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DESIGN AND CONTROL OF JASON

by

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ABSTRACT

The JASON ROV (figure 1) will be used for scientific applications to full ocean depth in concert with the ARGO vehicle. Computer control is crucial to many of the vehicle's scientific, survey, inspection, and manipulation activities. This paper summarizes the various subsystems that together give the system its unique capabilities.

High-performance control is a primary goal. The 6000-meter depth capability also motivates the design. Unique fiber-optic cables and sophisticated video and data handling electronics give the system very good communications capabilities.

ARGO/JASON's power transmission system is capable of transmitting 12KVA over 9 km of 17.3 mm diameter cable.

ARGO/JASON integrates on-board and topside computers with a digital network chosen to meet demanding requirements of bandwidth, latency, and packaging.

KEYWORDS

Design, Control, Fiber optic cables, Networks, Power, Deep Submersible

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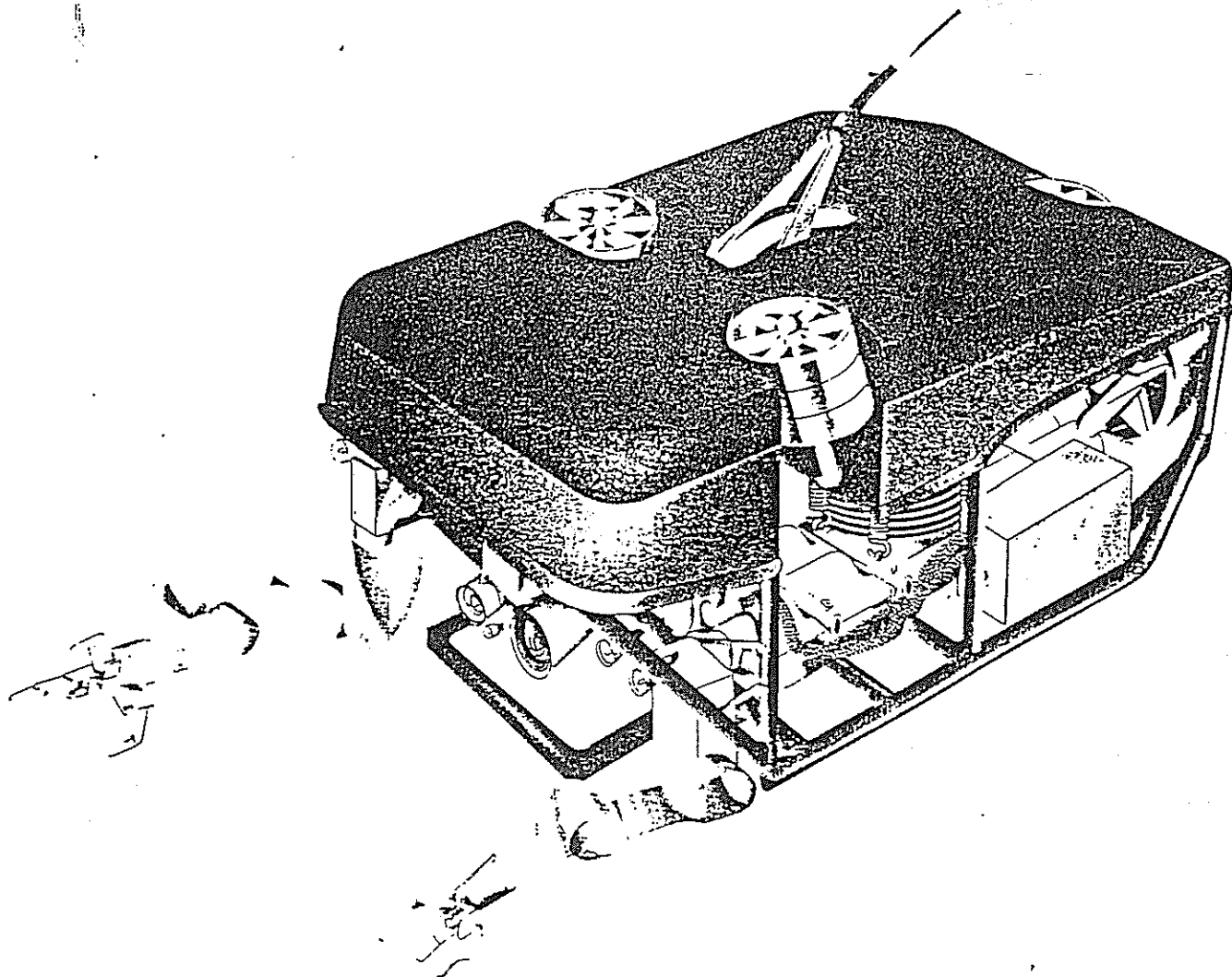


Figure 1: The JASON ROV

INTRODUCTION

ARGO-JASON is a dual vehicle system currently under development at the Deep Submergence Laboratory of the Woods Hole Oceanographic Institution. Its purpose is to provide an integrated capability for wide-area survey of the sea floor with close-up inspection and manipulation at depths to 6000 meters. The first vehicle in the system, ARGO, has been operational since 1985 when it was used to locate the TITANIC. JASON, which will perform close-up inspection and manipulation is currently being prepared for shallow water trials. JASON Jr., a precursor to JASON that operates from the manned submersible ALVIN, was used to survey the TITANIC in 1986.

The JASON vehicle has operational requirements that have strongly influenced its design. The vehicle must work to depths of 6000 meters, must be useful for a variety of scientific missions, and must be a portable system capable of working from a number of vessels in the scientific fleet. The vehicle must be economical to operate, maintainable at sea, and able to interface with a variety of scientific payloads. These requirements place constraints on the vehicles, their cables, and the shipboard handling equipment and laboratory space.

A major theme of the JASON program involves control system research and development. Through improved control systems, a vehicle such as JASON can perform better and be easier to operate. In particular, we are working within a paradigm called supervisory control, where people and automation work cooperatively.

A variety of tasks can be performed better if the motions of the ROV are controlled automatically. The most prominent scientific application is precise, repeatable survey of the sea floor or water column. Carefully controlled vehicle motions permit data to be gathered repeatedly over varying time scales to allow scientists to observe changes. Commercial applications that would employ similar techniques include the inspection of ship hulls, offshore platforms, and port facilities.

A substantial set of problems must be solved to implement high performance control. The dynamics of the vehicle, its sensors, and actuators must be well chosen for permit good control. The cables and telemetry systems must support high bandwidth communications between all computers in the system with low, predictable time delays.

DESIGN FOR CONTROL

A successful control system implementation requires careful attention to a number of issues. The open-loop dynamics of the vehicle should be chosen to eliminate behavior that would be difficult to modify through feedback control. The actuators should have good dynamic range and be well characterized. Finally, the sensors must be reliable and have sufficient dynamic range. In particular, obtaining position information with adequate precision and sampling rate is difficult.

Vehicle pitch and roll have been made as stable as possible (buoyancy high, weight low). Although the thruster arrangement does permit active control of pitch and roll over a limited range, closed-loop control of attitude is rarely required, and then only to damp out oscillations.

Every attempt was made to eliminate open-loop coupling between translations and rotations. Many vehicles pitch or roll as the

vehicle accelerates in translation. In a previous experiment with another vehicle [1], this coupling was found to be the most prominent limit on the bandwidth of the translational control. For JASON, these effects have been minimized by careful placement of the vehicle thrusters relative to the vehicle centers of mass and drag.

The ducted thrusters driven by variable speed DC electric motors are not ideal control actuators. For a given control input, the output thrust varies considerably with axial and cross-flow velocity. Also, output goes to zero at low values of commanded thrust due to seal and bearing friction and motor ripple torque effects. Static and dynamic testing of the JASON thrusters has reduced uncertainties about their thrust characteristics, and improved low-level control has extended the dynamic range of the thrusters. From an operational perspective, JASON's thrusters are well understood thanks to a wealth of experience with JASON Jr.

Good control requires good sensors. JASON's control sensors include instrumentation for acceleration, attitude and position. Heading is measured by a flux-gate compass and a directional gyro. Pitch and roll is measured using a two-axis inclinometer. Absolute depth and altitude are measured. Servo accelerometers measure acceleration in three axes.

Determining position in the horizontal plane is the most difficult measurement. For good control, high precision (approx 1 cm.) and high update rates (approx 5/sec) are desirable. JASON will use a high frequency (300 khz) pulsed system to achieve these goals. Initially, the baseline for the acoustic navigation is on ARGO, yielding relative positions of the two vehicles. In the future, the baseline will be placed on JASON and its position determined relative to a single bottom transponder.

The problems associated with the design of control laws for an ROV in translation are numerous. The dynamics of these systems are nonlinear and often poorly known. We have been investigating nonlinear and adaptive nonlinear techniques to make the control systems perform better and to make design easier. These methods have been applied to an RPV-430 [2], to JASON Jr. [3], and are currently being applied to JASON.

Supervisory control techniques will be used to help the operator make use of the automated capabilities of the vehicle while allowing the operator to make high-level decisions on-the-fly.

DESIGN CONSIDERATIONS

JASON's design, as with all ROVs, is being driven by its expected tasks. The vehicle is equipped with the capabilities necessary to accomplish a reasonable range of functions at depths of 6000 meters. A basic framework has been assembled which can be adapted in many

ways. Both electrical and mechanical systems are provided which serve not only basic vehicle functions, but also will allow changes in the future to enhance the JAOSN's operational value.

Given parameters such as payload, speed and dynamic response, basic decisions on the size of the vehicle and the overall system can be made. JASON has an air weight of 1135 kgf (2500 lbs) with a 34 kgf (75 lbs) payload. Thrust will permit operations in typical deep ocean currents. Emphasis has been placed on flexibility and maintainability. A major benefit of building JASON at Woods Hole Oceanographic is the tremendous resource represented by the individuals who design, fabricate and operate a wide variety of equipment. The best known example is ALVIN, which has a long history of successful daily operations. Careful design and competent maintenance are critical to making JASON similarly successful. Like ALVIN, ARGO/JASON differs from most commercial systems in that it will be operated by the team that designed and built it.

Structure

Three titanium housings lie along the base of the vehicle and are used to form the structural backbone of the vehicle frame. This approach exploits the tremendous strength of the housings and eliminates the heavy structural members that would otherwise be necessary. A basic tube frame serves as a mounting base for components and connects to the rigid buoyancy assembly. The tether is terminated on a drum which is directly attached to the base frame/housing assembly.

Wiring Harness

Each housing uses a 156-pin high pressure header for passing electrical signals. These headers are connected to blind mating connectors on the low pressure side. This technique allows for the removal of each electronic chassis without breaking any of the high-pressure electrical connections. On the high pressure side of the header, an oil-filled manifold mates the end cap to flexible tubing that carries the conductors to junction boxes. Here interconnections are made between housings, to sensors and to payloads. The junction boxes (port and starboard) also serve as enclosures for current sensors, fuses, and solid state switches. Thruster motors, lights, and auxiliary A.C. and D.C. power buses are switched from these oil-filled boxes. The extensive use of pressure-tolerant electrical devices frees precious one-atmosphere space.

Thruster Motors

Propulsion motors are provided with 120 VDC, which is supplied through the junction boxes from the transformer enclosure. JASON is equipped with seven brushless D.C. motors [5]; three vertical, two each horizontal and lateral. This combination provides for modest pitch and roll control and gives some tolerance to motor failure. All thrusters are supported by the syntactic foam.

Flotation Module

Because the syntactic foam has a major impact on overall volume and weight, a decision was made to procure material with the best available performance. Emerson Cuming produces syntactic with a density of .55gr/cm³ (34 pounds per cubic foot) which is rated to 6000 meters (20,000 ft.). The flotation block, with a weight of approximately 500 kg (1100 lbs.), is covered with an outer skin of Allied Chemical's Spectra 1000, impregnated with epoxy and coated with a high build urethane. This combination produces a flotation assembly with exceptional strength and resistance to damage from impact.

ARGO/Tether Management System

The design of ARGO builds heavily on the existing coax based system presently in service. One large difference, however, is the incorporation of a garage and tether management system (TMS) for JASON. A rotating drum/slipring TMS has been chosen, which is powered by brushless D.C. motors similar to those used in the manipulators and camera pan/tilt subassemblies. Driving the TMS with brushless D.C. motors allows a fine level of control to be attained. Speed, tension and drum/sheave lag/lead may all be set up without adjusting valves and system pressure as would be necessary with a hydraulic system. The TMS is also equipped with a compliant sheave which, under normal circumstances, prevents heave-induced loads from exceeding a safe working load for JASON's tether.

FIBER OPTIC CABLES AND TELEMETRY

A fiber optic telemetry system accommodates the diverse communications needs of JASON. Requirements include low-latency digital data communication for vehicle and manipulator control, several channels of high quality analog video, and telemetry for scientific sensors. Key elements of the system design are the cables, the slip rings, the electronics and the electrooptics.

ARGO and the surface are linked by a 9 km steel-armored cable. ARGO and JASON are connected by a neutrally buoyant cable less than 300 meters long. The strength members, fibers, telemetry, and slip rings for the two links are substantially different.

The Surface to ARGO Link

A cornerstone of the ARGO-JASON system is a 17.3 mm (0.68 inch) diameter steel armored fiber-optic cable. A steady evolution of non-optical cables in this format have been operated successfully for many years, and it is now an accepted standard throughout the US oceanographic fleet. The modest diameter keeps the purchase and operating costs low, and winches are readily available. A previous example is the first-generation ARGO cable which has a coaxial core transmitting one monochrome video channel, two sonar channels and full-duplex digital data at modest rates. AC power (1 KW) and data are frequency multiplexed on the coaxial core, and the cable has proven very reliable.

The ARGO-JASON system uses a cable with mechanical properties nearly identical to the successful coaxial cable, but with a new core. The core will contain three copper conductors and three single-mode optical fibers.

Any deep-ocean tow cable will be subjected to high mechanical stresses due to hydrostatic pressure, tensile forces, and bending stress when passing over sheaves. Fiber optic cables have to be designed to isolate the optical fibers from these stresses. Typically this is achieved by placing the optical fibers in a pressure housing formed by the armor or by placing the fiber in a loose metal tube and surrounding it with a soft gel. Unfortunately, if the armor or tube is to act as a pressure housing, the required sub-sea termination is complex, expensive, and difficult to repair or replace at sea.

The design chosen for ARGO is shown in figure 2 [6]. This design exposes the fiber to hydrostatic pressure, reducing size and weight and allowing a less exotic termination. The positions of the fibers in the cable have been chosen to minimize tensile loads and to ensure that the hydrostatic forces seen by the fiber will be isotropic. A prototype version of this cable is currently in production and testing will begin soon.

Optical reliability is significantly enhanced by the choice of fiber. The chosen fibers are rated to 250,000 psi proof stress and can withstand the elongation of the cable under full working load. Single-mode fibers were selected primarily for their resistance to microbending losses.

The three single-mode fibers are used to support a high speed digital network, data acquisition, and video transmission. Two video

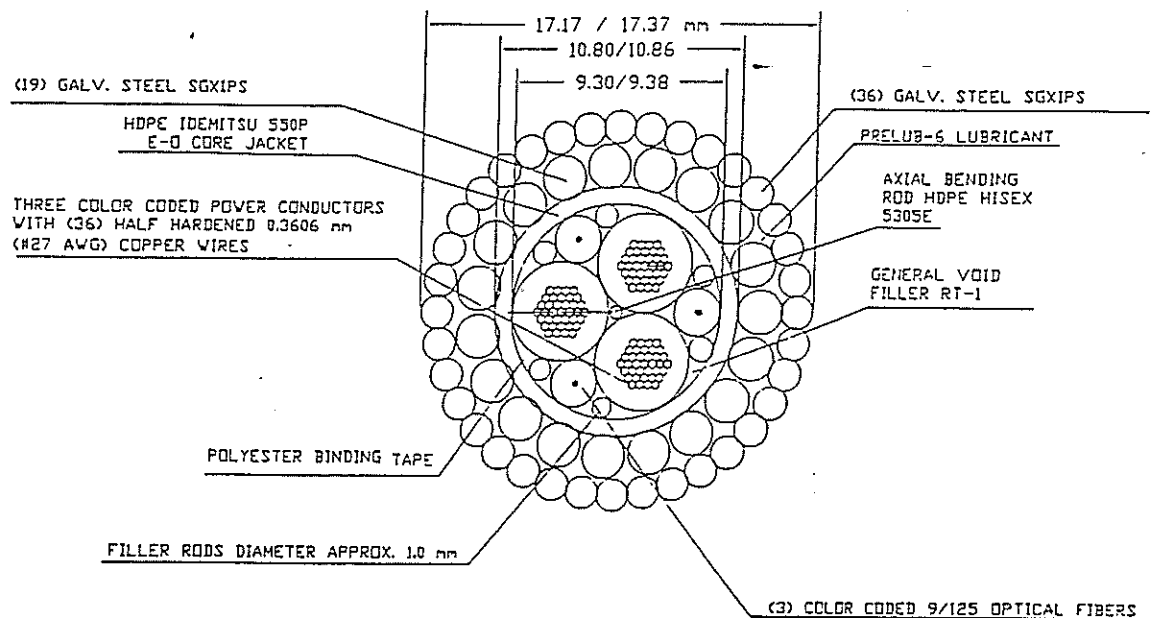


Figure 2: ARGO/JASON Single-Mode Armoured Cable

channels and a digital uplink can be put on a single fiber by using wavelength-division multiplexing (WDM) techniques.

The surface winch slip ring poses a difficult problem. Multi-pass single-mode optical slip ring assemblies with acceptable losses are not available. Fortunately, single-mode optical signals can be launched into multi-mode fibers with acceptable losses (but not vice-versa). A hybrid slip ring with one single-mode and two multi-mode channels will be used, since our application requires only one downlink fiber, for the digital data. The uplink channels (digital and video) will be run into multimode fibers in the winch drum, then transmitted through the multimode channels on the slip ring.

The ARGO to JASON Link

The link between ARGO and JASON is relatively short (under 300 meters), and is not subjected to constant loading. To reduce its influence on the dynamics of JASON, the cable must be neutrally buoyant and its diameter minimized. The cable must be stored on a small diameter drum aboard ARGO. The handling system must operate unattended and reliably at full-ocean depth.

The section of JASON's tether is shown in figure 3. The cable utilizes Spectra 1000 fiber as a strength member giving a safe working load of 2270 kgf (5000 pounds). The cable will pass 10 KVA

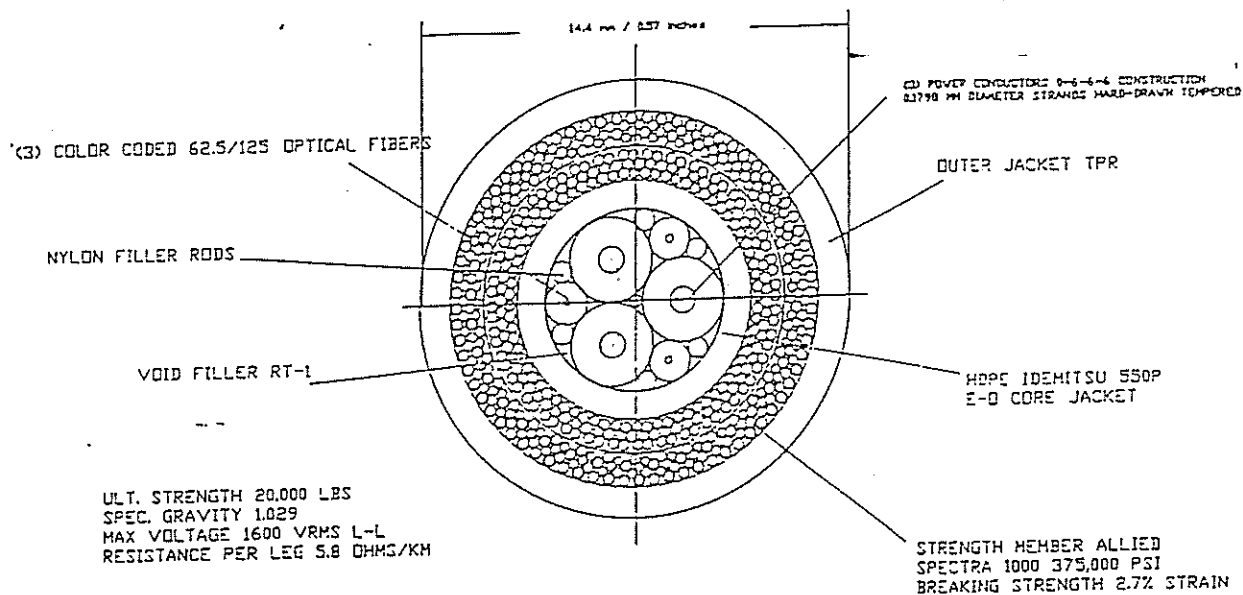


Figure 3: JASON Neutrally Buoyant Electro-Optic Tether

over a one kilometer length, and has an outside diameter of 15.2 mm (0.60 inches). The construction of the core of the cable is similar in concept to that of the ARGO cable; it is water blocked and jacketed with polyethylene. Four passes of the Spectra 1000 fiber are made around the core to establish a torque balanced cable with a ultimate strength of 9090 kgf (20,000 lbs).

Multi-mode transmission was chosen for the ARGO to JASON link for several reasons.

Over the shorter distance and at lower loads the increased microbending susceptibility of graded index multi-mode fibers is not important and bandwidth needs are easily met. A more critical factor is the availability of multi-pass multi-mode slip rings that can operate reliably at pressure.

The telemetry linking ARGO and JASON will strongly resemble the ARGO-surface link. A single high-speed digital downlink will be placed on one fiber. The digital uplink and several video channels can be put on one other fiber, with the third fiber as a spare.

POWER SYSTEM

Safely and dependably transmitting 12 KVA of electrical power down 9 km of small-diameter cable is a complex task. The ARGO/JASON power system consists of equipment at three separate locations: on the surface (shipboard), at ARGO and at JASON. The surface system is involved in power generation, voltage regulation, safety interruption, system control and other control/monitoring functions. The JASON AC power is switched and the majority of the system surge suppression is conducted at ARGO, the AC line is rectified to DC for use locally, and sub-sea voltage information is sent to the surface. Finally the JASON power system rectifies the AC power from ARGO for vehicle power and a small surge suppression unit protects the thruster motors. JASON also transmits local voltage measurements to the surface.

JASON Power Subsystem

JASON receives 400 hz, three-phase AC from ARGO via the tether cable. The voltage at the vehicle is nominally 1560 VRMS line-to-line. This is stepped down to 90 VRMS line-to-line by the transformers on the vehicle and rectified to a nominal 120 VDC with a 14Vptp swing about the nominal voltage and a peak of about 127V. This 120 VDC is capable of supplying the vehicle with 8000W power (66 amps at 120V). A small surge suppressor is installed across the 120V to clip voltage transients greater than 133V. This is intended to suppress voltage surges of a very short duration or until the main system surge suppression on ARGO activates and the surface controller reduces the surface voltage to negate the over-voltage condition. The vehicle 120V is continuously monitored to provide the surface controller with the true sub-sea voltage. No overall ARGO/JASON system ground fault interrupt hardware is installed on JASON. A separate sea water fault system only detects faults of 120VDC related voltages (i.e. voltages generated from the transformed, and therefore isolated, AC from the tether cable).

ARGO Power Subsystem

ARGO receives 400 hz, three-phase AC from the surface via the armored cable. The voltage at ARGO is also 1560 VRMS nominal line-to-line. This is stepped down and rectified as on JASON to provide 4000W of 120VDC power (33 amps). In reality, if JASON is drawing a full 8000W from the power system, the DC voltage difference between ARGO and JASON will be about 4V due to the resistance of the tether cable. For this reason the peak voltage at ARGO will be on the order of 131V.

During system operation, the electrical load of the vehicle will vary causing fluctuations of the sub-sea voltage. A surface controlled

surge suppression system on ARGO minimizes the effect of load changes by adding resistive load to the vehicle power buss when the vehicle power requirement decreases suddenly. This will keep the sub-sea voltage within acceptable ranges. A short term surge suppressor like the one on JASON suppress surges of a very short duration or until the main resistive suppressor is activated by the surface controller. As with JASON, a sea water fault detector will be present to monitor faults in the 120VDC system. Again no overall system ground fault is present on ARGO.

Surface Power System

A commercial aircraft power unit converts the 60 cycle ship power to 400 cycle power for the vehicle systems. This minimizes the size and weight of the sub-sea transformers. The converter is controlled by a surface computer which monitors surface voltage, current load, and sub-sea voltages from ARGO and JASON. By knowing the length of the armored cable (and therefore its resistance), the surface voltage and current information alone can be used to estimate the sub-sea voltage. When the sub-sea electrical demand changes, the surface controller commands the sub-sea surge suppressor to modify its load and changes the output voltage from the surface power converter. The explicit sub-sea voltage measurements are used to check that the sub-sea voltage is within acceptable ranges.

The surface power unit has a variable voltage output between 0 and 120VRMS line-to-line. This is stepped up to 2000VRMS (nominal topside voltage for a 9Km armored cable) using surface transformers. A ground fault detect system monitors each of the conductors of the armored tether for leakage paths to the armor of the tether. This is a separate system from the surface controller and should shutdown the power system in less than 30ms once a fault is detected.

COMPUTERS AND NETWORKING

JASON is an evolving vehicle, breaking new ground in vehicle control methods, among other areas. The control software needs to be accessible and easy to modify, and the computers running the control algorithms should be relatively powerful.

Fortunately, the use of fiber-optic cables offers the potential to move the computational load topside, leaving the slower on-board computers to supply sensor data and respond to commands from the surface. Data link performance, particularly round-trip latency, is therefore critical to overall controller performance. We are limiting latency and gaining considerable flexibility by using a standard 10-Mbps token-passing network between the vehicle and the surface. The topside control computer hardware can be independent of

the vehicle, providing an easy upgrade path as computers and software change.

On-Board Computers:

At the same time, building an ROV for 6000 meter operations puts one-atmosphere volume for electronics at a premium, and on-board computers must be small and space-efficient. The "Instrument Bus Computer" (IBC) selected for JASON is a general-purpose instrument controller and uses D-shaped cards mounted edge-wise in a 6-inch cylindrical chassis, giving efficient packaging inside JASON's titanium pressure cylinders. The Instrument Bus conforms to Multibus electrical standards, and can support multiple processors. The system has been used in a variety of oceanographic applications, including the controller for the ARGO vehicle. The present CPU uses the 80C86 microprocessor and is similar in performance to a standard IBM PC, though clock speeds can be increased to 8-10 MHz and new CPU cards are planned.

Three IBCs are used in ARGO/JASON, one each for ARGO's and JASON's controllers and one dedicated to JASON's manipulators, which are being developed at Woods Hole. JASON's IBCs use the VRTX real-time multi-tasking kernel with applications written in C. While the current ARGO controller uses the FORTH language, we expect to switch ARGO over to VRTX and C as well.

In addition to analog I/O, parallel I/O and counter/timers, the IBC board set boasts a motor controller card using an Intel 80C196 microcontroller to running motor servos. The manipulators and JASON's camera pan and tilt units use brushless DC motors with a controller board for each motor. The controller uses changes in winding reluctance to detect motion of the motor, avoiding the need for sensors on the motor itself and providing very precise positioning and speed control.

Network Implementation:

Initial JASON trials are using 9600 bps serial lines for communication, but we hope to soon be using a high-speed networking approach to avoid some of the limitations of the low-speed, point-to-point serial links.

The network implementation is critical to realizing the full potential of the ARGO/JASON system. It will handle large quantities of sensor and control data with predictable, minimal delays, and is also expected to carry data from a digital still camera and digitized sonar.

The 9 km overall length of the system and the requirement for predictability and high capacity dictate against the use of

collision-detect schemes such as Ethernet. The ProNET system we have selected is a proprietary network implementation developed by Proteon, Inc.. A token-passing architecture provides predictable response and unlimited range. ProNET includes a sophisticated fault detection and isolation scheme and is available on a variety of bus standards and media including fiber and twisted pair.

A ProNET interface for the IBC bus is under development at Wood Hole, with the cooperation of Proteon. The interface will occupy two 6-inch cards. The only other custom hardware required is a single-mode fiber-optic transceiver which will be adapted using an existing ProNET transceiver.

Network software will be based on industry standard network protocols, ensuring that topside hardware and software can be off-the-shelf, reliable and readily documented, and allowing the system to tie into existing wide-area networks.

Topside Computers:

The topside control computer can, as noted above, evolve independently of the vehicle itself. The current JASON topside control computer is an 80386-based personal computer with relatively simple, mostly sequential software written in C. The use of a local network on the surface allows flexible allocation of topside functions such as graphics, navigation and data logging to separate computers, avoiding the immediate need for sophisticated software or extremely powerful computers, while ensuring small delays.

CONCLUSION

JASON's first open-water trials will take place during the summer of 1988 and the first deep-water operations will be in early 1989. We look forward to reporting our results at ROV '89.

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Commercial suppliers mentioned:

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