The *Nereus* Hybrid Underwater Robotic Vehicle for Global Ocean Science Operations to 11,000m Depth

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***Abstract*— This paper reports an overview of the new *Nereus* hybrid underwater vehicle and summarizes the vehicle's performance during its first sea trials in November 2007. *Nereus* is a novel operational underwater vehicle designed to perform scientific survey and sampling to the full depth of the ocean of 11,000 meters — almost twice the depth of any present-day operational vehicle. *Nereus* operates in two different modes. For broad area survey, the vehicle can operate untethered as an autonomous underwater vehicle (AUV) capable of exploring and mapping the sea floor with sonars and cameras. For close up imaging and sampling, *Nereus* can be converted at sea to operate as a tethered remotely operated vehicle (ROV). This paper reports the overall vehicle design and design elements including ceramic pressure housings and flotation spheres; manipulator and sampling system; light fiber optic tether; lighting and imaging; power and propulsion; navigation; vehicle dynamics and control; and acoustic communications.**

I. Introduction

The goal of the *Nereus* project is to provide the U.S. oceanographic community with the first capable and cost-effective vehicle for routine access to the world's oceans to 11,000 meters [6]. This paper reports an overview of the the new *Nereus* hybrid underwater vehicle and summarizes its performance during its first sea trials. *Nereus* is a novel operational underwater vehicle designed to perform scientific survey and sampling to the full depth of the ocean of 11,000 meters — almost twice the depth of any present-day operational vehicle. *Nereus* operates in two different modes. For broad area survey, the vehicle can operate untethered as an autonomous underwater vehicle (AUV) capable of exploring and mapping the sea floor with sonars and cameras. For close up imaging and sampling, *Nereus* can be converted at sea to become a tethered remotely operated vehicle. The ROV configuration incorporates a novel lightweight fiber optic tether to the surface for high bandwidth real-time video and data telemetry to the surface, enabling high-quality remote-controlled teleoperation by a human pilot. Figure 1 depicts the tethered ROV mode mode concept of operations. Figure 2 shows *Nereus* in its AUV mode (left image) and ROV mode (right image).

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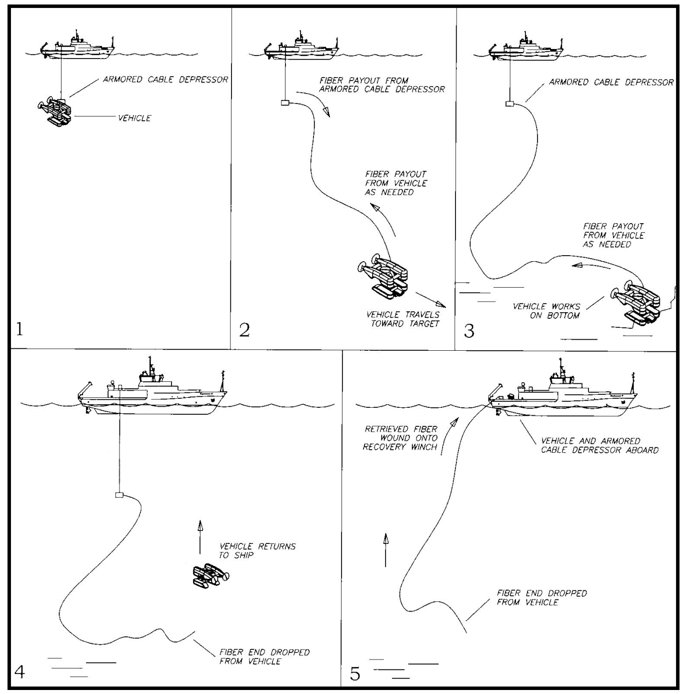

Fig. 1. *Nereus* ROV-mode concept of operations. In ROV-mode *Nereus* is remotely controlled by a lightweight expendable fiber optic tether which connects the vehicle to a surface support vessel.

Nereus's first sea trials were conducted in November 2007 from the *R.V. Kilo Moana* in the Pacific Ocean near Oahu, Hawaii. The sea trials demonstrated vehicle operations in AUV mode and ROV mode to a depth of 2270 meters. Figure 3 summarizes the *Nereus* sea trial dive statistics. Future sea trials are planned to demonstrate the vehicle's operational capability for operations at depths to 11,000 m and with extreme horizontal mobility.

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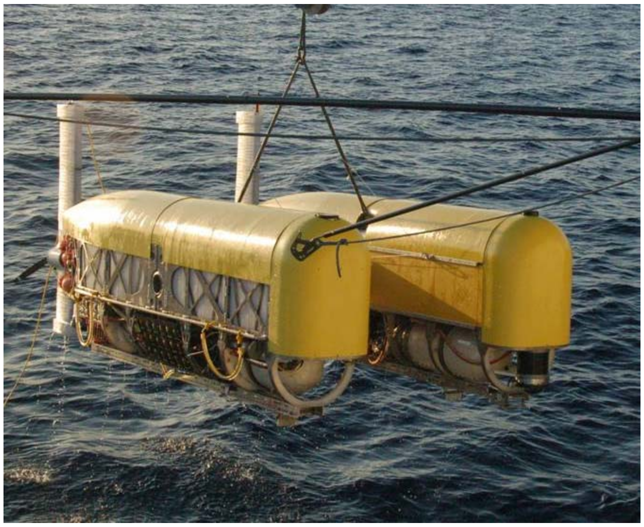

Fig. 2. The *Nereus* hybrid remotely operated vehicle, shown during its first engineering sea trials in the Pacific in November 2007, is designed to operate in two modes to depths of 11,000m. Left: *Nereus* configured for autonomous vehicle survey operations. Right: *Nereus* configured with a light fiber optic tether, a robot arm, sampling gear, and additional cameras for teleoperation of close-up imaging, sampling, and manipulation missions.

and the Russell Family Foundation.

II. Background and Scientific Rationale

Existing deep submergence vehicle systems have excellent capabilities and provide critical, routine access to the sea floor to a maximum depth range of 6,500 m — e.g. the 4,500 m Alvin human occupied submersible [7], [19], the 4,500 m ABE AUV [35], [36], and the 4,000 m Tiburon ROV [26]. Only a few presently operational U.S. vehicles are capable of diving to 6,500 m and conducting high resolution mapping and sampling — e.g. the 6,500 m Jason II ROV [33]. These capabilities have led to significant scientific discoveries over the past 30 years including identifying and sampling mid-ocean ridge volcanic processes, hydrothermal processes, and biological ecosystems which have revolutionized the biological sciences [1]. Progress in deep sea research at ocean floor sites between 6,500 m and 11,000 m has been hindered by a lack of suitable cost-effective vehicles that can operate at these depths. Given the need for full access to the global abyss, and national and international imperatives regarding ocean exploration, a variety of studies have identified the development of an 11,000 m deep submergence vehicle as a national priority [1]–[3], [28]

To date, only two vehicles have ever reached the deepest place on Earth — Challenger Deep of the Marianas Trench at 11°22'N, 142°25'E in the Western Pacific Ocean near the island of Guam [13]. On January 23, 1960 the human-piloted Bathyscaph *Trieste*, developed by Auguste Piccard, made one successful dive to the Challenger Deep [27]. In 1995 the remotely controlled ROV *Kaiko*, built and operated by the Japan Agency for Marine-Earth Science and Technology (JAMSTEC), made the first of several successful dives to the Challenger Deep [31]. Neither *Trieste* nor *Kaiko* is presently operational. Moreover, the design approaches employed in these two (very different) vehicles necessarily result in high operational costs — too costly to be routinely supported by United States oceanographic science budgets.

The depth capability of conventional tethered ROVs such as Jason II cannot be directly extended to 11,000 m because conventional steel-reinforced cables are self-supporting in sea water only to cable lengths up to about 7,000m. Alternative tension member materials for 11,000 m operations, e.g. Kevlar, result in large-diameter cables that exhibit poor hydrodynamic characteristics and that require very large cable handling systems

Light fiber optic tethers offer an alternative to conventional large-diameter steel and Kevlar cables. To date, light fiber tethers have principally been employed in military applications; relatively few light fiber tether systems have been employed for oceanographic research. In [5], [23]–[25] the authors report the development of the self-powered remotely operated vehicle *UROV7K* employing a fiber-optic tether. This vehicle is designed to operate exclusively as a tethered ROV, and does not have on-board computational resources necessary to operate autonomously. In [8], [10] International Submarine Engineering Limited reported the successful deployment of an autonomous underwater vehicle designed to deploy fiber optic communication cables on the arctic sea floor.

Our goal is to create a practical 11,000 m system using an appropriately designed self-powered vehicle that can (a) operate as an untethered autonomous vehicle (AUV mode) and (b) operate under remote-control connected to the surface vessel by a lightweight fiber optic tether of up to approximately 40 km in length (ROV mode).

III. Hybrid Vehicle Design Overview

The *Nereus* core vehicle employs twin free-flooded hulls. It can be re-configured at sea into ROV-mode or AUV-mode. All on-board electronics, batteries, and internal sensors are housed at 1-atmosphere in novel lightweight ceramic/titanium

Date	Dive	Vehicle Mode	Time Submerged	Distance Covered	Depth	Time On Bottom	Fiber Payout
11/20/2007	Freejoy	AUV	5h 56 min	3940 m	2 m	0 min	no tether
11/21/2007	NER000	AUV	2h 12 min	2319 m	4 m	0 min	no tether
11/23/2007	NER001	ROV	57 min	0 m	18 m	0 min	28 m
11/23/2007	NER002	ROV	5h 56 min	1751 m	398 m	4h 55 min	978 m
11/24/2007	NER003	ROV	1h 20 min	0 m	100 m	0 min	1368 m
11/24/2007	NER004	ROV	3h 47 min	2236 m	569 m	2h 43 min	1422 m
11/25/2007	NER005	ROV	6h 50 min	2270 m	2257 m	3h 21 min	2352 m
11/26/2007	NER006	AUV	11h 33 min	10843 m	22 m	12 min	no tether

Fig. 3. Dive Statistics: November 2007 *Nereus* Sea Trails

pressure housings developed specifically for this project [30]. Additional buoyancy is provided by lightweight hollow ceramic buoyancy spheres [29], [32]. Two 0.355 m OD ceramic pressure housings contain power switching and distribution systems, DC-DC power isolation, a Linux control computer, a Linux imaging computer, DC-brushless motor controllers, multiple gigabit Ethernet transceivers, strap-down navigation sensors, and external sensor and actuator interfaces. *Nereus's* power is provided by an 18 kWh rechargeable lithium ion battery pack, developed for this project, contained in two ceramic pressure housings. Cameras, emergency beacons, RF modem (for surface operations), and other electronics are housed separately in dedicated 0.191m OD ceramic and titanium pressure housings. Lighting is provided by lightweight ambient-pressure light-emitting diode (LED) arrays custom developed for the *Nereus* project [16]. Pressure balanced oil filled junction boxes and hoses provide vehicle electrical and optical interconnect. The vehicle navigation sensor suite is described in Section IX. The vehicle's large metacentric height provides passive stability in roll and pitch. Twin aft vertical stabilizers (i.e. fixed vertical tails) provide passive hydrodynamic stability in heading.

A. Nereus AUV Mode Configuration Summary

In AUV mode, Figure 2 (left), *Nereus* is neutrally buoyant with a displacement of 2,500 kg with 1,510 ceramic buoyancy spheres and a reserve payload buoyancy of 22 kg. This mode employs two independently articulated actively controlled foils (wings) located between the hulls at the aft and middle sections, respectively. AUV mode propulsion is provided by two 1 kW thrusters fixed on the aft tails and one 1 kW thruster on the articulated mid-foil. AUV mode has no lateral thruster actuation. The vehicle is hydrodynamically stable in pitch and heading when in forward flight. A downward looking survey camera and several LED arrays are mounted on the port hull.

B. Nereus ROV Mode Configuration Summary

In ROV mode, Figure 2 (right), *Nereus* is neutrally buoyant with a displacement of 2,700 kg with 1,670 ceramic buoyancy spheres and a reserve payload buoyancy of 45 kg. This mode adds a work package containing a 6 degree-of-freedom (6-DOF) electro-hydraulic robot arm, sampling tools, sample containers, an additional high-resolution digital camera, two utility cameras, and several LED arrays. ROV mode propulsion is provided by two 1 kW thrusters fixed on the aft tails, one lateral 1 kW thruster, and one vertical 1 kW thruster.

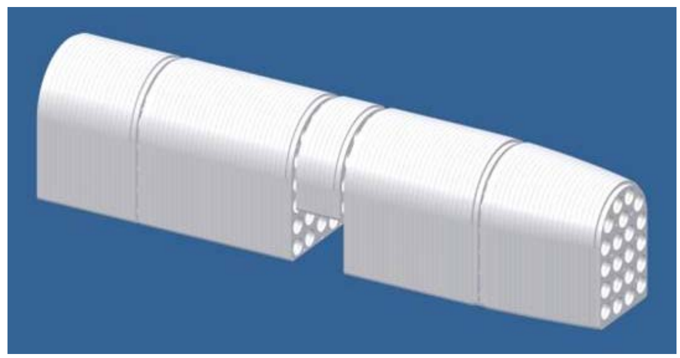

Fig. 4. Main vehicle flotation structure for one hull (one of two).

IV. Ceramic Housings and Buoyancy Spheres

Ceramic buoyancy spheres and custom ceramic-titanium pressure housings were essential to minimizing the vehicle overall size and mass. This section reviews their design and development.

Fig. 5. A main ceramic pressure housing being readied for fitting into *Nereus*.

A. Ceramic Buoyancy Spheres

Ceramic flotation was selected because of its low weight to displacement characteristics. 99.9% alumina ceramic seamless spheres, of 91mm OD, manufactured by Deep Sea Power and Light (DSPL) in San Diego, California, were chosen [32]. These spheres each weigh 140g and displace 404g in sea water, for a nominal 0.35 weight-to-displacement ratio. The spheres supplied by DSPL were individually tested to 30kpsi external pressure. The spheres are individually jacketed with 5mm thick elastomeric polyvinylchloride (PVC) "boots" that provide robust protection against impact loading, while providing an additional 19g of net buoyancy. The booted spheres each produce 283g of buoyancy at the surface. The spheres are less compressible than water, so at full operating depth of 11,000m they each generate 306g of buoyancy.

The main vehicle flotation consists of 1472 spheres arranged in the upper portions of the vehicle hulls, generating 417kg of net buoyancy. The spheres are housed in longitudinal tubes within buoyant polypropylene modules. The polypropylene modules are constructed as arrays of 25mm plate stock held together with aluminum tie rods. The plates are oriented vertically, and have patterns of circular cutouts that form tubular holes when the modules are assembled. The polypropylene structure supporting the main vehicle flotation has a total weight of 690kg and displacement of 778kg, for a net buoyancy of 88kg. Total buoyancy generated by spheres and polypropylene structural modules, Figure 4, is 505kg at the surface. Due to the fact that water is more compressible than both the spheres and the plastic structure, the total buoyancy at 11,000m depth is 573kg.

B. Ceramic Pressure Housings

Ceramic was selected for pressure housing material because its high compressive strength-to-weight ratio allows for near-neutrally buoyant housings capable of going to these extreme depths. Equivalent titanium housings of this size and quantity would weigh hundreds of kilograms in water and require expensive and voluminous additional flotation to offset their weight.

The housings, Figure 5, are composed of 96% alumina ceramic, and were custom manufactured for *Nereus* by CoorsTek in Golden, Colorado. Two size housings were developed — 355mm and 191mm OD. The vehicle main electronics and batteries are contained in four of the 355mm housings. For cameras and auxiliary electronics, the 191mm housings are used. The housings consist of a ceramic section formed by CoorsTek, and titanium joint rings manufactured at WHOI and bonded to the ceramic with a high-strength epoxy material.

The ceramic pieces are formed in both cylindrical sections (both ends open) and capped-cylinder sections (one end hemispherical). Due to manufacturing limitations, the length of the ceramic sections was limited to about 500mm, so for the main housing design a capped cylinder was joined with an open cylinder to provide sufficient length. Hemispherical titanium end caps are used as housing closures, and all necessary penetrations for electrical and optical conductors, as well as purge ports, were provided for in these titanium end caps.

Finite element analysis (FEA) was performed to ensure the matching of deflections of the ceramic and titanium components under pressure, to ensure even axial loading on the ceramic components. Strain gaging and acoustic emissions measurement were performed during pressure testing of all housings to a proof pressure of 18,000 psi. For additional information the reader is referred to [30].

V. Fiber Optic Tether

A key part of the HROV system is the light weight fiber optic cable used when operating in the ROV mode. Because HROV is a light weight battery powered system it is limited in its available energy and weight. The fiber optic tether transmits high bandwidth data only, not power.

Fiber Parameter	FOMC	Buffered Fiber
Diameter	0.8 mm	0.25 mm
Specific Gravity (FW)	1.74	1.36
Weight of 11 km in water	4.23 kg	0.173 kg
Working Strength	133 N	8 N
Breaking Strength	400 N	108 N
Survivability on Seafloor	Good	Poor

Fig. 6. Candidate Fiber Tether Mechanical Specificatoins

The preliminary design analysis of this cable for deep-ocean deployments is described in [37]. Two cable designs were selected as candidates for the HROV system: Fiber Optic Microcable (FOMC) and the Sanmina/SCI buffered fiber. Characteristics of these cables are given in Figure 6. After extensive simulation using the WHOICABLE program, [14], [15] the Sanmina/SCI tether was selected as the primary choice for the HROV system.

The basic concept of the deployment system involves the use of a snag resistant depressor and vehicle package to house the tether system as shown in Figure 7. The depressor was designed to get the upper tether deployment point below surface currents and below the most energetic and biologically active part of the water column. 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.

The cable deployment system was integrated with the actual Nereus HROV vehicle in fall 2007, and reported on in further detail in [11]. Initial sea trials were conducted near Hawaii in November 2007. Operational procedures for launch and recovery were developed and tested. Four dives were made in the ROV configuration using the fiber, culminating in a ROV mode dive to 2270 meters. During all ROV dives, the

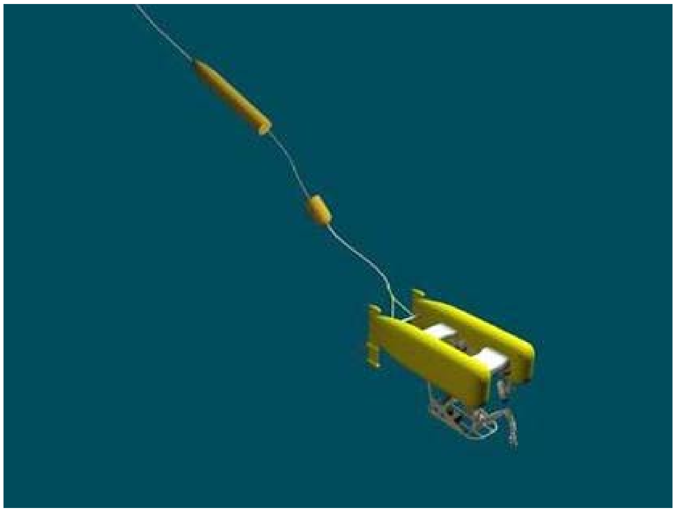

Fig. 7. Nereus showing the float-pack separating from the depressor pack.

fiber remained intact until purposely cut at the completion of operations.

VI. Nereus Manipulator and Sampling System

The Nereus sampling system consists of a 2.4 m x 1.2 m platform with a custom designed Kraft TeleRobotics manipulator and a WHOI designed hydraulic power unit. The manipulator is 7-function, 6 degrees of freedom, closed-loop, position controlled master slave system. The kinematics were developed to maximize the Nereus work space, and it has the following specifications.

Manipulator Parameter	Value
Horizontal reach	60”
Lift capacity at full extension	30+ lb
Controllable grip closure force	0-100 lbf
Stowed height	41.5”
Wrist rotate torque	180 in-lb
Weight in air (sea water)	105 lb (70lb)
Electrical Power Input	100W to 750W (max)
Operating depth	11,000 msw
Shoulder Azimuth	270°
Elbow Pivot	120°
Wrist Yaw	105°
Shoulder Elevation	120°
Wrist Pitch	154°
Wrist Rotate (slaved mode)	340°
Wrist Rotate (cont. mode)	0-10 rpm
Jaw Opening (4-finger)	8.75”

Fig. 8. Nereus Electro-Hydraulic Manipulator Performance Specifications

The Nereus hydraulic power unit (HPU) provides hydraulic pressure and flow to the manipulator. This is a WHOI designed modular hydraulic system that delivers 0-1000 psi at flow rates of 0-2 gpm. The HPU uses the same DC brushless motor and controller as employed for the Nereus propulsion system. It has a small, lightweight gear pump coupled to a brushless DC servo motor where speed and torque can be easily controlled. thereby offering control strategies resulting in minimal power usage at all times. The maximum power used at any time by the HPU is limited to 750 watts. The hydraulic fluid is a biodegradable mineral oil based, ISO 7 marine hydraulic fluid, developed specially for Nereus’s extreme ambient pressures.

A sampling platform is integral to the tool sled and provides storage facilities for science equipment and samples. Both the sampling platform and overall tool sled were designed in conjunction with the manipulator in an effort to harmonize the kinematic capabilities of the manipulator system with its work space. The manipulator is placed on the platform such that it has a full 270° of reach on the starboard corner of Nereus within the camera views. This provides a useful reach area of approximately 5.4 sq. m. of sea floor.

VII. Cameras and Lighting

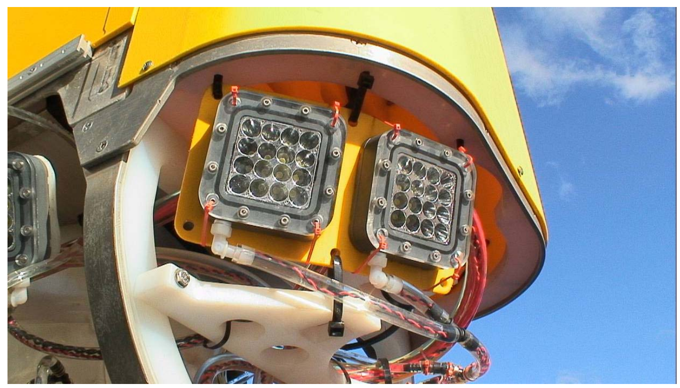

Fig. 9. Nereus’s ambient-pressure LED-arrays provide both strobed and continuous illumination.

The power limited nature of Nereus required careful consideration of the requirements for imaging, and resulted in a non-traditional approach of tightly integrating the imaging and lighting system. Early in the system design process, it was concluded that conventional full-frame rate imaging was not necessary for many of Nereus’ tasks, and that this could exploited to reduce imaging and lighting power requirements .Minimization of frame rates is particularly valuable in ROV mode, when light output is important to producing high quality color imagery. Such a system requires non-traditional lighting sources capable of tailoring their output to the needs of the imaging cameras. Newly available high brightness LEDs offered a means to strobe at high rates, as well as offering other benefits such as pressure tolance and precise control over lighting patterns. For ROV mode imaging, a full-motion-capable color imager based upon a machine vision camera used in previous deep sea work [16] has been employed. The camera is capable of capturing a high resultion color image whenever it is triggered, at rates up to 29.97 frames per second. The camera trigger causes LED strobe discharge with a selectable pulse length thus allowing effective intensity to be controlled. The resulting system thus uses power to make light of the required intensity only when required. A topside computer collects and buffers the imagery, so that the viewer only sees illuminated frames of imagery.

Triggering at these varying frame rates and durations required the development of a custom LED driver controller board.. The controller is told via software the expected frame rate. This rate is diven by the needs of the pilot and depends entirely upon the need for visual update about vehicle activities. In another attempt to save power, only areas viewed by the cameras are illuminated. A 16-LED assembly or puck was designed. The lighting array is composed of multiple, individually controlled pucks, each capable of illuminating a 30 degree frustum. By selecting the individual pucks to be triggered, we can direct the light only to areas requiring illumination. The LED controller is directed via software to trigger those individual pucks. The pucks were the result of a custom design effort. They contain 16 LEDs in a reflector carefully designed to create an even lighting pattern. The pucks are fully pressure compensated, and have been tested to 11000 meters. Pressure compensation of the assemblies results in dramatic weight savings over traditional pressure resistant lighting enclosures. The Nereus design includes 18 strobing LED pucks, arranged in an array on the nose of one of the hulls. Two other pucks, used in a continuous lighting mode (not strobed) are also included in the design as backups in the event of controller failure. In addition to the custom motion camera, two conventional subsea video cameras in 11000 meter housings support viewing of the work package and other utility tasks. Figure 9 shows a preliminary mounting of several of the pucks during the Nereus sea trials. All of the imagery, including the conventional video camera data, is brought to the surface for viewing and recording over gigabit Ethernet channels. Nereus AUV imaging is more conventional, utilizing an array of eight of the samedesign pucks, and the same LED controller, supporting cyan LEDs in support of a grey scale

VIII. Power and Propulsion

Nereus is powered by an 18 kWh rechargeable lithium-ion battery system configured to provide a 50 volt bus. Building upon lithium-ion experience with the ABE and REMUS AUVs, WHOI designed a modular building block of 12 cylindrical cells. The process included a comprehensive safety analysis followed by independent laboratory testing for conformance to United Nations shipping regulations. The 12-cell packs are assembled into two identical chassis on Nereus and combined electrically onto a common bus providing up to 3 kW continuous for all systems.

Power is distributed to low power devices from both sides of the vehicle in order to minimize cross-vehicle wiring. Both port and starboard chassis contain low power switches that feed individual power conversion units. These units provide electrical isolation, allowing for individual ground fault detection and minimization of ground loops, and are roughly sized according the loads for maximum efficiency. High power devices are few in number and are all switched from a single chassis. These include propulsion, control surface, and lighting devices, each consuming up to 1 kW. High power switches are built around solid-state relays, controlled by a custom interface circuit board that includes soft start as well as voltage, current, and temperature sensors.

The propulsion system is the largest load on the power bus, and therefore has the greatest impact on mission duration. Hydrodynamic modeling indicated the drag of the two-hull AUV geometry would be 230 N at the target speed of 1.5 m/s. The corresponding electrical energy fell within the overall capacity of the power system. AUV mission profile simulations, which estimated the energy used by the rest of Nereus systems as well as propulsion, yielded reasonable AUV mission lengths.

The design of the electric thrusters started with the propeller. The technique of Froude scaling allowed measured efficiency of different pitch and diameter propellers to be compared. Using this technique, a two bladed carbon fiber prop with 0.75 m diameter and 0.56 m pitch was specified and fabricated. A brushless permanent magnet electric motor and 7:1 planetary gearbox were selected to maximize transmission efficiency at 200 RPM. Using a gearbox instead of a larger direct drive motor yielded a 75% smaller and lighter thruster package.

As a result of design choices favoring AUV propulsion, ROV maneuvering is not fully optimized. Vertical thrust is limited to 350 N, so buoyancy must be monitored carefully, and yaw rate is limited by the long swing of the aft thrusters. A lateral thruster is added with the work package, improving worksite maneuverability.

The November 2007 sea trials demonstrated that Nereus in ROV mode is a power efficient yet capable sampling platform. During a dive on November 25, 2007, the vehicle was submerged for 6 hours and 50 min, with 3 hours, 21 min on bottom at 2270 m depth. Successful manipulation exercises were performed on glass bottles, a can, a large piece of metal debris, and several sediment push cores, all while covering 2200 m in horizontal distance. Including predive and recovery, 100.9 Ah battery charge was used out of a total 369 Ah available, approximately 27% of capacity.

IX. Navigation

Nereus's extreme operating depth presents challenges for navigation sensing and estimation. Externally mounted navigation sensors such as the pressure depth sensor, Doppler sonar, and LBL transducers must be capable of withstanding the pressure at 11,000m. In 11,000m operations, the long acoustic paths of conventional long baseline (LBL) acoustic navigation [17] gives rise to problems of signal attenuation, decreased accuracy, and limited update rates. These challenges motivate the need to combine LBL navigation with Doppler navigation [20], [34] and inertial navigation [4], [21], [22] in order to obtain the precise, geodetically referenced navigation necessary for closed-loop control and benthic science.

The *Nereus* navigation sensor suite includes a Paroscientific pressure depth sensor, a RDI 300kHz Doppler sonar, an Ixsea Phins IMU, a LBL transceiver, an WHOI Micro-Modem

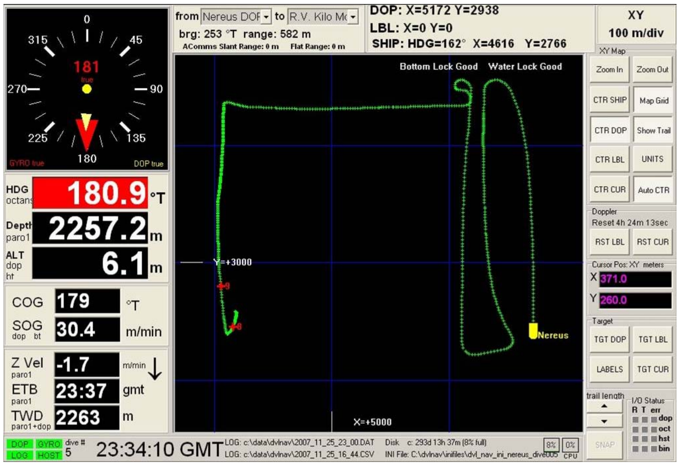

Fig. 10. *Nereus* Dive NER005: Screen shot of the DVLNav program, [20], during dive NER005 at 2,257 m depth during closed-loop trackline navigation and control testing.

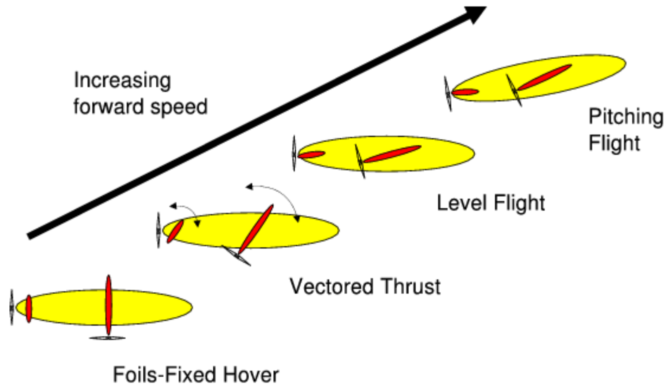

Fig. 11. *Nereus's* depth and pitch control modes [18]. Lift-dominated low angle of attack flight modes will enable efficient operation at high speeds. Thruster-dominated high-angle of attack hover modes will produce the climb angles necessary to negotiate steep terrain at low speeds. Foils-fixed hover and the two flight modes were demonstrated successfully in the recent sea trials.

[12], and a Microstrain gyro-stabilized attitude and magnetic heading sensor. The Doppler sonar provides 3-axis bottom-lock vehicle velocity with respect to the sea floor at over 200 m altitude, 3-axis water-lock 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 attitude and heading at $0.01°$ accuracy.

Navigation sensor data is received by *Nereus's* control computer. The navigation process NavEst computes vehicle state estimates. NavEst is navigation software developed by WHOI and JHU for use on deep submergence vehicles. Presently employed on the *Sentry* AUV and *Nereus*, NavEst is a multithreaded Linux program that supports multiple simultaneous navigation algorithms. Available navigation algorithms include the Doppler navigation algorithm employed by DVLNav [20] and the LBL algorithm extensively used by the *ABE* AUV [36]. Single beacon one-way travel time algorithms have also been implemented [9] .

During the November 2007 engineering trials, *Nereus* real-time navigation employed a pressure depth sensor, a Phins IMU, and Doppler sonar. Fixed seafloor transponders were not deployed, precluding the use of LBL navigation. The sensors and NavEst software provided vehicle state estimates that enabled closed-loop trajectory tracking control in ROV mode and in AUV mode. In ROV mode, navigation data is broadcast via Ethernet to computers topside and visualized using the DVLNav software package [20]. In AUV mode, DVLNav displayed basic vehicle navigation and engineering state information provided by the acoustic modem. Figure 10 shows a screen shot of the DVLNav program, [20], during ROV mode dive NER005 at 2,257 m depth during closed-loop trackline navigation and control testing.

X. Controls and Dynamics in AUV Mode

When configured as an AUV *Nereus* is designed to be efficient in forward flight at speeds up to $2\,\mathrm{m/s}$. Unlike most AUVs, *Nereus* can stop, hover, and reverse direction if necessary to negotiate steep terrain. The ABE vehicle has demonstrated the value of this latter capability for seafloor scientific surveys [35]. However, unlike AUVs with static thruster configurations (ABE, SeaBED) or more typical fin-actuated AUVs, *Nereus's* depth control strategy changes as a function of speed. This increased complexity comes with the substantial benefits of low cruising drag and alignment of the thrusters with the predominant flow direction except at very low speeds. Dynamics and controls experiments conducted during sea trials in fall 2007 were focused on demonstrating vehicle control in the longitudinal plane (surge, heave, and pitch) and identifying hydrodynamic parameters critical to maximizing vehicle performance during survey and high-efficiency homing descents.

A. Longitudinal Plane Control

Nereus's unusual foil-mounted-actuator configuration creates a variety of potential strategies by which the vehicle can control its depth. The efficiency and performance of each of these is dominantly a function of forward speed, with higher speeds favoring low-angle of attack motions to limit drag losses. Figure 11 illustrates *Nereus's* gain-scheduled strategy for depth control. Extensive simulation studies [18] were utilized to develop the following three depth controllers:

1) *Foils-fixed hover:* Hovering for low speed, high angle of attack maneuvers.
2) *Zero-pitch flight:* Level flight for intermediate to high speed survey at low to medium angles of attack.
3) *Zero-w flight:* Zero body-frame vertical velocity (zero-w) pitching flight for efficient high speed climbs at low angles of attack.

The three control modes were demonstrated successfully during the sea trials and tuned for acceptable performance. Automated switching between level flight and foils-fixed hover was demonstrated during a high-speed terrain-following experiment at $5\,\mathrm{m}$ altitude, as depicted in Figure 12.

B. Terrain-Following

The utility of *Nereus* as a imaging survey AUV is dependent upon its ability to terrain-follow (maintain a constant altitude above the seafloor). The terrain-following algorithm implemented on *Nereus* is modeled on the algorithm employed on the successful ABE AUV [35], [36]. The algorithm attempts to limit control action and provide robustness to noisy altimeter data by maintaining the depth setpoint within a prespecified envelope above the seafloor rather than servoing off altitude directly.

In the 2007 sea trials *Nereus* successfully flew a $5\ \mathrm{m}$ altitude photo-survey over modest terrain. The result (Figure 12) is noteworthy in that despite the relatively smooth seafloor encountered, two outcroppings were sufficiently steep to require higher climb angles than were expected to be possible in level flight mode. The control program responded to these obstacles by autonomously switching actuator allocation modes from level flight to foils-fixed hover. These results were attained without the benefit of feed-forward or integral action in the depth controllers. These features have been implemented and will be engaged in subsequent trials.

XI. Mission Controller

This section reports the progress towards developing a mission controller for the high level control of the *Nereus* HROV. The mission controller performs the job of the pilot in the absence of a telemetry system for *Nereus*. In AUV mode, the mission controller supports fully-autonomous survey missions. In ROV mode, the mission controller permits normal pilot-controlled teleoperation of the vehicle and in the event of the loss of tether telemetry will assume control of the vehicle and autonomously complete a preprogrammed mission.

The mission controller manages the mission by executing a high-level mission plan, and respond to events. At present the mission controller is capable of the following:

1) *Condition Monitoring*: continuous monitoring, detection and response to vehicle subsystem status including vehicle depth and Doppler sonar status.
2) *Telemetry Status Monitoring*: detection and response to status of fiber-optic Ethernet link.
3) *New Mission Execution*: the ability to dynamically load and execute new mission scripts.
4) *Simulation Mode*: fast-time simulated missions.
5) *Simple Command Primitives*: simple primitives for control of speed, depth, altitude, and heading.
6) *Trackline Following*: trajectory control for survey operations.
7) *Abort Mission*: the ability to perform a controlled mission abort.

XII. Acoustic Telemetry

The acoustic telemetry system is designed to send data acoustically between multiple vehicles including one or more surface ships. The system employs Micro-Modems, [12], designed at Woods Hole Oceanographic Institution (WHOI) and,

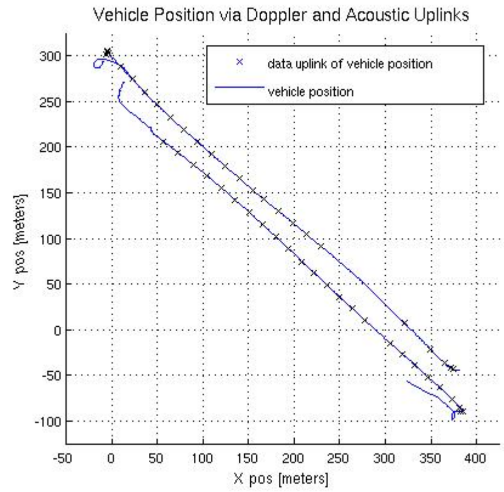

Fig. 13. Vehicle trackline overlaid on vehicle positions transmitted via acoustic uplink.

in the case of the *Nereus* vehicle, EDO/Straza SP23 acoustic transducers.

The Acomms program is a Linux daemon which runs on the *Nereus* control computer. It manages the WHOI Micro-Modem, serving two main roles. First, the Acomms process is designed to monitor and report on the status of the modem and keep it properly configured through modem reboots. Second, the Acomms process is designed to act as a transport layer between the vehicle program and the modem for sending and receiving acoustic data, providing basic format checking for messages sent to the modem and exhaustively logging all Acomms related data.

For the recent sea trials, *Nereus* was equipped with one Straza transducer mounted on the forward starboard hull of the vehicle facing upwards. A second transducer was deployed from of the stern of the ship (the *R/V Kilo Moana*) facing downwards. The ship transducer was lowered several meters underwater and held in place using a bridle that prevented side-to-side motion.

During vehicle-ship communication, the vehicle is designated as the master, initiating all acoustic communication. Messages are sent out in a time division multiple access (TDMA) cycle that is configured at run time. The slave acomms process on the ship responds to acoustic queries as necessary and can also send acoustic abort signals. During *Nereus* trials the following acoustic messages were employed:

- An *Abort message* indicates that the vehicle should run its abort script.
- A *Ranging Ping* interrogates another modem and returns a travel time between the sender and the receiver.
- A *Cycle Init message* requests data and designates which modem is to send and which is to receive.
- A *Vehicle Status message* consists of 32 bytes of data containing vehicle status information (position/attitude, velocity, and battery charge).
- An *LBL Ping* interrogates long baseline (LBL) acoustic

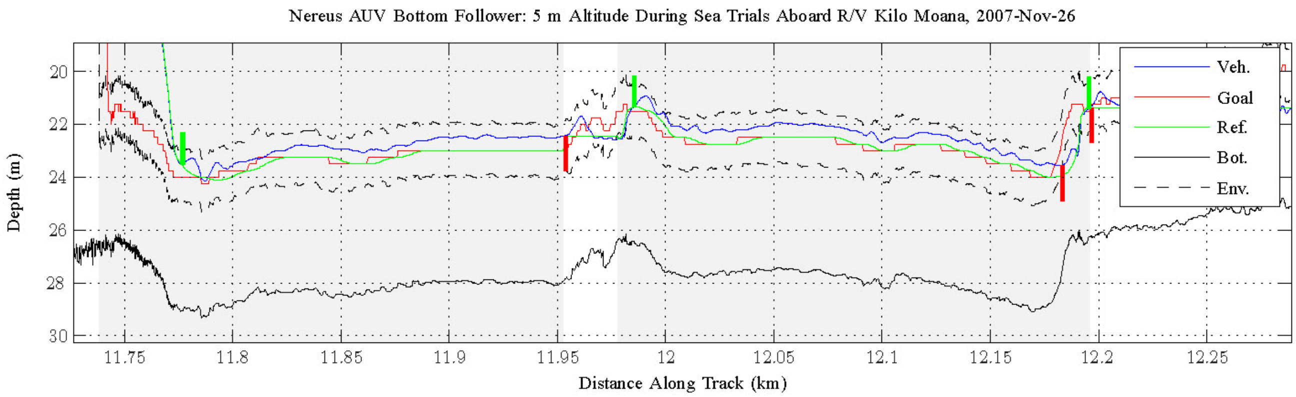

Fig. 12. Terrain-follower performance versus distance travelled during a mock photo-survey at 5 m altitude. Times when the terrain-follower was actively controlling depth are indicated by the grayed areas. The algorithm autonomously modulated speed to keep the reference trajectory within a 1 m envelope throughout the majority of the survey. This included autonomous switching into foils-fixed hover allocation from level flight allocation when the desired climb angle exceeded that attainable in level flight. Mode switch times are indicated by heavy vertical bars (green: hover→flight; red: flight→hover).

beacons at up to four distinct frequencies and reports travel times.

In the November 2007 sea trials we demonstrated the ability to send and receive abort packets as well as respond to data requests with a Vehicle Status message. This vehicle information proved invaluable during AUV trials, allowing the users to track the progress of the vehicle in real time during its mission. Figure 13 shows an example of status (position) data received acoustically at the ship in real time and the actual vehicle track line.

In addition, the LBL functionality of the Acomms process has been fully tested in an LBL transponder net subsequent to this cruise, where we have demonstrated the ability of the navigation program to parse Micro-Modem LBL messages and calculate the resulting vehicle position.

XIII. Conclusion

For the past 50 years, vehicle limitations have restricted routine direct access to depths of 6,500 m or less. Only a few deeper vehicles have ever been developed and successfully deployed. The scientific community has established substantive imperative to investigate the deep ocean floor at depths below 6500 m, yet a lack of practical technology prevents routine access to the deepest ocean. This virtually unexplored area of the ocean almost certainly offers the potential to make important biological and geologic discoveries. Preliminary sea trials with Nereus in November 2007 demonstrated basic functionality of capabilities in navigation, control, mission control, fiber optic tether, and acoustic telemetry necessary for AUV mode autonomous survey missions and ROV mode sampling missions in a single vehicle package. This development points to a way forward for both scientific and commercial operations through the use of a unique combination of adapted technologies. Future sea trials are planned to demonstrate the vehicle's operational capability for operations at depths to 11,000 m.

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