Field Tests of the Hybrid Remotely Operated Vehicle (HROV) Light Fiber Optic Tether

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Abstract-* The Hybrid Remotely Operated Vehicle (HROV), being designed and built by Woods Hole Oceanographic Institution (WHOI) with the support of the Space and Naval Warfare Systems Center San Diego (SSC San Diego), will provide a new level of accessibility for deep ocean research. HROV will be primarily an autonomous vehicle but will be reconfigurable to a teleoperated system by the installation of a fiber optic data link and a manipulator based work system. Development of the fiber optic link has been supported by both simulation and a series of field tests over the past 3 years. The November 2004 tests consisted of deploying two different types of fiber optic cable from an oceanographic elevator deployed from a ship to 2000m depth. Data collected from this test demonstrated the feasibility of using both the Fiber Optic Microcable (FOMC) and plain buffered optical fiber as a tether for the HROV. The December 2005 tests demonstrated the utility of the buffered optical fiber operating on an underwater vehicle using the WHOI ABE vehicle as a substitute for the future HROV. Five dives were made to 2000 m with real-time communication from the vehicle to the surface via the fiber. The May 2006 tests focused on the employment of a cable depressor and deployment system. Using a deep elevator as a substitute for HROV, the fiber was deployed from both the depressor and the elevator to a depth of 4200 m. Over the course of 4 deployments, over 16 km of fiber was deployed, operating for a total of 33 hours, demonstrating the feasibility of the planned approach.

I. Introduction

A. Objective

Our goal 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 vehicle employing a small diameter optical fiber tether for real-time telemetry of data as shown in Figure 1. We term this new class of vehicle a Hybrid Remotely Operated Vehicle (HROV).

HROV is being designed by Woods Hole Oceanographic Institution (WHOI), supported by the National Science Foundation (NSF) and the National Oceanographic and Atmospheric Administration (NOAA). In addition, the Space and Naval Warfare Systems Center San Diego (SSC San Diego) is developing the fiber optic tether for the system, supported by the Office of Naval Research (ONR).

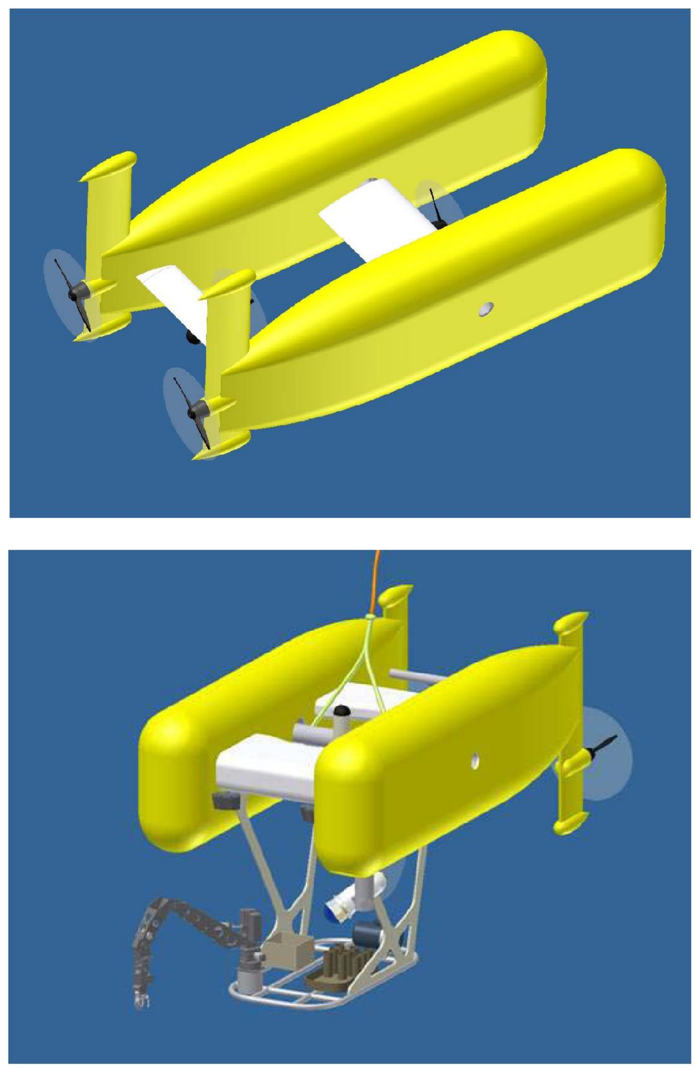

Figure 1: HROV in the autonomous and remotely operated configurations

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B. *Fiber Optic Cable Selection*

To date, light fiber optic tethers have principally been employed in military applications; relatively few light fiber tether systems have been used for oceanographic research. One example is the self-powered remotely operated vehicle UROV7K, which employs a fiber-optic tether [1,2]. This vehicle is designed to operate exclusively as a tethered ROV, and does not have on-board computational resources necessary to operate autonomously. A different application was the Theseus vehicle [3], in which an autonomous underwater vehicle deployed fiber optic communication cables on the arctic sea floor.

Because HROV is a light weight battery powered system it is limited in its available energy and weight. The function of the fiber optic tether is to transmit 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 chosen. With this system tether is deployed at low tension from both the vehicle and the support platform. As the vehicle moves through the water the tether is laid out behind it and is not dragged through the water by the vehicle. This decreases the energy load on the vehicle and the strength requirements for the tether; hence its size and weight are minimized. However, it does require the vehicle and support platform to carry large quantities of tether.

The fiber optic tether for the system must be able to be precision wound into deployment canisters in long lengths (20 km) in a manner that is light in weight, provides a uniform payout tension, and is pressure tolerant with respect to optical attenuation of the optical fiber. Cables that meet these requirements must have extremely tight dimensional uniformity and must meet a number of specialized requirements such as having a high bending stiffness relative to their diameter. Because the cable design is so closely married to the deployment canister design, we view the cable and deployment canister as two interrelated components of a system that cannot be evaluated separately.

A preliminary design analysis of this cable for deep-ocean deployments is reported in [4]. We eventually selected two cable designs: Fiber Optic Microcable (FOMC) [5] and the Sanmina/SCI buffered fiber. Both cables have been 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 [6, 7], 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 Payout System*

Most previous expendable tether systems have relied upon the inherent back tension provided by the cable dispenser to control tether payout. This tension is generally very uniform but it is only adjustable within very narrow limits. The nominal payout tension of the Sanmina/SCI fiber dispensers is between 12 and 45 grams.

In order to determine the optimum deployment tension, simulations were run for a variety of payout tensions, water depths, depressor depths, current profiles and mission profiles. At very low tensions two limiting problems were encountered: extremely long lengths of tether were deployed, and the tether tended to contact the seafloor after a few hours exposing it to what were considered unacceptable hazards. We found that by increasing the payout tension, we could conduct 30 hour missions with 20 km cable dispensers in the depressor and the vehicle under realistic environmental conditions and current profiles. This also delayed contact between the tether and the seafloor for many hours. Since it was not practical to modify the Sanmina/SCI dispensers to provide more tension we chose to incorporate a tension brake in the system.

II. FIELD TESTING

To date, three major field tests have been performed in support of the HROV fiber link design. The first, in November 2004, used an oceanographic elevator to deploy both the FOMC and the Sanmina/SCI tether to demonstrate the feasibility of using the fiber as a data link through the water column. The second, in December 2005, used the WHOI Autonomous Benthic Explorer (ABE) as a stand-in vehicle, demonstrating the feasibility of using the link on a mobile platform. The third, in May 2006, again used an elevator to evaluate the performance of the prototype HROV depressor system.

A. *Elevator Test: November 2004*

Description

The primary objective of the November 2004 testing was to verify the concept of passive payout of a fiber optic data link in deep water in a significant current environment. The test also collected data which was used to validate the simulation models. Among the parameters which were measured or verified are:

- Validation of concept
  - Continuity of fiber optic link versus depth
  - Cable coil attenuation at depth
  - Cable attenuation at depth and under tensile load
- Validation of WHOICABLE simulation
  - Cable expended from shipboard cable pack
  - Current profile depth
  - Simulated vehicle dispenser trajectory

The test hardware consisted of two main components; a shipboard package and an elevator package. 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 (Figure 2). 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. The positions of the elevator package and the ship were tracked as the elevator descended, allowing correlation of measured current velocities with elevator position. 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 2: Nov 04- Elevator showing fiber pack at top

Results

The results of the tests are summarized in Table 2. 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. The optical cable was monitored until after the elevator release, but the cable remained intact until it was purposely cut for recovery.

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. The hose was retrieved and the fiber end was recovered for analysis. The tension of the fiber in the flex hose was measured and found to be much higher than desired, and the broken end was analyzed to determine the failure mode. It appeared that the break was caused by excessive tension caused by contamination within the flex-hose. Subsequent design efforts focused on maintaining a constant tension on the tether, and elimination of the flex hose.

Table 2: Results of November 2004 Testing

Cable Deployed	Fiber Lifetime (H:M)	Deck Cable Deployed (meters)	Elevator Cable Deployed (meters)	Probable cause of failure
FOMC	5:33	484	5176	No failure
Sanmina/SCI buffered fiber	3:45	727	4942	Excessive tension

B. *Vehicle Test: December 2005*

Description

The key objective of the December 2005 tests was demonstration of the vehicle fiber optic tether as will be used in HROV operations. These tests were done using the ABE vehicle as a developmental surrogate for the HROV. These operations were conducted off of the Research Vessel *New Horizon*, which is operated out of San Diego by the Scripps Institution of Oceanography. Both the vehicle and the ship set were outfitted with fiber canisters, each containing 20 kilometers of buffered fiber, providing for a payout scheme similar to that used for the November 2004 tests.

This test required installation of several of the prototype buffered fiber tether system components required for both the vehicle and ship/depressor ends of the system. The test objectives were as follows:

1. Verification of buffered fiber deployment simulations in pertaining to vehicle maneuvers, water current profiles.
2. Improved understanding of the hardware installation and operational effectiveness of the buffered fiber payout system.
3. Confirm the potential of the HROV system to operate from a non-dynamically positioned support ship.
4. Development of an improved understanding of vehicle maneuvering constraints created by the buffered fiber tether.
5. Assist in final specification of the HROV fiber optic telemetry system

The fiber system was installed on the WHOI ABE vehicle for the December 2005 at-sea tests as shown in Figure 3. Installation hardware included the cable pack mounting at the base of 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 3: ABE Vehicle showing cable spool at bottom left and mast

Results

At-sea tests were performed with the Sanmina/SCI fiber optic link for HROV on 12-16 December 2005. Five dives were made in the San Clemente Basin off of San Clemente Island, each to a depth of about 2000 meters. Table 3 provides a summary of each dive, with the longest dive being nearly 17 hours and the shortest of 43 minutes. Figure 4 shows the acoustically navigated track line of the vehicle during its longest dive. Many lessons were learned that have affected the development program. The key areas identified relate to accurate control of fiber tension payout and maneuvering of the vehicle once on the sea floor.

Table 3: ABE Dive Summary

Dive Number	Fiber Lifetime (H:M)	Deck Cable Deployed (meters)	Vehicle Cable Deployed (meters)	Missions ended with failure of optical fiber Probable cause
1	**0:43**	**913**	**20**	**Fiber wrapped around vehicle**
2	**8:31**	**4177**	**771**	**Excessive tension from flex hose**
3	**1:38**	**1770**	**169**	**Excessive tension from flex hose**
4	**16:43**	**2370**	**4365**	**Fiber dragging on bottom**
5	**1:55**	**120**	**2315**	**Fiber wrapped around prop**

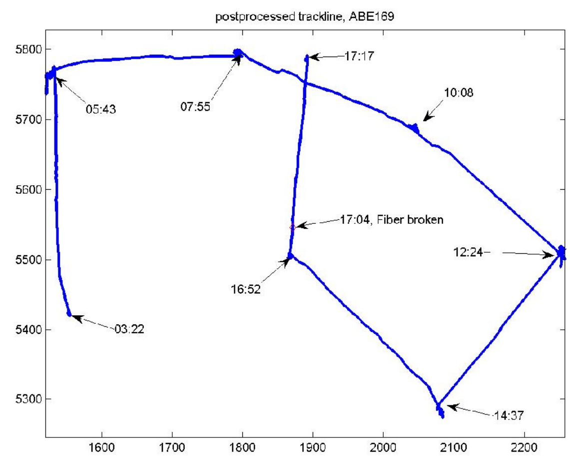

Figure 4: Path followed by ABE on Dive 4

C. Deployment System Test: May 2006

Description

The main objective of the May 2006 tests was demonstration of the prototype depressor and fiber optic deployment system that will be used in actual HROV operations. These operations were conducted off of the Research Vessel *Oceanus*, transiting between Charleston, SC and Woods Hole MA. These tests were done using a deep water elevator as a developmental surrogate for the HROV. The depressor was designed for deployment using a fiber optic CTD wire and CTD winch. Both the elevator pack and the depressor were outfitted with fiber canisters, each containing 20 kilometers of the Sanmina/SCI buffered fiber.

The basic concept of the deployment system involves the use of a snag resistant depressor and vehicle package to house the tether system as shown in Figure 5. 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. As the vehicle package descends, optical fiber pays out both from it and from the depressor.

Figure 5: Snag resistant depressor with fairing.

Results

Four full deployments of the system were made during this test period, and the results are summarized in Table 4. The objectives for the HROV Deployment System Test were clearly met:

1. The fundamental concept of using a snag resistant depressor to house the "shipboard" tether deployment system combined with a tether deploying vehicle package was demonstrated over 4 full system deployments, with repeatable and reliable results.

2. A launch and deployment scenario was developed for the coupled depressor and vehicle package. This scenario can be modified as required to accommodate the actual HROV system.

3. Fiber was deployed on 4 dives. The first dive ended prematurely due to a mechanical problem but on the remaining 3 dives fiber was deployed for a total of 33 hours 26 minutes with a total of 16.6 km of fiber in the water column. There were no optical fiber tether failures on the last 3 dives. This demonstrated the feasibility of our deployment system.

Table 4: Deployment System Test Summary

Deployment Number	Fiber Lifetime (H:M)	Depressor Cable Deployed (meters)	Vehicle Cable Deployed (meters)	Probable cause of failure
1	0:08	994	178	Flaw in fiber pack
2	18:26	3737	6157	No failure
3	11:49	2388	865	No failure (counter error)
4	3:41	695	2792	No failure

III. Summary

The Hybrid Remotely Operated Vehicle (HROV), being designed and built by Woods Hole Oceanographic Institution (WHOI) and Space and Naval Warfare Systems Center San Diego (SSC San Diego) will provide a new level of accessibility for deep ocean research. A progressive series of field tests over the past 2 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 11 km. Detailed HROV vehicle design, incorporating this tether system, is presently in progress. The overall fiber system will be integrated on the HROV next year. Testing of the full HROV fiber tether system will be performed in conjunction with the vehicle tests in 2007, culminating in a final system test in deep water in 2008.

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