Design of *Nereid-UI*: A Remotely Operated Underwater Vehicle for Oceanographic Access Under Ice

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***Abstract*—This paper reports the development of a new underwater robotic vehicle, *Nereid-UI*, with the goal of being capable of deployments in polar ocean regions traditionally considered difficult or impossible to access such the ice-ocean interface in marginal ice zones, in the water column of ice-covered seas, and the seas underlying ice shelves. The vehicle employs a novel lightweight fiber-optic tether that will enable it to be deployed from a ship to attain standoff distances of up to 20 km from an ice-edge boundary under the real-time remote-control of its human operators, providing real-time high-resolution optical and acoustic imaging, environmental sensing and sampling, and, in the future, robotic intervention.**

I. Introduction

The Woods Hole Oceanographic Institution and collaborators from the Johns Hopkins University and the University of New Hampshire are developing for the polar science community a remotely-controlled underwater robotic vehicle capable of being tele-operated under ice under remote real-time human supervision. The Nereid Under-Ice (*Nereid-UI*) vehicle will enable exploration and detailed examination of biological and physical environments at glacial ice-tongues and ice-shelf margins, delivering high-definition video in addition to survey data from on board acoustic, chemical, and biological sensors. The vehicle employs a novel lightweight fiber-optic tether that will enable it to be deployed from a ship to attain standoff distances of up to 20 km from an ice-edge boundary under the real-time remote control of its human operators, providing real-time high-resolution optical and acoustic imaging, environmental sensing and sampling, and, in the future, robotic intervention. The goal of the *Nereid-UI* system is to provide scientific access to under-ice and ice-margin environments that is presently impractical or infeasible.

Conventionally-tethered remotely operated vehicle (ROV) systems have been deployed under ice [18], [7] but are limited to horizontal ranges of a few hundred meters from their support ships or the ice-edge, and, consequently, impose severe restrictions in environments where under sea-ice and ice shelf ice is too thick to break. The inspection-class submersible capable of under ice navigation and imaging (SCINI) is an exception [8], having been designed for deployment through 8 inch diameter bore holes in sea ice. SCINI's operational record has demonstrated the value of an under-ice inspection capability but is unproven through the relatively deep holes that would be required to access the sub-glacial environment, and the vehicle's size limits it to a modest sensing payload. Autonomous underwater vehicles (AUVs) have operated successfully under sea-ice since the 1970s, e.g. Theseus, DEPTHX, Jaguar/Puma [9], [19], [12], [16], [20], [15], and under ice shelves, e.g. Autosub [17], [13], [11] These missions have yielded invaluable physical oceanographic measurements and maps of ice draft and seafloor bathymetry; however, close-up high-resolution inspection remains beyond the scope of present-day and long range acoustic telemetry.

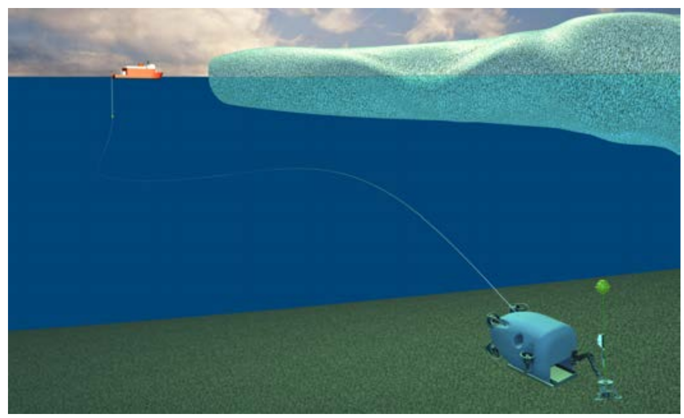

Fig. 1. A schematic representation of operators using *Nereid-UI* to interact with emplaced instrumentation beneath glacial ice kilometers away from the support vessel.

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Fig. 2. *Nereid-UI* during preliminary shallow water trials in May 2014

Close-up high-resolution inspection and survey operations in these complex under-ice environments require a tether providing high-bandwidth telemetry between the underwater vehicle and its human operators. Long-range light-fiber ROV tether technology, as pioneered on the *Nereus* vehicle for 11,000 m depth operation [6], [24], provides the high bandwidth (Gigabit Ethernet) link necessary for real-time control under the direction of the shipboard science party yet retains extreme horizontal mobility of the host vehicle. *Nereid-UI's* design and concept-of-operations are based on that developed for the *Nereus* hybrid remotely operated vehicle [4], [5]

This paper reports the design and preliminary vehicle trials of *Nereid-UI*. The trials, conducted in September 2013 were designed to test core vehicle systems particularly the power system, main computer and control system, thrusters, video and telemetry system, and to refine camera, lighting and acoustic sensor placement for piloted and closed-loop control, especially as pertains to working near the underside of ice. This paper also reports preliminary trials of the complete system, conducted in May 2014, including the depressor and tow-body and the concept of operations as envisioned for full-scale under-ice trials to be conducted from *R/V Polarstern* as part of a scientific expedition to the Arctic in July 2014.

II. Background and Scientific Rationale

It is becoming increasingly apparent that the polar regions, and particularly the Arctic, are a critical, but poorly understood nexus for many components of the global earth system. The polar regions play a central role in establishing climate feedback mechanisms that amplify the effects of global climate change. Many of the most dramatic changes occurring deal with the accelerated melting of ice — both sea- and land-based ice [1], [21]. As temperatures rapidly rise, the release of methane through the destabilization of shelf-edge hydrates, becomes a particularly serious concern. Understanding the reasons for the accelerated melting of ice and the impact of the potential release of methane are key to long-term climate and sea-level predictions and critical for a range of issues relating to human well-being, national security and economic development. To address many of these issues we must have access to, and be able to sample in, ice margin zones – regions that have until now, been virtually inaccessible.

For example, the most effective heat-transfer that leads to ice-thinning is at the underside of the ice, at the ice-water interface, rather than the overlying atmosphere-ice interface. Therefore, the ability to study physical processes close beneath the ocean-ice interface can be critical. Further, under-ice habitats may serve as biological refugia and, in the case of sufficiently thin ice-cover, there may even be sufficient light transmission through the ice and into the upper water column to drive through-ice photosynthesis [2], [3].

Traditionally, operations in ice-covered waters have involved ice-breakers surveying and sampling by instruments lowered into the water column after breaking ice to access the underlying ocean. However, such operations are limited to ice thicknesses that can be broken through by a research vessel and, for example, cannot provide access beneath thick sea-ice and/or glaciers extending offshore from continents (e.g. Antarctica, Greenland). Ice-breaker based operations are also hindered by the difficulty in supporting tethered vehicles in moving ice conditions and only limited success has been achieved with AUV systems and also with fixed ice-penetrating moorings. The Nereid-UI addresses these constraints by using advances in undersea communications and robotic autonomy to enable the performance of complex tasks in ice-covered seas without perturbing the ice-ocean interface and up to a depth of 2,000 meters. It is designed to operate both untethered as an AUV for survey operations, and also as a self-powered vehicle employing an extremely small diameter optical fiber tether for tele-operated ROV sampling and intervention operations at extreme tether lengths (20 km or more). The vehicle fiber-tether design decouples the ROV motion from the ice-constrained surface ship, thus enabling ROV-like operations from icebreakers in moving ice as well as the ability to operate for distances as great as 20 km under ice shelves.

TABLE I. SUMMARY SPECIFICATIONS.

Specifications	Range Air Weight Depth Rating Battery Time	40 km @ 1 m/s (preliminary, ex. reserve) 1800 kg 2000 m 18 kWhr Li-ion On board precision atomic clock synchronized to GPS, 1 ppb drift rate/year.
Navigation	Inertial Depth Acoustic	IXSea Phins INS/north-seeking gyro-compass; back-up magnetic compasses Paroscientific Nano-Resolution pressure sensor; SBE 49 FastCAT back-up up/down 300 kHz ADCP/DVLs; Blueview P900 imaging sonar for obstacle avoidance, One-way travel-time acoustic navigation at 10 Hz, 3.5 kHz.
Communication	Tether Acoustic	Single-mode fiber-optic (20 km range): Four wavelengths (CWDM)—Gb Ethernet, HD-SDI video, real-time optical time-domain reflectometry, spare Dual-frequency 3.5 kHz (20–300 bps, 20 km range) and 10 kHz (300 bps, 5 km range)
Imaging	Optical Acoustic	Real-time HD on internal pan-and-tilt (Kongsberg OE14-522 Hyperdome); 3 channels encoded SD (DSPL nanocam) Blueview P900 imaging sonar, 40 m range.
Physical Sensors		Seabird SBE FastCAT-49 pumped CTD
Biological Sensors		WetLabs ECO-FLNTURTD (Chlorophyll 0–30μg/l, backscatter 0-10 NTU)
Auxiliary payload allowance	bow/spine	Native support for 10 auxiliary sensors. 100 kg wet weight, 500 Whr Energy, 1000 W total (6 high-power channels with Gb Ethernet and/or RS-232, 100 W per channel, 6 low-power channels 3-15 W per channel, RS-232). 4 hardware trigger lines. All channels logged on board with real-time uplink.
Auxiliary payload allowance	spine, upward-looking, protected	240 mm x 450 mm x 500 mm (width, length, depth)
Auxiliary payload allowance	nose/chin, forward/down-looking, protected	0.8 m^3 total available volume, reconfigurable.

III. VEHICLE DESIGN OVERVIEW

A. Concept of Operations

Nereid-UI is designed to operate in close contact with the underside of glacial and sea-ice as well as the sea floor beneath glacial ice tongues and ice-shelves. These environments require vehicle, communications, and navigation systems to support operations to continental shelf depths of 1500 m and that are capable of overcoming a number of challenges related to ice. Broadly, glacial ice is too thick to break with a vessel, and *Nereid-UI* must be capable of returning autonomously from its maximum horizontal standoff distance of in the event of communications or other system failures. In contrast, operation in sea-ice is less risky in the sense that the vehicle can, short of catastrophic failure, drop ballast, pin itself under the ice and await recovery; however, unlike glacial ice, sea-ice is constantly moving, making ice-relative dead-reckoning subject to a systematic bias that stems from the unobservable (at the vehicle) rotation of the ice. Recovery through sea-ice is time-consuming at best, and large standoff distances increase the risk of loss as the fidelity of dead-reckoned navigation degrades over time with ice motion.

The concept of operations for both broad classes of ice rely on the same vehicle and ship-side equipment; however, the strategies employed by the vehicle's on-board autonomy with respect to recovery and self-preservation differ. In this paper, we focus on the sea-ice case because it is arguably the less risky of the two and because *Nereid-UI's* first field deployments will be beneath sea ice. The launch and recovery concepts call for an open pool of water to be maintained by the ship in an otherwise 8/10-10/10 coverage ice-pack.

B. Launch

Nereid-UI is launched as a single-point-lift two-body system comprised of the vehicle connected via a short umbilical to a mated tow-body/depressor system above the vehicle (fig. 3). The mated tow-body/depressor is lifted from a cart and raised into a vertical position above the vehicle through a snatch-block connected to one end of a short spreader bar. The system is then deployed over the side and the vehicle released with a pull-pin once in the water. No descent weights are employed, which leaves the vehicle under pilot control at all times. As the pilot drives the vehicle down, another operator lowers the mated tow-body/depressor to suitable depth beneath the keel of the support vessel. At this point various system checks can be executed before releasing the latch that mates the tow-body to the depressor (in the event of a problem, the entire system can be raised to the surface by hauling up on the depressor). Following system checkout, the pilot drives the vehicle down and away while operators actuate the latch into its low-tension setting allowing separation of the tow-body from the depressor and commencing tension-based payout of fiber from both the tow-body and depressor.

C. Piloted and Autonomous Control

As long as the fiber tether remains intact, operators will drive *Nereid-UI* like a conventional ROV system; with the significant difference that the motion of the support vessel need not be controlled (in sea-ice the support vessel will drift with the motion of the ice pack). For operation near the underside of ice, the tow-body is ballasted heavy to keep the fiber (itself negatively buoyant) away from the vehicle and potential entanglement. If the vehicle detects the fiber has failed, it can execute a number of context-dependent behaviors designed primarily to facilitate low-bandwidth operator interaction with the system over a dual-band acoustic communications system. With few exceptions, only in the event of a cascaded failure of the acoustic communications system will the vehicle execute completely autonomous behaviors that involve purposeful motion. Context in the sea-ice case is tied closely to navigation performance and range from the vessel.

D. Recovery

The depressor and vehicle are recovered independently and in a conventional manner. Should the fiber remain intact throughout a dive, operators will pilot the vehicle to the surface in a pool of open water maintained by the support vessel. Pilot control will then be transferred to an RF link and the fiber deliberately severed, permitting the depressor to be hauled back aboard. The vehicle is then piloted to where operators can snag its lifting bale with a loop of light-weight synthetic lift line sistered to a pole with breakaways and ultimately connected to the ship's crane. Once snagged, the vehicle is brought aboard and lowered onto a vibration and shock isolation pallet designed to reduce the risk of damage incurred during ice-breaking.

Fig. 3. *Nereid UI* with mated tow-body/depressor ready for launch. The depressor pictured is a prototype borrowed from the *Nereus* project capable of deploying an experimental larger-diameter fiber. We used block-and-tackle rig pictured for dock-trials but will use an air-tugger for trials off *R/V Polarstern* to permit lowering the depressor beyond keel depth.

Fiber failure is a possibility on any given mission, and indeed, operation to full 20 km standoff distance requires at least a semi-autonomous strategy for return to the vessel. Following the loss of high-bandwidth communication of the fiber, operators will issue commands acoustically to the vehicle's mission executive to direct the vehicle back to the ship and monitor its progress. Should the pool of open water available be too small to permit "acoustic-joysticking" of the vehicle to the surface, operators will land the vehicle on the underside of the ice near the vessel, and use a small ROV to aid recovery.

E. Auxiliary Systems

The ship-side end of the acoustic communications system is deployed in a cage separately from the vehicle system to afford operators independent control over its depth, which allows for some control over the acoustic path to the vehicle. For trials off *R/V Polarstern* in July 2014, two transponders will also be deployed from and remain affixed to the ship to provide near-field (1 km) ship-relative position fixes [12].

F. Mechanical

The overall mechanical design of *Nereid UI* is generally conventional, being comprised of a simple load-bearing aluminum frame coupled to syntactic foam floatation modules. However, the design layout deviates in several ways from convention as a result of its unique mission to enable both long range under ice survey while ensuring detailed mapping and examination of the under-ice is possible. A third requirement ensures the vehicle has the potential to support traditional ROV sampling and manipulation missions.

For long range, *Nereid UI* has a low-drag form enabling stable survey at ranges of up to 40 kilometers. In the future we anticipate the addition of a seven-function manipulator and associated workspace required for the collection of samples or deployment/recovery of instrumentation.

To enable installation of the required sensors suite, a payload bay has been integrated into the upper central section of the vehicle, as shown in Figure I. This payload bay allows a range of instruments to be placed so as to have an unobstructed view in the upward direction. As part of this particular attribute, the vehicle is designed to provide some limited protection of these sensors should the vehicle come into direct contact with the ice surface.

Given the hybrid tether employed to provide unprecedented range and flexibility from the host platform, *Nereid UI* must provide adequate payload and space for the required batteries used to power all of the vehicle's systems for the full duration of it's mission. In keeping with the overall desire for a vehicle having superior reliability, the propulsion system configuration provides critical redundancy for its come-home mission.

G. Electrical

1) DSL-Core: The vehicle utilizes a distributed electrical and interconnect architecture, centered around a single command and control bottle called the "DSL-Core". The DSL-Core was developed as a single housing providing the fundamental hooks for operating a vehicle, and can be used across multiple vehicle systems with fundamentally different purposes yet use a common software and basic sensor suite. Excluding propulsion drive, the DSL-Core could stand alone on a small vehicle platform, or be the core of a more complex vehicle system such as *Nereid-UI* via connection through an Ethernet backbone. On *Nereid-UI*, multiple additional housings are required to support science, telemetry and other functions, with those housings using the same types of power conversion, switching, and telemetry modules as the DSL-core. Additional housing(s) can easily be added in the future via connection to common multipurpose Ethernet ports and main battery power.

2) Energy Storage: Main batteries are made up of pressure tolerant lithium ion pouch cells. The cells are mounted in semi-rigid self-compensating tanks made of linear polyethylene and filled with silicone oil. These ambient-pressure housings provide good cooling and explosion immunity, and simplify high-power electrical penetrations, compared to one-atmosphere pressure housings. Eight 30 Ah Kokam lithium ion cells are contained in each battery module supplied by Southwest Electronic Energy. Modules are potted in polyurethane along with management electronics. Nine of these modules are in each box. A 90 volt bus was selected to provide adequate power with reasonable cable sizes and some redundancy in case of failures of individual battery modules or boxes. Each battery box contains 7.2 kWh with 129 kg mass and 70 liters displacement.

3) Propulsion: The original vehicle concept used ducted high-RPM ROV-type thrusters to protect propellers from contact with ice or other objects. However, acoustic testing showed that candidate thrusters would be too noisy to allow acoustic communication, at 20 km horizontal range, while underway. Ranging and navigation are required for autonomous return under ice. For quiet operation, a new thruster was designed using a direct drive frameless brushless motor (Allied HT03812) designed to run at 500 RPM. Injection molded Torqeedo 1901 propeller was selected for its good efficiency, light weight. Bollard test showed maximum thrust of 420 N with 1300W. Underway thrust testing showed higher efficiency than similar ROV thrusters, though the motor is larger and heavier and thrust is asymmetric.

H. Telemetry

1) Fiber-Optic Telemetry: Nereid-UI employs a novel, lightweight, expendable fiber-optic tether that provides high-bandwidth data and video telemetry and enables unprecedented horizontal and vertical mobility of the vehicle while tethered, yet avoids the significant operational limitations imposed by conventional large electro-optic tethers. The *Nereid-UI* tether system design is closely based upon the tether system originally developed for 11,000 m depth operations with the *Nereus* hybrid remotely operated vehicle [6], [24].

The tether deployment system is comprised of a snag-resistant depressor package and vehicle package to house the tether system. The depressor was designed to be lowered from the surface ship to get the tether deployment point below the ship and below the ocean-ice interface. The vehicle package contains the optical-fiber dispenser, brake, fiber counter and cutter, and it is designed to minimize drag and the chance of snagging the fiber. The depressor and vehicle package are mated together during launch, protecting the fiber during the transition through the air-water interface. Once the system has reached a designated depth, the vehicle package separates from the depressor. Fiber-optic tether pays out from both the vehicle and the depressor as the vehicle descends.

2) Acoustic Telemetry: The *Nereid-UI* vehicle and her support ship are both equipped with two WHOI Micro-Modems (one at 3.5 kHz and one at 10 kHz), enabling regular uplink of navigation, scientific, and engineering data from the vehicle to the ship, and downlink of commands from the ship to the vehicle.

3) Radio-Frequency Telemetry: Nereid-UI is equipped with a 900 mHz radio-frequency (RF) modem telemetry system providing bi-directional Ethernet communication when the vehicle is on deck and when surfaced on the sea at ranges of up to about 1 km.

I. Navigation

The *Nereid-UI* navigation sensor suite includes a 1-ppm Paroscientific pressure depth sensor, a SBE49 FastCAT CTD Sensor, two Teledyne-RDInstruments 300kHz Doppler sonars, an IXSEA Phins IMU, two WHOI Micro-Modems (one at 3.5 kHz and one at 10 kHz) [10], and a Blueview P900 imaging sonar for obstacle avoidance,

The upward-looking and downward-looking Doppler sonars provide 3-axis vehicle velocity with respect to the sea floor (downward looking) or overhead ice (upward-looking) at up to 200 m range, and 3-axis velocity of the vehicle with respect to the water, and 3-axis water column velocity profiles. The IMU contains a 3-axis, North-seeking, fiber-optic gyrocompass providing heading and attitude at 0.1° and 0.01° accuracy, respectively.

In addition to providing data telemetry uplink and downlink, the the WHOI mocromodems are equipped measure travel-times between vehicle and ship, from which we can compute range, and hence provide improved navigation [22], [23] These modems are also equipped to interrogate conventional 10 kHz Benthos transponders to enable long-baseline navigation with transponders mounted on the seafloor or lowered from the support ship.

Navigation sensor data is received by *Nereus's* control computer, where the navigation process NavEst computes vehicle state estimates. NavEst is navigation software developed by WHOI and JHU for use on deep-submergence vehicles. Currently employed on the *Sentry* AUV and *Nereid-UI*, NavEst is a multithreaded Linux program that supports multiple, simultaneous, navigation algorithms. Available navigation algorithms include the Doppler navigation algorithm employed by DVLNav [14] and the LBL algorithm extensively used by the *ABE* AUV [25]. Single-beacon, one-way, travel-time algorithms have also been implemented [22], [23].

IV. Conclusion

The design and operation approach of *Nereid-UI* combine the self-powered mobility of an AUV with the remote telepresence of an ROV capable of being tele-operated under ice under remote real-time human supervision. The performance goal of the *Nereid-UI* vehicle system is to enable deployments from a ship to attain standoff distances of up to 20 km from an ice-edge boundary under the real-time remote-control of its human operators, to enable real-time detailed close-range examination of biological and physical environments including glacial ice-tongues, ice-shelf margins, and sea ice, delivering high-definition video in addition to survey data from on board acoustic, chemical, and biological sensors, and, in the future, robotic intervention. If successful, this approach will complement existing capabilities for scientific operations under sea-ice provides by ships, conventionally-tethered remotely-operated vehicles, and autonomous underwater vehicles.

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