Development of Nereid-UI: 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
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)
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
Antecedent Technology:
Nereus 11 km Hybrid Underwater Vehicle

- Near-surface armored cable
- Depressor
- Fiber .010 inch dia (up to 40 km)
- Float pack
- 50 m secondary
- Vehicle

Micro-Fiber Tether System
Battery System
LED Lighting
Hybrid Control

Nereus 11 km Hybrid Underwater Vehicle

Human Hair
Optical Fiber

Antecedent Technology:
Nereus 11 km Hybrid Underwater Vehicle
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
- ROV Footprint of Operations: Small (~500 m) Under Ship, Moving with Ice
- Conventional ROV
Solution: Light-Tethered Nereid Operations from Icebreaker In Permanent Moving Ice

Steel Armored Cable
Depressor/Garage
Light Fiber-Optic Tether

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

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*
**Conventional ROVs**

**Capability**
- Mapping/Survey
- Inspection
- Manipulation

**Range**
- 100 m
- 1 km
- 10 km
- 100 km

**Systems**
- SIR*
- SCINI
- Nereid UI*
- MSLED*
- Multi-Node AUV Systems*
- Autosub
- Gliders

*Under development
Under-Ice Vehicle Systems

- Specialized hybrid AUV/ROV systems
- Conventional AUVs
- Conventional ROVs
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)

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

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 weighs 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.

Table 1: ENDURANCE vehicle specifications

<table>
<thead>
<tr>
<th>Specification</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimensions</td>
<td>Ellipsoid major axis (diameter): 2.13 m</td>
</tr>
<tr>
<td></td>
<td>Ellipsoid minor axis (height): 1.52 m</td>
</tr>
<tr>
<td>Mass</td>
<td>1.5 t including science payload</td>
</tr>
<tr>
<td>Depth rating</td>
<td>1000 m (excluding payload)</td>
</tr>
<tr>
<td>Onboard power</td>
<td>2 × 2.5 kWh lithium-ion rechargeable battery packs</td>
</tr>
<tr>
<td>Thrust</td>
<td>6 electric thrusters @ 110 N nominal thrust</td>
</tr>
<tr>
<td>Service range</td>
<td>5 km</td>
</tr>
<tr>
<td>Maximum transit speed</td>
<td>0.3 m/s</td>
</tr>
<tr>
<td>Cruise speed</td>
<td>0.24 m/s</td>
</tr>
<tr>
<td>Onboard instrumentation</td>
<td>Honeywell inertial measurement unit (IMU)</td>
</tr>
<tr>
<td></td>
<td>RDI Doppler velocity log (DVL)</td>
</tr>
<tr>
<td></td>
<td>2 Parascientific pressure depth sensors</td>
</tr>
<tr>
<td></td>
<td>32 Imagenex 100 m sonars</td>
</tr>
<tr>
<td></td>
<td>24 Imagenex 200 m sonars</td>
</tr>
<tr>
<td></td>
<td>Imagenex DeltaT multi-beam sonar</td>
</tr>
<tr>
<td></td>
<td>Sonardyne inverted ultra-short baseline (USBL) transceiver</td>
</tr>
</tbody>
</table>

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,
Autosub 3

400 km range
1,600 m depth
7 m x 1 m
3000 kg
Missions: Acoustic survey and PO survey.

**PROV Concept of Operations**

**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

Diagram showing a ship deploying equipment into water.
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: 1500 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, pre-launch washdown
- State of Knowledge -> Conservatism in design: reliability-driven
- Logistics -> Special design considerations: What can be learned from small, proxy vehicles?
Nereid-UI: Design Concepts

Conventional

Flatfish

Crab
# Nereid-UI: Specifications

<table>
<thead>
<tr>
<th>Performance</th>
<th>Range</th>
<th>20 km max horizontal excursion from launch point</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Displacement</td>
<td>1,800 kg</td>
</tr>
<tr>
<td></td>
<td>Depth Rating</td>
<td>1,500 m</td>
</tr>
<tr>
<td></td>
<td>Battery</td>
<td>19 kWhr Li-Ion</td>
</tr>
<tr>
<td></td>
<td>Manipulator</td>
<td>6-DOF Electro-Hydraulic (provisional)</td>
</tr>
<tr>
<td></td>
<td>Sample Payload</td>
<td>20 kg</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Navigation</th>
<th>Inertial</th>
<th>IXSEA PHINS</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Acoustic</td>
<td>300 kHz up/down ADCP/DVL; LF (3.5 kHz) communications; Imaging sonar for obstacle avoidance</td>
</tr>
<tr>
<td></td>
<td>Pressure/Depth</td>
<td>Paroscientific pressure sensor</td>
</tr>
</tbody>
</table>

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<thead>
<tr>
<th>Telemetry</th>
<th>Tether</th>
<th>20 km fiber-optic Gb Ethernet expendable tether</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Acoustic</td>
<td>LF (3 kHz) 20-300 bps acoustic telemetry to/from ship HF (10-30 kHz) acoustic telemetry to seafloor instruments</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Imaging</th>
<th>Optical</th>
<th>Real-time HD color video; high-resolution digital still; LED lighting</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Acoustic</td>
<td>R2Sonic 2020 or better, mounted up or down on per-mission basis.</td>
</tr>
</tbody>
</table>

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<thead>
<tr>
<th>Chem/Bio Sensors</th>
<th>Chemical</th>
<th>Seabird CTD; pH; OBS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Biological</td>
<td>Photosynthetically Active Radiation (PAR); Chlorophyll; Turbidity; Dissolved Oxygen</td>
</tr>
</tbody>
</table>

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<thead>
<tr>
<th>Auxiliary Payload</th>
<th>20 kg</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Up to 500Whr (affects range)</td>
</tr>
</tbody>
</table>
Nereid UI: Final Design
Nereid UI: Final Design
Design for Reliability/
Fault-Tolerant Control/Design

Photo courtesy S. McPhail, NOC
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.
Fiber Tether Sink-rate Simulation
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 of resources.