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Woods Hole Oceanographic Institution

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THE JASON REMOTELY OPERATED VEHICLE SYSTEM

by Dr. Robert D. Ballard
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Abstract - The JASON remotely operated vehicle (ROV) system has been under development for the last decade. After a number of engineering test cruises, including the discovery of the R.M.S. *Titanic* and the German Battleship *Bismarck*, this ROV system is now being implemented in oceanographic investigations. This paper explains its development history and its unique ability to carry out a broad range of scientific research.

INTRODUCTION

Prior to 1972, large-scale geophysical and geological investigations resulted in the emergence of a new global theory called Plate Tectonics which explained the structure and dynamics of the earth (ref. 1). Central to this theory is the Mid-Ocean Ridge (MOR); a 72,000-km (40,000-mile) long mountain range which is the largest feature on the earth (ref. 2). The MOR is of particular interest to earth scientists because it is along its axis that newly formed crustal material is being emplaced volcanically and subsequently rifted and transported laterally by tectonic forces associated with diverging crustal plates (ref. 3). The geophysical measurement techniques used to define this global theory (i.e., gravity, heat flow, magnetics, seismology, and regional bathymetry) lacked the resolution necessary to delineate the detailed geological processes taking place along the rifted axis of the MOR. Based on these large-scale investigations, however, it became clear in the mid-1970's that a better understanding of ridge axis processes required the application of traditional land-based field mapping techniques using manned submersibles (ref. 4).

The first major scientific program to investigate the MOR using manned submersibles was Project FAMOUS (French-American Mid-Ocean Undersea Study) and took place between 1972 and 1974 (ref. 5). The goal of this project was to use diving vehicles to address a number of important geological questions within the rift valley on a segment of the MOR called the Mid-Atlantic Ridge (MAR). The three manned vehicles used during Project FAMOUS were the French bathyscaph ARCHIMEDE and the submersible CYANA as well as the American submersible ALVIN (ref. 6). In all, forty-two dives were made, which collected 1,360 kg (3,000 lbs.) of carefully selected rock samples and over 100,000 photographs along a network of precisely navigated geologic traverses across the rift valley and in the adjacent transform faults (ref. 6, 7). Project FAMOUS was a highly successful program that resulted in a number of important scientific articles and proved the value of manned submersible operations in the deep sea (ref. 7).

FAMOUS was followed in rapid succession by a series of equally important scientific expeditions using manned submersibles in the Cayman Trough (ref. 8), Galapagos Rift (ref. 9), and East Pacific Rise (EPR) (ref. 10) and on return trips to the MAR (ref. 11). These subsequent efforts resulted in major new discoveries in marine science including hydrothermal vent fields and their unique benthic communities in the Galapagos Rift (ref. 9) and polymetallic-sulfide deposits and "black smokers" on the EPR at 21° North (ref. 10).

This ten-year period from 1972 to 1981 was clearly the "decade of manned submersibles." But despite their many successes which continue to this day (ref. 12), manned submersibles have certain inherent technological characteristics that will always limit their ultimate efficiency. An average dive on ALVIN, for example, results in three to four hours of actual bottom time (ref. 13). Manned presence also requires the submersible to be large and expensive for reasons of life support and safety and only one or two scientists can participate on each dive. A typical vehicle weighing twenty tons requires a large, expensive ship and sophisticated handling system. Space is also limited inside the pressure sphere which greatly reduces the supporting documentation a scientist can carry as well as instrumentation for data acquisition and analysis.

An average manned submersible expedition lasts 21 to 28 days, during which any one scientist in the science party may make 3 to 5 dives (ref. 13). In other words, three weeks to a month at sea will result, on average, in nine to fifteen hours on the bottom for each participating member.

Finally, it is important to point out that "manned" operations are not truly manned. Unlike the astronauts on the moon, a scientist cannot get out of the submersible and walk around on the bottom of the ocean using their hands freely to pick up samples or place instruments. An aquanaut is trapped inside the pressurized capsule, must look through a small window to see the outside world, and must use a mechanical arm to pick up samples or do desired manipulation. In other words, "manned" submersible operations are by definition partially "unmanned" at best.

Despite all these inherent limitations, the scientific community made the decision in the late 1970's and throughout the 1980's that taking a scientist to the bottom of the ocean was worth the expense given the unique contribution they could make in-situ. This decision proved wise and resulted in some of the most important discoveries ever made by marine scientists seeking to better understand the geology, geophysics, biology, and chemistry of the deep sea (ref. 7, 9, 10, 14).

By the early 1980's, however, new technological innovations made it possible to develop a new exploration vehicle system that would be neither manned nor unmanned but a hybrid of the two (i.e., a "teleoperated" system). A teleoperated system permits an operator to control a vehicle from a distance by means of either a tether or acoustic link. A distributed control system permits the operator to change easily from full robotic control to manual control as well as a continous series of combinations between these two extremes (ref. 15).

Teleoperated systems are particularly useful in the deep sea since, as previously stated, the operator cannot leave the pressure sphere and work under ambient conditions. The basic question is, "Where is the person located when they are looking out the viewport or operating the manipulators?". Since manipulator commands can move back and forth between the operator and the end effectors at the speed of light, being situated in the pressure sphere or on the surface makes little difference. The correct question to ask is "Is the view the operator has of the environment they are working in superior from inside a manned submersible or can that view be replicated by a teleoperated vehicle system controlled from the surface?". Compared to the early unmanned vehicles like Deep-Tow and ANGUS used during Project FAMOUS (ref. 16,17), manned presence was clearly superior. Neither of these vehicles could be dynamically controlled to the precision necessary to carry out manipulation and the bandwidth of the data link of Deep-Tow would permit only a slow-scan black-and-white image to be transmitted to the surface.

By the early 1980's, however, the development of fiber-optic cables, digital low-light level imaging systems, and advances in robotics and control (ref. 18) made the development of an advanced teleoperated unmanned vehicle system possible.

JASON DEVELOPMENT PROGRAM

(Basic Design Constraints)

In 1982, the Deep Submergence Laboratory (DSL) was formed at the Woods Hole Oceanographic Institution (WHOI) to develop the first deep water teleoperated exploration vehicle system for the scientific community.

Funding for this integrated exploration vehicle came from three primary sources: the Office of Naval Research (ONR), the Office of Naval Technology (ONT), and the Deep Submergence Systems Division of the Deputy Chief of Naval Operations for Submarine Warfare (Op-23). Additional support came from the National Science Foundation (NSF) to partially fund the development of the fiber-optic cable technology and a shipboard dynamic positioning system.

Figure 1 illustrates the basic elements of the JASON system which includes a dynamically controlled surface ship, shipboard control center, fiber-optic wire and winch system, the MEDEA relay vehicle, the remotely operated vehicle JASON, a satellite link, and shore-based control and data processing center(s).

The short-term goal of this development program was to place the human operators in an advanced control center aboard ship connected by a high-bandwidth fiber-optic tether to the vehicles below. The long-term objective of the program, however, is to permit a larger network of scientists to have full participation in the at-sea operations from shore-based satellite downlink sites, including full control of the vehicles from shore.

Figure 1: Schematic of MEDEA/JASON remotely operated vehicle system deployed from dynamically positioned surface support ship. Real-time signals transmitted up the fiber-optic cable are relayed to shore-based station by way of a satellite link.

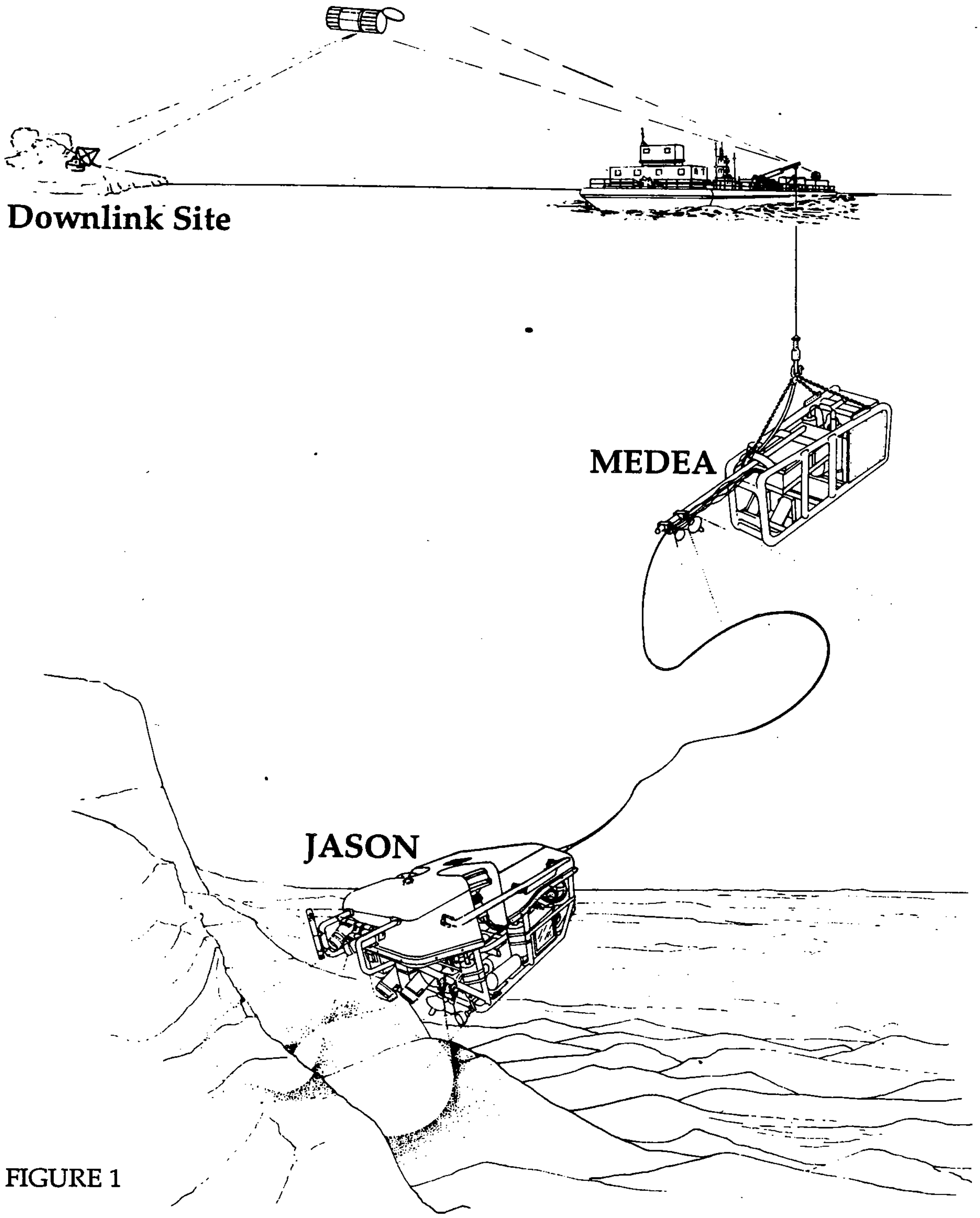


FIGURE 1

Although a teleoperated system like the JASON vehicle can perform a wide range of missions in the deep sea, the primary purpose for its development was an outgrowth of the earlier ALVIN geological mapping programs carried out on the Mid-Ocean Ridge.

Exploration and mapping in the MOR requires an overlapping family of vehicles and associated sensors that allow an investigator to look at a broad range of features varying in size from entire segments of the mountain range to individual lava flow forms. Figure 2 illustrates the spectrum of sensors used to span such a range of scales. It clearly demonstrates the classic trade-off in range versus resolution. Acoustic sensors like multi-narrow beam sonar systems and side-scan sonars are used to obtain a large-area view of the underwater terrain while visual systems like ANGUS and human observers inside a submersible can document small-scale features.

Historically, a gap existed between acoustic and visual imaging systems. Scientists found it difficult at times to cross-correlate acoustic and visual data sets. During Project FAMOUS, for example, scientists diving in ALVIN found the detailed multi-narrow beam sonar maps they carried with them to be a more generalized representation of the seafloor morphology than they initially expected. Depressions were found to be much deeper and adjacent volcanic peaks separated by narrow ravines were, at times, contoured as a single volcanic edifice, greatly complicating the mapping effort.

Given this traditional "gap" (shaded area in figure 2) in the mapping systems available to geologists at that time, the design objective of the JASON development effort as well as of the towed vehicles ARGO and the AMS-120 (ref. 19) was to bridge this gap with the combined use of high-frequency acoustic sensors and low-light level large-area visual sensors as well as by high-resolution visual-imaging devices and remote manipulation.

In short, the goal of the program was to make it easy for an investigator to move from one scale of geologic features to the next independent of whether one data set was collected with an acoustical sensor and the other with a visual imaging sensor. This approach to multisensor terrain modelling heavily influenced the development program (ref. 20, 21, 22).

In such a model, underwater features are viewed as a composite of three-dimensional spatial decompositions of cubical volume elements called voxels. A voxel is represented by a stochastic multisensor feature vector that characterizes the physical properties within each volume. Such modelling is an evolving process. As a new sensor is used in a previously mapped area, its data are merged with the previous data set using what has been termed a stochastic backprojection. Using this approach, information about the physical properties of the terrain occupying a particular voxel can be combined with earlier data regardless of whether these different sets of information

FIGURE 2

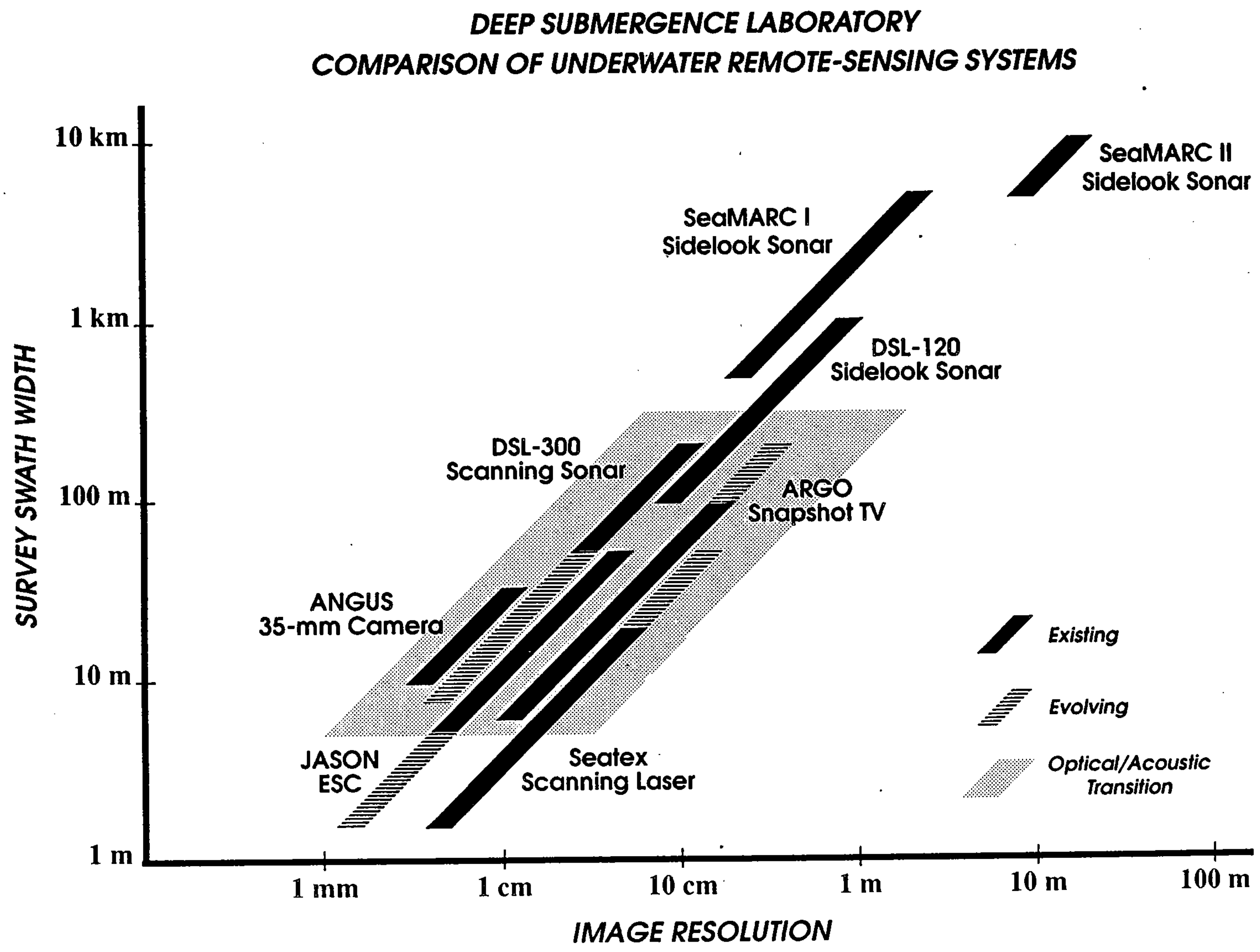


Figure 2: Comparison of various underwater mapping systems based upon their survey swath width versus their image resolution. The ARGO/JASON development program concentrated on shaded area where transition occurs between optical and acoustic sensors.

were obtained using a digital acoustical or visual sensor. One data set is no longer compared to a previous data set; it is combined to provide a better representation of the terrain under investigation.

But having the theoretical potential to develop multisensor modelling of various deep underwater terrains like the MOR is not the same as having the operational capability to produce high-quality data. To do that requires the development of vehicle system(s) equipped with high-resolution digital sensors operated at a level of precision and control not possible at the time the JASON development began in 1982. It was recognized early in the JASON development effort that hydrodynamic nonlinearities would dominate efforts to control the vehicle precisely enough to permit multisensor modelling and sophisticated manipulation (ref. 15).

At a number of levels, navigation is central to the precise vehicle control needed to accomplish the design goals of the JASON system. The first level of control needed was the development of a dynamic positioning system.

A number of dynamic positioning systems existed in the early 1980's, primarily within the offshore oil and gas industry, but their principal goal was to dynamically position a ship, not vehicles suspended at great depth beneath them.

To accomplish this task required a higher level of control dominated by the nonlinear behavior of the ship in varying wind and sea conditions, the behavior of the suspended fiber-optic cable connecting the teleoperated control center on the surface to the relay vehicle 7,000 meters (20,000 feet) below, and the hydrodynamics of the vehicle itself (ref. 23, 24, 25, 26).

To develop the software necessary to provide the desired level of dynamic control, an experiment was carried out in the Navy's AUTEC range, where the three-dimensional behavior of the cable under a variety of towed and stationary maneuvers could be carefully documented. A 0.68-inch tow cable similar to the JASON fiber-optic cable then under design was instrumented for high frequency motions, primarily those caused by vortex-induced vibrations, using self recording accelerometers. The highly accurate tracking system in the AUTEC range itself was used to measure low-frequency motions (ref. 27, 28, 29, 30). This experiment proved highly successful, confirmed the previous cable and vehicle dynamic modelling (ref. 23), and led to new insight into vortex-induced vibration for a deep-water ROV system.

Based upon these test results, an initial dynamic positioning test was carried out on the R/V KNORR in September of 1987. The tests were conducted in 2,700 meters of water under moderate sea conditions (sea state 2.5; winds of 8-15 knots) without a vehicle or cable. The station-keeping performance of the ship was excellent with a 25 meter root-mean-square (RMS) using an acoustic long-baseline system and 12 meters using a global satellite tracking system.

A final combined test of the ship-cable-vehicle system was conducted in August of 1988 with the R/V KNORR. Tests were carried out in water depths ranging from 700 to 3,000 meters using what would eventually become the MEDEA relay vehicle. The tests were successful and provided excellent results and further refinement to the modelling dynamics.

The next level of navigation and control dealt with the JASON vehicle itself. The dynamic positioning of the relay vehicle (MEDEA) within its 15-meter watch circle and the use of a neutrally buoyant tether connecting it to JASON, decoupled the surface motion propagated down the cable to the relay vehicle and did not transmit those motions to JASON. Therefore, JASON was free of surface action and capable of precise control.

Existing bottom-mounted acoustic-transponder tracking systems, however, lacked the precision necessary to control JASON for the highest level of multi-sensor modelling. To meet this requirement, two high-frequency navigation systems were developed. The first was called SHARPS and was developed with two initial applications in mind. Since the development of JASON would take over 5 years and involve a great deal of testing in a small test tank, a precision navigation system was needed which could operate in a small tank having numerous acoustic multipaths.

SHARPS filled this need. It is a 300-kHz broadband hardwired transponder navigation system that can operate inside a metal test tank. Angular resolution is about 1 degree, range resolution is better than 2 cm, and the maxium update rate is 10 samples/second. A three-transponder array can cover an area approximately 100 meters on a side. Since MEDEA is hardwired to JASON, the SHARPS system can also be used to precisely determine relative relationships between both vehicles while working in the deep sea.

The second system developed is called EXACT and has characteristics similar to the SHARPS system, only it is wireless and has a maximum update rate of 5 samples/second. This system is ideal for deep-water ROV operations where a hardwired system is impractical. The bottom transponder network is self-calibrating and can be used to navigate both MEDEA and JASON relative to the bottom or relative to a long-baseline transponder network fixed within geographical coordinates. Navigation relative to the bottom terrain using this system is better than 2 cm. With the EXACT system the desired navigational precision needed to control JASON for multisensor modelling can be achieved.

Good navigation, however, must be complemented by a good control design. In addition to a precise knowledge of the vehicle's x, y, and z positions, multi-sensor modelling requires a great deal of information about the vehicle's behavior, and special care must be given to its basic design. As a result, JASON's control sensors include instruments that measure acceleration and attitude. The vehicle's heading is determined by a flux-gate compass and a directional gyro. Acceleration is measured in three axes using servo accelerometers, and pitch and roll is measured using a two-axis inclinometer. Absolute depth and the vehicle's altitude off the bottom are also recorded.

(Early Operational Experience - JASON Design Phase-1982 to 1989)

Prior to the construction of the JASON vehicle, a variety of existing ROVs were tested in the Lab's tank and off the dock under dynamic closed-loop control using the SHARPS tracking system.

The dynamics of a vehicle in the deep sea are nonlinear, and care given during the design phase of a vehicle can greatly enhance its performance in the field. During these early tests, particular attention was given to eliminate open-loop coupling between translations and rotations by placement of the vehicle's thrusters relative to the vehicle's centers of mass and drag. An analysis was carried out of JASON's ducted thrusters, which are difficult actuators to control. This static and dynamic analysis of the thrusters, however, reduced the uncertainties associated with their thrust characteristics and improved their low-level control over the thrusters broad dynamic range (ref. 31).

During the JASON vehicle design a series of tests was conducted in the tank facility to determine how well an ROV could be controlled. These tests included automated track following and an interactive mode called "joystick auto." In the first case, the vehicle was commanded to follow prearranged tracklines. This could be a typical request from a scientist who wanted to make a detailed acoustic or visual survey of a small area like a hydrothermal vent field. Previous users of manned submersibles and other ROV systems have found that both classes of vehicles are very poor side-scan sonar platforms because they lack the ability to control their heading. The ROV used in the test, however, could control its heading to less than one degree and run automated tracks with RMS off-track errors of 0.36 meters (ref. 32).

Figure 3 illustrates the second trials conducted using an interactive automatic mode. During "joystick auto" the vehicle is in closed-loop control in all axes but the pilot can provide it with a continuous series of horizontal velocity commands that permit continuous involvement by the pilot during the survey runs but at a greatly reduced supervisory level of control. This greatly decreases the pilot's workload which is mandatory for JASON dive profiles that will last many days instead of a typical submersible dive lasting three hours on the bottom.

The first major vehicle development by DSL engineers was the ARGO search system (ref. 19). Since a new fiber-optic cable was still under design, the first vehicle effort was built around the then standard 0.68-inch coaxial cable used by the academic community.

Figure 3: Test tank results of ROV under closed-looped control using SHARPS tracking system. Dashed lines are desired tracklines while the solid line is the actual track the vehicle followed.

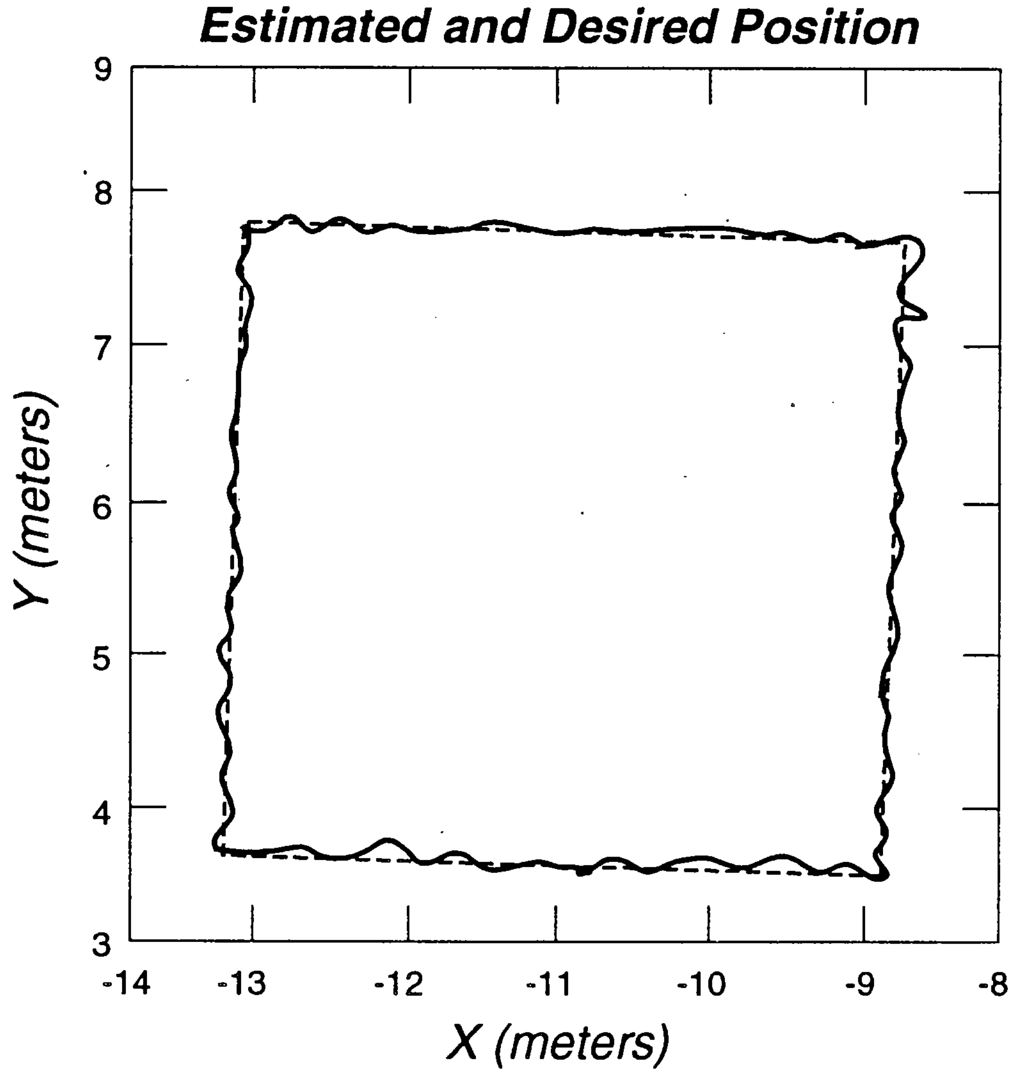


FIGURE 3

ARGO was designed to operate to 7-km (20,000-feet), and included a suite of both acoustic and optical imaging sensors. The acoustic sensors are a standard 100-kHz side-scan sonar and a down-looking altimeter. ARGO, however, is designed to maintain constant visual contact with the bottom. As a result, major emphasis was placed on its visual imaging capability. During its initial design phase, a number of test cruises were conducted with the submersible ALVIN on which was mounted a low-light-level Silicon Intensified Target (SIT) black-and-white video camera. These experiments helped in the design of ARGO's lighting system, which permits useful imagery to an altitude of 15 meters.

Three SIT cameras are mounted on ARGO: a forward-looking wide-angle camera, a down-looking, wide-angle camera, and a down-looking zoom camera. Incandescent running lights mounted approximately 4 meters aft of the cameras provide illumination for real-time video imaging while strobe lights are used in conjunction with color cameras. Color photography, however, can only be accomplished when the vehicle is flown at a lower altitude of approximately 5-7 meters. Later, a cryogenically cooled high-resolution digital electronic still camera (ESC) was developed, that made it possible to obtain high quality images while flying the vehicle at its normal 15-meter operational altitude (ref. 33).

ARGO's first test cruise was conducted in the summer of 1984 for the Navy. Its second cruise in the summer of 1985 resulted in the successful location of the British luxury liner R.M.S. TITANIC (ref. 34, 35).

Since 1985, ARGO has been involved in a number of scientific and military programs including the location of the sunken German Battleship BISMARCK in the summer of 1989 (ref. 36) and two major investigations of the volcanic and tectonic processes occurring along the axis of the East Pacific Rise (ref. 37, 38).

In 1986, following the discovery of the TITANIC by the ARGO search vehicle, the first fiber-optic cable was under design but not yet built, and testing of the dynamic positioning system was still underway.

For these reasons, a decision was made to move forward with the development of a JASON prototype vehicle called JASON, Jr., or JJ, which could be deployed from the submersible ALVIN. This provided additional experience in ROV systems including the development of tether management and vehicle-control systems. JJ's first field deployment proved successful resulting in a detailed inspection of the TITANIC (ref. 39).

In the summer of 1988, a cruise was conducted in the Mediterranean to test the new dynamic positioning system on the R/V KNORR as well as the system's first fiber-optic cable. Both tests proved successful and lead to the final JASON design followed by its construction.

Critical to JASON's ability to collect high bandwidth data is the fiber-optic telemetry system connecting JASON to the team of scientists and engineers working in shipboard control center.

As figure 1 illustrates, two cables are needed to perform this function. The first is a 7-km long 17.3-mm (0.68-inch) diameter steel armored fiber-optic cable, which connects the relay vehicle MEDEA to the surface. The cable contains three copper conductors and three single-mode optical fibers. It also has two contrahelical torque-balanced outer layers of high strength steel that provide a breaking strength corresponding to an 18,000-kg load (40,000 lbs.).

The second cable connects MEDEA to JASON. It is neutrally buoyant, 15 mm (0.60 inch) in diameter, and approximately 100 meters long. Like the tow cable, it also has three copper conductors and three single-mode optical fibers, but uses Spectra fibers instead of steel armor to provide strength at a reduced size and weight. This cable has a working strength of 1,300 kg (3,000 lbs) and a breaking strength of 5,400 kg (12,000 lbs).

MEDEA and JASON (figure 1) were both designed to take full advantage of the large bandwidth available on the three optical fibers. Four continuous video channels are available with up to three being used by JASON or up to two by MEDEA. Each vehicle can support eight different video sources which can be switched from the surface to the available channels. These channels are capable of transmitting near-broadcast quality video signals. Each vehicle also has two audio channels with a bandwidth of 15 kHz.

Both vehicles have a total of ten full-duplex high-speed serial lines, and each is capable of operating at a maximum synchronous rate of 10 Mbit/sec. On both vehicles, one of these full-duplex channels is split into ten low-speed serial channels running at a maximum rate of 9.6 Kbaud. One of the full-duplex high speed channels is used to implement a real-time oriented local area network that provides high level access between all computers in the vehicles and on the surface. The network is based upon an industry standard physical layer (pronet 10) and standard software protocols (TCP/IP). The network provides for improved performance that benefits advanced control of the vehicles and the manipulator. Through a link to an Ethernet on the ship, the network provides science users with high level, low latency access to many vehicle sensors for both data logging and real-time display. In addition to the network, several of the high speed serial lines are also available to the scientist.

PRESENT JASON VEHICLE AND RECENT OPERATIONAL EXPERIENCE

(Sub-Sea Systems)

The initial JASON vehicle design envisioned a relay vehicle that could carry JASON and its tether-management system during the descent and ascent phase of each dive. Once the combined system had reached its operational depth, JASON would drive out of the relay vehicle and carry out its assigned mission until returning to the vehicle for the trip back to the surface (ref. 19).

Since the original ARGO vehicle was not built for this function and it was designed to operate on a coaxial cable, a second and larger ARGO was built in 1989. It was called HUGO which stood for a Huge ARGO system.

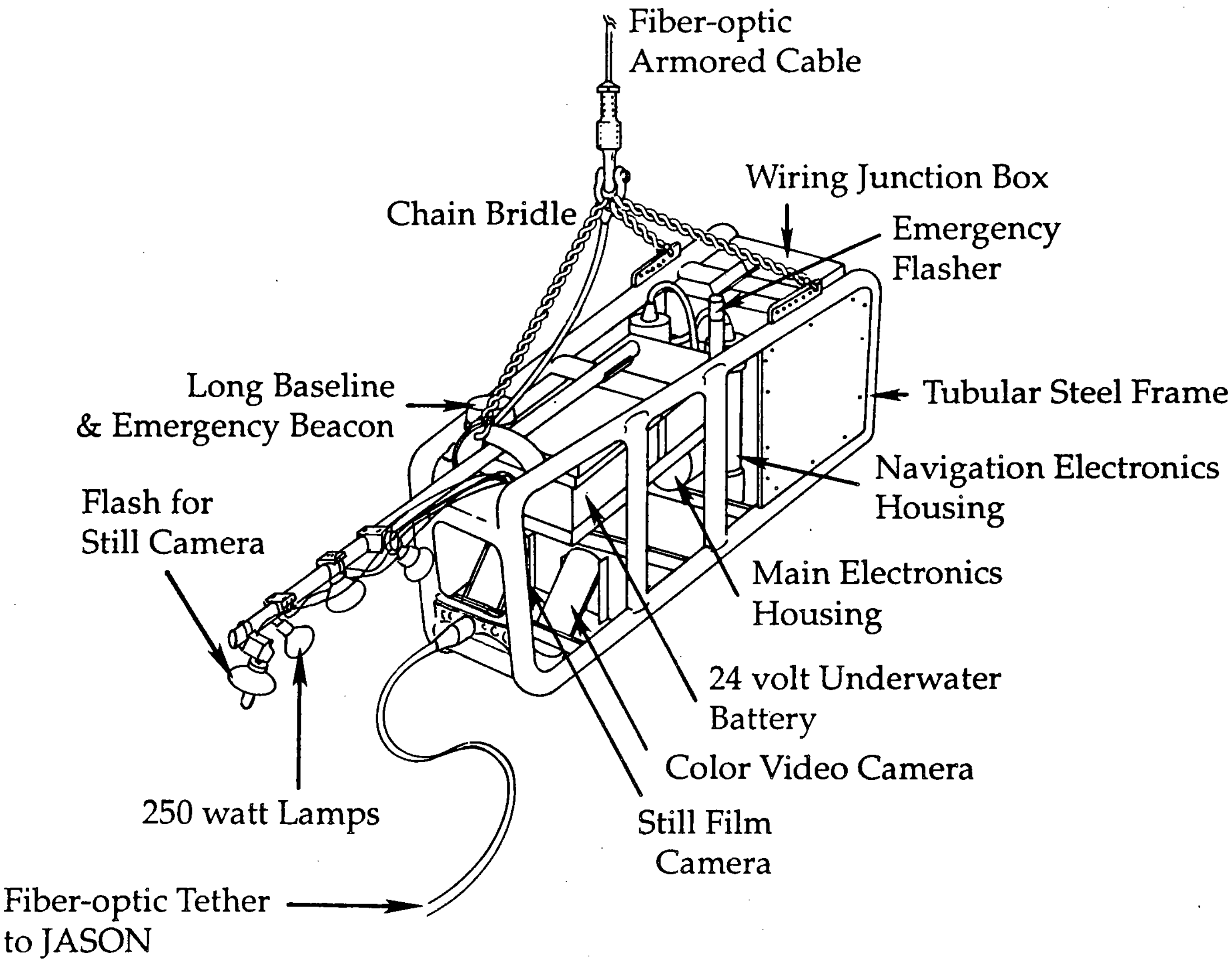
Unfortunately, when this combined system was launched on its first deployment in May of 1989, it proved too light, and severe snap loading during a storm led to the failure of the fiber-optic cable termination and the loss of HUGO and JASON in 3,000 feet of water (ref. 40).

Fortunately, the combined system was recovered using a test sled and the ship's dynamic positioning. Given this experience, however, it was felt a two-body system should be deployed in the future to eliminate such snap loading and greatly reduce the size of the launch and recovery system.

This decision led to the development of the MEDEA relay vehicle as illustrated in figures 1 and 4. MEDEA weighs approximately 500 kg and its main steel tubular frame is about 1.8 meters in length. Its various subsystems are shown in figure 4, most important of which are its black-and-white or color video cameras, navigational beacons, lights, and the junction box where the power lines and optical fibers in the armored cable coming down from the surface are connected to similar copper wires and fibers in the neutrally buoyant cable leading to JASON. It is the MEDEA vehicle which is dynamically positioned by the surface ship and maintains a watch circle of 15-20 meters above JASON. MEDEA serves two primary roles: the first is to decouple surface motions from JASON and the second is to provide the scientists and engineers in the control van with a high-altitude view of JASON. Manned and unmanned operations carried out close to the bottom are easily blinded by small topographic features. It is easy not to see the big picture. MEDEA, which is generally 15 to 30 meters above the bottom can oversee JASON in its work setting and observe a much larger area.

Figure 5 is the most recent illustration of the JASON vehicle. Although its basic subsystems change little from cruise to cruise, its array of sensors continues to evolve and change according to the mission. These major sensor systems are described in greater detail in the following pages.

FIGURE 4



Towed Camera Sled MEDEA

Figure 4: MEDEA vehicle used in conjunction with the JASON ROV. MEDEA acts as a relay vehicle between JASON and surface ship. It damps out surface motions and acts as an "eye in the sky" observing JASON's movements in the terrain below.

FIGURE 5

Remotely Operated Vehicle (ROV) JASON

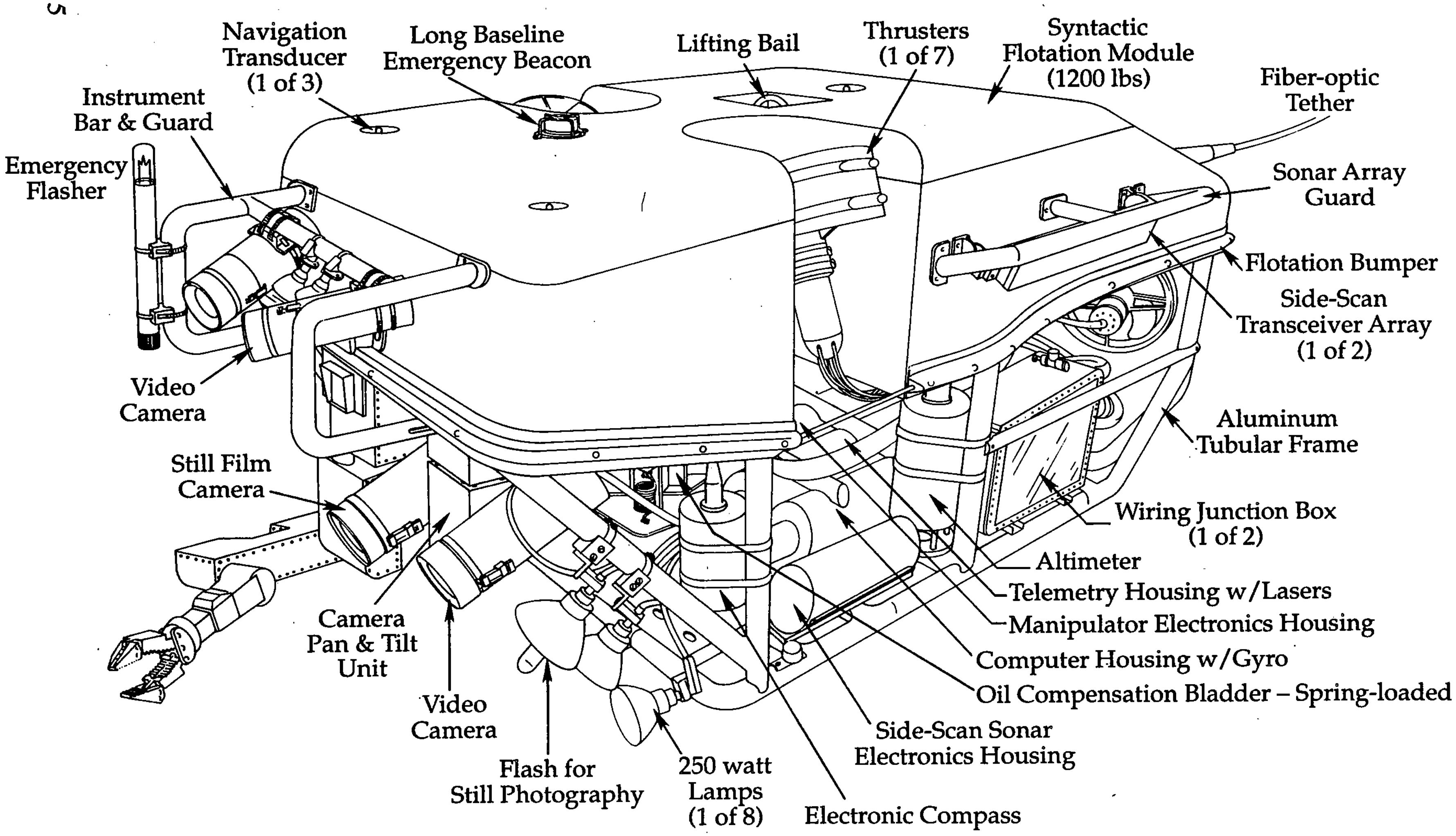


Figure 5: JASON ROV system and its various components. The actual configuration of these components varies as a function of the ROV's particular mission requirements.