The Hybrid Remotely Operated Vehicle (HROV): New Challenges and Opportunities

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ABSTRACT
The Hybrid Remotely Operated Vehicle (HROV), being designed and built by Woods Hole Oceanographic Institution (WHOI), will provide a new level of accessibility for deep ocean research. This battery-powered vehicle incorporates several new technologies and is designed with a maximum rated depth of 11,000 meters. A fiber-optic link, being designed and built by Space and Naval Warfare Systems Center San Diego (SSC SD), will allow real time communication and teleoperation. The basic design and concepts of operation will be discussed.

INTRODUCTION
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. We term this new class of vehicle a Hybrid Remotely Operated Vehicle (HROV).

The Hybrid Remotely Operated Vehicle (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 SD) is developing the fiber optic tether for the systems, supported by the Office of Naval Research (ONR).

Vehicle Types
A variety of vehicle types have been used to enter the deep ocean, both manned and unmanned. In 1960, the Navy’s bathyscaphe Trieste made a single dive to a depth of 10,915m in the Mariana’s Trench. In 1962 The French bathyscaph L’Archimede reached a depth of over 9000m in the Kouriles Trench. However, bathyscaphes have proved to be both expensive and unwieldy to operate. These and subsequent bathyscaphes were retired from service by the early 1980s. France’s L’Archimede and the U.S.’s Alvin were successfully deployed in Project FAMOUS in the 1970s (Jarry, 1975). Since 1960, only one vehicle has visited the bottom of the world’s deep trench: Japan’s Kaiko ROV, which in 1995 dove to 10,912 m in the Marianas Trench. Despite the stunning technical achievements of these deep vehicles, their size and cost has precluded their use by scientific research community for routine access to the deepest parts of the world’s oceans. At present, the world’s deepest diving robotic and inhabited vehicles can dive to 6,500m.

Remotely operated vehicles (ROVs) have long been used for scientific research and collection. These systems occupy an important place in the spectrum of tools designed to provide a multi-scale view of the deep sea environment. The ability to directly control them provides for on-site investigation and manipulation tasks such as collecting samples from an area of interest.

For conventional ROVs, an increase in operating depth requires a geometric increase in cost, complexity, size, and support vessel requirements. The JAMSTEC Kaiko ROV was built for reaching the deepest parts of the world’s oceans (Kyo, 1995). This vehicle was lost in 2003. Efforts to develop a replacement are
presently underway at JAMSTEC. Kaiko was large and had significant yearly operating costs for a dedicated ship, support personnel, and vehicle maintenance. For example, the Kaiko umbilical cable, its handling traction winch, and A-frame are so large that the system requires the 4,439 Ton 105 m (345 foot) dedicated support vessel Yokoska.

The new class of untethered Autonomous Underwater Vehicles (AUVs), using pre-programmed on-board control systems, is now successfully performing benthic survey operations (Tivey, 1998; Yoerger, 1998; Cormier, 2003). The low bandwidth and time-delay of acoustic telemetry, however, precludes real-time remote-control of these AUVs by human operators. In consequence, AUVs are presently unable to perform the complex sampling and manipulation tasks commonly executed with ROVs and inhabited submersibles (Ballard, 1991; Bachmayer, 1998).

The HROV is being designed to incorporate useful features and capabilities of both ROV and AUV systems, allowing maximum capabilities at an affordable cost. In its AUV mode, the HROV will operate fully autonomously, performing sonar and camera surveys, with an acoustic link for monitoring and mission updating. In its ROV mode, it will be remote-controlled by a human operator to perform close-up inspection, sampling, and other work tasks, all under direct control of the operator. The two modes provide for a robust operation: if the fiber cable connection is lost while in the ROV mode, the HROV will revert to the autonomous mode and will provide for the independent return of the system.

**New Missions Capabilities**

The capabilities provided by the hybrid nature of this system will provide a cost effective method for deep-ocean exploration and research. Significant portions of the ocean basins exceed the present depth capabilities of all deep diving submarines and robots worldwide. One of the key scientific results of recent detailed investigations of various sea floor terrains is that high resolution mapping and imaging reveals relationships between the geology, chemistry and biology of sea floor and deep ocean processes.

**Fig. 1: Sea Floor Depths**

The deepest sea floor, from 6500-11000 m, shown in red and yellow in Figure 1 represent a very small fraction of the total ocean floor, about 1-2%, but the types of processes that occur there and the nearly unexplored nature of this realm make it a compelling target for future scientific study. Deep ocean trenches (e.g. the Izu-Ogasawara Trench, the Puerto Rico Trench, and the Marianna Trench) are the locations at which the spreading seafloor is subducted into the earth’s mantle, yet these areas presently remain inaccessible to direct scientific observation and sampling.

**Mission Requirements**

To meet the needs of deep ocean research, our goal is to develop a vehicle capable of supporting a variety of operations and instruments including the following:

- High resolution acoustic bathymetry.
- Optical still and video imagery.
- Push coring of sediments
- Heat-flow probe
- Hi/Lo temperature probes
- Geotechnical/Geochemical sensors (pore pressure, CTD)
- Rock sampling/drilling
- Flexible science sensor payload interface
- Biological sampling (grabs, boxes)
- Water sampling (hot/cold)
- Water column sensing (e.g. methane)
- Servicing permanent seafloor installations
CONCEPT OF OPERATIONS

The scientific imperatives for development of an 11,000 m HROV are numerous. In addition to supporting deep diving that cannot be accommodated any other way at present, the HROV also has a significant implication for providing new capabilities to the US oceanographic fleet. The system we are developing is intended to be deployed on a wide range of ships, with a minimal amount of infrastructure required.

1. Deployment: The HROV will be deployed from the support vessel using a standard oceanographic cable. Primarily, this cable serves as a method to both physically launch the HROV and enable transition to the fiber cable in a controlled environment away from surface effects. The armored cable depressor would be deployed deep enough to keep the depressor clear of the vessel and to penetrate any surface currents.

2. Descent: Once the vehicle has reached the desired depressor depth, the vehicle is released from the armored cable depressor and begins a free fall to the seafloor using a descent anchor assembly. Fiber cable canisters on both the depressor and anchor assemblies allow cable to payout during the descent as required. The exact length of the fiber in each canister will be determined based on modeling and field testing. Both canisters will pay out passively as the tensions demand, the canister on the descent anchor will pay out primarily due to vehicle motion and the canister on the depressor will payout as the depressor moves due to vessel/surface motion. The total length of cable in the HROV system will not exceed 60 km. As with WHOI’s Autonomous Benthic Explorer (ABE), the HROV will home to the desired seafloor landing site using minimal power with a guidance algorithm modified to reduce the likelihood of tangling the cable around the vehicle or descent weight.

3. On Bottom: Once the vehicle has reached the bottom, the descent anchor assembly will be released from the vehicle. The HROV is then free to maneuver. The HROV is equipped with a cable payout canister containing various lengths of fiber (up to 10 km). The vehicle conducts its mission as required. During this phase, cable will pay out from the vehicle canister as the HROV traverses the bottom, and from the depressor canister due to any vessel motion. Horizontal currents could also draw more cable from the descent anchor assembly if needed.

4. Ascent: Once the HROV has completed its work, the vehicle jettisons the cable canister and drops its ascent weight for the trip to the surface. As with descent, the vehicle guides itself to a rendezvous with the armored cable depressor whereupon the HROV latches to the armored cable and ascends to the surface for recovery.

5. Cable Recovery: With the HROV aboard, the cable can then be recovered. While the armored cable depressor is being brought aboard, the descent anchor assembly is called (acoustically) to drop its ascent weight to begin transit to the surface. As this is underway, a small cable recovery winch on deck retrieves the cable. The descent anchor assembly is then recovered. We anticipate that the section of cable between the armored cable depressor and descent anchor assembly will be recoverable in nearly all cases, and in many cases we will be able to recover most of the cable between the descent anchor assembly and the vehicle. In some cases, recovery of the cable may not be possible due to entanglement on the seafloor or other obstacles.

PRELIMINARY VEHICLE DESIGN

A vehicle design to reach the bottom of the trenches requires innovative use of new materials and techniques while building on what has come before. The HROV is a cross between an autonomous system such as ABE and the tethered ROVs. While the vehicle is more like ABE in the sense that it is powered by self-contained batteries, it has a very small diameter tether to provide a communications link with the ship. An important and unique element of the vehicle’s physical design allows relatively simple conversion between it autonomous and tethered hybrid modes.

Design Philosophy

Our technical approach builds on the success of ROVs such as Jason 1 (Ballard, 1991; Whitcomb, 1993; Bachmayer, 1998) and Jason 2 (Whitcomb, 2003; Johnson, 2003), and AUVs such as ABE (Tivey, 1998; Yoerger, 1998; Cormier, 2003), that have proven to be effective for scientific operations. The goals are to be efficient in design and operation, using standardized components whenever possible. It is intended that a support team of 4 people will be required and the core system will be housed in a single 20 foot ISO shipping container. The system is designed to operate from a ship of opportunity, requiring a minimum of supporting infrastructure.
Vehicle Structure

The HROV vehicle will be unlike any previous vehicle in that it is designed to transform from an AUV into a hybrid tethered vehicle while at sea. To provide for this conversion, a tandem hull configuration has been chosen. The dominant consideration influencing this decision has been the requirement to provide full ROV-like maneuverability when the vehicle is operating in hybrid mode. In AUV mode [Fig 2], the vehicle will utilize three thrusters, one of which it place on a forward articulating foil for depth control when underway. In ROV mode [fig 3], the vehicle structure will be transformed to support a traditional four thruster layout. Technologies will be employed to allow for the increased operation depth include high performance syntactic foam used in tandem with alumina ceramic floatation spheres, composite titanium-ceramic pressure housings for electronics. Rechargeable lithium ion batteries, similar to those in ABE (Yoerger, 1998) will be located in separate ceramic pressure housings. When in hybrid mode, the vehicle will also utilize a 6 function electric manipulator based on an earlier design built for the Jason ROV (Yoerger, 1991).

Sensor Suite

HROV will carry a full sensor suite to address both the vehicle operational needs and scientific data collection. A typical suite envisioned includes:

Vehicle Sensors:
- Paroscientific 20,000 psia Depth Sensor,
- RDI Doppler Navigator, 300 KHz, Max Range 200m
- Inertial Navigation Sensor (INS)
- Altimeter, 200 KHz, Max Range 300m
- Benthos compatible Long Baseline Navigation, 7 – 15 KHz

Scientific Sensors:
- Profiling sonar: 675 KHz, 1.7° conical beam pattern, 100m range
- Imaging sonar: 675 KHz, 1.7° x 30° beam pattern, 100m range
- SeaBird 49 FastCAT CTD
- Honeywell HMR2300 3-Axis Digital Magnetometer
- Optical Backscatter Sensor

Visual Imaging:
- Color video camera
- Digital still camera
- Low light level camera
- Pan and Tilt

Lighting:
To provide lighting, both configurations will have light emitting diode (LED) arrays. LEDs offer substantial benefits in several important areas: tuned spectral output, precise control of lighting pattern, and variable output with the ability to sync to panned cameras, thus promoting efficient use of energy.

Pressure Vessels

HROV will use ceramic pressure vessels for both the dry housings and for floatation. The reason for use of this material is its high specific strength. In particular, compressive strength is of utmost importance for deep ocean pressure vessels. The design of the vehicle depends on the use of pressure resistant enclosures for electronics and batteries which are positively buoyant. To achieve this goal, the HROV will utilize pressure vessels fabricated from ceramic materials. The design objective is to fabricate
assemblies with a specific gravity of no more than .8 (figure 4). These housings will build on the knowledge gained at SSC SD (Johnson, 1993). In addition, the vehicle will have a portion of its floatation provided for by using 10 inch diameter alumina ceramic spheres with a specific gravity of 0.4.

**Figure 4: Ceramic Pressure Vessel**

**FIBER OPTIC CABLE DESIGN**

To date, light fiber tethers have principally been employed in military applications; relatively few light fiber tether systems have been employed for oceanographic research. In (Aoki, 1999; Aoki, 1999) the authors report the development of the self-powered remotely operated vehicle UROV7K employing a fiber-optic tether. This vehicle is designed to operate exclusively as a tethered ROV, and does not have on-board computational resources necessary to operate autonomously. In (Ferguson 1999) the authors report the successful deployment of an autonomous underwater vehicle designed to deploy fiber optic communication cables on the arctic sea floor.

**Cable Selection**

Several different fiber optic cables are being investigated for use on HROV. For this application, it is essential that the cable be as small and light as possible due to the size constraints of the vehicle. Two cables are currently under consideration for this system: Fiber Optic Microcable (FOMC) (Dombrowski, 1991) and the SCI Sanmina buffered fiber. Both cables have been pressure tested to 16,000 psi (32,000 fsw equivalent) and monitored for attenuation effects. A preliminary design analysis of this cable for deep-ocean deployments is reported in (Webster, 2003).

**Cable Analysis**

We are analyzing the dynamics of thin fiber-optic tethers using our WHOI Cable software for calculating the dynamics of moored and towed systems (Gobat & Grosenbaugh, 2000). The software uses an implicit finite difference, time domain simulation that is built around a mathematical model of cable dynamics. The cable model is fully three-dimensional and includes the effects of torsion, bending, and geometric and material nonlinearities. A generalized-α method that allows for the introduction of numerical dissipation is used for

**Table:**

<table>
<thead>
<tr>
<th></th>
<th>FOMC</th>
<th>SCI Sanmina Fiber</th>
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<tbody>
<tr>
<td>Diameter (mm)</td>
<td>0.8</td>
<td>0.25</td>
</tr>
<tr>
<td>SG (fresh water)</td>
<td>1.74</td>
<td>1.36</td>
</tr>
<tr>
<td>Weight of 11 Km in water (kg)</td>
<td>4.2300</td>
<td>0.1730</td>
</tr>
<tr>
<td>Working Strength (N)</td>
<td>133</td>
<td>8</td>
</tr>
<tr>
<td>Breaking Strength (N)</td>
<td>400</td>
<td>108</td>
</tr>
<tr>
<td>Relative Survivability on Seafloor</td>
<td>good</td>
<td>poor</td>
</tr>
</tbody>
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**Figure 5: Fiber Cable Characteristics**

**Figure 6: FOMC Spools**

**Figure 7: SCI Sanmina Fiber Canister**
the temporal integration (Gobat & Grosenbaugh, 2001).

Figure 8 shows the results of a representative
WHOI Cable simulation. This is a simulation of
an the following deployment:

- 11,000 meter deployment
- 0.5 m/s descent rate.
- 0.25mm diameter fiber tether, with 6.7
Newton payout threshold.
- Water current 0.25m/s for top 200m, linearly
decaying to 0.05 m/s at sea floor.

The Figure depicts the XZ tether position and
tensions 42 hours into the mission (32 hours
after reaching the sea floor). The simulations
show the tether tensions to remain within
working limits, and the tether to not entangle in
the sea-floor.

Figure 7: WHOI Cable Simulation Results

Cable Testing

In addition to pressure testing, initial at-sea tests
have been performed with both the FOMC and
buffered fiber. Vertical deployment of both types
of fiber optic cable was successfully
demonstrated in 2,000 m of water on 1-2
November. Working with Woods Hole
Oceanographic Institution, the fiber cable packs
were installed on an oceanographic "elevator"
which was deployed from the RV Atlantis. Two
drops were made: one with the SSC Fiber Optic
Micro Cable (FOMC) and one with a buffered
fiber from SCI Sanmina. Optical continuity was
monitored during the descent and for three
hours on the bottom. Data was also collected on
the current profile as a function of depth and the
track of the elevator. The FOMC maintained
optical continuity though the descent and 3
hours on the bottom, until it was detached during
ascent. The buffered fiber maintained continuity
through the descent and for 2.75 hours on the
bottom, when a break occurred relatively high in
the water column. Data collected from this test
will be used to validate the WHOICABLE
simulation, and it also validated the use of thin
fiber optic cable for use as a tether for the
HROV. Figure 8 shows the bottom-landing
elevator employed in the November 2004 fiber
tether experiments.

Figure 8: Photograph of elevator employed
in our November 2004 deployment of fiber
optic tether candidates to 2000m depth in the
San Clemente Canyon.

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 SD) will provide a new level of
accessibility for deep ocean research. The
AUV mode will provide the flexibility for wide
area surveys and real-time communication and
teleoperation will be made possible by the fiber
optic link.
Acknowledgements

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