An Un-Tethered ROV for Routine Access and Intervention in the Deep Sea

Andrew D. Bowen, Michael V. Jakuba, Norman E. Farr, Jonathan Ware, Chris Taylor, Daniel Gomez-Ibanez, Casey R. Machado, and Clifford Pontbriand

Applied Ocean Physics & Engineering
Woods Hole Oceanographic Institution
Woods Hole, MA USA
abowen@whoi.edu

***Abstract* — Certain enabling technologies coupled with recent advances in robotic systems make it possible to consider supplementing many of the functions performed by vehicles with appropriately designed semi-autonomous systems. These systems are effectively a hybrid cross between ROV and AUV systems and poised to enable an important new class of undersea vehicle capable of intervention tasks under direct human control. It is now possible to radically redefine the meaning of the words "tethered vehicle" to include virtual tethering via acoustic and optical means or through the use of an extremely small optical fiber, providing not power but only high bandwidth communications. Battery-powered, hybrid-tethered vehicles will be able to perform a range of tasks that might otherwise require a conventional ROV. These functions will be performed at much lower cost by requiring less complex ships because of a greatly reduced dependence on complex, large, specialized tether and vehicle handling equipment, and a reduced need for dynamic positioning capability. Several key emerging technologies and capabilities make such a vehicle possible. Advances in both acoustic and optical "wireless" underwater communications and mico-tethers as pioneered by the HROV *Nereus* offer the potential to transform ROV type operations. By utilizing multi-band acoustics and WHOI's newly developed through-water optical transceivers, variable bandwidth communications are possible. In late 2012, *Nereus* was interfaced to a specially configured acoustic and optical communications system and a series of field demonstrations conducted offshore, including highly interactive and complex manipulations, demonstrating what we term as the Nereid Technology.**

Keywords—Hybrid; Nereid; Optical Modem; Tetherless Intervention

I. INTRODUCTION

Recent advances in robotic systems and associated technologies now make it possible to consider performing a range of undersea tasks that have historically been divided between ROVs and AUVs. A new class of hybrid vehicles will bridge the gap between these two types of systems. It is likely that such semi-autonomous vehicles will be less expensive to operate in a hybrid tethered mode. These systems are effectively a hybrid cross between ROV and AUV systems and poised to enable an important new class of undersea vehicle. The recent development of the 11,000 meter-rated Hybrid Remotely Operated Vehicle (HROV) *Nereus* at Woods Hole Oceanographic Institution (WHOI), paves the way for a derivative vehicle type able to perform a range of interventions in deep water. Such battery-powered, hybrid-tethered vehicles will be able to perform a range of tasks that might otherwise require a conventional ROV while retaining several important benefits of untethered AUVs. These functions will be performed at much lower cost by requiring less complex ships due to a greatly reduced dependence on complex, specialized tethers and vehicle handling equipment, in addition to a reduced need for dynamic positioning capability. Indeed such novel communications and control strategies will enable seafloor activities without any direct surface support vessel at all, opening up the possibility of remote interventions in new environments such as under ice. Several key emerging technologies make such a vehicle type possible. Advances in both autonomy and opto-acoustic "wireless" underwater communications offer the potential to transform ROV type operations. When married to micro tethers as pioneered by WHOI's *Nereus* and other vehicles, a range hybrid tethers can be envisioned. By layering these communication modes with an adaptive control system, vehicles can perform complex operations; bridging the gap between ROV and AUV.

In addition to important work in the area of acoustic communications and micro-tethers, WHOI is also pioneering high-data-rate optical communications. If the range between the communications node and the ROV can be maintained at 100m or less, then it is possible to operate the optical link at communications speeds of 10Mbps, thus providing essentially zero latency data and sufficient throughput for video transmission. In cases where extreme horizontal ranges are desired, such as under ice, communications can be provided through the use of a small diameter glass fiber up to 40 kilometers long. While the utility of the micro-tether has been demonstrated with the successful dives of the *Nereus* vehicle to the bottom of the Mariana Trench in 2009, the same vehicle was recently interfaced to a specially configured acoustic and optical communications system. A series of field demonstrations were then conducted offshore, including highly interactive and complex manipulations. We report here on the underlying technology employed and the results of those trials. We refer to this combination of technologies under the name Nereid.

II. ENABLING TECHNOLOGIES

A. Nereus

The hybrid ROV (HROV) *Nereus* is the first cost-effective technology for regular and systematic access to the world's oceans to 11,000 meters [1,2]. The vehicle is able to operate untethered as a fully autonomous vehicle, and also as a self-powered ROV employing a 245 micrometer diameter expendable optical fiber tether for real-time telemetry of data

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and video to its human operators on a surface ship. The optical tether is managed via a unique deployment system that allows vehicle ranges up to 30 kilometers from the support ship. While operating untethered, the vehicle acts as an AUV, suitable for a range of autonomous missions. While connected to the surface with its lightweight fiber optic tether, high-bandwidth two-way communications permit the return of high quality video and sensor data, enabling close-up inspection, sampling, and instrument deployment/recovery operations to be conducted under the command of pilots and scientists. The vehicle can be converted from AUV to Hybrid-ROV at sea, enhancing science mission capabilities on any single cruise. Further, the *Nereus* vehicle system can operate from modest surface support vessels with no need for dynamic positioning. The vehicle builds on the success of WHOI's Jason ROV and ABE/Sentry AUV teams.

B. Optical Communications

High speed optical communications is seen as a "game changing," or disruptive technology for the underwater communications world. The ocean is essentially opaque to electromagnetic radiation except over the visible light range, and hence the best alternative to acoustics lies with optical technology where high data rates (10-20 Mbit/s or more) are achievable over ranges in excess of 100 m. Optical communications (Ocomms) enables applications ranging from data harvesting from seafloor nodes to the wireless control of vehicles, as described in this paper, and is important to the scientific community, defense, and the oil and gas industry.

The optical link used for this trial (Fig. 1) achieved data rates >10 Mbps by using 450nm light to transmit data. The e-folding scale (i.e., the distance over which light intensity decreases by 1/e ~ 0.37) in the blue-green band (400 to 500 nanometers) is ~20 to 50 meters in clear ocean water. Communication can be carried out over ranges of ten or more e-folding scales (at these data rates), thus the working range of underwater optical modems is on the order of 100 to 200 meters [5]. The energy required for optical data transmission is much less than acoustics (Table 1) when considered on a bits per Joule basis, which translates into modest battery usage for large data transfers.

Telemetry Method	Range	Data Rate	Efficiency
Acoustic	Several km	1 kbps	*100 bits/Joule*
Optical	150 meters	10 Mbps	*300,000 bits/Joule*

Table 1, Performance comparison of acoustic and optical telemetry.

The system used for this test consisted of a one way (simplex) optical link from the vehicle to a lowered communications node and a bidirectional (half-duplex), low-latency acoustic link from the lowered node to the vehicle designed specifically for these trials. The optical link provided the necessary bandwidth to transmit a video channel along with 1 Hz high quality still images and essential vehicle status to operators on the surface. Joystick, manipulator, and other commands from operators were delivered to the vehicle using the low-latency acoustic link.

Fig. 1. Long range omnidirectional optical modem with remote emitter.

C. Low-Latency, Short-Range Acoustic Communications

Acoustic modems as typically employed on AUVs are optimized for maximum throughput over long distances. Acoustic travel times from vehicle to the receiver may be up to several seconds, and packet lengths of several seconds are typical. The associated latency is both unavoidable and usually irrelevant for low-rate data transfer and mission status monitoring, whereas such latencies would be intolerable for direct piloting of a vehicle.

In order to reduce acoustic latency to tolerable level for direct pilot control, we worked with acoustic modem developers both at WHOI and Sonardyne, creating custom packet protocols that achieved latencies of ~0.9 seconds for messages up to 30 bytes long. Each packet consisted of an acoustic transmission of approximately 0.8 seconds in duration. Transmissions were sent every 0.9 to 1.2 seconds when directly piloting the vehicle over this link. Because of the high repetition rate, acoustic response from the vehicle was not possible in this mode and all communication from the vehicle was sent over the optical link.

Both WHOI and Sonardyne modems were evaluated during this cruise. Unknown during the cruise, the WHOI modem experienced a connector failure that produced intermittent operation. After the first dive, the Sonardyne modem was used for all subsequent dives. As expected, transmission of the low latency link affected the ability of the shipboard USBL system to track the vehicle. Over the course of several dives, acoustic transmission levels, packet repetition and USBL interrogation rates were adjusted to balance manipulator control responsiveness and vehicle positioning information.

D. Adaptive Control

Hybrid systems present new challenges in the realm of vehicle control and operator interaction that are intimately coupled to the communications modalities employed. High throughput, low-latency links permit traditional teleoperation but either limit vehicle mobility as in the case of tradition high-strength tethering systems, or impose other constraints like limited range (the optical/acoustic system used during the trials reported here), or risk (the *Nereus* light fiber tether). Acoustic communications methods in general offer far lower throughput but span a much larger range of distances over which practical communication is possible. Acoustic communications systems introduce a further tradeoff in that throughput decreases as a function of range (40 km·kbps under ideal conditions [4]). Table 2 summarizes the state of proven underwater communications modalities available today (very short range systems are not included).

Method	Bit rate	Max range	mobility considerations
conventional tether	multiple Gbit/s	< 1 km horizontal, 6 km vertical	restricts maneuverability substantially.
lightweight fiber-optic tether	multiple Gbit/s	> 20 km horizontal or vertical	high maneuverability, some concerns for entanglement
acoustic comms	100-30 kbit/s; latencies 0.1-10 s	strongly linked to bandwidth and power. Typically several km	almost no restriction on maneuverability within usable range
through-water optical comms	1-10 Mbit/s	< 150 m	Almost no restriction within usable range

Table 2 : State of the art in subsea telemetry.

High-throughput communications links like those available on traditional ROVs permit pilots to essentially control every aspect of vehicle operations, from basic vehicle safety management through to complex manipulation tasks. The integration of automatic control systems within the traditional ROV paradigm, in particular for automatic positioning and increasingly for interaction with instrumented infrastructure, has begun to blur the distinction between purely teleoperated systems and purely autonomous systems. At the other end of the spectrum, operators of nominally autonomous vehicles, high-speed survey AUVs in particular, have increasingly leveraged the availability of long-range acoustic communications to monitor vehicle behavior, preview data, and even adjust missions in response [3].

The Neried concept represents a new class of vehicle that leverages both trends, but requires more sophisticated communications management and control than is necessary for vehicles that communicate with their operators through a single modality with a fixed throughput, range and latency. The *Nereus* system in its original embodiment included the necessary infrastructure - subsea computing, acoustic and fiber-optic communications, and a control system that could fly the vehicle completely automously as an AUV, or operate as a teleoperated ROV. Prior to the demonstration reported here, however, the only high-level autonomous action carried out by the control system with *Nereus* configured as an ROV was to manage vehicle ascent at the conclusion of a mission. (Operators sever the tether at the conclusion of *Nereus* ROV-mode dives.) The principal enhancement introduced during the trials we report here is the fluid use of both AUV and ROV control methodologies and of multiple communications modalities simultaneously during individual dives.

To coordinate the positioning of the vehicle and ship prior to establishment of the optical link we relied primarily on capabilities integrated over the several years of operational use of the *Nereus* system in AUV configuration, in particular:

- the ability to reprogram missions on-the-fly using acoustics (or any available) communications modality;
- the availability of standard AUV behaviors like bottom-following and flying tracklines on a vehicle otherwise configured as an ROV; and
- software hooks for overriding automatic control upon command from a pilot's joystick.

Relatively minor changes at the behavioral level were necessary to provide for safeguards in the event of loss of regular updates from the pilot's joystick or manipulator master when within optical communications range, and to permit mission modification at a finer granularity than typically employed for AUV operations.

Once in optical range, the asymmetric throughput and latency of the near-field optical/acoustic link required more extensive changes to the control system in order to permit the pilot to fly the vehicle as an ROV and to perform manipulation tasks. We pared down the commands necessary to perform these tasks to a bare minimum and developed compact message types for transmission and reception by software daemons topside and subsea that translated their contents into existing or new message types conforming to the standard already employed on the vehicle. Each acoustic command and control packet, 240 bits long, and delivered at roughly 1 Hz, carried joystick position, manipulator master position, and an optional command from a small lexicon necessary to, for example, turn on lights or modify the state of the hydraulic system.

In preparation for this demonstration, several modifications were made to *Nereus* manipulator system. Normally this system requires symmetrical bandwidth of 100 kb/s with end-to-end latency less than 10 ms; however, the commands sent subsea consist of only joint position commands and various parameter settings, the feedback loop being closed subsea, thus imposing no stability concerns. The master control console was reconfigured, eliminating unnecessary and redundant data, and a subsea software deamon developed to emulate the usual high-bandwidth connection with the manufacturers topside console.

For the pilot, handling the latency of the system was most challenging during manipulation tasks, as expected, based on laboratory trials we conducted ahead of the cruise (Fig. 2). The laboratory work proved invaluable as it illustrated the need to smooth the trajectory of the slave manipulator between the joint-postion commands received acoustically. The smoothing algorithm automatically adjusted its acceleration limit proportional to the realized command update rate, so that the subsea arm followed the commanded trajectory as quickly as possible without introducing oscillation or shock during rapid movement.

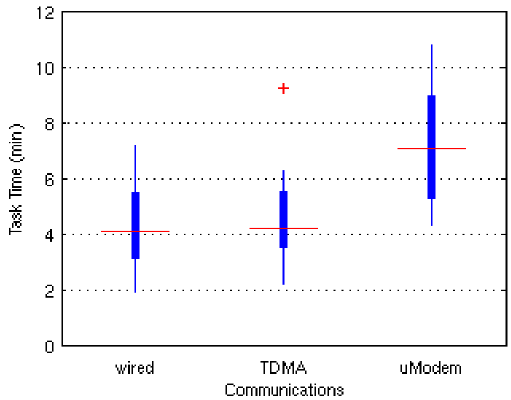

Fig. 2. We performed a series of laboratory experiments ahead of the cruise to verify that useful manipulation work was possible given the expected latencies and throughput restrictions of the system. Four experienced ROV pilots performed a series of 3 archetypal manipulation tasks under various simulated communications modalities. The standard for comparison is the “wired” category. In this mode, the manipulator is connected to its operator via a full bandwidth physical connection. In the TDMA configuration, a delay expected of a bi-directional (half-duplex) optical link was introduced and a series of benchmark tasks performed by several qualified operators. For the trails undertaken from *Alucia*, we were constrained to a uni-directional optical modem, with uplink via optics and command downlink via specially modified acoustics. As expected, the latencies associated with the acoustics did impact the speed with which operators could perform manipulations. Testing did confirm however, that useful work could be performed with such a link.

From a control-system perspective, the demonstration reported here represents only the first steps toward a system more aware of the communications modalities available to it, able to monitor their real-time performance, and capable of informing operators of the range of capabilities the current configuration enables. Half-duplex TDMA optical communications will eliminate the need for the low-latency acoustic downlink we employed for piloted flight and manipulation with its attendant restrictions on throughput and high latency, but will not obviate the need for a control system capable of executing higher-level actions semi-autonomously, especially over longer-range acoustic channels, as well as capable of handling rapid and unexpected changes in available communications modalities (dropouts).

III. Demonstration System

The purpose of the project was to demonstrate the viability and readiness of the Nereid concept to perform as a hybrid-tethered ROV, capable of performing complex, highly interactive work under direct, real-time human operator control. To achieve this objective, we brought a suite of technology together into a system intended to demonstrate the concept. Key to this was adapting the *Nereus* vehicle by adding the communications infrastructure as illustrated in Fig. 3.

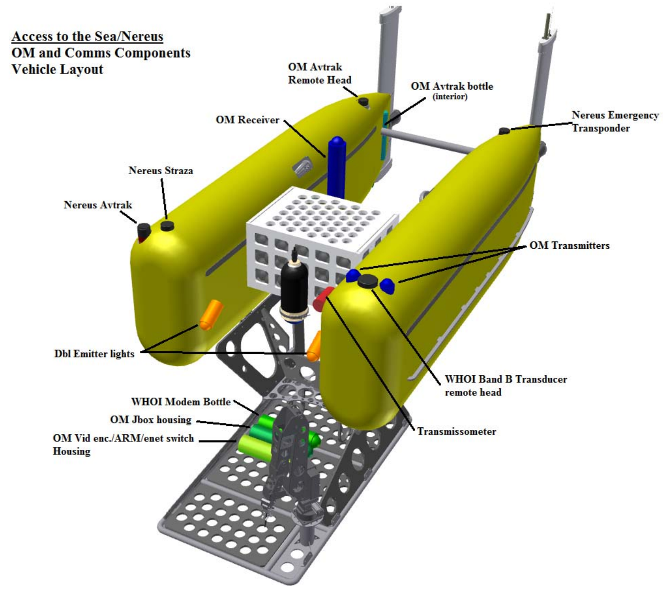

Fig. 3. The *Nereus* vehicle was modified with several key components as illustrated here. Addition of the low-latency acoustics and optical modems were the main additions. To enable the required manipulations, the standard *Nereus* sampling and manipulation tool-sled was added, including a seven-function master-slave manipulator.

In addition to the installation of the required communications systems and modification to the *Nereus* control software, a small winch and communications depressor were configured for this work. The winch and cable chosen were based on a typical winch used for conductivity, depth and temperature (CTD) measurements utilizing a 8mm (.322 inch) diameter electro-optical cable. Terminated to this cable was a modest communication depressor consisting of the components related to the navigation and communication task The overall signal pathways are illustrated in Fig. 4.

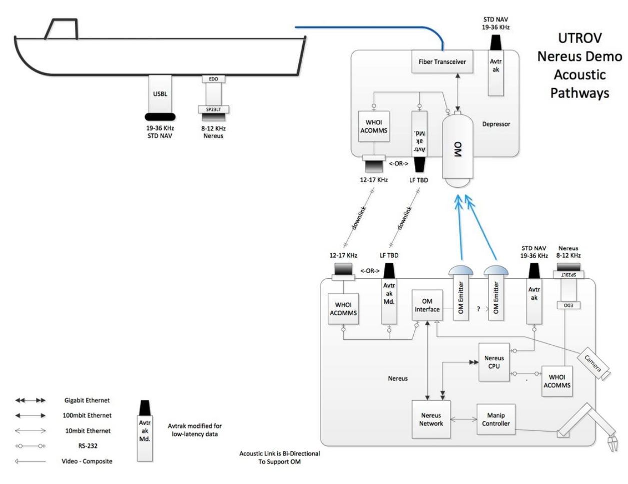

Fig. 4. The initial demonstration of the Nereid vehicle concept involved a combination of acoustic and optical communications to allow real-time control of the *Nereus* vehicle and its manipulator. The optical modem provided uplink of video and vehicle state information. Downlink

control of the vehicle and its 7-function master-slave manipulator was enabled with a specialized low-latency acoustic link. During times when *Nereus* vehicle was not within optical communications range, high-level control was provided through use of low frequency acoustic telemetry only. Navigation and control of the vehicle was enabled with use of the Sonardyne Ranger 2 and the vehicle's onboard Doppler velocity log, other sensors integrated into WHOI's vehicle control software.

IV. Field Trial

A. Logistics

The field demonstration was possible because of internal WHOI funding made available by its Access to the Sea Fund. This funding not only supported the engineering and preparations but also included a vessel capable of supporting the planned work. The motor vessel *Alucia* (Fig. 5) is the former French research vessel *Nadir* which has been refit into an expeditionary yacht while maintaining many of its research vessel attributes. In this case, the ship was standing by in Guam and available for five days at sea to support the trails. Once the equipment had been assembled and tested at WHOI, it was shipped to Guam via conventional ocean freight on a single 40 foot "flat rack". Following 3 days of mobilization for the vehicle, winch and navigation system, *Alucia* was ready to begin the field trials

Fig. 5. The M/V *Alucia* is 183 ft. with a gross tonnage of 1396 tons and outfit as an expeditionary yacht, capable of oceanographic research. In this case, the *Nereus* system was mobilized onboard. The vessel possesses twin screws and a bow thruster, but is not equipped with dynamic positioning.

With 5 days of ship time available in September 2012, transits were kept to a minimum and the tests conducted within the surrounding waters of Guam in water depths ranging from 30 meters in the early stages to depths as great as 1,700 meters.

B. Dive Summaries

With only 5 valuable dive days available to us, it was critical that all the systems arrived, tested and ready for sea. After the initial loading mobilization, *Alucia* adjourned to the outer Apra harbor where a set of handling system and functional tests were completed. As part of these initial tests, we also completed a communication trial with the opto-acoustic link to confirm the adequacy of the link for direct pilot control over *Nereus*.

With this initial testing of the WHOI equipment complete, our focus turned to evaluating the maneuvering capabilities of the *Alucia* and its ability to hold station to within the 100 m maximum range of the opto-acoustic communications system. To test the ship and navigation/tracking interactions, an acoustic transponder was deployed and tracked using the Sonardyne USBL system installed during the mobilization. Once the calibrations of the USBL tracking system were complete, the *Alucia's* pilots demonstrated their ability to hold the opto-acoustic communications depressor over the acoustic transponder on the seafloor at a depth of approximately 1000 m, and generally to within 50 m.

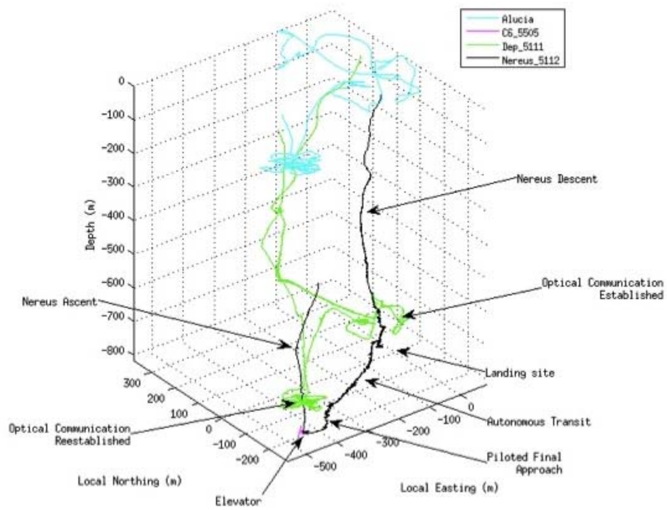

Fig. 6. The final dive of the trials was the most complex of the series. With an elevator configured as a test article already on the bottom, *Nereus* was deployed, reaching the bottom approximately 400 meters from the elevator. Through the acoustic communications link, *Nereus* was commanded to autonomously move toward the elevator. While this move was underway, *Alucia* maneuvered the communication depressor to a location over the test elevator to await the arrival of *Nereus*. As the vehicle approached to a range of approximate 100 meters, optical communications was established. The pilot onboard *Alucia* then manually maneuvered the vehicle into position at the elevator, where a series of manipulations were performed.

The team headed to deeper water to deploy *Nereus* offshore of Anai Island where the depth is approximately 1700m. Despite achieving successful transmission of video from *Nereus* to the ship via the optical modem, the dive was plagued by several difficulties principally caused by a failing hard disk on *Nereus's* control computer. As a result, the mission was aborted and the disabled vehicle recovered for troubleshooting. With the hard disk replaced, *Alucia* moved to the Northwest of the island where *Nereus* was again deployed. Over the next three days a series of increasingly ambitious dives were undertaken to explore the capabilities and performance of the wireless ROV control system. Fig. 6 shows the final dive of the series, where all modes of control were exhibited. As an important part of these dives, *Nereus* was able to perform complex, real-time manipulations under the control of a human operator. During these manipulations, the ability to take scientific samples and perform some complex tasks such as mating a de-mating an underwater electrical connector were demonstrated (Fig. 7).

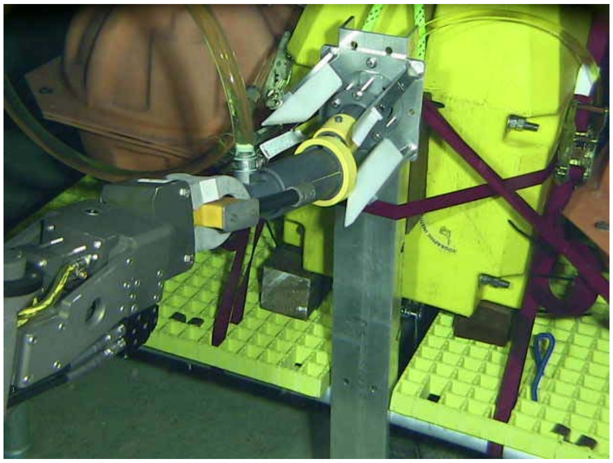

Fig. 7. For the Nereus trials, a test article was placed on the seafloor. Its primary purpose was to provide a target to enable various activities. In the still frame the vehicle is making a wet-mate electrical connection.

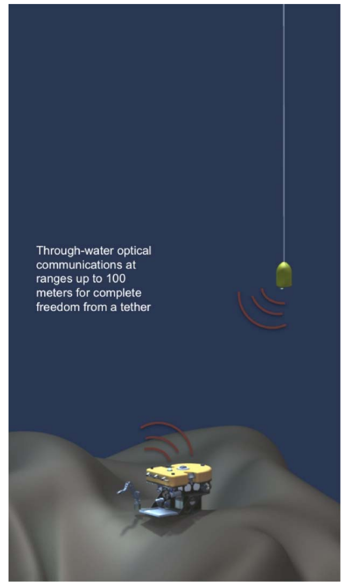

Fig. 7. WHOI is presently building a Nereid vehicle based on the test presented in this paper. The vehicle will have several modes of communications, including real-time video and control utilizing a newly developed bi-directional optical modem.

V. CONCLUSIONS

Our trials with the *Nereus* vehicle in demonstrate that a perfect storm of opportunity exists to bring a new vehicle type into reality now. Although such semi-autonomous systems have been imagined for some time, it is only now that a combination of factors align to enable capabilities that result in new, efficient subsea vehicle operations. Our results demonstrate the viability and readiness of the technology to support such new hybrid systems with scaled autonomy appropriate to the task, even allowing human operators to perform complex tasks based on tetherless hybrid control and communication paradigms. WHOI is now developing a more suitable intervention vehicle based on the Nereid technology concept as illustrated in Fig. 7. This vehicle will be rated for light work to 2,500 meters and be in trials before the end of 2013.

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