC
Woods Hole Oceanographic Institution

World’s largest private ocean research institution

~900 Employees, 143 Scientific Staff
$160M Annual Budget

- Biology
- Chemistry
- Geology
- Physical Oceanography
- Engineering
- Marine Policy
A Family Tree of Vehicles
A New Era in Vehicle Technology

Nereus (in tethered mode)
Hybrid Remotely Operated Vehicle
Depth: 36,089 feet (11,000 meters)

Nereus (in autonomous mode)
Hybrid Remotely Operated Vehicle
Depth: 36,089 feet (11,000 meters)

Sentry
Autonomous Explorer
Depth: 19,680 feet (6,000 meters)

Jaguar/Puma
Autonomous Explorer
Depth: 16,400 feet (5,000 meters)

SeaBED
Autonomous Explorer
Depth: 6,962 feet (2,000 meters)

ABE
Autonomous Benthic Explorer
Depth: 16,404 feet (5,000 meters)

Remus 6000
Remote Environmental Monitoring Units
Depth: 19,680 feet (6,000 meters)

Glider
Autonomous Explorer
Depth: 656 feet (200 meters)

Remus 3000
Remote Environmental Monitoring Units
Depth: 4,000 feet (1,200 meters)

Remus 600
Remote Environmental Monitoring Units
Depth: 1,968 feet (600 meters)

Remus 100
Remote Environmental Monitoring Units
Depth: 328 feet (100 meters)

Jason Jr.
Remotely operated vehicle (ROV)
Depth: 19,680 feet (6,000 meters)

Alvin
Human occupied submersible
Depth: 14,764 feet (4,500 meters)

Jason II
Remotely operated vehicle (ROV)
Depth: 21,325 feet (6,500 meters)
Deep Ocean Oceanography:
The D.S.V. Alvin 4500m Submersible

Crew: 3 = 1 pilot + 2 scientist
Depth: 4500m (6,500m soon)
Endurance: 6-10 Hours
Speed: 1 m/s
Mass: 7,000 Kg
Length: 7.1m
Power: 81 KWH
Life Support: 72 Hours x 3 Persons
Dives: >4,700 (since 1964)
Passengers: >14,000 (since 1964)

Ph.D. Student James Kinsey
Jason II ROV

Specifications:

- Size: 3.2 x 2.4 x 2.2 m
- Weight: 3,300 kg
- Depth: 6,500 m
- Power: 40 kW (50 Hp)
- Payload: 120 Kg (1.5 Ton)
- First Dive: 2002
- Dives: >600
- Dive Time: >12,500 Hours*
- Bottom Time: >10,600 Hours*
- Longest Dive: 139 Hours*
- Deepest Dive: 6,502 m*
- Distance: >4,800 km*

* As of Feb, 2012

Electric thrusters, twin hydraulic manipulator arms.
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
1200kg robot vehicle
Vent discoveries in the Lau Basin (near Fiji), Southern Mid-Atlantic Ridge, Southwest Indian Ridge.

(German, Yoerger, et al, 2004)
Global Ocean depth chart

Robinson projection
How to visit the deepest part of the ocean in a cost-effective way?
11,000 Meters an Easier Way

• A Hybrid cross between autonomous and remote-controlled underwater vehicle
  • Untethered autonomous underwater vehicle (AUV) for mapping
  • Tethered remotely operated vehicle (ROV) for close inspection, sampling and manipulation

• New Class of vehicle intended to offer a cost effective solution for survey/sampling and direct human directed interaction with extreme environments through the use of new technologies
The *Nereus* Hybrid Remotely Operated Vehicle
New Technologies
Enabling the Nereus System Design

Ceramic Buoyancy and Pressure Housings

Low Power High Quality Imaging/Lighting

Low Power Capable Manipulators

Micro-Fiber Tether System

Energy Storage

Hybrid Control
Nereus 2009 Mariana Expedition

Bathymetry of the Southern Mariana Islands Region

Dive 007: 880 m
13N36.75 144E43.00

Dive 008: 3500 m
12N58.80 145E11.75

Dive 009: 6500 m
13N12.00 146E00.00 (mud volcano)

Dive 010: 9050 m
12N59.50 146E00.00

Dive 011: 10900 m
11N22.10 142E35.48

Dives 012 and 014: 10900 m
11N19.59 142E12.99

Dive 015: 3000 m
12N42.00 143E31.50

Toto Seamount
Nereus Dive 11 to 10,903 m Depth
Nereus Sampling
Nereus Sampling
Light Fibre Tether Concept

- High bandwidth (GigE) communications
- Unconstrained by surface ship
- Operable from non-DP vessels
Problem: Conventionally Tethered ROV Operations from Icebreaker in Permanent Moving Ice

- Icebreaker Constrained to Move with Moving Ice Pack
- Steel Armored Cable
- Depressor/Garage
- Conventional ROV
- ROV Footprint of Operations: Small (~500 m) Under Ship, Moving with Ice
Solution: Light-Tethered Nereid Operations from Icebreaker In Permanent Moving Ice

PROV Footprint of Operations: Large (~20 km) and Decoupled From Ship

Steel Armored Cable
Depressor/Garage
Light Fiber-Optic Tether

Nereid UI
The Under-Ice Scientific Imperative

- Near-Ice Inspection and Mapping
- Boundary Layer Investigations
- Grounding Line Inspection
- Sediment Sampling
- Ice Shelf Cavity Physical Oceanographic Mapping
- Instrument Emplacement*
Range

Capability

- Mapping/Survey
- Inspection
- Manipulation

Conventional ROVs

Retention

- SIR*

GLADERS

- SCINI

Multi-Node AUV Systems*

- Nereid UI*

- MSLED*

- Autosub

*Under development
Under-Ice Vehicle Systems

- Specialized hybrid AUV/ROV systems
- Conventional AUVs
- Conventional ROVs
Sub-Ice ROVer (SIR)

For through-ice-shelf deployment via ~70-75 cm bore holes. Max diameter 55 cm in “folded” configuration. Unfolds into ROV configuration. Under development. 1500 m. Missions: Optical imaging, acoustic imaging, PO,

Vogel et al. (2008), "Subglacial environment exploration – concept and technological challenges for the development and operation of a Sub-Ice ROVer (SIR) and advanced sub-ice instrumentation for short and long-term observations", In Proceedings IEEE/OES Autonomous Underwater Vehicles
Submersible Capable of under Ice Navigation and Imaging (SCINI)

15 cm diameter for deployment through 20 cm holes drilled in sea ice. 300 m depth rated.

Missions: Optical imaging, acoustic imaging, and PO.

SCINI: Logistics

Figure 12: Walking to the survey site from the Becker point field camp. The entire SCINI ROV setup weights less than 350 kg and can be person-hauled by three or more people, on two sledges.

Cazenave et al. (2011), "Development of the ROV SCINI and deployment in McMurdo Sound, Antarctica," Journal of Ocean Technology
SCINI: McMurdo Sound

Cazenave et al. (2011), "Development of the ROV SCINI and deployment in McMurdo Sound, Antarctica," Journal of Ocean Technology
Micro-Subglacial Lake Exploration Device (MSLED)

8 cm x 70 cm for deployment through bore holes drilled in ice.
1,500 m depth rated.
Camera, CTD
Fiber-optic tether
2 hour endurance

Missions: Optical imaging and PO.

Theseus AUV

1.27 m x 10 m for long-endurance fiber-optic cable deployment.
8,000 kg
1,300+ km range
2,000 m depth rated.

Fiber-optic tether deployment.

More recent versions of Theseus developed by ISE for Canadian UNCLOS Arctic bathymetric survey operations.

Richmond et al. (2011), “Sub-ice Exploration of an Antarctic Lake: Results from the Endurance Project”, UUST’11,
Richmond et al. (2011), “Sub-ice Exploration of an Antarctic Lake: Results from the Endurance Project”, UUST’11.
Ice Cold Unit for Biological Exploration (IceCube) ROV

Modified Deep Ocean Engineering Phantom S2 – 450 m depth rated, 100 kg

Instruments
1. CTD (uCTD, FSI)
2. Fluorometer (FLNTU, Watlabs)
3. HD Camcorder (HD-SR12, Sony)
4. 2-L discrete water sampler
5. 20-position indexing suction sampler
6. Scanning sonar (107T, Mesotech)
7. Continuous water pumping system (not shown)
8. Ice scraper
9. Flow meter (2031H, General Oceanics, Inc.) (not shown)
10. 4-port serial port multiplexer (STS4, Perle) (not shown)
11. High-speed router (3241, Patton Electronics)
12. Custom tool sled
13. Plankton Sample Net

Iceberg C-18a

Fig. 2. Partial view of the tabular iceberg C-18a investigated by the ROV in 2009. Photo credit: Rob Sherlock.
**Mission:**
- Penetrate under *fixed ice* up to 20 km as a tethered vehicle while supporting sensing and sampling in close proximity to the under-ice surface
- Return safely to the ship

**Notional Concept of Operations:**
- Install acoustic Nav/Comms as required near ice-edge
- Deploy from vessel at ice edge as tethered system
- Transit to ice-edge and begin survey activities under-ice to the maximum range of the tether.
- Complete mission and return to the vessel as an AUV and recover onboard in open water
Use Case 1: Near-Ice Inspection and Mapping

**Instrumentation**
- Multibeam
- HD Video
- Water and Suction Samplers
Use Case 2: Boundary Layer Investigations

Instrumentation

Sonde:
- Fast Response CTD
- ADV
- Shear Probes

Vehicle:
- ADCP
- CTD
Use Case 3: Grounding Line Inspection

Instrumentation
- HD Video
- Manipulator*, coring tools*
Use Case 4: Sediment Sampling

Instrumentation
Siting:
- Video
- multibeam
Coring tools
- multicorer
- push cores (w/ manip.)
Use Case 5: Ice Shelf Cavity
Physical Oceanographic Mapping

Instrumentation
- Multibeam
- ADCP
- CTD
- OBS, Fluorometers, etc.
Use Case 6: Instrument Deployment/Recovery

Instrumentation
HD Video
Manipulator*
Design Parameters

- Bathymetry -> Depth rating
- Ice Draft -> Maneuverability/Sensing
- Water column structure -> Need for, and capacity of VBS
- Circulation and Tides -> Minimum speed
- Sea-Ice and Sea State -> LaRS complexity
- Phenomena -> Special design considerations
- State of Knowledge -> Conservatism in design
- Logistics -> Special design considerations, field-planning

- Regions Studied:
  - Antarctic Ice Shelves
  - Greenland Glaciers

- Assumptions:
  - Ship-based, open-water launch/recovery, sub-type for through-ice deployment
Design Constraints: Antarctica

- Bathymetry -> Depth rating: 2000 m
- Ice Draft -> Maneuverability/Sensing: mission-driven/??
- Water column structure -> Need for, and capacity of VBS: mission-driven, potential for creative solutions
- Circulation and Tides -> Minimum speed: 0.5 m/s
- Sea-Ice and Sea State -> LaRS complexity: simple, AUV-like
- Phenomena -> Special design considerations: minimize entrained volume, thermally couple as much as possible, detect ?, pre-launch washdown
- State of Knowledge -> Conservatism in design: reliability-driven
- Logistics -> Special design considerations: What can be learned from small, proxy vehicles?
Concepts

Conventional

Flatfish

Crab
<table>
<thead>
<tr>
<th>Specifications</th>
<th>Range</th>
<th>20 km horizontal excursion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air Weight</td>
<td>1800 kg</td>
<td></td>
</tr>
<tr>
<td>Depth Rating</td>
<td>1000 m</td>
<td></td>
</tr>
<tr>
<td>Battery</td>
<td>16 kWhr lithium-ion</td>
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<tr>
<td><strong>Navigation</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Inertial</td>
<td>Phins INS</td>
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</tr>
<tr>
<td>Acoustic</td>
<td>LF 1000 m range up/down altimetry; up/down ADCP/DVL; LF (3.5 kHz) homing; imaging sonar for obstacle avoidance</td>
<td></td>
</tr>
<tr>
<td><strong>Communication</strong></td>
<td></td>
<td></td>
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<tr>
<td>Tether</td>
<td>Fiber-optic Gb Ethernet, 20 km</td>
<td></td>
</tr>
<tr>
<td>Acoustic</td>
<td>LF (3 kHz) 20-300 bps for ship to vehicle; HF (10-30 kHz) 300 bps for vehicle to sensor; vehicle to vehicle</td>
<td></td>
</tr>
<tr>
<td><strong>Imaging</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Acoustic</td>
<td>Reson 725 multibeam or Mesotech 675 profiling (upward-looking)</td>
<td></td>
</tr>
<tr>
<td>Optical</td>
<td>Real-time color HD video; high resolution digital camera; LED lighting</td>
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<tr>
<td><strong>Chemical/Physical Sensors</strong></td>
<td>Seabird CTD; pH; micro-structure probes on deployable sonde</td>
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<tr>
<td><strong>Biological Sensors</strong></td>
<td>Optical backscatter; Photosynthetically Active Radiation (PAR); Chlorophyll; Turbidity; Dissolved Oxygen</td>
<td></td>
</tr>
<tr>
<td><strong>Auxiliary payload allowance</strong></td>
<td>20 kg; 500 Wh</td>
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</table>
Fiber Tether Sink-rate Simulation
Acoustic Communications and Navigation

Short range, 10 kHz
- ITC 3013 (hemispherical coverage)
- Use for 5-8 km horizontal and similar for slant range in deep water, depending on propagation conditions.
- Data rate/efficiency 100-1000 bps, 4-40 bits per joule.

Long range, 3 kHz
- ITC 2002 (slight toroidal beam-pattern)
- Use for up to ~20 km, path dependent performance.
- Data rate/efficiency: ~50-100 bps, 2-4 bits per joule.
Supercooled Water and Frazil Ice

- Formed in supercooled water, 0.01-0.03 C below freezing: polynyas, water-layer interfaces, glacial interfaces, brinicles

http://www.bbc.co.uk/nature/15835017
Design for Reliability/Fault-Tolerant Control/Design

Photo courtesy S. McPhail, NOC
ABE and Sentry failures in 350 dives

Human error
- 3 setup
- 7 mission programming
- 2 incorrect ballast

Algorithm
- 5 bottom-following
- 9 abort process
- 5 lbl

Software
- 2 inadequately tested change
- 2 programming blunder

Hardware
- 4 lbl elec/acoustics
- 2 connector failure
- 2 faulty battery
- 7 release failure
- 13 (4) Thruster elec/mechanical
- 1 computer failure

Unavoidable
- 1 entanglement

23 FATAL UNDER ICE
Come-Home Capability

- Act upon loss of tether
- Timeout before Bailout
- Standown
- Home Acoustically
- Breadcrumbs
- Deadman Initiation
- Constant Depth
- Top-Follow
- Bottom-Follow
- Visualize Bailout
- Recall Election


Conclusions

• More detailed exploration under permanent fixed ice will be enhanced by the Nereid Under Ice vehicle and lead to important new knowledge difficult to gather with autonomous systems having limited bandwidth communications.

• Both operational and scientific techniques developed during this project should be of interest to those contemplating missions on other planets.

• Teaming of human explorers to robotic tools over high bandwidth links promises most efficient use of resources.