PAPER

Exploring the Deepest Depths: Preliminary Design of a Novel Light-Tethered Hybrid ROV for Global Science in Extreme Environments

AUTHORS
Andrew D. Bowen
Dana R. Yoerger
Louis L. Whitcomb
Daniel J. Fornari
Woods Hole Oceanographic Institution

ABSTRACT

This paper describes a new project to build an operational underwater vehicle that can perform scientific survey and sampling to the full depth of the ocean (11,000 meters). The vehicle, called a hybrid remotely operated vehicle (HROV), will operate in two different modes. For broad area survey, the vehicle will operate untethered as a autonomous underwater vehicle (AUV) capable of exploring and mapping the seafloor with sonars and cameras. After targets of interest have been found, the vehicle will be converted at-sea to become a remotely operated vehicle (ROV) that will enable close up imaging and sampling. The ROV configuration will incorporate 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. This paper outlines the scientific motivation for the project as well as the feasibility of our design concept. Analysis of the fiber optic cable shows our approach to be practical even with fairly extreme current profiles. An overall approach to the vehicle design is also presented, including options for pressure housings and buoyancy materials.

INTRODUCTION

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 11,000 meters. The vehicle will be able to operate untethered as a fully autonomous underwater vehicle (AUV) for benthic survey operations, and also as a self-powered remotely operated vehicle (ROV) for sampling operations employing a sub-millimeter diameter optical fiber tether for real-time telemetry of data and video to its human operators on a surface ship. We term this new class of vehicle a Hybrid Remotely Operated Vehicle (HROV).

The HROV, depicted in Figure 1, will have capabilities of both an AUV and ROV. While operating untethered, the vehicle will enjoy the freedom of movement of an AUV, which has proven highly effective for a variety of survey operations (Tivey, 1998; Yoerger, 1998; Cormier, 2003). While connected to the surface with a lightweight fiber optic tether, high bandwidth two-way communications will 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 remote control of pilots and scientists onboard a research vessel. Our vehicle concept allows conversion from an AUV to a Hybrid-ROV (HROV) while at sea, thereby enhancing the science mission capabilities on a single cruise.

Our technical approach builds on the success of Woods Hole Oceanographic Institution's (WHOI) 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. Additionally, we have established collaborations with other research groups that have pioneered the use of lightweight fiber optic tethers and ceramic pressure housings for 11,000 m operation. This project is presently underway at WHOI with expected testing and trials of the vehicle system in late 2006.

Background

Existing U.S. deep submergence vehicle systems have excellent capabilities and provide critical, routine access to the seafloor primarily in the 2,000-5,000 m depth range (e.g. the 4,500 m Alvin human occupied submersible; the 5,000 m ABE AUV; and the 4,000 m Tiburon ROV), with only one U.S. vehicle capable of diving to 6,500 m and conducting high resolution mapping and sampling (the 6,500 m Jason 2 ROV). These capabilities have led to significant scientific discoveries over the past 30 years including identifying and sampling mid-ocean ridge volcanic processes, and hydrothermal processes and biological communities which have revolutionized the biological sciences (The Future of Marine Geology and Geophysics, 1996). Progress in deep sea research at ocean floor sites down to 11,000 m has been hindered by a lack of suitable, cost-effective and science-effective vehicle systems that would enable multidisciplinary remote investigations and collection of biological, geological and fluid samples. Given the need for full access to the global abyss, and national and international imperatives regarding ocean exploration, a variety of studies have indicated that cost effective development of an 11,000 m deep submergence vehicle has been identified as a national priority (The Future of Marine Geology and Geophysics, 1996; Ocean Exploration Panel, 2000; Shepard, 2002; DESCEND Workshop, 2000).

For conventional ROVs, an increase in operating depth requires a geometric increase in cost, complexity, size, and support vessel requirements. Recently, only one deep submergence system has been capable of reaching the deepest parts of the worlds oceans; the Kaiko ROV, built and operated by JAMSTEC (Nakajoh, 1998). This vehicle was unfortunately lost in 2003 and efforts to secure a replacement are presently underway at JAMSTEC. Kaiko was extremely large and had significant yearly operating costs for a dedicated ship, support personnel and vehicle maintenance. For example, the Kaiko umbilical alone has an estimated cost of over $2M, and 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 depth capability of conventional deep ROVs such as Jason 2 cannot be extended to 11,000 m because the overboard weight of traditional steel reinforced oceanographic cables is simply too high. For example, 11,000 m of UNOLS standard 17 mm electro-optic cable employed by Jason 2 would exert a force of nearly 100 kN (22,000 lbs) at the surface, well above the allowable working load of 62 kN (14,000 lbs) of the cable. Providing more steel in the cable to increase its maximum working load also increases the over-the-side weight in proportion; there is simply no way to use such cables for ultra deep applications. Synthetic strength members, such as the Kevlar cable used for Kaiko, offer higher strength to weight ratios but are large, very expensive and have limited lifetimes. Additionally, the low density and relatively large cross-sectional area of synthetic cables result in a high-drag system that cannot easily be moved horizontally or towed like WHOI's existing ROVs and towsleds. While the Kaiko is an outstanding technical achievement, we feel a simpler, more streamlined system will offer meaningful capability; ultimately producing more science at far less cost; both in terms of initial outlay and routine operating expense. The HROV system's initial development and construction costs (~ $5M) will be a fraction of that of traditional tethered or human occupied systems and it will be portable and able to be deployed from a wide range of vessels (including non-DP vessels), far less expensive to operate, and will provide a more appropriate mix of survey and sampling capability that will benefit a wide range of multidisciplinary oceanographic research.

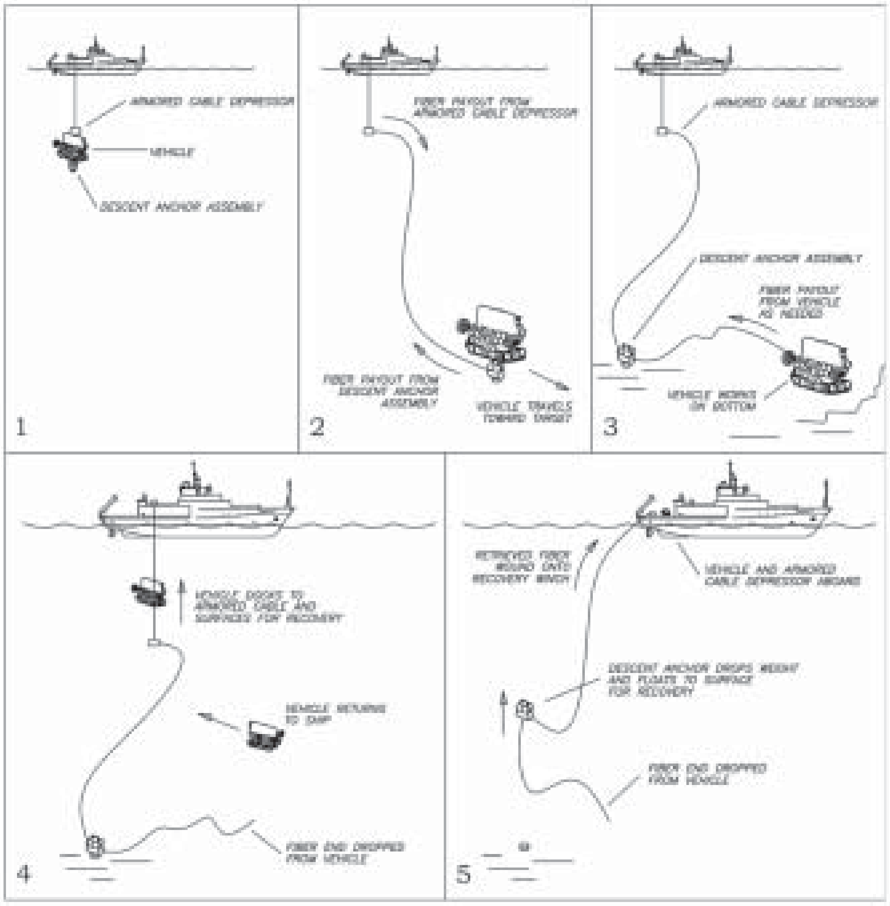
To date, light fiber tethers have principally been employed in military applications; relatively few light fiber tether systems have been employed for oceanographic research. In Aoki (1999) and Murashima (1999) the authors report the development of the self-powered remotely operated vehicle UROV7K employing 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 et al. (1999) the authors report the successful deployment of an autonomous underwater vehicle designed to deploy fiber optic communication cables on the arctic sea floor.

HROV Concept Overview

Our goal is to create a practical 11,000 m system using an appropriately designed self-powered vehicle connected to the surface vessel by a small, lightweight reinforced glass fiber of up to 40 km in length, as depicted in Figure 1. This sub-millimeter diameter fiber has been used for many years in various US defense related applications where it is known as fiber optic micro cable (FOMC) (Dombrowski, 1993).

FIGURE 1

The Hybrid HROV Design Concept: The HROV will be capable of operating to 11,000 m depth as an ROV with a micro fiber optic tether, and operating without a tether as an AUV. Panels 1-5 depict deployment, operation, and recovery. An animation of the vehicle in operations can be found at: http://www.whoi.edu/media/hrov.html



While oriented to a deepest ocean mission, the concept of an HROV can also be employed in "traditional" mid-ocean ridge crest settings for event response or other tasks where the limited demands on the support vessel size and capabilities are beneficial. Our operational model requires only a single 20 ft container for shipping and the vehicle would be able to be deployed from non-dynamically positioned research vessels such as the UNOLS Endeavor Class, which are equipped with CTD hydrographic winches. The system will operate with similar positioning and weather requirements established for traditional CTD work. Because of the extreme fiber lengths adopted in our design, it will also be possible to conduct HROV operations where long horizontal excursions are required. A primary example of such a deployment would be under ice missions where the surface support vessel may not be able to directly position over the desired work area or hold station independent of the ice motion.

The project focus will be directed in two areas: 1) the development of the 11,000 m HROV itself and 2) the FOMC link. Initially, the FOMC-link system will be tested in engineering trials to investigate the operational envelope of a light-fiber tether for deep-submergence vehicles and instruments in limited endurance missions. In addition, we hope that the submersible ALVIN might benefit from a real-time fiber optic link to the surface, which could provide both scientific and public outreach capabilities.

An 11,000 m vehicle presents some technical challenges. Components capable of 11,000 m operation such as flotation, connectors, pressure housings, and camera domes do not generally exist as standard off-the-shelf components for a small, lightweight vehicle working at such depths. However, these components are well within the capabilities of the oceanographic/engineering community working with commercial suppliers. The FOMC link is a key-enabling element of our concept for which a strong engineering base exists, but it will require further development for our application. A significant amount of preliminary engineering has been internally funded at WHOI to verify the proof of concept. The U.S. Navy's Space and Naval Warfare Command (SPAWAR) pioneered the field of fiber optic tethers (Dombrowski, 1993) and has done extensive work on torpedo guidance systems utilizing FOMC. We have established a formal collaboration with SPAWAR on the FOMC system design for the HROV application.

Based on SPAWAR experience combined with our pressure testing and analysis, we are confident that the light fiber model will work for the HROV application. The engineering problems associated with ultra deep systems are well within present engineering capabilities. These facts, coupled to the maturing technology base for AUVs and their power systems creates an appropriate and appealing opportunity to fuse these deep submergence technologies and develop them to serve deep ocean science via an innovative 11,000 m HROV.

Scientific Need for Access to Extreme Environments

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 application of our HROV concept has significant implications for providing new capabilities to the U.S. oceanographic fleet. The HROV system is intended to be deployed on a wide range of ships with the only requirement being the ability to host a fiber-optic CTD cable (of UNOLS Standard 0.322" diameter to maintain compatibility with existing UNOLS standard CTD cable winches and sheaves) on a standard CTD winch, without the need for dynamic positioning of the vessel.

We highlight below several of the key scientific missions that would greatly benefit such a development. These are consistent with many scientific objectives stated in recent reports from national panels and meetings conducted over the past decade (The Future of Marine Geology and Geophysics, 1996; Ocean Exploration Panel, 2000; Shepard, 2002; Johnson, 2003). Broadly stated the scientific objectives of an 11,000 m vehicle fall into the following four categories:

1. Investigation of seismic, geo-hydrological and macro/microbiological problems in accretionary prisms on the inward slopes of oceanic trenches in subduction zones worldwide, primarily at the margins of the Pacific Ocean basin.
2. Investigation of ultra-slow spreading sea floor geology, biology and geochemistry (rock and fluids) (Dick, 2000). Many ultra-slow MORs occur in geographic regions where weather windows are extremely narrow or there is ice cover (e.g. the Southern Ocean between 40°-50°S, Australian-Antarctic Discordance, and in the Arctic - the Gakkel Ridge (Edwards, 2001).
3. Investigation of magmatic, hydrothermal and volcanic activity in the deepest portions of oceanic transforms in extensional tectonic settings – i.e. pull-apart basins, propagating rifts, and microplates.
4. Event response—tied to mid-ocean ridge (RIDGE, 2000) and subduction zone magmatism and tectonics and to human events (e.g. accidents) where planes, ships or other debris must be located and surveyed at the deepest ocean depths quickly and efficiently.

Subduction Zones

The greatest depths on the surface of Earth are found in oceanic trenches. The complex effects of subduction of oceanic lithosphere beneath both continental and oceanic lithospheric plates are subjects of intense interest in the marine geological and geophysical community because they are prime areas where oceanic lithosphere is recycled back into the mantle (The Future of Marine Geology and Geophysics, 1996; Coffin, 1998; MARGINS Science Plan, 1996-2003).

For example, many of the important subduction zone decollements and other key fluid conduits occur at depths greater than 4,500-6,500 m. The science of seafloor monitoring and perturbation experiments is rapidly developing and an 11,000 m HROV would be an essential component of this type of future research. The actively spreading back-arc basins of convergent margin regions are the sites of production of a unique oceanic lithosphere and form some of the potentially richest reserves of metallic ores on Earth. The study of the formation of lithosphere in these basins is very poorly understood (Coffin, 1998; MARGINS Science Plan, 1996-2003). Without detailed stratigraphic investigations of lithologic units and an understanding of these structures, attempts to develop models that will allow us to extrapolate *in situ* studies to interpretation of subaerial exposures will remain inadequate. In addition, the biological communities that flourish in subduction zones and back arc-basin hydrothermal settings are likely to have unique properties.

Ultra Slow Spreading Mid-Ocean Ridges

With the recent identification and first-order mapping studies of ultra-slow spreading ridges in the Arctic and SW and SE Indian Ocean, (Fisher, 1997; Grindlay, 1998; Edwards, 2001), scientists are poised to make breakthroughs in our understanding of this important end-member of seafloor spreading environment. The ability to sample and observe detailed geological, biological and chemical processes occurring at the slowest spreading MORs will undoubtedly revolutionize our understanding of how seafloor spreading is manifested in these settings. In addition, we expect that a host of new and novel biological communities and chemical-biochemical processes are associated with ultra-slow spreading MORs.

Transforms, Propagating Rifts and Microplates

Deep troughs in transform and oceanic rift settings provide access to large sections of the oceanic crust in the abyssal depths of the ocean basin. Whereas transform valleys allow a look at what is happening very early in the formation of the oceanic lithosphere, deep mid-plate troughs are a potential window into the aging of the crust. The 11,000 m HROV would be an ideal tool for the mapping, observation and sampling of such tectonic windows into the oceanic lithosphere.

Event Response—An Ideal Application of HROV Technology

The science plan for RIDGE 2000 (R2K) aims at a comprehensive understanding of the relationships between the biological, geological, and chemical processes associated with plate spreading at mid-ocean ridges (RIDGE, 2000). This whole-system approach is integral to understanding how seafloor and sub-surface ecosystems are sustained by crustal accretion processes. The goal of the Time-Critical Studies program element of R2K is to understand the nature, frequency, distribution and geobiological impacts of magmatic and tectonic events along the global mid-ocean ridge system (Edwards, 2001). Currently, the Time-Critical element of the R2K program is restricted to the northeast Pacific where real time detection is possible through the U.S. Navy's SOSUS hydrophone array (Dziak, 1995; Fox, 1995; Dziak, 1996; Dziak, 1999; Fox, 1999). The capabilities for rapidly deploying a hybrid vehicle on the Juan de Fuca Ridge without the need for a DP capable ship and with the variable weather conditions of the NE Pacific would provide an enormous boost to Event Response scientific research.

Under-Ice Operations

The HROV will be highly applicable to operations under-ice, such as those that will be required for survey, close-up inspection, and sampling of sites on the ultra slow spreading MOR recently discovered in the Arctic (Edwards, 2001). While operating from an icebreaker in ice, the vessel will not be able to hold station nor follow precise track lines as is done in conventional ROV or towsled operations. The vehicle configuration will be able to be launched through an opening in the ice, operate either in tethered or untethered mode, and then return to the armored cable depressor for recovery. The large horizontal offsets allowed by the fiber optic tether will permit the vehicle to operate independently of the vessel motion. Should the fiber optic tether fail, the vehicle can return to the depressor in AUV mode.

Other Operations

Finally, but by no means of lesser importance, development of an 11,000 m HROV has the potential to greatly enhance U.S. strategic capabilities for search, location, and inspection tasks, and to render this capability effective for the entire global ocean geographically and to full ocean depth.

Feasibility of HROV Fiber Optic Vehicle

Fiber Optic Micro-Cable (FOMC) development for underwater vehicle applications dates back to the early 1980s by the United States Navy (Wernli, 2001). The primary laboratory involved is presently known as the Space and Naval Warfare Systems Center or SPAWAR in San Diego, CA. This group has a long and distinguished history of accomplishment in deep submergence engineering, including ROV and AUV development and communications systems. In addition, the Japan Marine Science and Technology Center (JAMSTEC) has done substantial work in the development of similar systems (Aoki, 1992; Murashima, 1999).

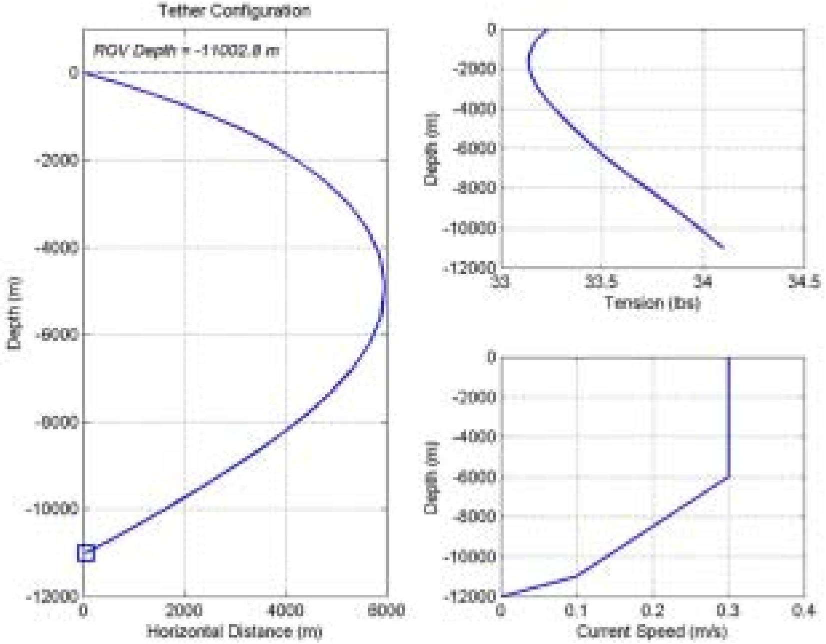
Twenty kilometers of FOMC can be wound into a self-supporting spool the size of a cookie tin (~30 cm diameter x 15 cm tall). One kilometer of fiber weighs slightly less than 0.5 kg in water, and it has a breaking strength of approximately 450 N (100 pounds). During the initial development work with the FOMC, pressure tests were conducted to an equivalent depth of 13,500 m (nearly 45,000 ft) with minimal optical attenuation.

HROV Operating Paradigm

The HROV requires an innovative deployment technique, as shown in Figure 1. The FOMC has been used for several horizontal applications (torpedoes for example). In our design, the light fiber will be used in a vertically oriented manner. The principals of HROV operations outlined below are applicable to any of the expected operating environments enumerated above. Figure 1 graphically illustrates the HROV deployment concept.

FIGURE 2

Optical Fiber Tension and Shape: Results of our numerical simulation studies of fiber optic micro-cable (FOMC) tether tension and shape in response to ambient current (profile 2) (Webster, 2003).



1. Deployment: The first panel in Figure 1 shows the HROV deployed from the support vessel using 0.322" diameter fiber optic CTD cable. While fiber optic CTD cables are not presently standard on UNOLS vessels, they are commercially available and will work with standard winches, sheaves and slip rings. Primarily, this cable serves as a method to both physically launch the HROV and enable transition to the FOMC 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. FOMC canisters on both the depressor and anchor assemblies allow fiber to payout during the descent as required. The total length of FOMC in the HROV system will not exceed 60 km.

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 FOMC payout canister containing various lengths of fiber (up to 10 km). The vehicle conducts its mission as required.

4. Ascent: Once the HROV has completed its work, the vehicle jettisons the fiber 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 depressor and is winched to the surface for recovery.

5. FMOC Recovery: With the HROV aboard, the fiber system can then be recovered. While the armored cable depressor is being brought aboard, the descent anchor assembly is signaled (acoustically) to drop its ascent weight to begin transit to the surface. As this is underway, a small fiber recovery winch on deck retrieves the FOMC for repacking and reuse.

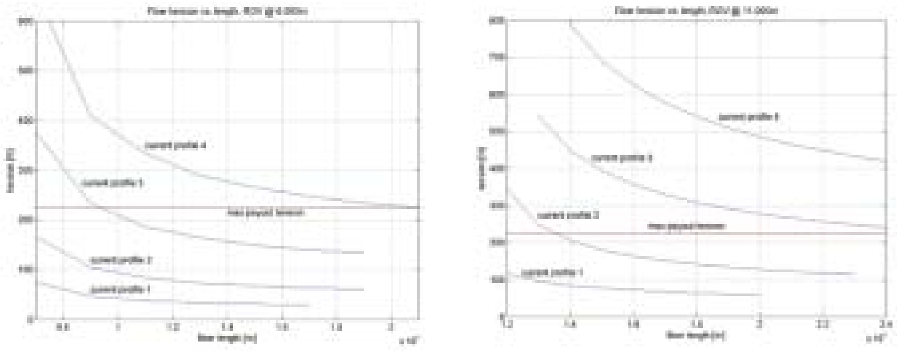
Descent/ascent times of 30 m/min for the HROV are the design goal. We believe this will be readily achievable in the streamlined AUV mode of operation; in the higher drag HROV mode of operation the rate may be lower. Mission endurance for the HROV will of course depend on power use. This will be variable but the design goal is for on-bottom missions of up to 24 hours.

HROV Fiber Feasibility: Analysis of Optical Fiber Tension

The success of the proposed HROV deployment system hinges on predicting and controlling the loads experienced by the FOMC. To evaluate the feasibility of this approach, we have conducted an extensive set of numerical simulations to estimate the axial and longitudinal loading of the FOMC in the expected current conditions, and to show how the FOMC tension varies with the length of fiber in the water column (Webster, 2003). The static cable analyses were performed using 'WHOI Cable', a general-purpose code for calculating the static and dynamic response of moored and towed oceanographic systems (Gobat, 2000). The

FIGURE 3

FOMC tension versus length for a 6,000 m deployment (left graph) and for an 11,000 deployment (right graph). These results show acceptable operation at either 6,000 or 11,000 m for a current profile of 0.3 m/s half way to the bottom (Webster, 2003)


FOMC Tension vs. Length: 6,000 m Deployment

FOMC Tension vs. Length: 11,000 m Deployment model is fully three-dimensional and includes the effects of torsion, bending, and geometric and material nonlinearities.

Figure 2 shows a sample of the output of the WHOI program for a 17,000 m long fiber with the HROV underneath the ship. The plot on the left shows the physical layout of the FOMC in the water column. The upper right plot shows the tension of the FOMC along its length. The bottom right plot shows the specified current profile as a function of depth.

The simulation was first run using four different idealized current profiles with the vehicle at 11,000 m and 6,000 m. The idealized profiles included a constant current of 0.2 m/s from surface to the seafloor, and two other variations on the profile seen in Figure 2 but with maximum currents of 0.45 and 0.6 m/s to establish the viable operating regime. These results (Figure 3) show that the system could work in the 0.3 m/s tapered current profile from Figure 2: the cable tension will balance the payout force with approximately 8,000 m of cable in 6,000 m of water and 14,000 m of cable length in 11,000 m of water. The more extreme profiles (0.45 and 0.6m/s) were not achievable with our design limit of 20,000 m of cable.

We have also expanded the analysis to use measured current profiles from three potential operating areas: Arctic (Aagaard, 1981; Woodgate, 2001), Juan de Fuca (Cannon, 1997), and the Izu-Ogasawara Trench (Fugio, 2000). The Arctic currents in 4,000 m of water have a maximum of 0.32 m/s at the surface that drop off quickly after 300 m to 0.04 m/s at the bottom. The maximum Juan de Fuca currents in 3500 m of water are more extreme, starting at 0.41 m/s on the surface and dropping to 0.17 m/s at 500 m (based on the mean currents plus a 0.10 m/s offset for tidal variations). In each case, the results showed that the vehicle could reach the bottom with safe tension levels using cable lengths only slightly longer than the water depth (well within the 20,000 m limit). This is not surprising, as the measured profiles are less demanding than the acceptable idealized profile. This indicates that the FOMC, with a 100 lb breaking strength and 30 lb working load, is more than adequate for operating under these conditions.

Core Vehicle Structural Design

A preliminary design approach is based on the Sentry AUV (Jakuba, 2003) in shape, layout, mission, and sensor suite but with a 100% increase in depth capability. Sentry features a hull shaped like a symmetric wing on edge. This shape combines low drag with sufficient vertical separation between the centers of buoyancy and gravity for good stability at low speed. Planes equipped with thrusters are fitted fore and aft. The planes can be tilted, providing actuation force either by vectored thrust or through lift. The setup can be configured in a variety of modes for transit, maneuvering in rough terrain, and operation at very low speed. In ROV mode, the vehicle will also have a side thruster to provide full hover capability. Technologies will be employed to allow for the increased operation depth including higher strength syntactic foam and ceramic pressure housings for electronics. A rechargeable lithium ion battery, similar to that in ABE (Bradley, 2000) but with increased capacity, will be located in the main pressure housing.

FIGURE 4

The HROV in Autonomous Survey Mode.

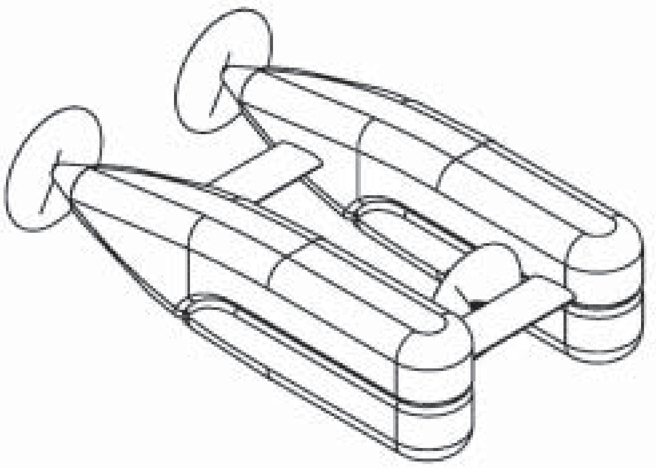


FIGURE 5

The HROV in Tethered ROV Work Mode. Fiber is deployed and tool package is attached, providing additional thrusters, batteries, and sampling tools.

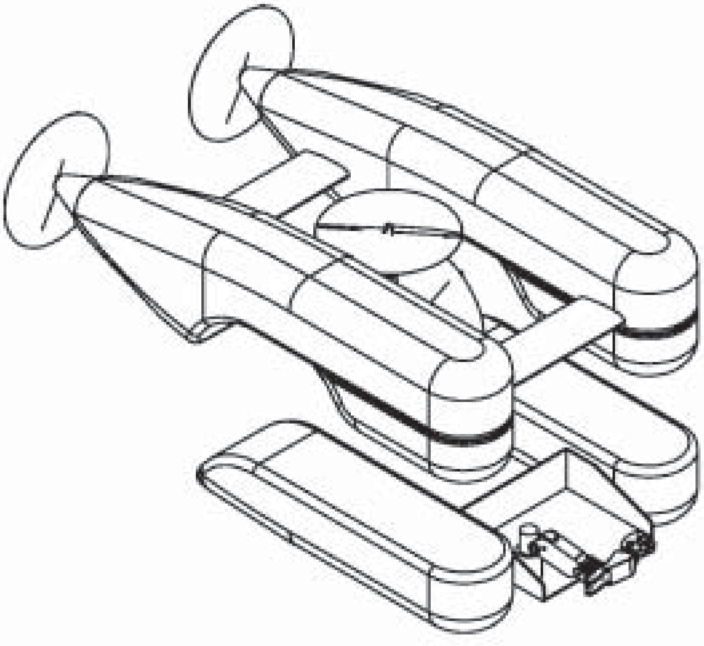


TABLE 1

HROV Technical Specifications

Dimensions, L×W×H	3m x 2m x 2m
Air Weight	2100 kg
Payload Capacity	25 kg
Battery	Rechargeable Lithium Ion. 6 kWH in main pressure housing, 6kWH in tool package housing
Speed	3 knots (1.5 m/s), 2 knots (1.0 m/s) with work package
Manipulator	Electric, 5 DOF, 20kg lift at 1 m
Thrusters	2 aft, 2 vertical, 1 lateral
Lights	Variable output LED array, strobes
Sonar	Scanning sonar, forward look and profile, 675 kHz
Sensors, other	Magnetometer, CTD

TABLE 2

Comparison of Titanium and Ceramic Pressure Housing Specifications

	Air Weight (kg)	Water Weight (kg)	Flotation Vol (m^3)	Flotation Air Weight (kg)	Total Air Weight (kg)
Titanium	239	74	0.241	174	413
Ceramic	114	-23	-0.074	-54	60
Savings	125	96	.315	228	353

Ceramic Pressure Housings

The use of ceramics for pressure housings for oceanographic systems, where buoyancy is at a premium, is not new technology—in fact it has been researched and tested extensively (Johnson, 1993; Stachiw 1993). In the late 1980's and early 1990's, NRaD (now SPAWAR) conducted a program to establish design criteria for ceramic pressure housings for oceanographic use. SPAWAR is a collaborator on the project.

A comparison of titanium and ceramic candidate designs is shown in Table 2. The ceramic housing, including hemispherical endcaps, reduces the housing weight by 274 lb (125 kg), provides net positive buoyancy and significantly reduces the amount of flotation required. Given the relatively high density of the 11000 m. foam (specific gravity 0.72), the weight saved in the housing translates into a large savings in required foam and overall vehicle weight of 353 kg.

Ceramic Spheres for Flotation

Alumina ceramic can be readily formed into spheres for flotation purposes using manufacturing and testing methods developed by the Navy similar to those used for cylindrical housings. These spheres can have a weight to displacement ratio (W/D) of 0.45, compared to the 0.65 ratio anticipated for syntactic foam. The drawback to using spheres for flotation in submersibles is their relatively low packing efficiency and the increased risk of catastrophic failure. The preliminary weight balance indicates the need for 28 12 inch (305 mm) spheres to provide 517 lb (235 kg) of buoyancy.

Thrusters

The thrusters will be derived directly from the successful pressure-tolerant ABE thrusters, which have worked very well in over 100 deep ocean dives. Without changing components, we can extend these thrusters from their present 300 watt capacity to over 600 watts. Early in the development, we will qualify the new thrusters (the existing ABE thrusters have been tested to 6000 m) for 11,000 m operation.

Control System

The HROV control system will require the following new capabilities not found in the antecedent AUV or ROV control systems:

1. **ROV/AUV Interoperability:** The control system will have the ability to automatically switch from ROV mode to AUV mode should the FOMC fail.
2. **Two-way acoustic communications:** The HROV will be equipped with a low-bandwidth acoustic modem communication system to allow mission progress to be monitored when operating untethered. It will permit the mission to be altered in real time, and enable a human operator topside to take control if the telemetry is interrupted.
3. **Controlled Descent, Docking, and Ascent:** Presently ABE drops its weights and ascends passively to the surface. Our HROV concept will include the ability to ascend to a spot, and then dock to the armored cable depressor to permit recovery through the ice.
4. **Total Mission Power Management:** The HROV must complete its missions within the energy limits of its on-board Lithium battery pack—respecting both the peak current capabilities of the batteries as well as the total energy budget of the overall mission. We will adapt the existing Jason 2 power management to continuously monitor power consumption and regulate it to stay within a specified peak value.

The HROV control will adopt the high-level autonomous-mission-execution software modules developed and successfully deployed on the ABE vehicle. These include mission planning software, simulation capabilities used to verify and test missions, fully autonomous long-baseline acoustic navigation, and the elements that implement and supervise autonomous operation. The autonomous elements include a set of procedures for capabilities such as descent to the seafloor, track line following, bottom following, and return to the surface. The supervisory layer includes capabilities for monitoring critical vehicle functions and aborting the mission if needed.

Navigation

In 11,000 meter operations, the long acoustic paths of conventional Long-Baseline (LBL) Acoustic Navigation (Hunt, 1974) give rise to the problems of signal attenuation, decreased accuracy, and slow update rates. To provide the highly precise vehicle navigation required for benthic science, the HROV will employ an on-board navigation system combining conventional Long-Baseline (LBL) Acoustic Navigation, (Hunt, 1974), Doppler navigation (Brokloff, 1994; Whitcomb, 1999; Kinsey, 2003) and inertial navigation (Alameda, 2002; Larsen, 2002).

The HROV's inertial navigation system (INS) will be initialized to a GPS fix at the surface prior to deployment, and will provide navigation for the vehicle descent and ascent phases, aided by water-track Doppler velocity log (DVL). For these proposed initial deployments, we will use one of WHOI's existing IMU units. At about 175 m off the seafloor, the HROV will combine bottom-lock 300kHz Doppler navigation with inertial navigation for improved accuracy, and provide long-term drift correction from slant-range interrogation between the HROV and the surface ship. This system will provide precision navigation for exploratory dives without requiring the deployment of a LBL transponder network.

Imaging and Sensing

Imaging and sensing will be a key component of the 11,000 m vehicle. It will carry both an imaging and profiling sonar like those on Jason 2 and ABE (Jakuba, 2002). Packaging the cameras and lights for the 11,000 meter working depth while meeting weight constraints constitutes a challenge that will be met by using the smallest possible components housed in smaller "general purpose" ceramic housings. A high dynamic range digital CCD camera currently supported on several AUVs and ROVs will be incorporated, in both a stand-alone AUV mode and in HROV mode.

The successful application of cameras and interfaces is highly dependent upon successful lighting systems. LED lighting is increasingly powerful and inexpensive, and is proposed for use with the new vehicle. The goal of this part of the effort will be a lighting system useful for both strobed and variable power (low altitude/low power, high altitude/high power) applications, packaged in an effective manner for 11,000 mm depths. Camera control will allow stereo imaging when necessary or useful.

Manipulation and Sampling

A principal motivation of providing a real-time fiber optic telemetry capability is to provide the ability to perform complex manipulative tasks requiring a human operator in the loop. A summary of jobs the HROV will be called upon to perform are as follows:

1. **Push coring** – standard push cores with core catchers
2. **Heat-flow probe** – e.g. the Alvin probe is ~5-10 kg and ~1-1.5 m long. It must be pushed into the sediment by the manipulator in a controlled manner.
3. **Geotechnical/Geochemical sensors** – these devices measure *in situ* pore pressure in sediments and cold to hot fluid properties and basic chemistry.
4. **Rock sampling/drilling** – basic sampling of rocks of various lithologies with the possibility new small-scale drilling tools might be adapted to this vehicle.
5. **Biological sampling** – support of small suction samplers, nets and use of traditional "bio boxes" for sample storage/recovery.
6. **Water sampling** – both hot and cold water sampling while monitoring exit fluid temperature in real-time.

An Advisory Panel of oceanographic research scientists and engineers is providing guidance for this part of the project by helping the design team develop comprehensive capabilities oriented to getting the science work done. While we hope to utilize many of the existing sampling tools, the unique nature of HROV operations may require development of specific sensors and sampling equipment. Our initial meeting of this panel has been completed and we expect important input that will help guide both the basic vehicle develop and improve sensors/tools.

This vehicle will incorporate a single 6 degree of freedom electrical manipulator that will improve upon the arm used on the early Jason vehicle (Yoerger, 1991). The reason for choosing an electrical design relates to a need for power efficiency that cannot be achieved with the use of a hydraulically powered system. In addition, an electric arm will only draw power when work is actually being done and thus avoid consuming significant amounts of power when idling. This is of critical importance for a system relying on battery power alone.

DSL has particular expertise in the area of electric manipulation because of our experience gained during many years of operating the Jason ROV (Bachmayer, 1998). This vehicle accomplished a great deal with its WHOI designed electric manipulator, and we also learned about specific weaknesses in the design of the arm, its control system, and the relationship between the arm, the cameras, and the overall vehicle workspace. We propose an improved version of such an arm as a suitable tool for the HROV, combining our experience with the electric Jason arm and the more capable arms on Jason 2.

Conclusion

For the past 50 years, vehicle limitations have restricted direct access to depths of 6,500 m or less. Only a few deeper vehicles have ever been developed—notably the Trieste, which Piccard and Walsh piloted to the floor of the Marianas Trench in January 1960, and Japan's Kaiko ROV, which dove to 10,912 m depth in 1995. The scientific community has established substantive imperative to investigate the deep ocean floor at depths below 6500 m, yet a lacuna of practical technology prevents routine access to the deepest ocean. This virtually unexplored area of the ocean includes a wide range of tectonic regimes that pose significant questions about broad, fundamental problems in the earth and ocean sciences. The HROV vehicle, intended to enter service in 2007, will attempt to address these scientific challenges through innovative application of technologies thereby offering the research community new opportunities for cost effective access to some of the world's final frontiers.

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