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Navigation and Control of the *Nereus* Hybrid Underwater Vehicle for Global Ocean Science to 10,903 m Depth: Preliminary Results

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Abstract— **This paper reports an overview of the navigation and control system design for the new *Nereus* hybrid underwater robotic vehicle (HROV). Vehicle performance during its first sea trials in November 2007 near Hawaii, and in May and June 2009 in the Challenger Deep of the Mariana Trench is reported. During the latter expedition, the vehicle successfully performed scientific observation and sampling operations at depths exceeding 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 tethered 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), an electro-hydraulic manipulator arm, and sampling instruments. The *Nereus* vehicle is designed to render all parts of the Earth's seafloor accessible to oceanographic science.**

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 Challenger Deep of the Mariana Trench in the Western Pacific [9]. 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 reports an overview of the navigation and control system design for the new *Nereus* hybrid underwater robotic vehicle (HROV) and summarizes the vehicle's navigation and control performance during its first sea trials in November 2007 near the island of Oahu, Hawaii, and in May and June 2009 in the Mariana Trench. In October 2009, *Nereus* will be deployed to the Cayman Trough with the goal of locating and sampling hydrothermal vents at depths approaching 7,000 m.

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. The second deepest underwater vehicle currently operational worldwide can dive to 7,000 m maximum depth [15]. *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 1, bottom). For close-up imaging and sampling, *Nereus* can be converted at sea to become a tethered, remotely operated vehicle (ROV) (Figure 1, top). The ROV configuration incorporates a novel, lightweight, fiber-optic tether (Figure 2) for high-bandwidth, real-time video and data telemetry to the surface, enabling teleoperation by a human pilot.

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.

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 of 7,000 m — e.g. the 4,500 m *Alvin* human occupied submersible [3] and the 4,500 m *ABE* AUV [31]. 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 [29] and the 7,000 m *Kaiko 7000* [15]. Progress in deep sea research between 7,000 m and 11,000 m has been hindered by the absence of suitable cost-effective vehicles capable of operating 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 such as the newly-designated Mariana Marine National Monument area, [30], 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 [4], [17], [18], [20] .

Two vehicles have previously reached the deepest ocean depth — the Challenger Deep of the Mariana Trench. On January 23, 1960 the human-piloted Bathyscaph *Trieste*, made one dive to the Challenger Deep [19]. In 1995 the

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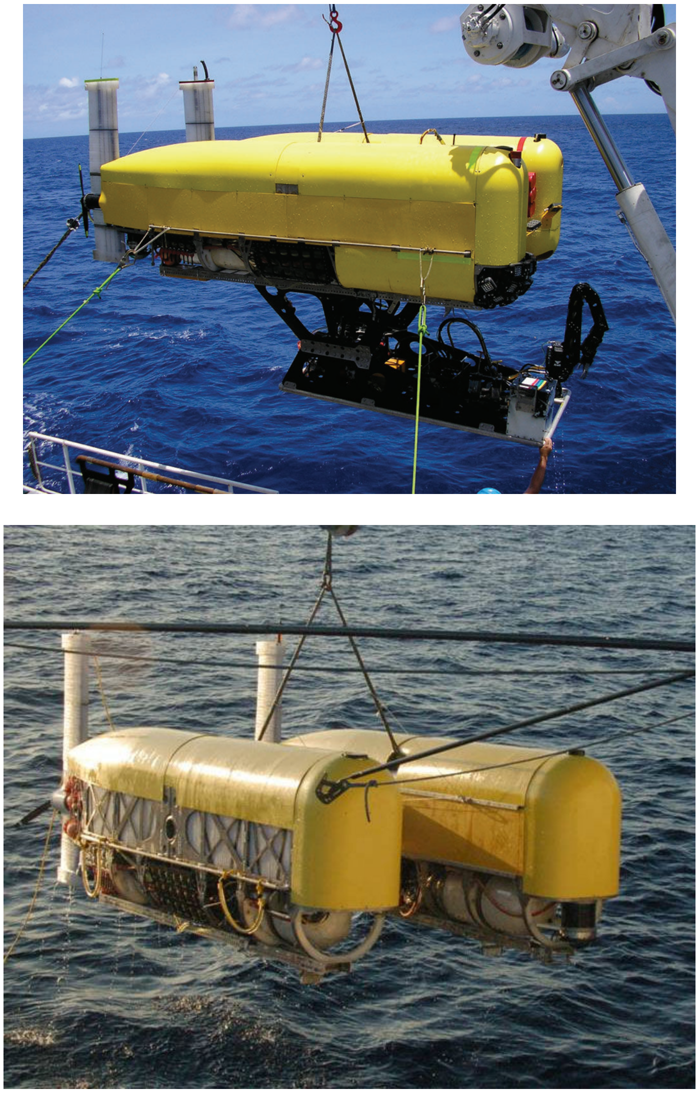

Fig. 1. The *Nereus* hybrid remotely operated vehicle is designed to operate in two modes to depths of 11,000m. Top: *Nereus* configured in ROV mode in May-June 2009 with a light fiber-optic tether, a robot arm, sampling gear, and additional cameras for teleoperation of close-up imaging, sampling, and manipulation missions. Bottom: *Nereus* configured in AUV mode for autonomous vehicle survey operations in November 2007.

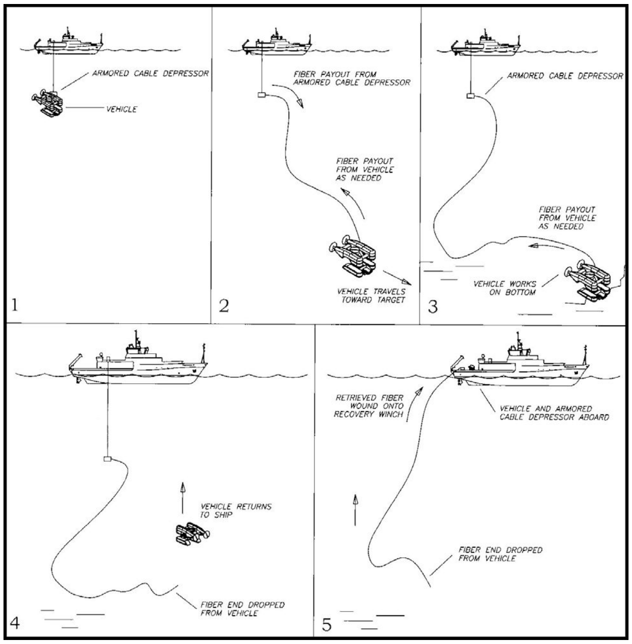

Fig. 2. *Nereus* ROV-mode concept of operations. In ROV mode *Nereus* is remotely controlled by a lightweight, expendable, fiber-optic tether which connects the vehicle to a surface support vessel.

remotely controlled ROV *Kaiko* made the first of several successful dives to the Challenger Deep [24]. Neither vehicle 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. This challenge motivated the *Nereus* project's development of novel technologies including light fiber-optic tethers, ceramic pressure housings, and hybrid vehicle design.

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 cables. The self-powered, remotely operated vehicle UROV7K employed an expendable fiber-optic tether [16]. ISE, Ltd., developed an AUV to deploy fiber-optic cables on the Arctic sea floor [6]. 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 [14].

III. HYBRID VEHICLE DESIGN OVERVIEW

Nereus was designed to be a practical 11,000-m capable, 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. The *Nereus* core vehicle employs twin free-flooded hulls. All on-board electronics, batteries, and internal sensors are housed at atmospheric pressure in novel, lightweight ceramic/titanium pressure housings developed specifically for this project [23]. Additional buoyancy is provided by lightweight, hollow ceramic buoyancy spheres [22], [27]. Two 0.355-m, outside diameter (OD), ceramic pressure housings contain power switching and distribution systems, DC-DC power isolation, computers, motor controllers, multiple gigabit Ethernet transceivers, and navigation sensors. *Nereus's* power is provided by a 16-kWh, rechargeable lithium-ion battery pack, developed for this project and 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 pres-

Date (UTC)	Dive	Vehicle	Depth (m)		Time (hh:mm)		Fiber Payout (m)		
(mm/dd/yyyy)		Mode	Vehicle	Depressor	Submerged	Bottom	Vehicle	Depressor	Total
11/20/2007	freejoy	AUV	2	—	05:56	00:00	—	—	—
11/21/2007	0	AUV	4	—	02:12	00:00	—	—	—
11/23/2007	1	ROV	18	0	00:57	00:00	—	—	—
11/23/2007	2	ROV	398	100	05:56	04:55	556	422	977
11/24/2007	3	ROV	400	400	01:20	00:00	191	1,177	1,368
11/24/2007	4	ROV	569	200	03:47	02:43	679	743	1,422
11/25/2007	5	ROV	2,270	1,000	06:50	03:21	1,214	1,138	2,352
11/26/2007	6	AUV	22	—	11:33	00:12	—	—	—

TABLE I

DIVE STATISTICS: 2007 *Nereus* HAWAII SEA TRIALS.

Date (UTC)	Dive	Vehicle	Depth (m)		Time (hh:mm)		Fiber Payout (m)		
(mm/dd/yyyy)		Mode	Vehicle	Depressor	Submerged	Bottom	Vehicle	Depressor	Total
05/25/2009	7	ROV	912	587	05:48	03:46	699	331	1,030
05/26/2009	8	ROV	3510	3,022	11:06	02:13	626	400	1,026
05/27/2009	9	ROV	6,424	5,887	11:18	00:34	41	1,353	1,394
05/28/2009	10	ROV	9,029	5,777	18:03	04:50	8,424	1,969	10,393
05/30/2009	11	ROV	10,903	5,869	25:38	10:40	3,479	3,308	6,787
06/01/2009	12	ROV	10,902	5,871	18:03	02:30	2,058	4,014	6,072
06/03/2009	14	ROV	10,166	5,706	13:06	00:00	1,943	2,965	4,908
06/04/2009	15	ROV	2,960	2,406	11:48	06:56	802	556	1,358

TABLE II

DIVE STATISTICS: 2009 *Nereus* MARIANA TRENCH SEA TRIALS

sure housings. Lighting is provided by lightweight, ambient-pressure, light-emitting-diode (LED) arrays [11]. *Nereus* is passively stable in roll and pitch, and its fixed vertical tails provide passive hydrodynamic stability in heading.

Additional details on *Nereus's* manipulator arm system, lighting, imaging systems, battery system, propulsion system, fiber-optic tether, and buoyancy design are reported elsewhere [1], [2].

A. AUV Mode Configuration

In AUV mode (Figure 1 bottom) *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 [12]. 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.

B. ROV Mode Configuration

In ROV mode (Figure 1 top) *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, a high-resolution digital camera, three 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.

IV. PROPULSION

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, chosen for 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 [1], [2].

V. NAVIGATION

The *Nereus* navigation sensor suite includes a 1-ppm Paroscientific 9000-20K-101 pressure sensor, a custom SBE49 FastCAT CTD Sensor, a Teledyne-RDInstruments 300 kHz Doppler sonar, an IXSEA Phins IMU, a WHOI LBL transceiver, a WHOI Micro-Modem [8], and a Microstrain gyro-stabilized attitude and magnetic-heading sensor. Vehicle depth was calculated from recorded pressure using standard methods [7]. 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

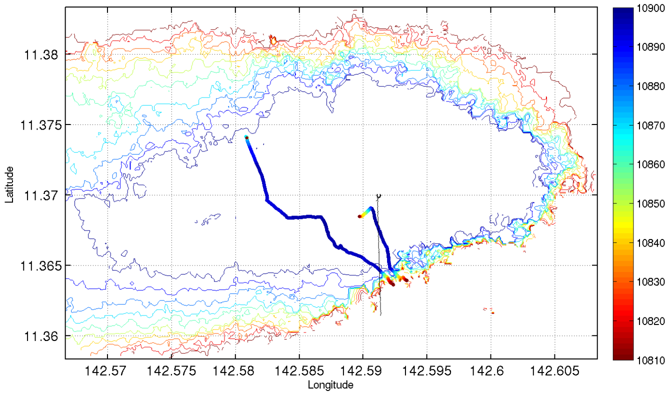

Fig. 3. *Nereus* bottom track during during dive NER011, showing *Nereus's* extreme horizontal mobility in tethered ROV mode enabled by its light fiber-optic tether. This navigation track was computed from bottom-lock Doppler velocities, fiber-optic gyrocompass, pressure depth, and one-way acoustic travel times between *Nereus* and the R/V *Kilo Moana*. Bathymetric data for depths less than 10810 m has been clipped allow comparison between vehicle depth and the sea floor.

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 [13] and the long-baseline (LBL) acoustic trilateration algorithm extensively used by the *ABE* AUV [32]. The DVLNav program provided a real-time topside display of *Nereus'* position, overlain on EM120 bathymetry. During the 2009 expedition, fixed seafloor transponders were not deployed, precluding the use of LBL navigation; however, ranges derived from one-way acoustic travel times between the vehicle and support ship (Sec. VIII) were utilized to geo-reference vehicle's dead-reckoned track (Figure 3).

VI. CONTROLS AND DYNAMICS

When configured as an ROV *Nereus* employs conventional ROV control methods [28]. When configured as an AUV *Nereus* is designed to be efficient in forward flight at speeds up to 2 $\mathrm{m/s}$. *Nereus's* two independently-articulated, actively-controlled foils (wings) and a foil-mounted thruster, enable *Nereus's* to stop, hover, and reverse direction if necessary to negotiate steep terrain. 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.

A. Longitudinal Plane Control

Figure 4 illustrates *Nereus's* gain-scheduled strategy for depth control in AUV mode. Extensive simulation studies [12] were utilized to develop the following three depth controllers:

1) *Foils-fixed hover:* Hovering for low speed, high angle of attack maneuvers.

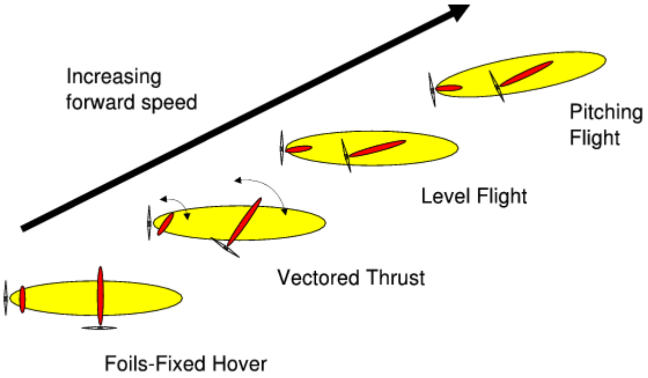

Fig. 4. *Nereus's* depth and pitch control modes [12]. Lift-dominated low angle of attack flight modes enable efficient operation at high speeds. Thruster-dominated high-angle of attack hover modes produce the climb angles necessary to negotiate steep terrain at low speeds. Foils-fixed hover and the two flight modes were demonstrated successfully during the 2007 sea trials.

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 2007 and 2009 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 m altitude, as depicted in Figure 5.

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 [31], [32]. 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 m altitude photo-survey over modest terrain. The result (Figure 5) 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.

VII. 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

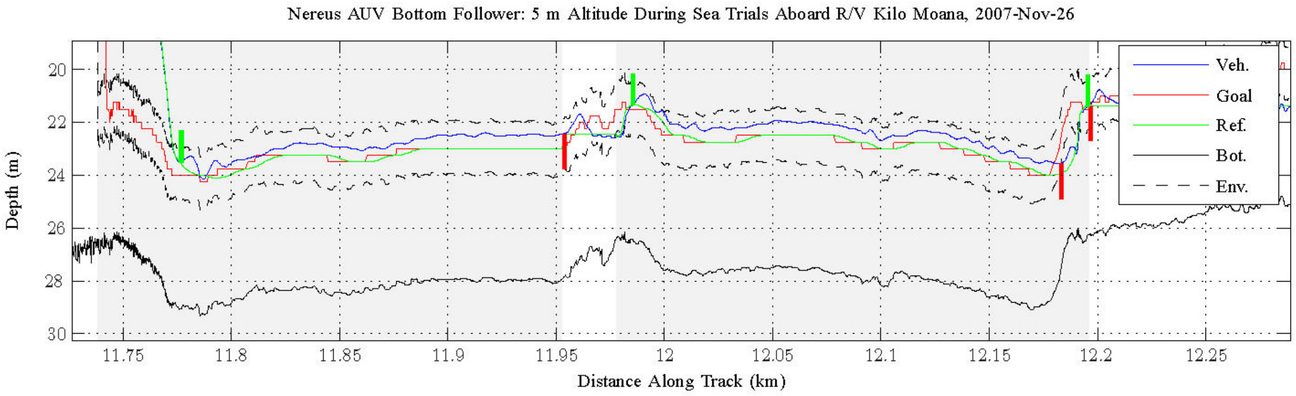

Fig. 5. Terrain-follower performance versus distance travelled during a mock photo-survey at 5 m altitude. Times when the terrain-follower was actively controlling depth are indicated by the grayed areas. The algorithm autonomously modulated speed to keep the reference trajectory within a 1 m envelope 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).

the vehicle and autonomously completes a preprogrammed mission. During the 2007 and 2009 sea trials, all ascents were executed autonomously under the guidance of the mission controller.

VIII. 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 [8]. The setup for the *Nereus* sea trials included 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 2-3 m below the surface of the water. This transducer was surrounded by acoustic baffling to reduce the effect of ship noise. For the 2009 sea trials, a third transducer and modem were installed on the depressor with the transducer facing downward.

The 2007 sea trials included both ROV mode and AUV mode operations. During the 2009 sea trials all dives were completed in ROV mode, wherein the vehicle has a fiber-optic link to the ship during descent and bottom operations, however the fiber-optic tether is cut prior to ascent and *Nereus* preforms an autonomous ascent. During the ascent, acoustic communications are the only telemetry between the vehicle and the surface vessel and provided crucial vehicle tracking and monitoring. Regardless of the vehicle mode, the acoustic telemetry system always operates as if the vehicle were in AUV mode, broadcasting vehicle state and health information every 30 to 45 seconds.

The vehicle, depressor, and ship operated with precision clocks, [5], [26], that enabled the measurement of one-way travel times (and thus inter-vehicle ranges) with every data packet. Slant ranges derived from these travel using the measured sound speed profile were utilized to geo-reference vehicle position (Figure 3). 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 enabled the acoustic telemetry system to operate with multiple masters, each initiating its own communications, which made acoustic communications both more reliable and more efficient. The general acoustic communications architecture is reported in [25]. An analysis of acoustic communication performance during the 2009 trials is reported in [21].

Fig. 6. 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.

IX. SEA TRIALS OPERATIONS

A. 2007 Hawaii Sea Trials

The 2007 sea trial dive locations were South West of the Island of Oahu, Hawaii in the Central Pacific Ocean. The principal engineering objective of these field trials was to perform comprehensive tests of the newly completed vehicle in both AUV mode and ROV mode, including tests of the vehicle subsystems. Subystem tests were performed on the batteries, LED lighting, high-resolution digital cameras, electro-hydrailic manipulator arm, thrusters, fin actuators, navigation sensors, acoustic comminication system, vehicle controller (both ROV and AUV mode), mission controller,

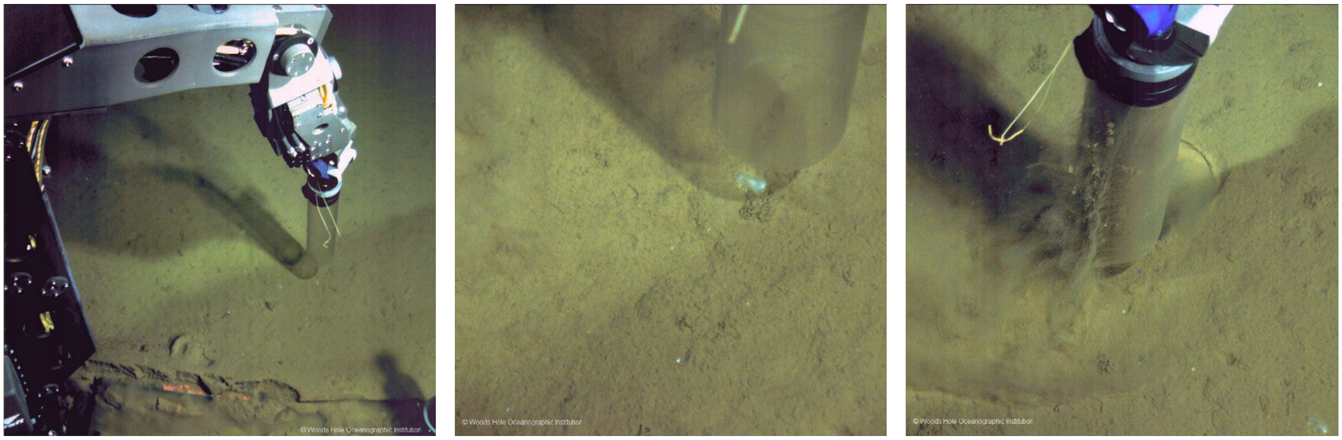

Fig. 7. Core sampling at 10,898 m depth, *Nereus* dive 12, June 2, 2009.

navigation system, buoyancy model, and launch/recovery systems. A total of seven dives were conducted on this expedition (Table I) culminating with an ROV mode dive to 2,270 m on November 6, 2007. The 2007 sea trials are reported in greater detail in [2].

B. 2009 Mariana Sea Trials

The 2009 sea trial dive locations were concentrated at the southeastern part of the Mariana arc region and the south axis of the Mariana Trench in the Western Pacific Ocean [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. A critical objective was empirical validation of *Nereus's* mathematical buoyancy model. 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. 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 total of eight dives were conducted on this expedition (Table II).

Nereus reached a depth of 10,903 m on Dive 11, our first dive attempt in the Challenger Deep. The dive started near the deepest known spot in the Challenger Deep. After reaching the bottom, *Nereus* transited south approximately 0.5 km and explored the edge of the subducting plate, taking rock samples with the manipulator (Figure 7). The vehicle then transited northwest 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 bouyancy model verification, lighting and imaging tests, and navigation sensor tests. Acoustic communications between the vehicle and the surface were operational throughout the dive. *Nereus's* actual buoyancy matched the expected buoyancy computed by the buoyancy model.

Subsequent dives on the expedition included a second dive to 10,902 m — during which additional engineering tests were performed and tube cores and biological samples were obtained. A third dive to 10,900 m was attempted but did not reach the bottom due to failure of the light fiber tether. The dive was aborted automatically by the mission controller when the fiber-optic telemetry was lost, the ascent weights were dropped 15 minutes later, and the vehicle ascended autonmously to the surface. A final dive was conducted at a previously discovered hydrothermal vent site at 3,000 m depth enabling scientists to obtains numerous geological and biological samples.

C. 2009 Cayman Trough Expedition

In October 2009, *Nereus* will be deployed to the Mid-Cayman Rise in the Caribbean Sea with the goal of locating, surveying, and sampling hydrothermal vents. In the first phase of this expedition, *Nereus* will be deployed in AUV mode to search systematically for previously undiscovered hydrothermal vents (e.g., [10]). Operations during this phase of the expedition will test vehicle terrain-following capabilities and navigation in the absence of DVL bottom-lock velocities. The second phase of the cruise will utilize the vehicle's ROV mode to perform scientific observation and sampling operations on the sea floor.

X. 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 has prevented 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* 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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