Field Trials of the *Nereus* Hybrid Underwater Robotic Vehicle in the Challenger Deep of the Mariana Trench

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***Abstract*— This paper reports the results of sea trials of the *Nereus* hybrid underwater robotic vehicle (HROV) conducted in May and June 2009 in the Challenger Deep of the Mariana Trench, where the vehicle successfully performed scientific observation and sampling operations at hadal depths of 10,903 m. The *Nereus* underwater vehicle is designed to perform scientific survey and sampling to the full depth of the ocean — significantly deeper than the depth capability of all other present-day operational vehicles. For comparison, the second deepest underwater vehicle currently operational worldwide can dive to 7,000 m maximum depth. *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. *Nereus* can be converted at sea to become a remotely operated vehicle (ROV) to enable close-up imaging and sampling. The ROV configuration incorporates a lightweight fiber-optic tether for high-bandwidth, real-time video and data telemetry to the surface enabling high-quality teleoperation. A manipulator, lightweight hydraulic power unit, and sampling instruments are added to provide sampling capabilities. This paper reports a brief overview of the *Nereus* vehicle design, and reviews the initial results of the eight dives conducted on this expedition, including two dives to more than 10,900 m depth. The Nereus vehicle is designed to render all parts of the Earth's seafloor reachable and the sea trials of its full-ocean depth capability in May and June 2009 were successful.**

I. Introduction

On May 31, 2009 the *Nereus* hybrid remotely operated vehicle (HROV) successfully completed its first dive to the hadal ocean depth of 10,903 m at 11°22.1'N, 142°35.4'E in the Mariana Trench in the Western Pacific. This 26-hour dive was comprised of an 8.5 hour descent to 10,903 m, a 10.75 hour bottom interval during which the vehicle provided live video via its fiber-tether multi-gigabit optical telemetry and performed geological and biological observation and sampling, and a 6.5 hour autonomous ascent to the surface. This paper gives a brief overview of the *Nereus* vehicle design, and reports results of *Nereus* sea trials conducted in May and June 2009 culminating in the Challenger Deep of the Mariana Trench (Figure 1) in the Western Pacific Ocean near the island of Guam [12].

The goal of the *Nereus* project is to provide the U.S. oceanographic community with the first capable and cost-effective vehicle for routine scientific survey, sea floor and water-column experimentation, and sampling to the full depth of the ocean of 11,000 m — significantly deeper than the depth capability of all other present-day operational vehicles. For comparison, the second deepest underwater vehicle currently operational worldwide can dive to 7,000 m maximum depth [17]. *Nereus* operates in two different modes. For broad area survey, the vehicle can operate untethered as an autonomous underwater vehicle (AUV) capable of surveying and mapping the sea floor with sonars and cameras (Figure 2, right). For close-up imaging and sampling, *Nereus* can be converted at sea to become a tethered, remotely operated vehicle (ROV) (Figure 2, left). The ROV configuration incorporates a novel, lightweight, fiber-optic tether (Figure 3) for high-bandwidth, real-time video and data telemetry to the surface, enabling high-quality, remote-controlled teleoperation by a human pilot. *Nereus's* first sea trials were conducted in November 2007 from the R/V *Kilo Moana* in the Pacific Ocean near Oahu, Hawaii. The 2007 sea trials demonstrated vehicle operations in AUV mode and ROV mode to a depth of 2,270 m, as reported in [2], [3].

The *Nereus* vehicle project is lead by the Woods Hole Oceanographic Institution with collaboration of the Johns Hopkins University and the U.S. Navy Space and Naval Warfare Systems Center Pacific. The Nereus field trial science team is from the University of Hawaii and the Woods Hole Oceanographic Institution. The *Nereus* vehicle project is supported principally by the National Science Foundation, with additional support provided by the U.S. Navy Office of Naval Research, the National Oceanic and Atmospheric Administration, the Woods Hole Oceanographic Institution,

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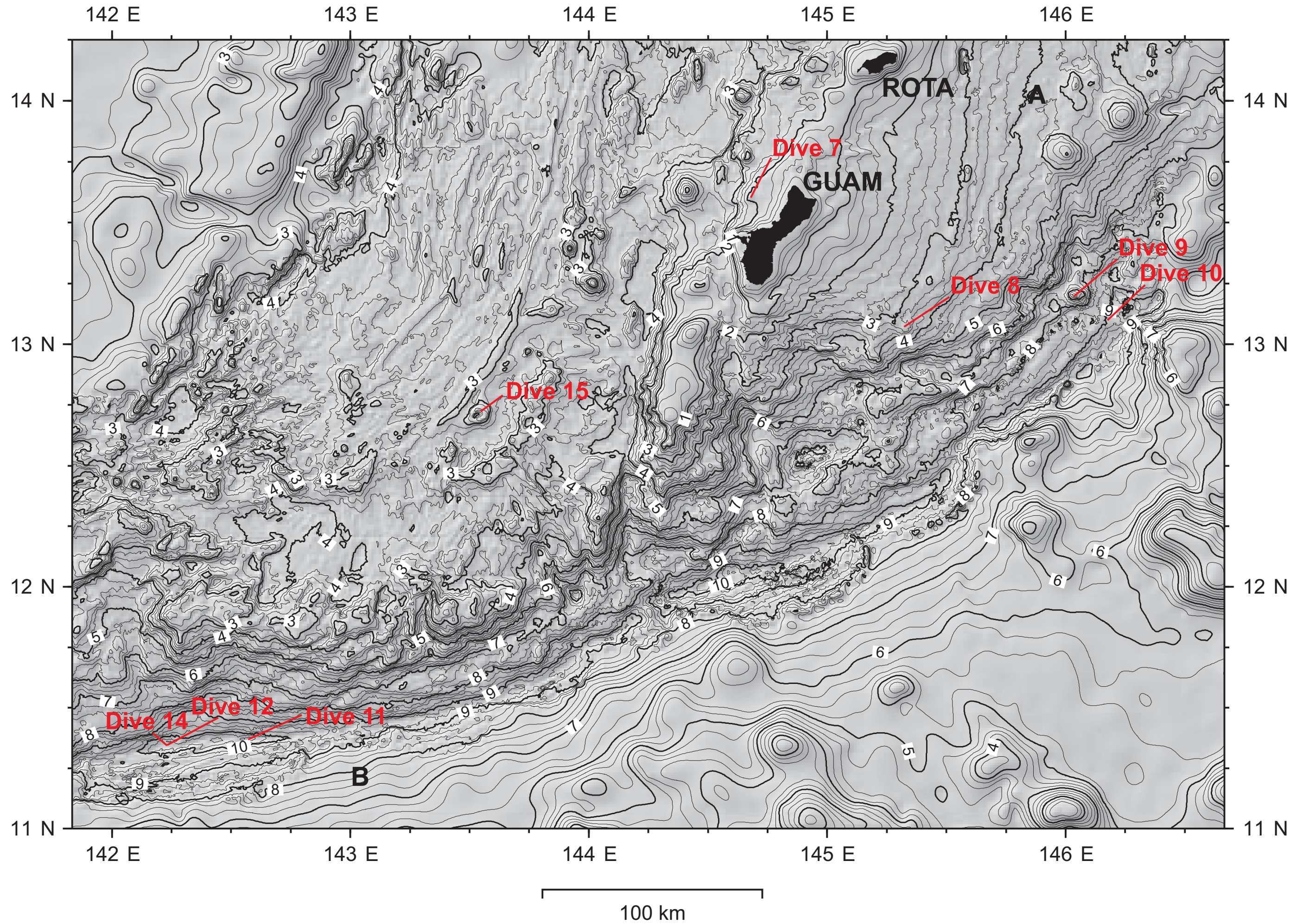

Fig. 1. Shaded contour map (250-m contour interval) of the southern Mariana region showing locations of *Nereus* dives during R/V *Kilo Moana* cruise KM0912, May 23-June 5, 2009. Contour labels indicate 1,000 m isobaths.

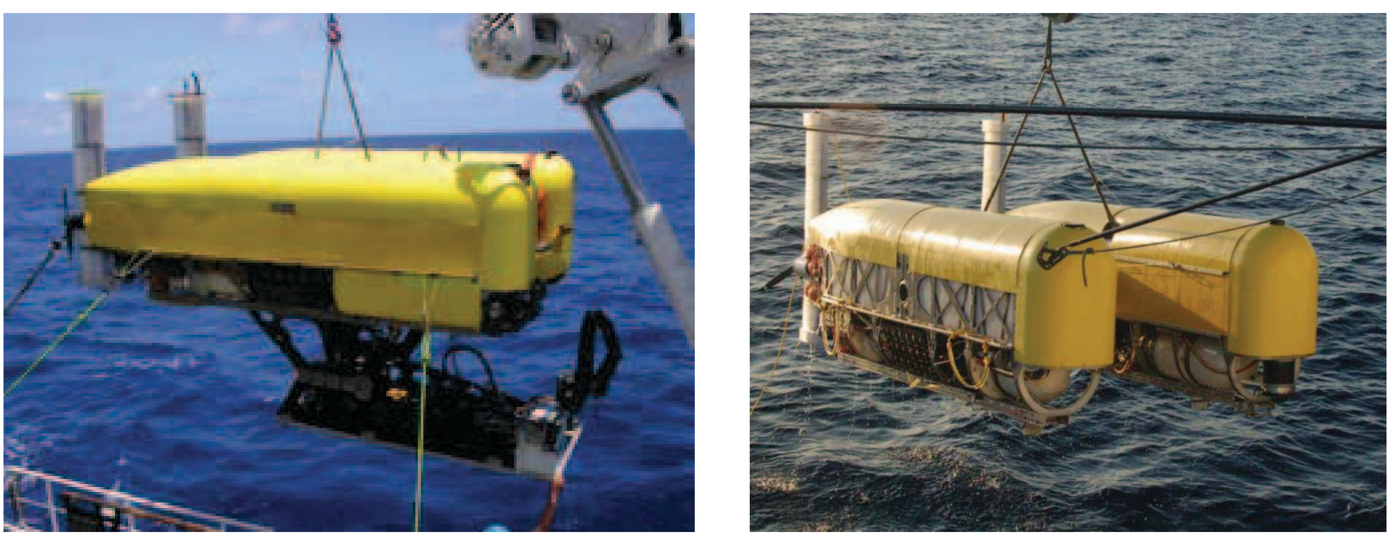

Fig. 2. The *Nereus* hybrid remotely operated vehicle is designed to operate in two modes to depths of 11,000m. Left: *Nereus* configured in ROV mode in May-June 2009 with a light fiber-optic tether, a robot arm, sampling gear, and additional cameras for teleoperation of close-up imaging, sampling, and manipulation missions. Right: *Nereus* configured in AUV mode for autonomous vehicle survey operations in November 2007.

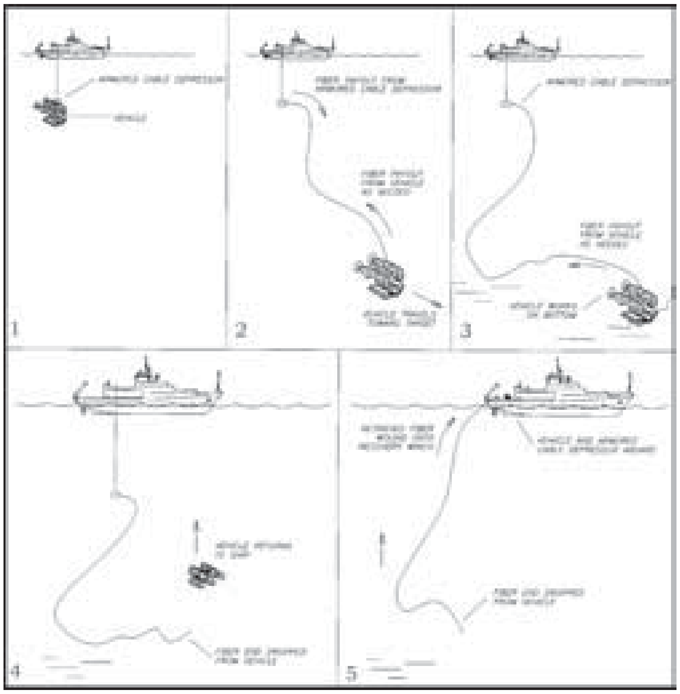

Fig. 3. *Nereus* ROV-mode concept of operations. In ROV mode *Nereus* is remotely controlled by a lightweight, expendable, fiber-optic tether which connects the vehicle to a surface support vessel.

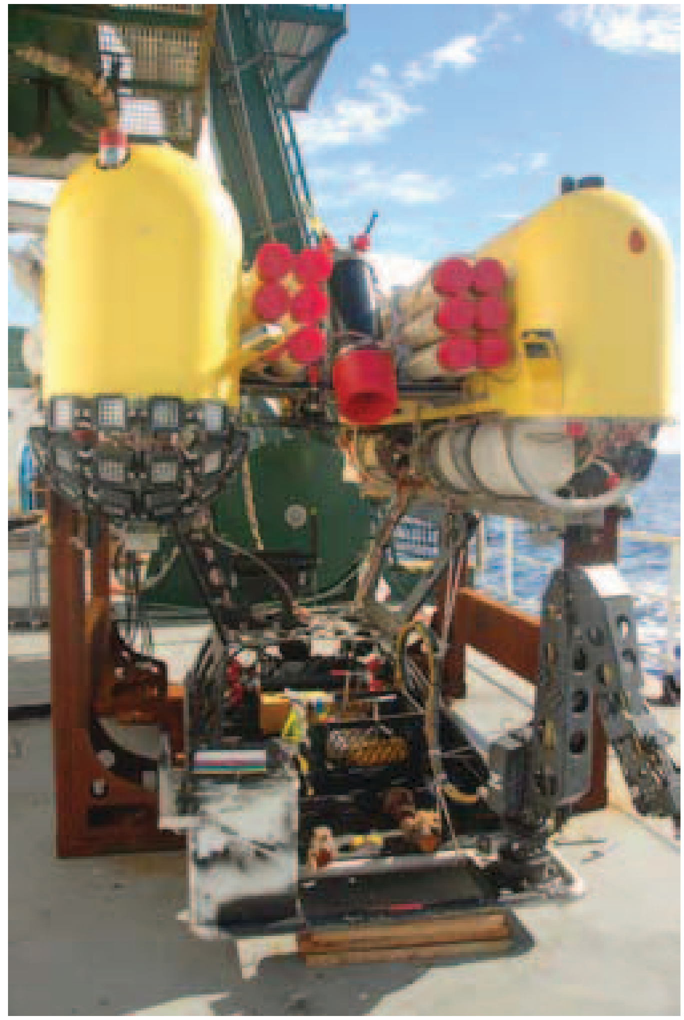

Fig. 4. The newly developed *Nereus* in tethered ROV mode aboard the R/V *Kilo Moana* in May 2009 showing main ceramic pressure housings, lateral and vertical thrusters, auxiliary ROV-mode flotation spheres mounted in 12 red-capped cylinders, robotic arm, digital imaging cameras, LED lighting arrays, biological and geological sample containers, scanning sonar, acoustic modem transducer, and LBL transducer.

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 7,000 m — e.g. the 4,500 m *Alvin* human occupied submersible [4], the 4,500 m *ABE* AUV [34], and the 4,000 m *Tiburon* ROV [19]. Only a few currently operational vehicles are capable of diving to between 6,000 m and 7,000 m — e.g. the 6,500 m *Jason II* ROV [32] and the 7,000 m *Kaiko 7000* [17]. These and other similar capabilities have led to significant scientific discoveries over the past 50 years including identifying and sampling mid-ocean ridge volcanic processes, hydrothermal processes, and biological ecosystems which have revolutionized the biological sciences [21]. Progress in deep sea research at ocean floor sites between 7,000 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, the mandate to survey and understand the geologic and biologic complexities of deep trench systems in the newly-designated Mariana Marine National Monument area, [33], 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 [5], [20], [21], [23]

Only two vehicles have previously reached the deepest place on Earth — the Challenger Deep of the Mariana Trench. Five decades ago, on January 23, 1960 the human-piloted Bathyscaph *Trieste*, developed by Auguste Piccard, made one successful dive to the Challenger Deep [22]. 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 [27]. Neither *Trieste* nor *Kaiko* is currently 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 7,000 m. 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 and significantly restrict maneuverability, 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. The self-powered, remotely operated vehicle UROV7K employed a expendable fiber-optic tether [18]. This vehicle was designed to operate exclusively as a tethered ROV, and did not have on-board computational resources necessary to operate autonomously. 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 [7]. To the best of our knowledge, McFarlane was the first to report the conceptual design of a 11,000 m capable vehicle employing a small diameter (3/8 in) electro-optic tether [16].

Our goal was to create a practical 11,000 m system using an appropriately designed, self-powered vehicle that can (a) operate as an untethered autonomous vehicle in 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 in ROV mode.

III. Hybrid Vehicle Design Overview

Nereus was designed as a portable vehicle system that can be rapidly deployed from a ship of opportunity, without requiring dynamic positioning of the ship, thus enabling it to be deployed from regional class as well as ocean class ships. 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 pressure housings developed specifically for this project [26]. Additional buoyancy is provided by lightweight, hollow ceramic buoyancy spheres [25], [31]. Two 0.355-m, outside diameter (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 a 16-kWh, rechargeable lithium-ion battery pack, developed for this project, contained in two additional 0.355-m ceramic pressure housings. Cameras, emergency beacons, RF modem (for surface operations), and other electronics are housed separately in dedicated, 0.191-m OD, ceramic and titanium pressure housings. Lighting is provided by lightweight, ambient-pressure, light-emitting-diode (LED) arrays, custom-developed for the Nereus project [13]. Pressure-balanced, biodegradable-oil-filled junction boxes and hoses provide vehicle electrical- and optical-interconnect. The vehicle navigation sensor suite is described in Section III-I. 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 (right)) *Nereus* is neutrally buoyant with a displacement of 2,625 kg with 1,472 ceramic buoyancy spheres and a reserve payload buoyancy of 30 kg. This mode employs two independently-articulated, actively-controlled foils (wings) located between the hulls at the aft and middle sections, respectively. In addition to forward-flight at non-zero advance velocities, the vehicle is capable of hovering, ascending, and descending at zero advance velocity [14]. The vehicle is hydrodynamically stable in pitch and heading when in forward flight. 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. A downward looking survey camera and several LED arrays are mounted on the port hull.

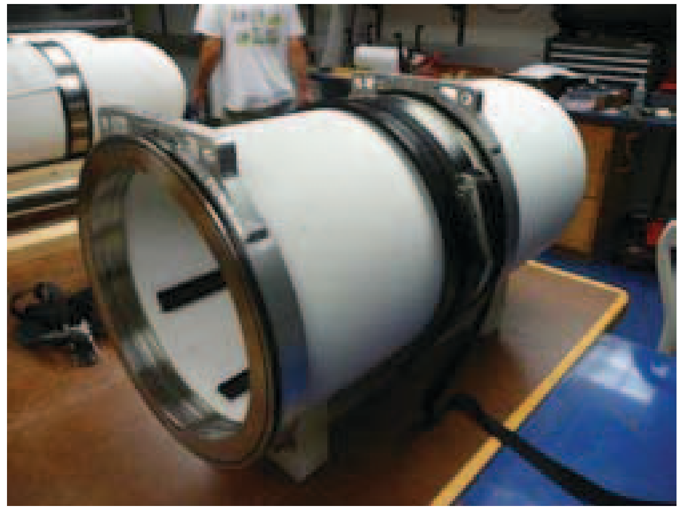

Fig. 5. A main ceramic pressure housing being readied for fitting into *Nereus* [2], [26].

B. Nereus ROV Mode Configuration Summary

In ROV mode (Figure 2 (left) and Figure 4) *Nereus* is neutrally buoyant with a displacement of 2,920 kg and 1,680 ceramic buoyancy spheres providing a reserve payload buoyancy of 40 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 two vertical 1-kW thrusters.

C. Ceramic Housings and Buoyancy Spheres

Ceramic buoyancy spheres and custom ceramic-titanium pressure housings were employed to minimize vehicle size and mass.

1) Ceramic Buoyancy Spheres: Ceramic flotation was selected because of its low weight to displacement characteristics. 99.9% alumina ceramic seamless spheres, of 91-mm OD, manufactured by Deep Sea Power and Light (DSPL) in San Diego, California, were chosen [25], [31]. These spheres each weigh 140 g and displace 404 g in sea water, for a nominal 0.35 weight-to-displacement ratio. The spheres supplied by DSPL were individually tested to 30 kpsi external

Date (UTC)	Dive	Vehicle Mode	Depth (m)		Time (hh:mm)		Fiber Payout (m)		
			Vehicle	Depressor	Submerged	Bottom	Depressor	Vehicle	Total
May 25, 2009	7	ROV	912	587	05:48	03:46	699	331	1030
May 26, 2009	8	ROV	3510	3022	11:06	02:13	626	400	1026
May 27, 2009	9	ROV	6424	5887	11:18	00:34	41	1353	1394
May 28, 2009	10	ROV	9029	5777	18:03	04:50	8424	1969	10393
May 30, 2009	11	ROV	10903	5869	25:38	10:40	3479	3308	6787
Jun 1, 2009	12	ROV	10902	5871	18:03	02:30	2058	4014	6072
Jun 3, 2009	14	ROV	10166	5706	13:06	00:00	1943	2965	4908
Jun 4, 2009	15	ROV	2960	2406	11:48	06:56	802	556	1358

TABLE I

DIVE STATISTICS: 2009 *Nereus* MARIANA TRENCH SEA TRAILS

pressure. The spheres are individually jacketed with 5-mm thick, elastomeric, polyvinylchloride (PVC) "boots" that provide robust protection against impact loading, while providing an additional 19 g of net buoyancy. The booted spheres each produce 283 g of buoyancy at the surface. The spheres are less compressible than water, so at full operating depth of 11,000 m they each generate 306 g of buoyancy. The main vehicle flotation consists of 1,472 spheres arranged in the upper portions of the vehicle hulls, generating 417 kg of net buoyancy. The spheres are housed in longitudinal tubes within buoyant polypropylene modules.

2) Ceramic Pressure Housings: Ceramic was selected for the pressure housing material because its high compressive strength-to-weight ratio, which allows for near-neutrally buoyant housings capable of going to these extreme depths. Equivalent titanium housings of this size would result in a significantly larger vehicle, weighing several hundered kilograms more. The housings consist of a ceramic section formed by CoorsTek Inc., and titanium joint rings manufactured at WHOI that are bonded to the ceramic with a high-strength epoxy material. For additional information the reader is referred to [2], [26].

D. Fiber Optic Tether

We developed a novel, lightweight, expendable fiber-optic tether for *Nereus* 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 as noted in Section II. The preliminary design analysis of this cable for deep-ocean deployments was described elsewhere [36]. The basic concept of the deployment system involves the use of a snag-resistant depressor and vehicle package to house the tether system (3). 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 first integrated with the actual Nereus HROV vehicle in fall 2007, and is reported in further detail elsewhere [8], [9], [28], [36].

E. Manipulator and Sampling System

The *Nereus* sampling system (Figure 2 (left) and 4) 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.

The *Nereus* hydraulic power unit (HPU) provides hydraulic pressure and flow of biodegradable hydraulic fluid to the manipulator. This is a WHOI-designed, modular, hydraulic system that delivers 69 bar at flow rates of 7.5 lpm.

The maximum power used at any time by the HPU is limited to 750 watts. A sampling platform is integral to the tool sled and provides storage facilities for science equipment and samples [2].

F. Cameras and Lighting

For ROV-mode imaging, a full-motion-capable color-imager based upon a Uniq UC-1830CL-12B machine-vision camera used in previous deep-sea work has been employed [13]. The camera is capable of capturing a high-resolution color image, whenever it is triggered, at rates up to 29.97 frames per second. Two NTSC Insite Aurora subsea video cameras in 11,000 m housings support viewing of the work package and other utility tasks. We developed a novel, lightweight 16-element, pressure-compensated LED assembly (or "puck") for *Nereus*. The *Nereus* design includes 17 strobing LED pucks arranged in an array on the nose of the starboard hull (Figure 4). Three other pucks, used in a continuous lighting mode (not strobed), are also included in the design as backups in the event of controller failure and to illuminate sample storage areas not covered by the main array (Figure 4). Additional details are reported elsewhere [2], [13].

G. Power and Propulsion

Nereus is powered by a 16-kWh rechargeable, lithium-ion battery system, configured to provide a 50 volt bus. Building upon the design of lithium ion powered ABE [34] and REMUS [1] AUVs, WHOI designed a modular building block of 12 cylindrical cells. The maximum power output of the batteries is 3 kW. Typically, non-propulsion loads total 300 W. The propulsion system is the largest load on the power bus, and therefore has the greatest impact on mission duration. The design of the electric thrusters started with the propeller, which was optimized for autonomous operation. Hydrodynamic modeling estimated the drag in AUV mode to be 460 N at 1.5 m/s. Froude scaling of existing propellers was then used to specify a new two-bladed carbon-fiber propeller with a 0.75-m diameter and 0.56-m pitch, which maximizes propulsion efficiency. A brushless permanent magnet electric motor and 7:1 planetary gearbox were selected to maximize power transmission at 200 RPM. Using a gearbox instead of a larger direct drive motor yielded a 75% smaller and lighter thruster package [2]. The 2007 and 2009 sea trials demonstrated that Nereus in ROV-mode is a power efficient yet capable sampling platform.

H. Buoyancy Modeling and Control

At hadal depths, natural variation in sea water temperature and pressure (pressure increases by one atmosphere per 10 m depth) result in more than a 5% increase in sea water density, which increases the buoyancy of a given displacement volume. The substantial pressure compresses the vehicle's entire structure, thus reducing its displacement and buoyancy. Our mathematical model for vehicle buoyancy predicted that *Nereus's* buoyancy would increase by over 70 kg at 11,000m depth, which far exceeds the vehicle's vertical thruster capability. A means of adjusting *Nereus's* buoyancy is required for successful operation. Our studies indicated that the development of a variable buoyancy trim system would be undesirable because of its cost, weight, and power requirements. We designed *Nereus* with modular ballast and buoyancy modules, which are added or removed as needed prior to launch such that the vehicle will be neutrally buoyant at the target depth.

I. Navigation

The *Nereus* navigation sensor suite includes a 1-ppm Paroscientific 9000-20K-101 pressure depth sensor, a custom SBE49 FastCAT CTD Sensor, a Teledyne-RDInstruments 300kHz Doppler sonar, an IXSEA Phins IMU, a WHOI LBL transceiver, a WHOI Micro-Modem [11], and a Microstrain gyro-stabilized attitude- and magnetic-heading sensor. Depth was calculated from Paroscientific pressure data, see [10]. The Doppler sonar provides 3-axis, bottom-lock, vehicle velocity with respect to the sea floor at up to 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, 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 *Nereus*, NavEst is a multithreaded Linux program that supports multiple, simultaneous, navigation algorithms. Available navigation algorithms include the Doppler navigation algorithm employed by DVLNav [15] and the LBL algorithm extensively used by the *ABE* AUV [35]. Single-beacon, one-way, travel-time algorithms have also been implemented [6]. The DVLNav program provided a real-time plot of the location of Nereus on screen, overlain on EM120 bathymetry (Figure 6).

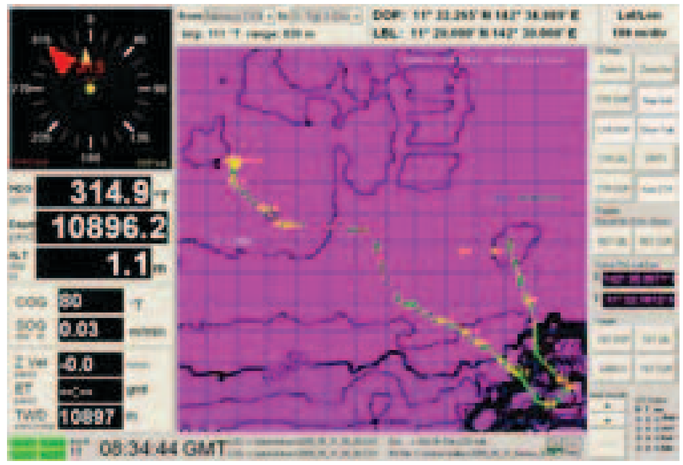

Fig. 6. *Nereus* Screen shot of the DVLNav program, [15], during dive NER011, showing *Nereus's* extreme horizontal mobility in tethered ROV mode enabled by its light fiber-optic tether. The plot shows the position of the R/V *Kilo Moana*, *Nereus's* position, and *Nereus's* bottom track after 8 hours and 45 minutes bottom time.

During the 2009 field 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.

J. Mission Controller

Nereus's mission controller performs the job of the pilot in the absence of high-bandwidth telemetry [2]. 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, assumes control of the vehicle and autonomously completes a preprogrammed mission. During the 2009 Mariana sea trials, all ascents were executed autonomously under the guidance of the mission controller.

K. Acoustic Telemetry

The acoustic telemetry system is designed to send data between multiple vehicles including one or more surface ships. The system employs WHOI Micro-Modems [11]. The setup for the 2009 Nereus sea trials involved one EDO/Straza SP23 transducer mounted on the forward starboard brow of the vehicle, facing upwards. A second transducer was lowered from the stern of the *R/V Kilo Moana* facing downwards approximately

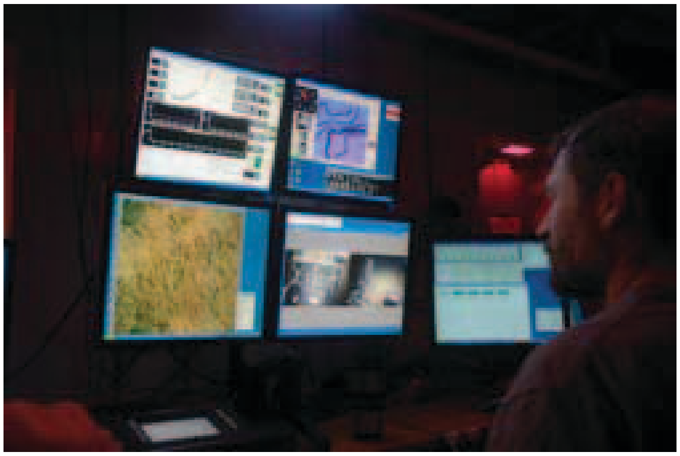

Fig. 7. WHOI research engineer Matthew Heintz remotely pilots *Nereus* during Dive 10. Vehicle controls and displays include (from lower left) robot manipulator master control, high-resolution imaging camera display, depressor navigation and control panel, vehicle navigation display, vehicle control panel, and utility camera displays.

2-3 m below the surface of the water. This transducer was surrounded by acoustic baffling to reduce the effect of ship noise. A third transducer and modem were installed on the depressor with the transducer facing downward.

All of the dives on this cruise were executed in ROV mode, whereby the vehicle has a fiber-optic link to the ship during descent and bottom operations, but performs an autonomous the ascent to the surface after cutting its fiber-optic tether. The acoustic telemetry system operated as if the vehicle were in AUV mode for the duration of the dive, broadcasting vehicle state and health information via acoustic data packets every 30 to 45 seconds. During the ascent, acoustic communications from the vehicle were critical for tracking the vehicle.

The vehicle, depressor, and ship operated with precision clocks, [6], [30], that enabled the measurement of one-way travel times (and thus inter-vehicle range) with every data packet. In addition, synchronized clocks at all three nodes (vehicle, depressor, and ship) allowed each node to predict accurately when other nodes were transmitting and when the acoustic channel was clear. This enables the acoustic telemetry system to operate with multiple masters, each initiating its own communications, making the acoustic communications both more reliable and more efficient. The general acoustic communications architecture is reported elsewhere [29]. A analysis of the May-June 2009 communication performance is reported elsewhere [24].

IV. 2009 Mariana Sea Trial Operations

This section briefly summarizes vehicle operations of the 2009 *Nereus* sea trials. The dive locations were concentrated, southeastern part of the Mariana arc region and the south axis of the Mariana Trench (Figure 1). The principal engineering objective of these field trials was to test *Nereus's* mechanical, electrical, and optical subsystems and its buoyancy at progressively greater depths — and therefore higher pressures. Although every vehicle component was individually pressure tested multiple times during development, these field trials were the first opportunity to test them as an assembled vehicle. A critical objective was empirical validation of *Nereus's* mathematical buoyancy model. The *Nereus's* expedition mobilized and demobilized aboard the R/V *Kilo Moana* at the U.S. Naval Base Guam, Apra Harbor, Guam.

Dive 007: The goal of Dive 007 was to deploy *Nereus* to 900 m at 13°36.75'N, 144°43.00'E.

This mission consumed 37.04 percent of battery capacity. This mission included a ballast test to verify our buoyancy model, lighting and imaging tests, a manipulator test, a DS7000 range test, and a test of the performance of the DVL. Sensor test showed all sensors to be functional. Scientific observation and sampling operations (coral and sponges) were conducted.

Dive 008: The goal of Dive 008 was to deploy *Nereus* to 3,700 m at 12°58.80'N, 145°10.64'E. This mission consumed 51.6 percent of battery capacity. This mission included a ballast test to verify our buoyancy model, lighting and imaging tests, and a manipulator test. The dive was terminated because of an intermittent (biodegradable) oil leak from the manipulator throughout the dive because of a defective seal. Sensor tests showed most sensors to be functional. Scientific observation and sampling operations were conducted.

Dive 009: The goal of Dive 009 was to deploy *Nereus* to 6,500 m at 13°12.00'N, 146°01.34'E. This mission consumed 67.29 percent of battery capacity. The descent weight dropped prematurely after separation from the depressor. This mission included a ballast test to verify our buoyancy model, lighting and imaging tests, navigation sensor tests, and a manipulator test. Shortly after reaching the sea floor, fiber telemetry became intermittent and then telemetry was lost permanently because of a fiber break. The mission was aborted by an acoustic abort command. Post-mission analysis revealed the light fiber-optic tether break was a consequence of tether entanglement with the depressor, because of excessive torsion-induced rotation of the depressor from a one-time, torsional relaxation of the steel 17-mm, electro-optic cable (which connects the depressor to the surface ship) when the float-pack separated from the depressor.

Dive 010: The goal of Dive 010 was to deploy *Nereus* to 9,000 m at 12°59.5'N, 146°00.0'E. — a depth deeper than the capability of any other currently operational underwater vehicle. This mission consumed 85.0 percent of battery capacity. DVL water lock tests were performed at 1,900 m. This mission included a ballast test to verify our buoyancy model, lighting and imaging tests, navigation sensor tests, a manipulator test, DVL tests, lighting and imaging tests, and a test of the scanning sonar. Tube cores, rock samples, and biological samples were collected. The vehicle fiber cutter failed to cut the fiber tether before ascent, resulting in excessive fiber payout from the vehicle.

Dive 011: *Nereus* reached a depth of 10,903 m at 11°22.1'N, 142°35.4'E on this, our first dive attempt in the Challenger Deep. The dive started near the deepest known spot in the Challenger Deep. The vehicle then transited south approximately 0.5 km and explored the edge of the subducting

Fig. 8. Core sampling at 10,898 m depth, *Nereus* dive 12, June 2, 2009.

plate, taking rock samples with the manipulator (Figure 8), which was fully operational. The vehicle then moved north-west across the trench floor toward the overriding plate, taking tube cores and biological samples for approximately 2 km. This mission consumed 94.1 percent of battery capacity. Engineering tests included verification of our buoyancy model, lighting and imaging tests, and navigation sensor tests. Acoustic communications between the vehicle and the surface were operational throughout the dive. Commands from our conventional 12-kHz long-baseline navigation system were not successfully received by the vehicle. The actual buoyancy of *Nereus* matched the expected buoyancy of *Nereus* computed by the buoyancy model.

Dive 012: The goal of Dive 012 was to deploy *Nereus* to 10,902 m at 11°19.6'N, 142°12.3'E. This mission consumed 67.88 percent of battery capacity. On descent, a mid-water DVL Test was performed. This mission included a ballast test to verify our buoyancy model, lighting and imaging tests, navigation sensor tests, and a manipulator test. Tube cores and biological samples were collected. Dive 12 terminated after fiber tether failure after 2 hours on the bottom, after which the on-board mission controller autonomously commanded the vehicle to the surface.

Dive 014: The goal of Dive 014 was to deploy *Nereus* to 10,900 m at 11°19.18'N, 142°12.00'E. This mission consumed 51.13 percent of battery capacity. The dive was aborted because of failure of fiber tether near the depressor during vehicle descent. The dive was aborted automatically by the mission controller when the fiber-optic telemetry was lost for over 30 minutes, and the ascent weights were dropped 15 minutes later following an acoustic abort command from the ship's DS7000.

Dive 015: The goal of Dive 015 was to deploy *Nereus* to 3,000 m at 12°42.68'N, 143°32.6'E at a known hydrothermally active site. This mission consumed 75.99 percent of battery capacity. During this mission a ballast test, lighting and imaging tests, navigation sensor tests, additional DVL engineering test, and a manipulator test were performed. During this mission it was occasionally difficult to maneuver *Nereus* because of high currents at the site. Numerous geological and biological samples were collected. The mission was terminated via an acoustic abort command.

Fig. 9. WHOI biologist Tim Shank (at right) and Patricia Fryer (left), a geologist with the University of Hawaii, examine the samples retrieved by *Nereus*.

Multi-beam Bathymetric Mapping: The R/V Kilo Moana deep-water multibeam echo sounder (Simrad EM120) was used to produce high-resolution maps of the sea floor during the cruise. The Simrad EM120 is a 12 kHz, 191-beam system that produces bathymetric data and seafloor acoustic backscatter imaging in water depth up to 11,000 m. Width of coverage is generally six times water depth up to 2,000 m and up to 20 km width in deeper water. The sonar transducers are mounted in the port hull. Surveys of the trench region were performed during transits between dive sites. The unique SWATH hull form of the R/V *Kilo Moana* is designed to provide a comfortable, stable platform in high sea conditions. The sea conditions during our cruise were generally less than State 3, which provided for excellent conditions for mapping in high detail. The data collected will be collated with existing swath bathymetry and sidescan data [12] of the Mariana Trench.

V. 2009 Mariana Sea Trial Scientific Results

The scientific objectives of the cruise were to examine sites of potential fluid seeps on the inner slope of the Mariana Trench and in the trench axis and to examine the contact between the Earth's crust and upper mantle at deep fault scarps near the trench. We hoped to observe and sample sediment, rock and faunal specimens from these localities to study the interrelationships between geochemical and biological systems. Thus, navigation, maneuverability, and manipulator dexterity for the vehicle system were of critical importance. Synergy between the *Nereus* operations group and the scientific investigators is the most valuable aspect of using the vehicle system. Discussions regarding dive objectives and tactics are an essential and lively practice during operations. The high-resolution bathymetry maps created at sea with the ship's EM120 system were invaluable in assisting with navigation during the dives. Using high-resolution maps as an underlay on the navigation screen permitted vehicle tracking over morphologic features and the Imagenex forward-looking sonar provided approach confirmation. These systems enabled scientists and vehicle operators jointly to make real-time decisions regarding observation objectives and sampling strategies.

The cameras and lighting system on Nereus provided a varied viewing capability of the bottom during transects and sampling efforts. Both broad forward views for traversing the sea floor and close-up, high-definition images for publications and presentations are possible. Bracketing critical high-definition images to optimize lighting conditions, while taking extra time, ensured the best possible imagery for research purposes.

Manipulation tasks involved in sampling require a versatile robotic-arm system and a practiced operator. The Nereus and its operators proved capable in both regards. We collected numerous tube cores of bottom sediment, over 17 different rock types, several hydrothermal mineral samples and over 13 species of organisms from these dives (Figure 8 and 9). Sampling at the hydrothermal vents on the Toto Seamount on Dive 15 was complicated by extreme variability in currents as a consequence of "chimney effect" forces in the water column in proximal situations. Adjustments for these dynamics were made quickly and strategies for approach and successful sampling were devised relatively rapidly, but initially the response of the vehicle to these conditions was a surprise. This was the first use of Nereus in an active, vigorous smoker locality and it performed superbly.

Users of this vehicle in the future will have had experience with more powerful occupied and robotic systems such as Jason 2 and other large ROV systems. The experience of observing the sea floor using the operations center on board gives the user exactly the same sense of "being there" as with the larger ROV systems. It will be tempting to assume identical performance capability. The Nereus vehicle system provides the same superb data acquisition capabilities, but will require the user to recognize that finesse in approach to sea floor targets must be borne in mind. The payload of the Nereus vehicle is relatively small, but despite its 30 kg limit the ability to acquire samples, deploy experiments, and observe the deepest and never-before studied regions of the world's oceans will serve as a unique and exciting stimulus for ever bolder discovery in the world's oceans.

VI. Conclusion

For the past 50 years, vehicle limitations have restricted routine benthic access to depths of 7,000 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 7,000 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 May-June 2009 demonstrated basic functionality of capabilities in ceramic housings, fiber-optic tether systems, manipulators, cameras and lighting, navigation, control, 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 technologies.

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