# An Interface System for Autonomous Undersea Vehicles

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***Abstract*—Central to the successful operation of an autonomous undersea vehicle (AUV) is the capability to return from a mission, in that there is consistent recovery or docking of the AUV. In addition, some missions may require communication with and power transfer to the AUV after docking. This paper describes an inductive system that provides a nonintrusive power and communications interface between the dock and the AUV. The system makes up to 200 W of ac or dc power available to the AUV. The communications interface is 10BaseT ethernet and is platform- and protocol-independent. The overall design of the system is given as well as results from wet laboratory and field tests.**

***Index Terms*—AUV docking interface, AUV interface, contactless power, data interface, data transfer, inductive data transfer, inductive power transfer, power transfer.**

## I. Introduction

ADVANCES in the past decade in the areas of micro-computer systems combined with smaller, lighter, more efficient propulsion systems and lower power actuators have made missions previously requiring large manned systems now feasible for smaller autonomous systems. This is specifically true for undersea systems, where there are numerous proposals to replace previously manned undersea, often deep water, vehicles with smaller and cheaper autonomous systems. An example of this can be found in [1]. In some advanced applications, this approach has advanced through technology development, and for early applications working hardware is currently in use. The number of applications is large, varied, and covers many specific areas. This paper does not address these specific applications, but only that part of the autonomous mission where the vehicle must return to a home base and then receive power from the home base. In addition, the vehicle must communicate with the home base to export data and to receive instructions for the next mission. It may also be desired that the dock provide a safe haven in the event of storms, or if some of the vehicle's subsystems are damaged or fail. Therefore, it is usually required that the vehicle remain below the surface and the interface function at the operational depth of the autonomous underwater vehicle (AUV).

The objectives of the AUV/Dock interface are thus nonintrusive data and power transfer at depth. The main requirement of the communication link is a transfer rate such that data transfer occurs in a time much less than that required for battery charging. In addition, the communications hardware and protocols should be somewhat standard so that existing common hardware and software can be easily used. For this reason, we chose to support ethernet, specifically 10Base T, with an actual signaling rate of 10 Mb/s. This permits the scientist and support personnel to interact with the AUV either on a local-area network (LAN) which might be deployed on a support vessel located near the dock, or from a laboratory on shore via the Internet, with a satellite link to the AUV dock. Thus, investigators using an AUV such as the MIT Odyssey II can log in directly to the AUV computer to transfer data from the AUV, update mission profiles, and, given sufficient authority, revise the AUV control software from a remote location.

In addition to nonintrusive data transfer at depth, sufficient power transfer must be available to operate the AUV electronics and to charge its batteries. Finally, because one side of the interface is mounted on the dock and the other side on the AUV, the interface must be able to mate during or after docking. Thus, it is important that the mating tolerances not be excessively tight. Options considered to achieve these requirements were optical, capacitive, and inductive. An optical interface has several desirable features for communications, but power transfer at the desired efficiencies, above 80%, did not seem practical. Optical interfaces are also susceptible to fouling and interference from ambient light. Capacitive coupling was deemed to require tighter mating tolerances than the inductive interface. Thus, an inductive interface was selected. A prototype system was wet tested at simulated depths using a pressure chamber. Subsequently, the system was installed on one of the Odyssey IIb AUVs from the MIT Sea Grant program. This AUV has been described by Althsuler *et al.* [2]. An omnidirectional dock was used in these tests with acoustic homing. The docking system, developed at the Woods Hole Oceanographic Institute, is described by Singh *et al.*[3]. A number of successful field tests at depth were conducted.

## II. Description of the Communications and Power Interface

The power and communications interface is via an inductive coupling, in which one part of the coupling or transformer is mounted on the AUV and the other part of the transformer is mounted on the dock. In operation, the dock portion of the coupling or transformer is mated with the AUV transformer and forms an inductive link or a transformer. When the AUV is to leave the dock, the two parts separate, and the coupling or interface is broken. The geometric configuration of the Power and Communications Interface Transformer is shown in Fig. 1. This figure shows the two components of the transformer core, the line on which the cores separate, and the overall dimensions.

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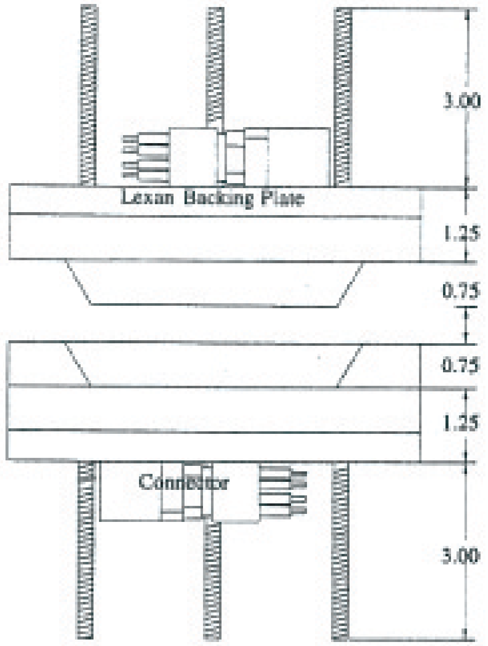


Fig. 1. Drawing of the interface transformer or inductive link geometry used for the power and communications interface.

There are three sets of winding, two are required for the ethernet communications link and one for the power transfer link. The winding for the power link is on the tapered portion of the core. One of the ethernet links is through a winding on the inner circumference of the core, the other through a winding on the periphery of the core. Electrical connection to the three windings is via Impulse connectors, which are shown in Fig. 1.

In operation, the dock design and mounting configuration of the transformer on the AUV must be integrated for successful operation. Thus, the power and communications interface must be designed as part of an integrated system between the dock and the AUV. The present system requires the two transformer halves to be pressed together, but does not require angular alignment. That is, the two cores are axially symmetric and thus do not require precise angular positioning. The shape of the interface transformer, shown in Fig. 1, reflects a compromise between acceptable magnetic properties and ease of mateability. Varying the shape to achieve minimization of leakage inductance could result in less variation in the voltage output with mating quality, better control of external magnetic fields, and more robust ethernet performance when the power transfer is active. However, the resulting structure would be less self-aligning and more difficult to mate properly.

As installed on the Odyssey IIb and the WHOI dock mentioned above, the inductive couplers mate passively during the docking procedure and do not require an active mating or insertion mechanism.

As presently implemented, the interface transformer is used in a double resonant mode, which exhibits a shunt impedance that is low for all off-resonant frequencies. A square-wave inverter was initially developed, since this was deemed the simplest and most efficient topology. The rich harmonic content of the square-wave inverter output proved troublesome, however. Harmonic components which were in-band to ethernet caused interference with the data transfer. The square-wave transitions, together with the unavoidable leakage inductance of the separable transformer required the use of higher voltage active devices and transient snubbers, both of which reduced the inverter efficiency. A sine wave inverter was developed which eliminated these problems.

As shown in the block diagram of Fig. 2, the power transfer electronics consist of a sine-wave inverter, rectifier, and power conditioner. The sine-wave inverter uses an adaptive topology that maintains the inverter frequency at the transformer resonance and attempts to minimize losses and maintain power transfer when the cores are poorly mated. Increasing physical separation between or misalignment of the two transformer components forces the magnetic flux generated by the primary component to traverse a longer path through a nonferromagnetic medium (air or water). This results in a decreasing shunt inductance on both the primary and secondary sides. Since each half is resonant, the resonant frequency of both transformer halves is increased. The sine-wave inverter uses a phase-locked loop, which adjusts the inverter operating frequency to match the transformer primary resonance. An error signal based on the slope of the sine wave just prior to and just after a zero-crossing is used to adjust the frequency of operation. Since the transformer is electrically symmetrical, the resonant frequency of the secondary component tracks that of the primary, and resonant operation is maintained for both halves. The frequency of operation varies from about 65 kHz when the transformer components are well mated and to about 80 kHz when they are widely separated.

The rectifier converts the high-frequency sine wave to dc. The present topology is a simple inductive input full-wave rectifier using Schottky diodes. A prototype using a synchronous rectifier has been demonstrated and provides some improvement in efficiency. The output voltage is affected by variations in the dock source voltage, and the precision with which the separable transformer is mated. The power conditioner is a dc-to-dc converter which converts the output of the rectifier to the voltage and current levels, and to the particular V/I characteristic required by the AUV power system.

The separable transformer core is machined from type 78 ferrite material produced by FAIR-RITE Products Corporation of Flat Rock, IL. This material was chosen because of its low-loss high-frequency properties and because it was available in a convenient size and shape for the purpose at hand.

Power is transmitted via windings located on the sloped portion of the primary and secondary transformer halves. Each power core is wound using 28 bi-filar turns of #22 Heavy Poly-Thermaleze insulated magnet wire. This winding conformation has an aspect ratio of 2 to 1 and was chosen to minimize the profile of the winding.

Full duplex ethernet data are transferred in one direction by means of coils wound around the periphery of the primary and secondary halves, and in the other direction using coils wound around the inner circumference. Pre- and post-equalization and amplitude scaling of the ethernet signals permits error-free operation at data rates of 10 Mb/s.

The ethernet electronics consist of data transmitters which convert standard 10Base T ethernet into a form suitable for

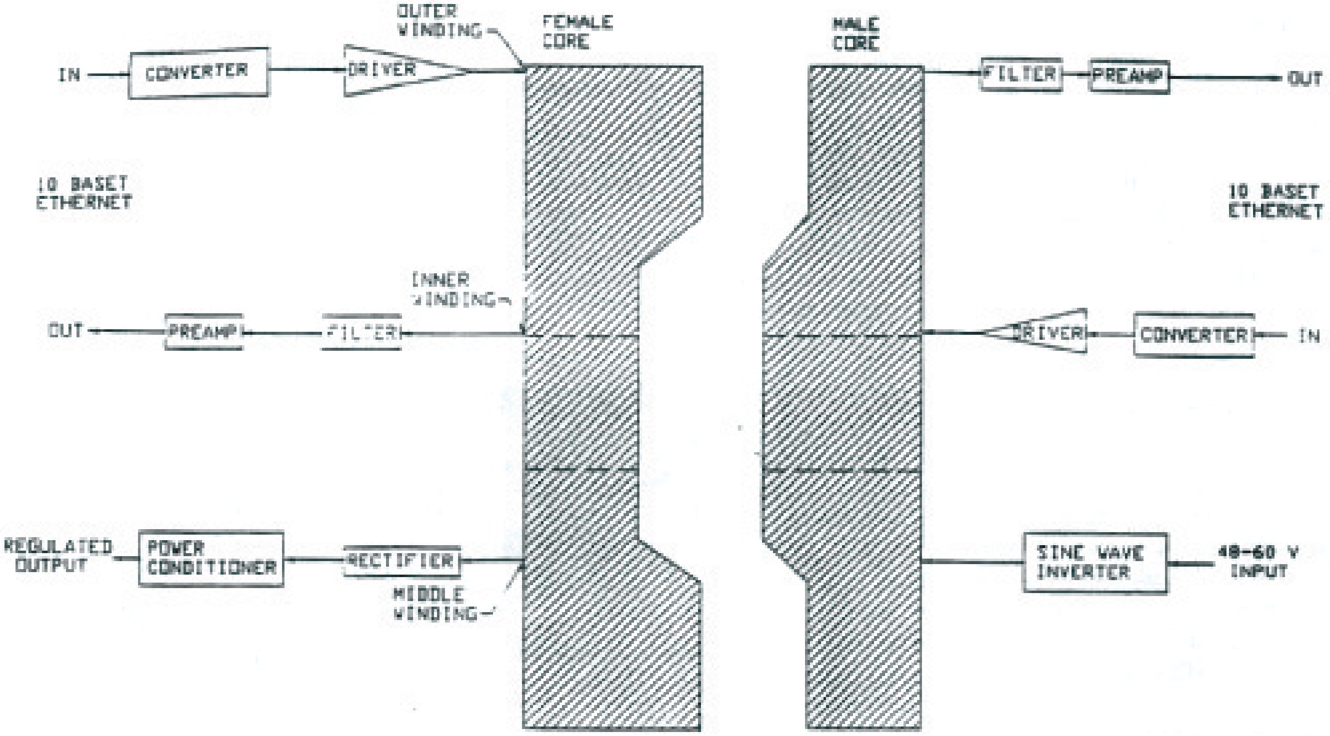


Fig. 2. Block diagram of the components that make up the power and communications interface.

transmitting across the interface transformer and receivers which convert it back to 10Base T. The ethernet link is bi-directional and is compatible with 20-Mb duplex ethernet. Bandpass filters are used to pass the ethernet and minimize interference by the power transfer.

The ethernet interfaces connect directly to any 10Base T network interface card or ethernet hub and is thus computer-platform-independent. The link is also protocol-independent, working with TCPIP, Netware Compatible, and other ethernet packet types.

The transformer cores used in this work were designed to provide high efficiency with passive mating and to be as tolerant as practicable of poor mating. Another requirement was to allow simultaneous power and data transfer with well-mated transformer halves. Relaxing these criteria would permit a considerably higher rate of power transfer with the transformer used or to permit a smaller transformer to transfer the power level achieved.

## III. Testing of the Interface System

To date, the system has been bench tested in both atmospheric and high-pressure salt water. In addition to these bench tests are a limited number of tests in which the present power and communications interface was installed on the joint MIT/WHOI Odyssey IIb [3]. This system employed acoustic homing, with an omni-directional dock. Thus, the geometric configuration of the AUV/dock latch and the location of the interface transformer were defined by this dock system. The field tests are described by Singh *et al.* [3]. However, the performance of the power and communications interface from both sets of tests is briefly given here.

The pressurized salt-water bench tests were conducted with the transformer components secured together with duct tape, ensuring good alignment. The tests were conducted in a high-pressure test chamber filled with salt water, and the pressure varied from atmospheric pressure to 3000 psi. Communications and power transfer were tested simultaneously, with power transfer typically at 200 W. Power transfer efficiency was approximately 83% in the bench tests. No measurable power loss has been detected in the salt-water medium as compared to operation in air.

As indicated above, to date the only field tests of the power and communications interface has been with the MIT/WHOI Odyssey. Power levels at approximately 200 W have been demonstrated with efficiencies of about 79% [4]. In these tests, a power conditioner was not used, the rectifier output being directed into a resistive load. The output power tended to fluctuate as the core alignment changed due to heaving of the mooring, varying from 130 to 200 W.

For bench testing of the communications link, the setup was the same as for bench tests on power transfer, which is described above. In these tests, data packets were generated on one Wintel PC computer and received on a second one. The software used was the "Diagnose" program distributed by SMC Corporation with their ethernet drivers. With power transfer active, data transfer was error-free through the test period of over 12 h. Data rates of 10 Mb/s were achieved with transformer separation up to one half inch of separation in the absence of power transfer. When power transfer is active, data transfer is less tolerant of poor mating. Error-free data transfer could generally be achieved with well-mated cores at power levels of 200–250 W.

Data transfer was also demonstrated in these field tests. However, failures of the commercial dc/dc converters used to power the ethernet electronics prevented the extended use of the communication interface. Because of these failures and other failures unrelated to power/data transfer, acquisition of communication statistics in the ocean has not been accomplished. Investigation of the dc/dc converter failures was not possible, because they were potted on the transformer cores. The ethernet transmit and receive electronics are now being housed in a separate oil-filled pressure-compensated compartment mounted on each transformer core. In addition, the dc/dc converters have been migrated into the dry compartment on the dock and AUV. No failures of the data link have occurred subsequent to these modifications.

## IV. Summary and Conclusion

An inductive interface for communications and power transfer between an Odyssey IIb AUV and a dock has been developed, built, and successfully bench and field tested. The interface consists of two mating transformer cores, one which attaches to the AUV, and one which it attaches to the dock. The interface provides a communications link to the AUV via 10baseT ethernet and has demonstrated duplex data transfer rates of up to 10 Mb/s. The same interface also provides an inductive link for power transfer from the dock to the AUV battery system. Power transfer at rates to 200 W have been achieved in bench and salt-water field tests. Field tests were conducted by having an Odyssey IIb locate and attach to a dock. The two interface components then passively mated, and communications with and power transfer to the Odyssey IIb were tested. Data under these conditions are given in the paper. Performance of both the communications and power transfer links degrade when the transformer cores are separated, or poorly mated. This can occur because of poor mating when the AUV docks, or due to wave action after docking. However, acceptable performance, as defined above, can be achieved with less precise mating. The most obvious degradation is in the communications data rate when it is simultaneous with high-power transfer and poor mating. Limited data are given in the paper. Future work will be directed toward increasing power transfer levels to accommodate the high rate of energy acceptance of lithium ion batteries, and to improve efficiency at low power levels. Work is also planned to reduce the size and weight of the magnetics and to modify the conformation of the magnetics in order to provide power/data transfer for AUV docking systems that are specifically designed to home and attach to a cable.

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