Proof of Concept Demonstration of the Hybrid Remotely Operated Vehicle (HROV) Light Fiber Tether System

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***Abstract*- The Hybrid Remotely Operated Vehicle (HROV) *Nereus*, developed by the Woods Hole Oceanographic Institution (WHOI) with the support of the Space and Naval Warfare Systems Center San Diego (SSC San Diego) and the Johns Hopkins University, is intended to provide a new level of access for deep oceanographic research to a maximum depth of 11,000 meters. *Nereus* operates in two different modes. The vehicle can operate untethered as an autonomous underwater vehicle (AUV) for broad area survey, capable of exploring and mapping the seafloor with sonars, cameras, and other on-board sensors. *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 to the surface for high bandwidth real-time video and data telemetry to the surface to enable high-quality teleoperation, additional cameras and lights, a manipulator arm, and sampling gear. Development of the fiber tether system was supported by both simulation and extensive field testing over a three year period. These tests demonstrated that an unprotected optical fiber could survive in the water column for greater than 24 hours and be effectively used as a high bandwidth data link by a remotely-operated, self-powered vehicle. Based on the data from the fiber trials, a robust tether deployment system was designed. The tether deployment system was integrated with the vehicle and demonstrated during field trials in November 2007.**

I. INTRODUCTION

A. Overview

The goal of the Nereus vehicle project is to provide the U.S. oceanographic community with the first capable and cost-effective technology for regular and systematic access to the world's oceans to depths of 11,000 meters. The vehicle will be able to operate both untethered as a fully autonomous vehicle and also as a self-powered remotely operated vehicle employing a small diameter optical fiber tether for real-time telemetry of data. This new class of vehicle is termed a Hybrid Remotely Operated Vehicle (HROV) and is shown in Figure 1.

Nereus was developed by Woods Hole Oceanographic Institution (WHOI), with support from the National Science Foundation (NSF), the National Oceanographic and Atmospheric Administration (NOAA), the Woods Hole Oceanographic Institution (WHOI) and the Russell Family Foundation. In addition, the Space and Naval Warfare Systems Center San Diego (SSC San Diego) developed the fiber optic tether for the system, with support from the Office of Naval Research (ONR).

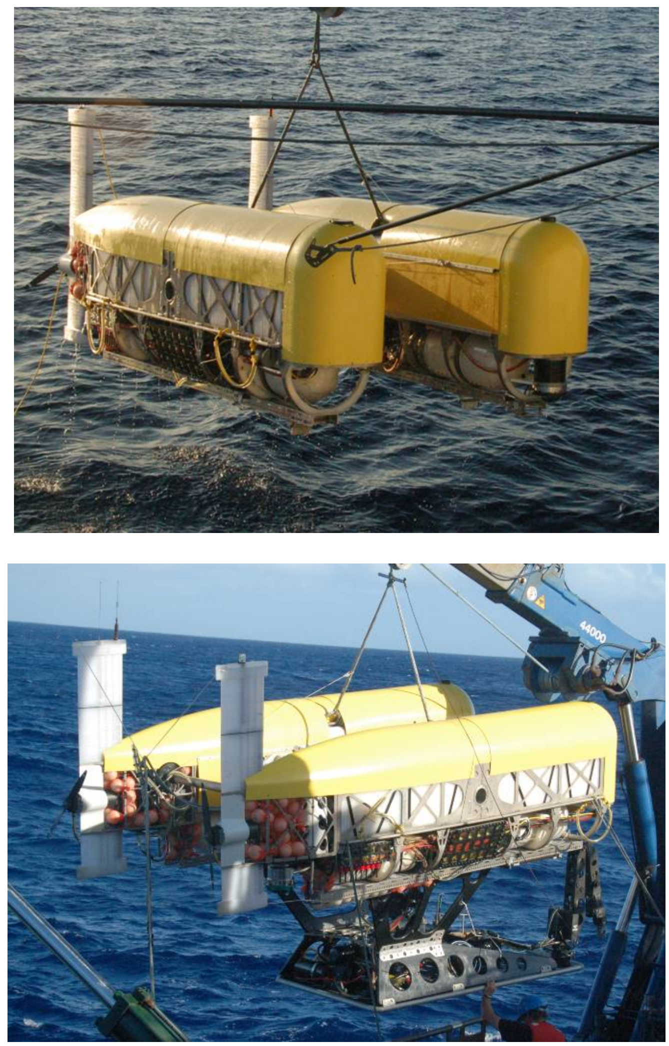

Figure 1: HROV in AUV mode (top) and ROV mode (bottom)

B. Light Fiber Tether

A key part of the HROV system is the light weight fiber optic tether used when operating in the ROV mode. Because HROV is a light weight battery powered system, it is limited in its available energy and payload, so a lightweight cable is essential. The fiber optic tether transmits high bandwidth data only, not power. In order to meet the vehicle requirements, an expendable tether system similar to that used in expendable bathythermographs and torpedoes was developed. With the HROV system, tether is deployed at low tension from both the vehicle and the launch platform. As the vehicle moves through the water, the tether is laid from the vehicle, avoiding any dragging of the tether through the water. This decreases the energy load on the vehicle and the strength requirements for the tether; hence its size and weight can be minimized.

The preliminary design analysis of this cable for deep-ocean deployments is reported in [3]. Two cable designs were selected as candidates for the HROV system: Fiber Optic Microcable (FOMC) and the Sanmina/SCI buffered fiber. Both cables were pressure tested to 16,000 psi (36,000 fsw equivalent) and monitored for attenuation effects. Characteristics of these cables are described in Table 1. After extensive simulation using the WHOICABLE program [1,2], the Sanmina/SCI tether was selected as the primary choice for the HROV system.

Table 1: Fiber Characteristics

	FOMC	**Sanmina / SCI Fiber**
Diameter (mm)	0.8	0.25
SG (fresh water)	1.74	1.36
Weight of 11 km in water (kg)	4.23	0.173
Working Strength (N)	133	8
Breaking Strength (N)	400	108
Relative Survivability on Seafloor	Good	Poor

C. Tether Deployment System

The basic concept of the deployment system involves the use of a snag resistant depressor and vehicle float pack to house the tether system as shown in Figure 2. 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 float pack is attached to the vehicle via a 20 meter ruggedized cable and contains the optical fiber dispenser, brake, fiber counter and cutter. It floats above the vehicle and is designed to minimize drag and the chance of snagging the fiber on either the vehicle or sea floor. The depressor and the float pack are mated together during launch, protecting the fiber during the transition through the air-water interface. The depressor-float pack and the vehicle descend together to a designated depth. Once an appropriate depth has been reached, the vehicle and float pack separate from the depressor. As the vehicle and float pack descend, optical fiber pays out both from it and from the depressor. The complete operational sequence is shown in Figure 3.

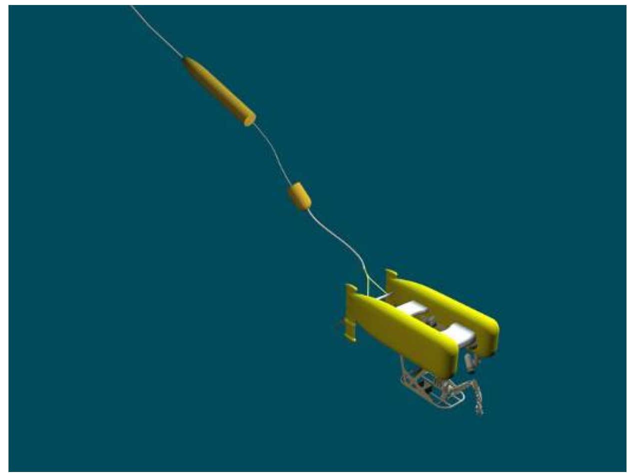

Figure 2: Nereus showing the separation of the float pack from the depressor

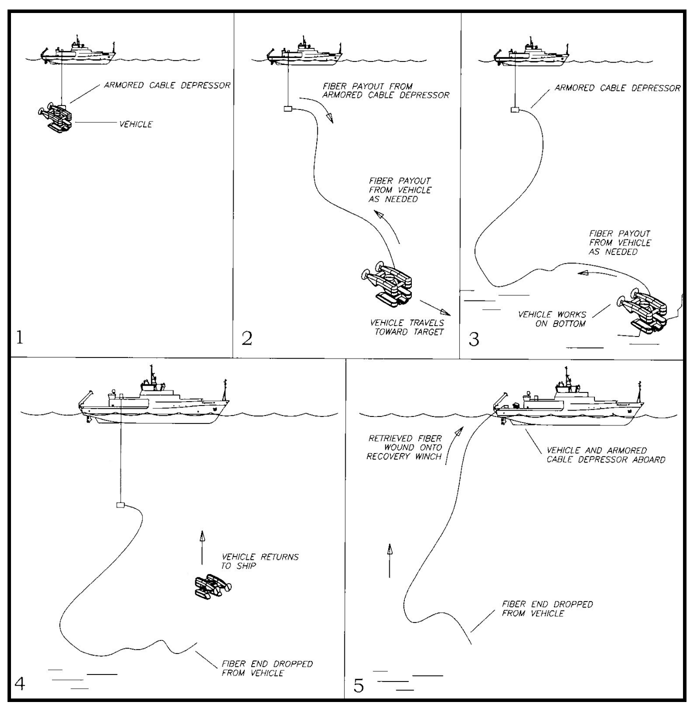

Figure 3: Operational sequence of ROV mode

II. FIELD TESTING

To date, three major field tests have been performed in support of the HROV fiber link design, which are summarized below and were described in detail in reference [5].

A. Elevator Test: November 2004

The primary objective of the November 2004 testing was to verify the concept and numerical simulations of passive payout of a fiber optic data link in deep water in a typical current environment. The test hardware consisted of two main components: a shipboard package and package mounted at the top of an oceanographic elevator test fixture. The shipboard package consisted of a cable pack and a flex hose depressor assembly to deploy the cable clear of the bottom of the ship. The cable from the shipboard cable pack was connected to a cable deploying from a cable pack mounted on the elevator package as shown in Figure 4. The elevator package was allowed to free-fall to the sea floor measuring and recording depth and current on the way. Together these systems deployed a continuous fiber optic cable link as the elevator package descended to the sea floor and as the ship drifted with the wind and current. Continuity of the fiber optic link and the amount of cable paid out was monitored from the surface via an optical time domain reflectometer (OTDR).

Figure 4: Elevator showing fiber pack at top

For the first deployment, the elevator was configured with the FOMC. The cable was monitored continuously through the descent phase of approximately 1 hour, and for 3 hours after reaching the seafloor. There was no significant change in the optical performance of the link over that period. For the second deployment, the elevator was reconfigured with the buffered fiber. The fiber maintained optical continuity through the descent and for 2.75 hours on the bottom, when a break occurred 143 m from the shipboard pack, 105 m from the end of the flex-hose depressor assembly. It appeared that the break was caused by excessive tension caused by contamination within the flex-hose through which the fiber passed. Subsequent design efforts focused on maintaining a constant tension on the tether and elimination of the flex hose. With these design modifications, the buffered fiber was seen as sufficiently rugged to be considered the primary choice for use on the HROV system.

B. Vehicle Test: December 2005

The key objective of the December 2005 tests was demonstration of the vehicle fiber optic tether as would be used in HROV operations. These tests were done using the ABE vehicle [4] as a surrogate for the HROV. The fiber system was installed on the vehicle as shown in Figure 5. Installation hardware included the cable pack mounting within the vehicle, a pressure compensated optical-junction, and a mast to permit cable payout away from the propellers. The topside equipment included a cable pack, flex hose to guide the cable through the air-water interface, and connection to the ABE computer.

Figure 5: ABE Vehicle showing cable spool at bottom left and mast

At-sea tests were performed with the Sanmina/SCI fiber optic link for HROV in December 2005. Five dives were made in the San Clemente Basin, each to a depth of about 2000 meters. The longest dive was nearly 17 hours and the shortest of 43 minutes. Many lessons were learned that affected the subsequent deployment system development. The key areas identified related to accurate control of fiber tension payout and maneuvering of the vehicle once on the sea floor. These lessons were incorporated into a deployment system design that was constructed and tested in May 2006.

C. Deployment System Test: May 2006

The main objective of the May 2006 tests was demonstration of the prototype deployment system that would be used in actual HROV operations. The deployment system consisted of a long, snag-resistant depressor (Figure 6) and a float pack attached to the vehicle. The depressor and the float pack were mated and lowered to a pre-determined depth below the active water layer by a standard oceanographic winch. At a predetermined depth, the depressor is stopped and the vehicle and float pack released to continue the dive. Both the float pack and the depressor were outfitted with fiber canisters containing 20 kilometers of the Sanmina/SCI buffered fiber. A deep water elevator similar to that used in the November 2004 tests was used as a developmental surrogate for the HROV. The depressor was designed for deployment using a fiber optic conductivity/temperature/depth (CTD) wire and CTD winch.

Figure 6: Snag resistant depressor with fairing.

Four deployments of the system were made to 4000 m during this test period, with one deployment in excess of 18 hours and another close to 12 hours. Over 10,000 meters of cable was deployed during the long deployment, and it was purposely cut to conclude the test. The objectives for the HROV Deployment System Test were met, demonstrating the feasibility and utility of the deployment concept.

III. PROOF OF CONCEPT DEMONSTRATION

The cable deployment system was integrated with the Nereus vehicle in fall 2007. Initial sea trials were conducted near Hawaii in November 2007. Operational procedures for launch and recovery were developed and tested. Four dives were made in the ROV configuration using the fiber, culminating in a 4.5 hour dive to 2257 meters. During all ROV dives, the fiber remained intact until purposely cut during operations.

A. Deployment System Operation

The fiber deployment system consists of the depressor and the float pack, each containing a fiber canister. In preparation for launch, the optical fibers in the float pack and in the depressor are connected by fusion splicing. The float pack is secured to the depressor with the adjustable–tension latch. The vehicle is attached to the depressor/float pack assembly via a 20 m long reinforced cable. Signal continuity through the vehicle system is confirmed prior to deployment.

The depressor with attached float pack is then deployed, using the ship's A frame, Figure 7. The vehicle is then deployed, and allowed to sink with its descent weights. The descent rates of the vehicle and the depressor are monitored through the fiber link and the descent of the two components are synchronized. At a predetermined depth, the lowering of the depressor is stopped and the latch is opened, releasing the float pack to follow the vehicle. The vehicle continues its descent, with fiber primarily paying out from the float pack. Fiber pays out from the depressor pack to accomodate any ship motion or heave of the depressor.

The vehicle performs its mission, operating on the optical fiber for the bi-directional transmission of telemetry. Upon completion of the mission, the optical fiber is cut at the vehicle and clamped at the depressor. The vehicle is then commanded to drop its weights and return to the surface. The depressor is then recovered, and the fiber is recovered using the fiber recovery winch. The vehicle, with the attached float pack, is recovered using the ship's crane once it returns to the surface.

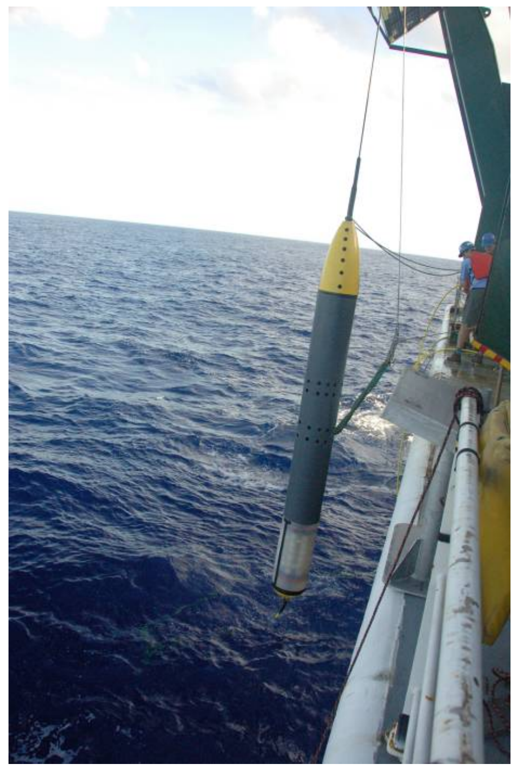

Figure 7: Deployment of the Depressor showing attached float pack at bottom

B. Tests Run

During the November 2007 sea tests, the vehicle was configured as an ROV by adding the work package and float pack. Over three days, a series of four ROV dives of increasing depth and duration were performed. These are summarized in Table 3.

The first deployment demonstrated ROV operation to 398 meters. This was a full system operation, including bottom time with operation of the manipulator and sampling tools. The fiber was not cut at depth, but rather allowed to remain intact through ascent of the vehicle. It was used to control the vehicle at the surface, and it was cut for recovery of the system.

During the second deployment, the float pack separated prematurely from the depressor at the surface due to wave induced loads at the air/water interface. As the fiber remained intact, the decision was made to continue the dive. The vehicle and depressor were lowered to 400 m, at which point the vehicle aborted the dive due to a software error. Communication through the fiber was maintained throughout the vehicle ascent, further demonstrating the ruggedness of the fiber, even in the surface waters.

The third dive was a straightforward deployment with over three hours of vehicle operation at 569 meters. The fiber was left intact during the vehicle ascent, and it was cut when the vehicle was on the surface.

The fourth dive demonstrated a wide range of HROV capabilities. Diving to 2270 meters, the vehicle demonstrated the capabilities of an ROV including effective power-efficient lighting, high bandwidth video telemetry, and robust manipulation and sampling capability. In addition, a long horizontal transit and ladder pattern were executed, effectively demonstrating extreme horizontal mobility independent of the surface vessel. Nereus ended the dive separated from the support ship by 1.5 km horizontally. A standard recovery was performed, cutting the fiber at the vehicle and clamping it on the depressor weight. Once Nereus dropped ascent weights and cut its tether, the ship steamed to the expected rendezvous location to meet the autonomously ascending ROV.

Each of these four dives demonstrated the benefits of the fiber optic tether, showing unexpected ruggedness of the light fiber.

Table 3: Nereus ROV Dives

Dive	**NER002**	**NER003**	**NER004**	**NER005**
Date	23 Nov	24 Nov	24 Nov	25 Nov
Depth (m) Depressor / vehicle	100/398	400 / 400	290 / 569	1000 / 2270
Time fiber deployed (h:m)	3:24	0:25	3:33	4:40
Distance Covered (m)	1751	0	2236	2250
Depressor fiber deployed (m)	422	1177	743	1138
Float pack fiber deployed (m)	556	191	679	1214

C. *Lessons Learned*

The deployment system performed well, demonstrating the utility of the depressor / float pack concept. This has the potential to redefine how a ROV can be tethered to a support vessel, and it is reflected in current patent applications. During the testing, several opportunities were identified for improvement in the fiber deployment system and operation.

Premature separation of the depressor and float pack occurred twice during deployment as the system first made contact with the water. Upon inspection it was determined that the coupling was seeing a significant amount of torque which triggered the premature separation. Improvements in the coupling geometry and materials will reduce the risk of early separation.

When the fiber is cut for recovery of the vehicle, it is clamped at the depressor. During dive four, this was done, but there was still significant payout from the depressor after cutting. The clamp needs to be adjusted to minimize the amount of fiber expended during the recovery process.

Finally, the cut and clamp procedure is intended to allow the recovery of the fiber. While there was a prototype fiber recovery winch used during the trials, very little fiber was actually recovered. Successful fiber recovery will require additional engineering on the winch system, as well as development of ship handling procedures to minimize the stress on the fiber.

IV. SUMMARY

The Hybrid Remotely Operated Vehicle (HROV) Nereus, developed by the Woods Hole Oceanographic Institution (WHOI) with the support of the Space and Naval Warfare Systems Center San Diego (SSC San Diego) and the Johns Hopkins University, is intended to provide a new level of access for deep oceanographic research up to a maximum depth of 11,000 meters. A series of field tests over the past 4 years has demonstrated the feasibility and utility of using a buffered optical fiber link for real-time command and control of the vehicle in ROV mode. The result has been a robust tether management system which is suitable for use on a light ROV operating at a depth of up to 11 km. Initial sea trials were conducted near Hawaii in November 2007. Four dives were made in the ROV configuration using the fiber, culminating in a 4.5 hour dive to 2270 meters. During all ROV dives, the fiber remained intact until purposely cut during operations. After additional at-sea testing, dives are planned in the Marianna Trench in the future.

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