Oceanographic Research Using Remotely Operated Underwater Robotic Vehicles: Exploration of Hydrothermal Vent Sites On The Mid-Atlantic Ridge At 37°North 32°West

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Abstract
This paper describes three 6000 meter tethered underwater vehicles - DSL-120 sonar, ARGO II mapping system and Jason/Medea remotely operated vehicle - used during the summer of 1996 for an oceanographic expedition to investigate hydrothermal vent sites at the "Lucky Strike" segment (37°N 32°W) of the Mid-Atlantic Ridge as part of the RIDGE (Ridge Inter-Disciplinary Global Experiment) Initiative (RIDGE,1993). This suite of vehicles has dramatically augmented the suite of deep submergence vehicles available to oceanographers and has resulted in new approaches to deep-sea research.

1. INTRODUCTION
The last decade of oceanographic research has seen underwater remotely operated vehicle (ROV) technology evolve from fragile laboratory engineering prototypes into mature field tools for oceanographic science. These new ROV systems provide unprecedented techniques for oceanographers to explore the world's oceans. Since 1985 when the ARGO was used to discover the wreck of the H.M.S. Titanic in the North Atlantic, ROVs have explored hydrothermal vent fields in both the Atlantic and Pacific Oceans, conducted mid-water acoustical, biological, and physical oceanography experiments, and performed under-ice surveys in both the Arctic and Antarctic Oceans (Bellingham, 1994).

The underwater ROV systems which are used successfully for scientific research appear to share several distinguishing features. First, the engineering research teams developing these ROVs work in close collaboration with practicing oceanographers (Biologists, Geophysicists, Geologists, Marine Chemists, and Physical Oceanographers) to design systems capable of performing surveying, sampling, and manipulation tasks essential to quantitative oceanographic science. Hence, these ROVs are designed to support a great variety of oceanographic instrumentation, navigate precisely, and provide comprehensive multi-modal data-collection. Second, the ROVs are used to perform tasks that are expensive, impractical, or not feasible with other oceanographic field methods such as manned submersibles, surface acoustics, and satellite remote sensing. Third, lessons learned in the field are used to improve the design of current systems, and are incorporated in the designs of subsequent generations of ROVs.

The goals of this paper are to describe the role of ROVs in the context of deep-ocean scientific research, to illustrate the capabilities of present-day systems by describing three underwater systems that were used during a recent oceanographic field expedition as part of the National Science Foundation’s RIDGE Initiative, and to identify engineering research problems that currently limit the performance of operational underwater ROV systems in scientific missions.

2. DEEP-OCEAN SCIENTIFIC FIELD RESEARCH: PAST, PRESENT, AND FUTURE
Two different approaches have traditionally been used for observations and sampling of the seafloor beyond the continental shelf. The first involves lowering different types of instrument packages (to collect acoustic and/or photographic imagery) or sampling devices (to collect geological or biological samples) to the seafloor on the end of a wire from a surface ship. Much of the early seafloor observational research was conducted in this way, and this approach still provides an efficient and relatively inexpensive method of investigation that is best suited to completing scientific objectives requiring sampling over large areas. However, there are a number of limitations associated with these techniques. For example, a camera sled has to be recovered in order to retrieve the photographic film, which then must be processed, reviewed and co-registered with the navigation from the tow in order to geodetically locate features of interest. A dredge haul of rocks provides samples of the types of material present along a given track, but the geologic relations between seafloor features and their different lithologies are lost unless other near-bottom visual or acoustic data are collected.

A considerable advance was made with the increasing use of human-occupied submersibles for deep-sea research (Estabrook, 1977, Mavor, 1966, Vincent, 1963). These allow one or two scientists per dive to make direct observations of the geologic and tectonic relationships of seafloor features, and to make real-time sampling decisions. Every sample, whether geological, chemical, or biological, is precisely located on the seafloor relative to its well-characterized geologic setting or ecological habitat. In addition, dexterous manipulative capabilities of submersibles, and their capacity for large payloads, enable researchers to deploy and service instruments and experimental equipment on the seafloor at precise locations. Several submersibles, operated by
different countries, have been used routinely for oceanographic research for many years. For instance, the DSV Alvin, operated by the Woods Hole Oceanographic Institution, has completed over 3000 dives, with a >95% success rate over the last 10 years. Although considerably more expensive than instrument deployments from surface ships, observations from submersibles have been key to discovery of unique geological, geochemical and biological phenomena, and to furthering our understanding of many important seafloor processes.

The latest technological developments in fiber-optics and robotics, and their application to deep-sea investigations, have added additional capabilities that complement the two approaches described above and provide new strategies for carrying out deep submergence research programs (Kyo, 1995, Yoerger, 1992). The use of fiber-optic cable to transmit data - with both towed instrument packages and remotely-operated vehicles (ROVs) - allows scientists on board a surface ship to view and react to sensor data and acoustic and video/photographic imagery in real-time. Real-time capabilities permit nested survey strategies, in which data collected at a broad scale with one vehicle can be used immediately to plan subsequent smaller-scale surveys during the same cruise (Fornari et al. 1997). Nested surveys are especially important when working in logistically remote locations where staging expenses prohibit timely return to a site.

The new deep submergence systems and survey strategies are proving extremely valuable to the RIDGE scientific community because they allow measurement and sampling strategies to be tailored to each situation encountered during a cruise. This is particularly critical to studies aimed at understanding the dynamic physical, chemical and biological processes occurring at hydrothermal systems - a key objective of the RIDGE Initiative (RIDGE, 1993).

A 1996 RIDGE cruise to the Lucky Strike hydrothermal field located on a seamount near 37°17'N in the rift valley of the Mid-Atlantic Ridge (Figure 1) provides an example of how scientific exploration can be optimized using a nested survey strategy. Scientific goals of the field program included examining the hydrothermal activity within the context of the structural geology of the region (at a scale of km²), as well as study of the biological and chemical characteristics of the hot springs themselves (at a scale of m²). The DSL-120 sidescan sonar system was first used to collect 120 kHz sonar data (in 1 km swaths) and co-registered bathymetry over a 26 km-long portion of the rift valley to investigate relations between crustal accretion processes at the segment-scale. This was followed by more detailed investigation of the summit of the seamount using the ARGO II optical/acoustic imaging system to collect high-resolution acoustic and photographic imagery to establish the geotectonic setting and distribution of hydrothermal vents. Based on these data, several hydrothermal sites were then selected for detailed imaging and collection of samples using the ROV Jason. The creative use of this combination of vehicles proved very powerful in terms of achieving the scientific objectives of the cruise. The large amounts of data that were collected at a variety of scales provided both synoptic overviews as well as detailed, high-resolution observations.

An added advantage of data transmission to the surface from a mapping vehicle or an ROV is the ability for several scientists to simultaneously make observations and participate in the real-time decision-making process, rather than one or two scientists in a submersible working in relative isolation. This is particularly helpful during field programs that are multidisciplinary, such as studies at hydrothermal sites on mid-ocean ridges. Having geologists, chemists and biologists "present" at all times allows the work to proceed along a strategy based on integrated interpretation of all the data. Observations can be made by the appropriate specialists and directly entered into a computer logging program as the work proceeds. This results in more consistency in the description of seafloor features and biological organisms/habitats than is achieved by scientists who each participate in a limited number of dives during a submersible field program. In addition, the database constructed in real-time can be used for preliminary mapping of major geologic units and biological communities within a short period of time (<24 hours) following collection of the data and merging of the navigational information. Sample collection and experimental manipulations are also optimized by the "presence" of multiple scientists. The appropriate specialists can select their own sampling sites and can direct the experimental or sampling procedures, thus avoiding others having to take this responsibility.

Another important function of the tether cable is to supply electrical power to the vehicles from the surface rather than from subsea batteries built in the towed instrument package or submersible. This means that tethered ROV lowerings can last for many days with data being continuously collected. ROV and tethered vehicle field programs require three teams of scientists to provide direction and maintain the data and sample collection process throughout each 24-hour period, making it very people-intensive. For example, on the Lucky Strike cruise, the ARGO II lowering lasted five days, during which over 24,000 digital images of the seafloor (Figure 2) (together with other photographic and acoustic imagery) were collected.
Figure 1: Simrad 100 m gridded bathymetry (from Derick, 1995 unpublished data) for the Lucky Strike segment showing general areas surveyed using the DSL-120 sonar system. (S. Humphris and Dan Fornari/WHOI © 1996)
For remotely operated vehicles, the extended on-bottom time (compared with submersibles which have to be recovered every 8-12 hours to recharge batteries and rest personnel) is partially offset by two factors. First, in order to move the ROV beyond its tether length (i.e. 35 m in the case of ROV Jason), coordinated and sometimes time-consuming maneuvers of the ship are necessary. Second, the small payload of current ROVs relative to submersibles for instrumentation, sampling devices, and samples results in the use of elevators to take equipment/samples down to the bottom and return them to the surface. Consequently, driving to the elevator site and transferring equipment and samples can be time-consuming. Improvements to elevator design and deployment are needed to minimize the transfer times.

Although ROVs do not, as yet, have as great a payload capability or the human stereoscopic cognitive presence that submersibles offer, they can carry out many of the traditional tasks that submersibles have performed in the past, and they can remain submerged for long periods of time continuously transmitting data to the surface. They also offer vastly increased performance in high resolution sonar and image-based mapping investigations of small areas compared to submersibles.

3. ENGINEERING AND OPERATIONS: DSL-120, ARGO II, AND JASON/MEDEA

3.1 Operations

Jason/Meadea, ARGO II, and the DSL-120 are normally deployed from a dynamically-positioned surface ship such as the 3000 ton R/V Knorr (Figure 3). The vehicles are connected to the ship via custom-manufactured fiber optic cable with a diameter of 0.68", a length of 9 km, and a strength of 200 kN. Inside the triple-layer tension elements of the cable are 3 copper conductors and 3 optical fibres. Copper conductors supply the vehicle with about 20 kVA of electrically isolated 1800 Volts AC power at 400 Hz. This is transformed and rectified on the vehicles to supply 120V DC. One of the three optical fibers is reserved for digital data telemetry from the vehicles. The other two fibers provide four video channels. The capacity of a single fiber is 1.2 Gbits/sec, and at present the digital data telemetry rate is about 125 Mbits/sec. This type of cable must be spooled and stored with near-zero residual tension. The 24500 kg DYNACON cable handling system consists of three main parts: a drum with cable (13200 kg), a level-winder unit (1100 kg), and traction winch unit (10200 kg). The unit is able to spool with the normal 4500 kg operating load at a maximum 120 meters/minute.
Two 20' shipping containers have been specially modified to bolt-together to form a portable “mission control center” for conducting vehicle operations (Figure 4). The Woods Hole DSOG (Deep Submergence Operating Group) crew can install the entire system on a surface ship in about 3 days. Once installed, operations are directed by five key people in the control van in close collaboration with the officers and crew on the ship's bridge. The pilot maneuvers the ROV and remotely operates its on board equipment. The navigator monitors the vehicle acoustic navigation and pilots the surface ship via closed-loop dynamic positioning. The engineer keeps track of all life functions of the vehicles and instruments and assists the pilot. These three individuals coordinate their efforts to collect scientific data and samples under the direction of the chief scientist. On a long duration cruise, the vehicles are typically operated 24 hours a day by three complete crews of operational personnel.

3.2 Navigation

The physical location of surveys and sampling operations must be carefully documented in a standard international geographical coordinate system. Military submersibles commonly employ inertial navigation systems (INS) for absolute 3-D navigation, but the high cost of these systems has precluded their widespread use in underwater ROVs. Acoustic navigation is the most commonly employed technique for absolute 3-D navigation of underwater ROVs.

Two types of Long Baseline (LBL) acoustic navigation systems are commonly used and commercially available. One system operates at frequencies around 10kHz over baseline lengths about twice the water depth.

Its accuracy ranges around two meters. The other type of LBL systems typically operate at frequencies from 100 kHz to 1 MHz and deliver a range resolution of a few centimeters. Due to the attenuation of high frequency sound in water, the range of this system is limited to a few hundred meters. Update rates for both types of systems are limited by the speed of sound in water, about 1500 meters per second, which determines the travel time of an acoustic pulse. The low frequency LBL navigation was used for the Lucky Strike field program. It works on the principle that distances between any two transponders can be computed directly from the round trip time of an acoustic pulse traveling between the two transponders. The LBL navigation systems components are: (i) seafloor based transponders, (ii) relay-transponders on the vehicles, (iii) transducers on the vehicles, (iv) hull-mounted transducers onboard the surface ship, and (v) a highly accurate GPS (differential GPS or military P-code GPS) on board the surface vessel. The relative position of the vehicle in the transponder network can be computed from the known positions of the anchored transponders (determined by a ship survey of the transponder net) and the sound velocity profile. The accuracy of LBL navigation can be as good as +/-2 m with a 1 km baseline. When the terrain is not flat, the transponders are moored above the sea-floor on long tethers (100-300 m) to reduce acoustic shadowing due to the terrain, although this makes the system susceptible to bottom currents, frequently as a result of tides, that periodically "move" the transponder positions.

3.3 DSL-120 SONAR

The DSL-120 vehicle (Figure 5) is a deep-towed side-looking sonar platform designed for continuous operations down to 6000 meters depth. It was developed by Dr. Kenneth Stewart's research team of the WHOI Deep Submergence Laboratory in collaboration with the Applied Physics Lab at the University of Washington.

DSL-120 is a 120 kHz high-resolution swath sidescan sonar designed to detect both magnitude and phase information of sonar pulses. These data can be used to generate high resolution (1-2 m vertical and horizontal pixel resolution) acoustic backscatter and bathymetric maps. The vehicle is neutrally buoyant, and is connected to a 1000 Kg depressor weight by a neutrally buoyant tether 50 m in length. The depressor weight serves to isolate the vehicle from the ship's motion. Vehicle depth is controlled by varying the length of the main cable. The vehicle is normally towed at approximately 2 km/h at an altitude of about a 100-200 m above the seafloor. At this height, the transponder span extends about 0.5 km to either side of the vehicle, and the swath of phase bathymetry is about 800 m wide.

A computer-based processing system on board the surface ship receives real-time telemetry from the vehicles via optical fibers, displays the sidescan data in real-time, and time-stamps the data to permit cross-referencing to vehicle navigation data, and logs the data...
to disk and tape. These data, including vehicle attitude, are then used to generate high resolution backscatter and bathymetric maps in near-real-time.

3.4 ARGO II

ARGO II (Figure 6) is a 2100 kg optical and acoustic imaging sled designed to operate at depths to 6000 meters. The original ARGO was a coaxial camera platform developed at the WHOI Deep Submergence Laboratory in the early 1980s. In 1994, ARGO II was constructed (using ARGO’s original steel frame) as a next-generation computer-controlled fiber-optic vehicle. As with the DSL-120, ARGO II’s depth is controlled with the traction winch that varies the cable length. ARGO II is equipped with two laterally mounted thrusters that enable the pilot to remotely control the vehicle heading and lateral position under joystick control. ARGO II is normally towed at about 10 m above the sea-floor at a speed of about 1 km/h.

ARGO II is equipped with three Silicon Intensified Target (SIT) b/w cameras, one color camera, one 35mm film camera, and an Electronic Still Camera (ESC). All cameras can be viewed in real-time on the surface ship. Illumination is provided by 2500 Watts of incandescent flood lighting and four 800 Watt/second strobe lights. The ESC produces 576x384x12-bit images of the seafloor. With altitude and position information, scientists use the ESC images to construct mosaics of the sea-floor. The vehicle can be equipped with a transmissometer, a conductivity-temperature-depth (CTD) sensor, 3-axis magnetometer, 100kHz (for obstacle avoidance) or 200kHz split-beam sidescan sonar, scanning pencil-beam sonar, and a variety of additional scientific instruments. Analog, digital, and serial interfaces are provided to support a wide variety of science instrumentation. All data is time-stamped and logged in real-time on the surface ship.

3.5 Jason/Medea

Jason (Figure 7) is a 1200 kg ROV designed for operations at depths to 6000 m. The Jason/Medea system was developed at the WHOI Deep Submergence Laboratory, and first deployed in the Mediterranean in 1989. Since that time Jason/Medea has been deployed on several scientific missions around the world. Like ARGO II, the Jason/Medea system became part of the Deep Submergence Operations Group, a U.S. national research facility, in 1995.

Jason is neutrally buoyant, and is connected to a 1000 kg depressor weight (Medea) by a neutrally buoyant tether 35 m in length. The ROV is fully actuated with 7 brushless DC thruster motors that enable the pilot to freely maneuver Jason with a top speed of about 2 km/h. The vehicle is passively stable in roll and pitch; position and heading are actively controlled. It can be operated in either open-loop or fully closed-loop positioning modes.

In 1992, Jason was upgraded with a new, modern 32-bit control system with extensive data processing and I/O capabilities (Yoerger, 1992 and Whitcomb, 1994). Jason and ARGO II now share this common computer control system. The custom on-board computers, telemetry, and power electronics occupy three cylindrical titanium pressure housings 15cm in diameter and 1m long.

Video images from Jason’s cameras plus video from Medea’s black and white camera are up-linked in real-time to the control room on the support ship, where they are viewed by a pilot who flies the vehicle remotely under joystick control. In addition, Jason supports a variety of instruments not supported on ARGO II, including a pan/tilt camera platform. Jason is also
equipped with a custom-designed 5-axis robotic arm that is operated by the pilot. This arm, coupled with the vehicle’s high maneuverability, enables Jason to perform a wide variety of scientific tasks including temperature measurements, deployment of experiments, and sampling of water, rocks, sediments and biological organisms.

Figure 7: JASON, a 6000 meter underwater ROV for oceanographic research developed and operated by the Woods Hole Oceanographic Institution. (Margaret Sulanowska/WHOI ©1996)

3.6 Elevator System

Tool and sample storage on Jason quickly become limiting during extended deployments. When the vehicle's maximum payload capacity is reached, samples and/or tools must be off-loaded into an independent vehicle deployed at the work site. The elevator (Figure 8) consists of a basket (volume of ~4m$^3$) equipped with five 17” glass flotation spheres and one 17” acoustic transponder. The device is released from the surface ship after careful consideration of its likely drift direction during descent to land as close as possible to the worksite. After the elevator is filled with samples and tools by Jason, the anchor release is triggered acoustically from the surface ship or manually by the ROV. During the summer 1996 cruise, eight elevators were deployed and recovered at various locations.

Figure 8: An elevator being deployed from R/V Knorr. (Margaret Sulanowska/WHOI ©1996)

A variety of open issues in the dynamical modeling and control of both vehicles and their actuators have yet to be resolved. Improved navigation is an essential prerequisite of improved closed-loop vehicle control. Our ability to reliably manipulate subsea objects and perform tasks with on-board robot arms in closed-loop control is primitive. Moreover, improved vehicle control performance and manipulation capability is essential to the development of the next generation of untethered underwater vehicles. These untethered vehicles present novel engineering challenges due to their inherent power and telemetry constraints.

The enormous multi-modal data sets generated by underwater vehicles (often amounting to Tera-bytes of data) present unique data-processing challenges. The data-set generated during a typical deployment might include still film images, digital electronic images, video, several different types of sonar data, navigation data, data from perhaps dozens of scientific instruments, and actual physical samples. New computational tools for accessing, integrating, searching, and visualizing these data sets will dramatically increase their utility and dissemination among ocean scientists.

4. CONCLUSION

The engineering development of ARGO II, Jason/Medea, and the DSL-120 has been driven by the goal of collecting high-quality scientific data sets and samples. Close collaboration with ocean scientists interested in exploring new methodologies of subsea scientific research has been key to the success of this endeavor.

A number of technical problems remain to be solved. The need for more accurate and reliable subsea navigation methods is acute. While long baseline acoustic navigation is likely to remain the standard methodology for large scale survey operations, significant improvements are needed in the range, sensitivity, and accuracy of LBL instrumentation. Novel hybrid navigation methodologies incorporating technologies such as LBL, ultra-short baseline acoustic, doppler acoustic, optical, and inertial navigation hold promise of dramatically improving operational navigation capabilities and enhancing scientific productivity.
scientific problems, will have a major impact on future approaches to deep-sea research, exploration and monitoring experiments at seafloor observatory sites.

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