Power Systems for Autonomous Underwater Vehicles

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***Abstract*—In this paper, we examine the issues involved in designing battery systems and power-transfer (charging) techniques for Autonomous Underwater Vehicles (AUVs) operating within an Autonomous Ocean Sampling Network (AOSN). We focus on three different aspects of the problem, battery chemistry, pack management and in situ charging. We look at a number of choices for battery chemistry and evaluate these based on the requirements of maximizing power density and low temperature operation particular to AUVs. We look at the issues involved in combining individual cells into large battery packs and at the problems associated with battery monitoring, and the charging and discharging of packs in a typical AUV application. Finally, we present a methodology for charging an AUV battery pack in situ in support of long term deployments at remote sites.**

***Index Terms*—AUVs, batteries, underwater mobile robots.**

I. Introduction

AUVs IN the service of science have been around for many decades, but they have mostly served relatively narrow niche applications. In the past few years however, advances in technology have led to AUVs invading mainstream science. As we look forward to AOSN [1] systems, the role of AUVs able to do autonomous docking with reliable power and data transfer becomes critical to the system's success. Docking methods, power transfer and data transfer are the focus of much current AUV research. This paper focuses of the battery systems suitable for AOSN vehicles and presents one approach to power transfer from the dock to the AUV. We briefly touch on the problem of data transfer when it is integrated with the power transfer system.

Power considerations dominate the design of small AUVs as energy is usually the most limiting resource on these vehicles. Although there are other options, (nuclear, closed cycle diesel, fuel cell) we limit ourselves herein to the consideration of relatively straightforward primary and secondary batteries as AUV power sources. The other possible options are either too costly or are significant research projects in themselves to be accessible to most AUV projects. Additionally, nuclear sources have environmental and legal concerns which make them inaccessible to most groups.

Currently available battery technologies do not have the energy densities required to satisfy the range of operations and the variety of high-power sensors that have been or are being proposed for AUVs. Battery technologies themselves are the subject of intense research driven by consumer-based demand for applications as diverse as electric cars, cell phones, and portable computing devices. Unfortunately, these market forces do not directly overlap with the specific needs of the relatively small AUV community. Our philosophy has been to leverage available battery technologies while critically and independently evaluating the choices as they specifically relate to the AUV community. In order to achieve our scientific goals of long term monitoring, *in situ* recharging will be required.

We first examine the issues related to power systems for the current and future generations of AUVs operating within the context of an AOSN. In succeeding sections, we elaborate on the relationship between power, range and speed (Section I-A); the factors that are crucial for AUV applications from the standpoint of battery chemistry (Section II); systems for battery maintenance, monitoring and charging (Section III); and systems for *in situ* power and data transfer suitable for long term operations (Section IV).

A. Power, Range and Speed

It would be useful to be able to quantify the efficiency of a particular AUV design. Unfortunately, the multidimensional space of mission characteristics, sensor configurations, size and speed (Table I) that goes into the design of an AUV make developing a useful figure of merit unproductive.

For a particular implementation however, from a purely power standpoint, one can derive a useful relationship between power, range, and speed [6], [7]. If we assume that power is devoted solely to propulsion and that the drag on the vehicle is proportional to the square of the speed then

$$R = \left(\frac{E}{K_d}\right) u^{-2} \tag{1}$$

where

- R range in meters;
- E energy available in Joules;
- K_d effective drag coeff in W s^3/m^3;
- u speed in m/s.

A more realistic range estimate can be derived by considering the hotel load, that is essentially all the other loads—navigation, sensor and control—independent of the propulsion load in which case the range equation becomes

$$R = \left(\frac{E}{K_d + \dfrac{P_h}{u^3}}\right) u^{-2} \tag{2}$$

where P_h is the hotel load in Watts.

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TABLE I
THE US ACADEMIC AUV FLEET AND ITS POWER CHARACTERISTICS

Name [Ref]	Size	Battery Chemistry	Depth
Remus [2]	1m	Lead Acid	150m
Odyssey IIB [3]	2m	Silver Zinc	4500m
ABE [4]	2m x 3 hulls	Lead Acid	5500m
FAU Explorer [5]	2m	Ni Cad	300m
Autosub	7m	Alkaline	300m
FAU Morpheus	1.5-3m	NiCad	?

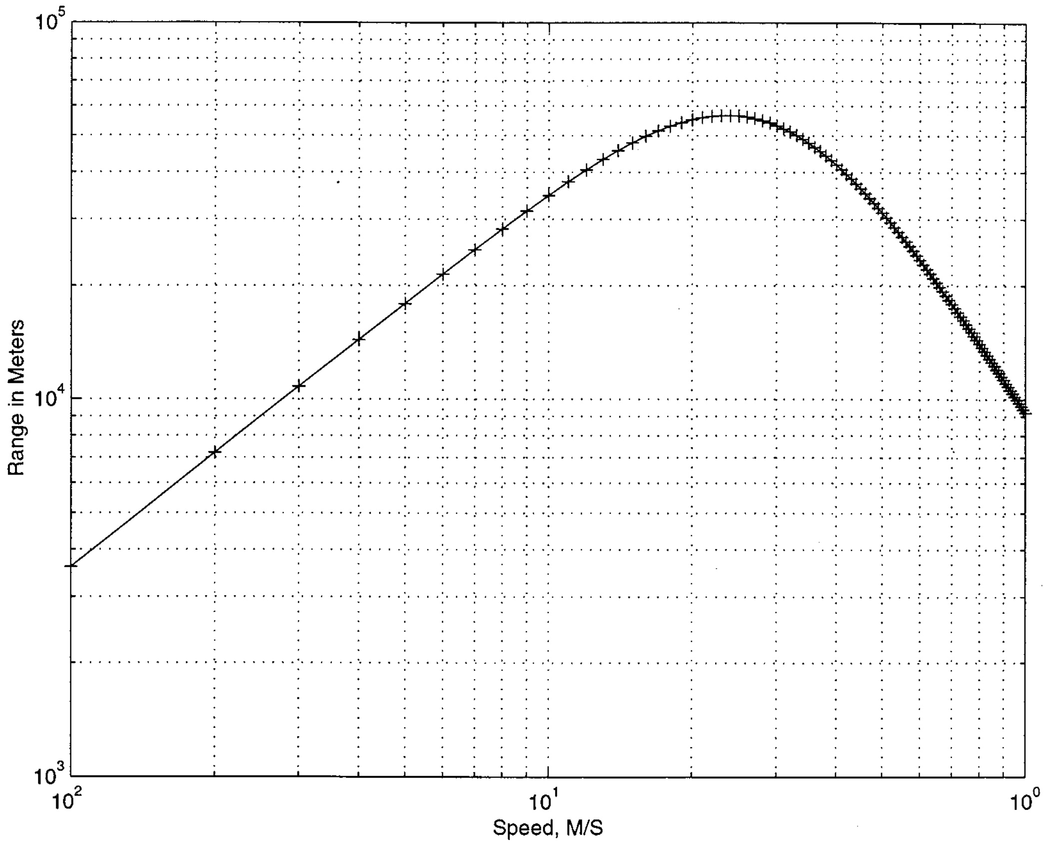

Fig. 1. Range versus speed curves for the ABE AUV.

Fig. 1 shows the form of this relation plotted on log–log axes. The high-speed asymptote (slope $= -2$) corresponds to the energy being dissipated in the turbulent water behind the AUV, while the low-speed asymptote (slope $= 1$) corresponds to the sensors and other components of the hotel load burning up the power before the vehicle has gone very far. This relationship, although admittedly of limited applicability, shows that for a given energy capacity, there is an optimum speed for maximizing the range of the AUV mission. For ABE, the optimum speed is about 25 cm/s which is often too close to the near bottom currents when it operates. We usually accept the loss in range and run ABE at 70 cm/s.

II. Battery Technologies for AUVs

A complete discussion of battery technologies is beyond the scope of this paper. Our emphasis is on the characteristics that are specific to AUVs. Extensive references are available which detail the more generic issues associated with these technologies [8].

Table II lists the major battery chemistries of interest that we consider in this section. Our study is weighted more toward secondary (rechargeable) cells than primary cells due primarily to the current applications of these technologies in the AUV community, where the majority of the packs are rechargeable except for very specific missions.

TABLE II
BATTERY CHEMISTRIES AND THEIR CHARACTERISTICS

Chemistry	Energy Density (Whr/kg)	Pressure Compensatable (Whr/kg)	Outgassing	Cycles	Comments
Alkaline	140	No	Possible, at higher temperatures	1	Inexpensive, easy to work with
Li Primary	375	No		1	Very high energy density
Lead Acid	31.5	Yes (46)	Yes, even with sealed cells	~100	Well established, easy to work with technology
Ni Cad	33	No	If overcharged	~100	Very flat discharge curves
Ni Zn	58.5	Possibly (160)	None	~500	Emerging Technology
Li Ion	144	No	None	~500	In wide use in small packs
Li Polymer	193	Possibly	None	~500	Only "credit card" form factor currently available
Silver zinc	100	No	Yes	~30	Can handle very high power spikes

A. Alkaline Cells

These are the simplest batteries to use. They are cheap, safe, and inexpensive, although they do tend to outgas hydrogen when stored for long periods of time. This can be a significant problem if they are in a sealed pressure housing for an extended period of time for the purposes of shipping or long-term deployments. The outgassing increases rapidly with temperature. In normal operation the major problem with using these cells is the voltage sag associated with discharge. They start at over 1.5 V with their end of life often arbitrarily defined as 0.8 V. With the high-efficiency-wide-input range inverters available today, this is not much of a handicap. The internal resistance of these cells is often significant at rapid discharge rates and is also higher at low temperatures associated with deep oceanic waters. Fig. 2 summarizes our experiments in quantifying these effects for standard D and AA size cells.

We discharged a number of cells at constant power (as opposed to a purely resistive load) to the end of their life. These discharge tests were conducted at 20 °C and 2 °C. We see a very large spread in the total energy delivered by each cell as a function of the time of discharge and temperature. AA cells have better performance than D cells and thus are slightly better suited for higher discharge rates particularly at low temperatures. This graph also shows that the empirical rule of thumb, derating the capacity of an alkaline pack by 20% for the effect of temperature, is often not valid due to the effect of discharge rate. For very large packs, self heating of the cells can be a concern and possibly an advantage if operating in cold water. Autosub [9] uses an 80-kWh alkaline pack necessitating close attention to the thermal modeling and management of their battery system.

In conclusion, we can state that if these cells are used at low temperatures, in an AUV mission with a high discharge rate where cells are expended in less than a few days, they will only deliver a fraction of their stored energy. Alkaline cells continue however to be one of the cheapest and easiest chemistries to work with in the field.

B. Li Primary

When energy density is of paramount importance, lithium primary cells represent the best choice. Their major drawback is cost although attention must also be paid to the variability of the load with these cells. If the load consists of high-power pulses with long rests in between, these cells can lose a significant fraction of their chemical energy due to the re-establishment of a passive layer over the lithium plate between pulses.

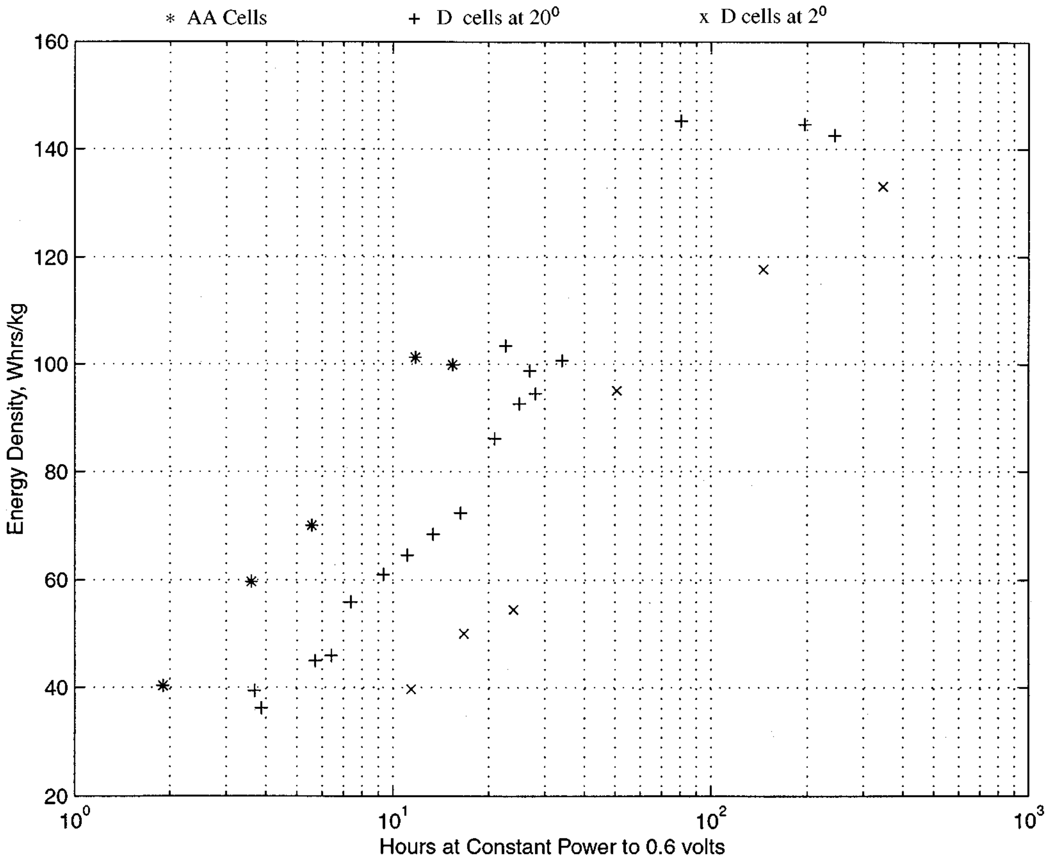

Fig. 2. The effect of discharge rates and temperature on the available energy density of alkaline cells.

C. Lead Acid

Lead acid cells are perhaps the easiest of the secondary cells to work with. For large systems lead acid wet cells can be pressure compensated in an oil filled box, yielding considerable savings in the expense and weight associated with pressure housings. For smaller systems, gelled electrolyte, "sealed" cells are generally used. We should point out that these cells always leak some hydrogen. This is generated internally during the final stages of charging and eventually leaks out of the cell over a period of hours to days. In the ABE AUV, which used gel cells, this hazard is dealt with by monitoring the internal pressure. Temperature is also monitored to compensate for thermal expansion and the housing flushed with dried air whenever the pressure of enclosed gas rises by a few percent. As an additional safety precaution, the endcap on the main housing is sealed with only a face seal and a partial internal vacuum of about half an atmosphere. We do not use any bolts or clamps to hold the endcap on the cylinder, so if the internal pressure rises, the endcap will just fall off. If there is an internal hydrogen explosion, the internal pressure can't rise much before it vents. (About 4% hydrogen in air is an ignitable combination.) It would be better to flood the housing with an inert gas like nitrogen to eliminate the oxygen, but the difficulty of shipping large nitrogen tanks precludes such a solution in practice. Another approach to eliminate the explosion hazard would to fill the spaces between the cells with sand to prevent an explosion from propagating. This, however, adds weight to the housing and further is only reasonable when the batteries are in a dedicated housing and occupy most of its volume.

Lead acid cells are easy to interface with a vehicle from a purely electrical standpoint. The state of charge can be gauged adequately by measuring cell voltage alone and simple charging circuits may be used. The exact voltages which indicate end of charge and end of discharge vary slightly between cell types so the user is cautioned to study vendor specific data in using these cells.

D. Ni–Cad

Nickel Cadmium cells are a mature and well understood system which are sometimes used in AUVs [5]. They offer only a slight improvement over lead acid in energy density. Their primary weaknesses lie in the difficulty of ascertaining the state of charge and the heat evolved near end of charge by the cell which can be inconvenient in a large pack.

E. Ni–Zn

A relatively new and so far unknown entry in the area of battery technology is the nickel zinc system [10]. These cells are sealed but use a liquid electrolyte (potassium hydroxide—KOH) with a small air space. These sealed cells may see a small and temporary overpressure if overcharged but a secondary reaction recombines the evolved gas. These cells are aimed at the light electromotive industry (electric bicycles and scooters) and outperform lead acid in terms of both energy density and cycle life.

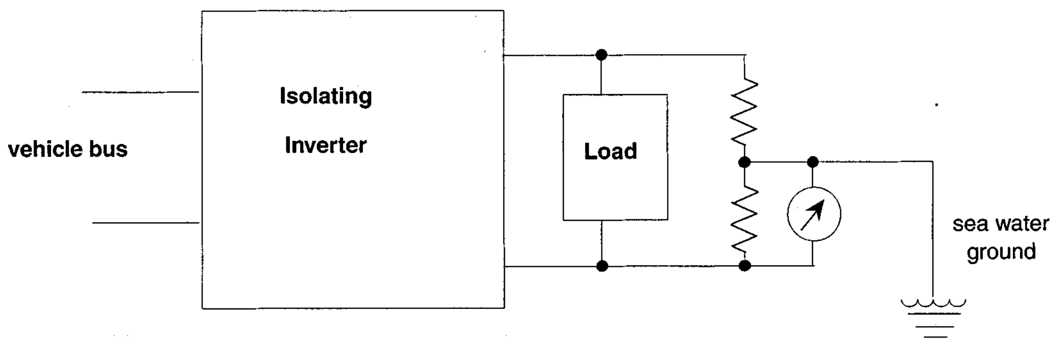

Fig. 3. Ground fault detection for a battery pack.

From an AUV perspective, these cells hold out the possibility that they can be used at ambient ocean pressures with an oil layer above the electrolyte. Some cycle life will probably be lost in such a situation, but the overall specific gravity of these cells is much lower than that of lead acid and thus they could yield an enticing power density at a modest cost.

F. Li–Ion

Lithium Ion cells have been used extensively in cell phones and laptop computers for several years and are an attractive alternative for the AUV designer because of their high energy density and long cycle life. These cells have a liquid electrolyte and a stainless steel case with a small gas pocket to allow for thermal expansion. The presence of this void precludes their use at deep ambient ocean pressures. The disadvantages of these cells include high costs, modest sizes, and complexity of the circuitry required to operate them in a system. While on charge their voltage must be limited (typically to 4.1 V) failing which the cell will be damaged. Similarly, on discharge the cell cannot be allowed to go below about 3 V.

G. Lithium Polymer

The term lithium polymer refers to lithium ion chemistry with the electrolyte trapped in a gel or other absorbing material. Prototype cells are a sandwich structure in a sealed plastic envelope and in our initial tests have survived hydrostatic pressure to 10 000 psi several times without apparent damage. They have a very low density and if operated in an oil bath at ambient ocean pressure could become a very attractive alternative to Li–ion. Several manufacturers [11], [12] are working to produce these cells in commercial quantities and they are currently undergoing extensive evaluation at pressure for use in AUVs by Bluefin Robotics [13].

H. Silver Zinc

Odyssey originally used wet Ag–Zn cells to meet their vehicle's target specifications. These cells are expensive and have a very limited cycle life. They are orientation sensitive (spilling the electrolyte) and require close attention when charging and discharging to avoid cell damage. Except for very short missions where the battery must deliver its energy in a few hours or less, Li–ion cells are a more attractive option.

III. Battery Supervisor Systems

We now turn our attention to battery supervisory and monitoring systems necessitated by the requirements of the higher performance battery chemistries. In this context we examine the role of bus voltage, power distribution, and ground fault detection before we present three examples of battery supervisory systems being used or developed for the ABE and Odyssey AUVs.

A. Bus Voltage

Bus voltage for an AUV usually varies with the size of the vehicle. Small radio controlled submarines are often powered by a 6 or 12 V battery; the REMUS AUV ($\sim$1 m in length) has a 24- V battery; Odyssey and ABE ($\sim$2–3 m in length) use a 48-V bus; the manned submersible Alvin ($\sim$7 m in length), while not an AUV, uses a 120 -V bus. The choice of bus voltage is usually based on the power levels required and the rule of thumb in electromotive design that "volts are cheaper then amps." In practice, this rule may be viewed as a methodology for limiting the weight of the power wires in a vehicle.

B. Power Distribution

There are two basic approaches to power distribution with variations in between. At one extreme, the bus powers several inverters that generate the voltages needed by all the system components. These voltages are then distributed around the vehicle. At the other extreme every load has its own inverter which is powered directly from the main bus. The thrusters are usually powered directly from the bus although they might need additional voltages for their control circuitry. The easy availability of inexpensive and efficient inverters in different power ranges usually makes the latter method preferable. The inverters can be sized to their loads for optimum efficiency. Individual inverters can also provide valuable ground isolation which can be critical in many subsystems. A disadvantage is that they also generate electrical (and sometimes acoustic) noise, commonly in the 50–500-kHz range. Inverters may be modeled as noise sources equivalent to a square wave generator at the bus voltage in series with several hundred pico-Farads between the "isolated" grounds. We should point out that commercially available inverters, while being extremely efficient at peak power, are usually quite inefficient at lower power outputs. Thus, if the

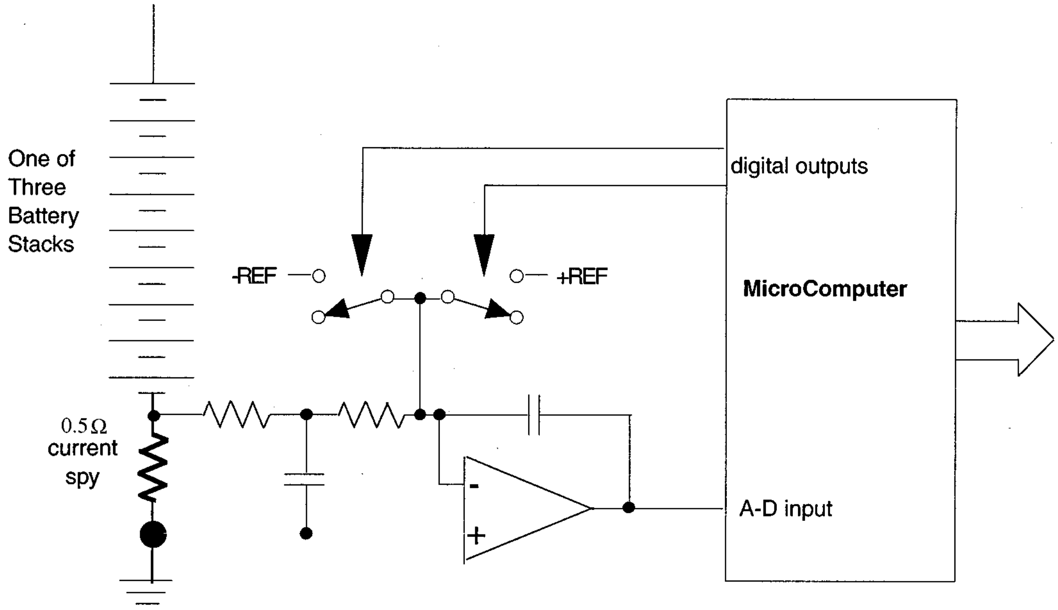

Fig. 4. Measuring charge in and out of battery.

load the AUV presents to an inverter is expected to vary over a wide range or spend most of its time at a fraction of its peak power, then the overall efficiency will suffer. For example, a typical PC104 computer stack with a flash disk requires about 6 W when running, but requires more then double that when starting up.

C. Ground Fault Detection

Using individual inverters for each load facilitates ground fault isolation. If the inverters are of the dc-isolating type, each load can have its own independent ground fault detection circuit. One method for accomplishing this is shown in Fig. 3. On the load side, a resistive divider generates an intermediate voltage which is grounded to seawater. This voltage is monitored and if there is no leakage this intermediate voltage should be the voltage expected on the divider. If there is a fault, this voltage will generally be pulled high or low.

D. Charge/Discharge Circuitry for Battery Packs—Three Case Studies

Circuitry associated with the battery pack in an AUV is usually required for dealing with the higher performance secondary cells. Such circuitry ranges from the trivial (for example a series voltage regulator on an alkaline pack) to the complex systems required for use with Silver Zinc or Li–Ion cells. In this subsection we present three examples and discuss their strengths and weaknesses.

1) ABE's Lead Acid Gel Cell Pack: The ABE AUV originally used lead acid gel cells. We made this conservative choice for cost and reliability. The pack is wired as three series strings of 24–12.5 Ah cells. The three strings are diode isolated and used in parallel to produce a nominal 48-V bus. As illustrated in Fig. 4, each of the strings has a 0.05-Ω current monitoring resistor at the negative end which goes to vehicle ground. The voltage across each of these spy resistors is integrated with an op-amp to produce a voltage signal that is proportional to charge in or out of the string. A microcomputer reads the op-amp's output and injects calibrated pulses into the integrator's summing junction to prevent it from approaching its limits.

These pulses are then counted and used as a "fuel gauge" for each string. This count is a direct measurement of the coulombs in or out of the string. Combining a microcomputer with an analog integrator gives the system adequate dynamic range while ensuring that there is enough bandwidth to correctly sense loads that are fluctuating rapidly. (One example of such a load would be the chopper drive to a thruster motor.) The offset drift rate of the op-amp is the practical limit to the accuracy of the system. We have found that offsets equivalent to a drift rate of one full battery charge in several years are easy to achieve and the overall accuracy is about one percent. Careful calibration and compensation could significantly improve this performance if required.

The vehicle measures the voltage on the three-battery stacks and shuts down the AUV, aborting the dive when they reach a preset limit. There is a tradeoff between battery life and cycle depth and this cutoff can and has been adjusted based on the mission at hand. Charging is controlled by three programmable current sources in the vehicle, one for each stack. The voltages of the individual stacks are monitored by firmware in the vehicle and charging is stopped when each stack reaches a preset value. This system has been reliable and is extremely easy to work with. Pack maintenance involves the occasional testing of each cell in the series strings with a individual cell being replaced as required. The current pack has been used for eight years and has endured a lengthy testing program plus over forty science dives typically lasting between six to twelve hours.

2) Odyssey: For MIT's Odyssey vehicle, which needs much higher performance than lead acid batteries can provide, the design team choose silver zinc cells manufactured by Yardney. The vehicle specification includes a need to recharge in situ from a docking fixture to realize long term deployments. We

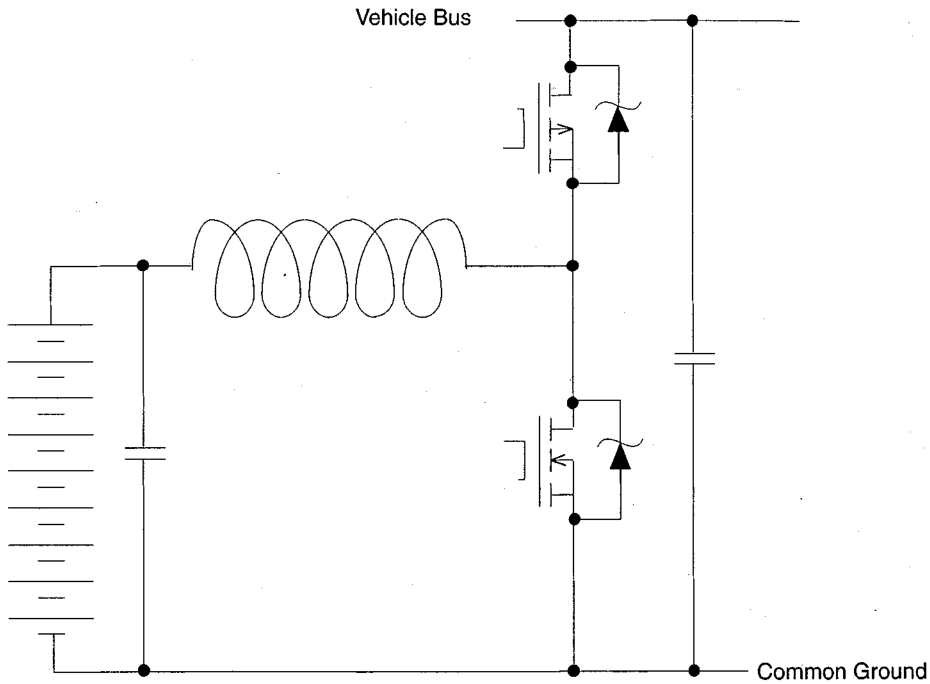

Fig. 5. The bidirectional inverter topology.

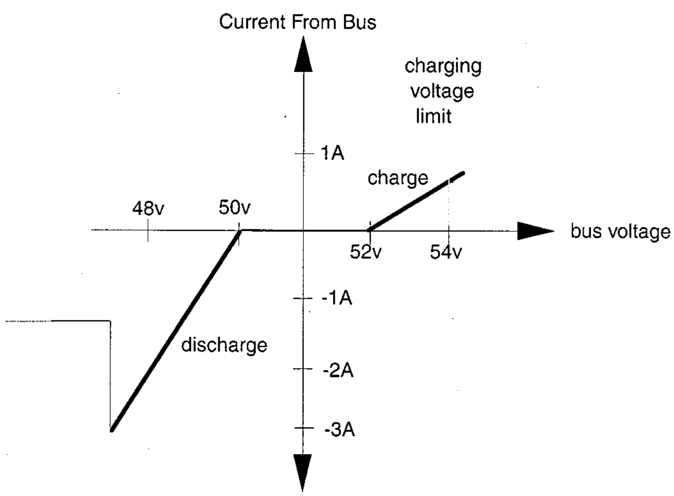

Fig. 6. The current versus voltage characteristic for the AUV bus.

have developed a battery management subsystem to supervise the charge and discharge of these cells with minimal overall system interaction. In particular, the vehicle's main computer does not have to deal with the details of the battery system as the power system is designed to be autonomous. This system has been tested extensively on the bench but not used in the water as of this writing. Our approach seeks to synthesize an idealized battery by adding an intelligent inverter between the batteries and the vehicle bus. The inverter is bidirectional and can both charge or discharge the cells efficiently. Over all reasonable ranges of voltages, this inverter can be commanded to deliver current (up to a specified maximum) either into or out of the vehicle bus. Fig. 5 shows the topology of the inverter while Fig. 6 plots the artificially synthesized i–v characteristic that the battery system presents to the vehicle bus. If the vehicle starts to draw energy from the bus, the voltage falls below 50 V and the inverter starts delivering current. The inverter pulse rate is proportional to the voltage drop below 50 V, thus the current variation as a function of voltage mimics a Thévenin equivalent source. If an external source of power is available to charge the vehicle, it delivers current into the bus, pulling it above 52 V and causing the inverter to charge the cells.

For vehicle reliability, it is advantageous to have several battery packs, each with its own inverter. This redundancy allows the AUV to continue with a mission in the event of a single pack failure. The stability of multiple packs requires a deadband between 50 and 52 V. Without this deadband, slight variations in each pack's voltage calibration might lead to one pack attempting to charge another, thereby wasting energy. The finite slope of the charge and discharge sections ensures that all packs will carry an approximately equal share of the load. Some packs will invariably have less energy than others, yet all need to be depleted at the same time. The Thévenin voltage or resistance can be dynamically adjusted depending on the pack's state of charge to ensure that the cells are used in an optimum manner. Our design measures integrated current in and out of the silver zinc cells in addition to measuring each cell voltage to determine approximate state of charge and adjust the effective Thévenin values accordingly. As each pack discharges, it increases its equivalent series resistance (or decreases its open circuit voltage) slightly so it is always taking its optimum share of the load. Charge behavior is similar, with the Thévenin equivalent resistance going to infinity (charging shut off) as the cells reach maximum charge.

These silver zinc cells had a strict limit of 1.85 V maximum under charge and 1.45 V minimum under discharge. They have a relatively short cycle life and when used in a series string quickly become unbalanced as some cells deteriorate faster then others. Thus it is necessary to monitor the voltage on each cell to make sure it is within safe operating limits. Our battery su-

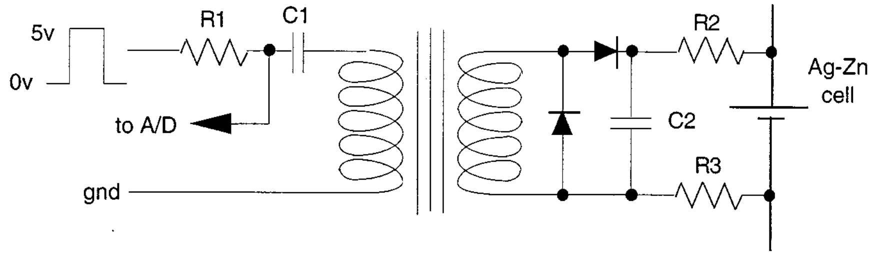

Fig. 7. The isolated transfer for individual cell voltage measurements.

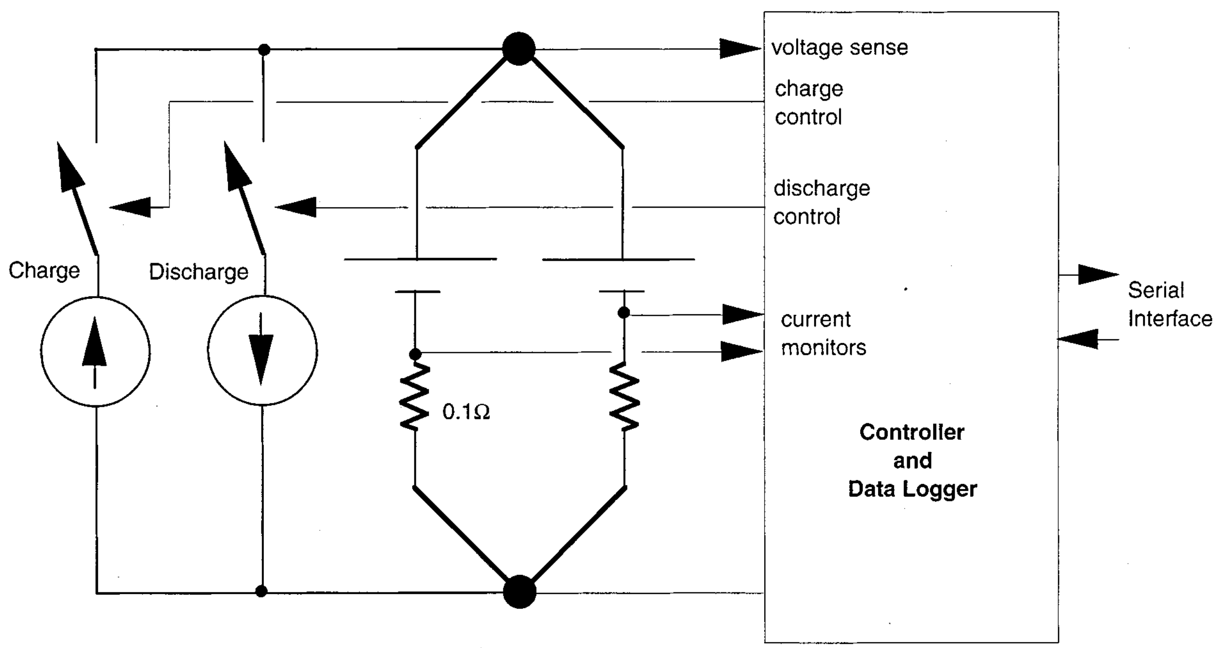

Fig. 8. The battery testing circuitry charge discharge voltage sense charge control discharge control current monitors 0.1- W controller and data logger serial interface.

pervisor design achieves this with a transformer isolated circuit which allows a true differential voltage measurement to be made even in the presence of considerable common mode noise. Fig. 7 shows the circuit that was designed for this purpose. The transformer secondary voltage is clamped by the cell voltage plus a diode drop for a positive pulse, and by a diode drop alone for a negative pulse. These voltages are reflected to the primary side and can be measured by a fast analog to digital converter, with the difference being the cell voltage alone. This circuit is replicated for each cell in the system and connected to a single microcontroller. This controller shuts off the inverter whenever an individual cell voltage exceeds the preset limits.

The Odyssey system was made of four series strings of silver zinc cells each with its own inverter sized to handle 150 W. If the bus is pulled below 46 V, the system reverts to a constant current supply. At this juncture the main computer recognizes that the bus voltage is low and sheds load to recover. The metabolic drain of the inverters is of the order of 5–10 mW and its efficiency in transferring power in or out of the battery is between 90% and 95%. In this design the required interaction with the vehicle's main computer is minimal. The battery system also includes a serial communication bus to the main computer that is used to view the state of charge of the cells and all individual cell voltages. Ideally, the main computer simply interrogates the battery subsystem regularly to determine the state of charge and available energy, and to log the performance of the cells if required.

3) Li–Ion Design: We recently built a 6-kWh Li–Ion battery based on cells from Eagle Pitcher as a replacement for the 1.5 -kWh lead acid pack previously used in ABE. This methodogy is also being used to design a replacement pack for the Odyssey AUV due to the short cycle life of silver zinc cells and safety concerns with that chemistry. Our Li–Ion design is based on "D" sized cells and a bus voltage range of 45 V to 60 V.

The basic problem in designing such a pack is that most COTS Li–Ion pack designs only use a single string of one to four cells, and hence circuits to control these are aimed at this relatively small configuration. Unfortunately, these circuit methodologies do not scale for higher voltages and capacities. In order to reduce the complexity of dealing with ~400 cells, our design operates modest groups of cells in parallel. The voltage–charge curve for Li–Ion cells appears to be strictly monotonic, suggesting that after initial equalization there should be no parasitic circulating currents between cells connected in parallel. Vendors believe that this may be an acceptable and safe mode of operation, but have not done extensive testing. To evaluate the feasibility of this concept

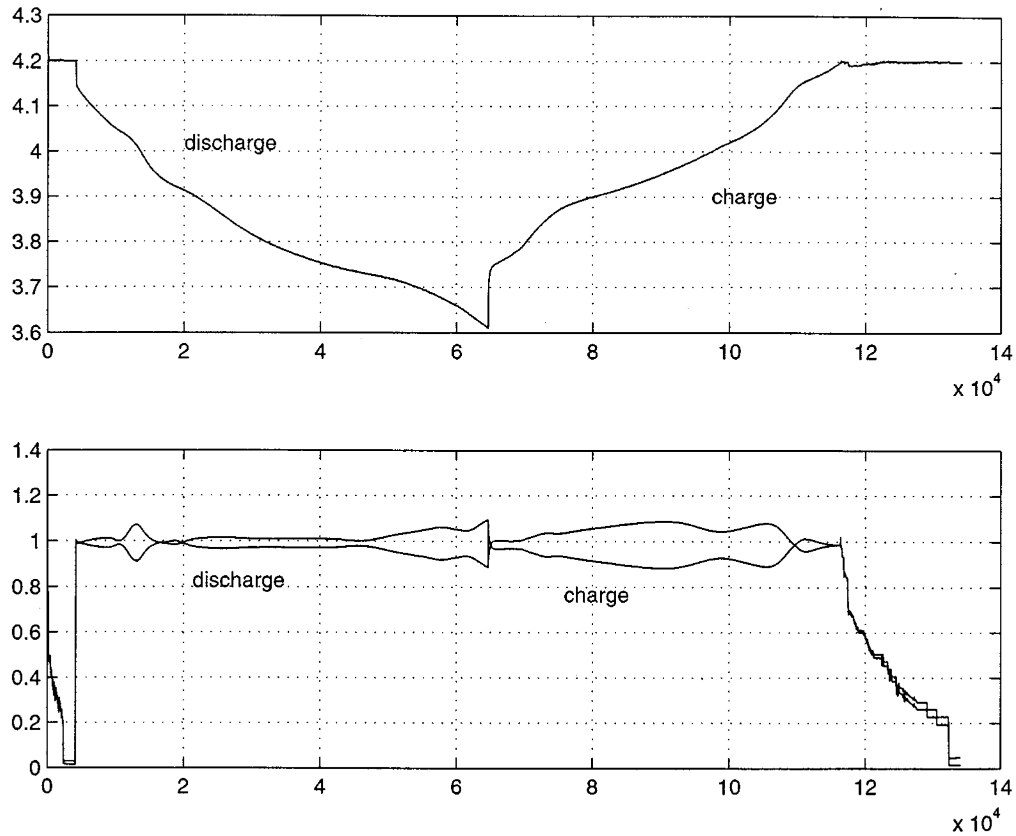

Fig. 9. The voltage and current plots for a complete charge–discharge cycle of two Li–Ion cells in parallel. The top graph shows the voltage of the two cell pack while the bottom graph shows the magnitude of the current for each of the two cells.

we built a test rig to cycle sample cells and monitor their performance when operated in parallel groups. The test circuit is shown in Fig. 8. Two cells are initially balanced by connecting them together with a 1-Ω resistor and waiting until the current between the cells drops to zero. Then, they are connected directly in parallel. Finally, the two cells are cycled in parallel, in the test circuit between 3.6 V and 4.2 V while the individual current from each cell is monitored with a 0.1-Ω spy resistor monitoring each branch current. We eventually worked up to cycling eight cells in parallel, while monitoring the currents in each of the two groups of four. Our results from this exercise are plotted in Fig. 9. The upper half of Fig. 9 shows the cell voltage during a cycle. A clear i-R drop from cell internal resistance is evident at the transitions from charge to discharge. The voltage–charge relation while monotonic is not very linear. We found in testing over 400 cells that the exact shape of this curve could vary slightly from cell to cell. These differences are evident in the lower half the figure which shows the charge and discharge current magnitudes. Although the current is shared between the cells reasonably well, they differ by up to 12% at some points due to their different capacity and variability of the voltage–charge curves of the two cells. When more cells are operated in parallel, these variations tend to average out.

To meet the voltage, capacity and packaging requirements, we wired groups of nine cells in parallel and wired fourteen of these groups in series, delivering 50.4 –58.8 V. These 126 cell assemblies along with monitoring and protection circuitry formed a convenient pack. Three such packs make up the 378-cell, 6-kWH battery for ABE. For Odyssey, we used a single 126-cell pack with a capacity of 2 kWH. In order to charge each series string without allowing an individual parallel group to exceed 4.2 V, voltage clamps were added to each group of nine paralleled cells. The voltage clamp is made of active devices, but is equivalent to an ideal zener diode of 4.15 V in series with 0.01-Ω resistance. When the string is charged at an externally limited current of 5 A, each pack will accept current until it reaches 4.15 V, and then as the cell voltage rises, the clamp will shunt excess current around the pack until at 4.20 V all the current is being bypassed. Slight variations cause some cell groups to reach this bypass range before the others. Charging is complete when all groups in the series string are bypassing the full charge current. This method does suffer from the drawback that the heat generated by the voltage clamps near end of charge is considerable and must be dissipated. The voltage on each group of nine cells is monitored by a similar technique to that used in the Odyssey silver zinc packs to check the health of the cells and to prevent discharge below a settable cutoff point. A single series power FET disconnects each string when the first group reaches this cutoff on discharge. A charge measuring circuit as in Fig. 4 is included as a fuel gauge to monitor pack performance although only voltage monitoring is used to warn the vehicle controller when power is running low.

This battery system has been used at sea in ABE for a series of measurements on the Juan de Fuca spreading center in August 2000. It increased ABE's powered range from 12 km with the original lead acid cells to 60 km. The longest dive lasted 34 h with 30 of these hours, driving the assigned survey pattern at depth. The dive was terminated when one of the three packs sensed one of its parallel cell groups drop below the assigned 3 volt limit.

The controller then stopped the thrusters and dropped the ascent weight. As the propulsion load was removed, the battery voltage recovered, giving ABE a comfortable energy margin to sustain basic functions until it was on deck. Charge time was about 10 h and was determined by ability of the voltage clamps to dissipate the heat they generated as the cells approached maximum voltage. We found that the increase in cell internal resistance when operating at depth at 3 °C was about a factor of two. At ABE's discharge rate, this represented an energy loss of about 2%. At higher discharge rates this effect would be more significant. We carefully monitored the internal pressure in the housing that contained ABE's batteries and electronics and were, as expected, unable to detect any evidence of outgassing. These batteries are now undergoing cycle testing on the bench. After over 100 cycles at typical ABE rates they still retain over 95% of their capacity. These tests are continuing and the results will be presented in a future paper.

IV. Power/Data Transfer

To be used for repetitive missions in a long-term deployment, a truly autonomous AUV and its dock must incorporate a means of transferring power from the dock to the AUV. Sufficient power must be available to simultaneously supply the AUV hotel load and to charge the batteries. In addition, data transfer must be available to download the results of the previous mission, and to upload commands for the succeeding one. Due consideration must be given to the practical problems of unattended long-term deployment such as bio-fouling, imperfect mating, reliability, and efficiency.

Several means of power/data transfer were given serious consideration for use with the Odyssey in the context of an AOSN. These included direct electrical contact; automatic replacement of the battery pack; optical transfer; and inductive transfer. We now look at each of these methods in turn.

A. Direct Electrical Contact

Direct electrical contact has the advantage that, once an effective connection has been established, the power transfer is potentially very efficient. Mating is also straightforward if only power transfer is required. Disadvantages include susceptibility to biofouling, need for sealing the connection electrodes from sea water, necessity for precision mating if more than one circuit is to be established, and the difficulty of accommodating variations of vehicle attitude, which may result in both axial and rotational missalignment of the electrodes. Direct contact electrical power transmission might seem to eliminate the need for inverter/rectifier components required by other methods, resulting in an improvement in efficiency. Alternating current has the advantage, however, of minimizing the electrolytic corrosion of electrical contacts if sea water were to leak into the coupling and establish a parasitic link. The recent availability of multiple connection hot-mateable connectors may facilitate direct power transfer, but it remains to be seen if simple mating means can be developed to provide and maintain reliable and repeated insertion.

B. Automatic Replacement of the Battery Pack

Automatic replacement of the battery pack has the advantage that the AUV immediately obtains a renewed energy supply, and, except for the requirement of mission data and command transfer, and has in principle an efficiency of power transfer of 100%. The discharged pack can then be evaluated and recharged at the dock, and replaced if it is deemed to have become marginal. One obvious disadvantage is the need for a battery insertion and retrieval mechanism which is likely to be complex. In addition, a connection still needs to be established from the battery pack to the AUV, which is likely to be a wet connection. The size of the battery pack used in the Odyssey II vehicle was also a factor, seeming to require a fairly hefty and robust exchange mechanism. Finally, the battery pack would have to be sealed against sea water, as well as provide a means for venting evolved gasses.

C. Optical Transfer

Optical power transfer was considered too inefficient using available devices, in spite of recent improvements in solar cell technology. Optical data transfer however has the advantage that coupling between the power and data path could be eliminated. Optical data transfer was therefore attempted using infrared leds and visible laser diodes as sources and PIN diodes as receivers. With the devices available to us, the receiver bandwidth necessary for 10 MBd ethernet could only be achieved by a laser diode and even then the performance was marginal. Alignment proved more critical than anticipated for a unidirectional link. The optics necessary for a misalignment tolerant bidirectional link were more complex than was considered practical. In addition, susceptibility to bio-fouling and other sources of attenuation and dispersion ruled out optical data transfer for this project.

D. Inductive Transfer

Inductive power and data transfer has the advantage of being extremely tolerant to inaccurate mating while providing acceptably high efficiency. This method effectively eliminates the need for physical contact of electrical contacts, and in fact does not require physical contact of the connection devices at all (although intimate contact generally results in better operation).

Significant biofouling can be tolerated since it does not affect the magnetic fields, and a physical electric circuit is not required. Careful design of the magnetic mating components can result in an inductive connection that is tolerant of 360 deg of rotation, as well as providing tolerance for poor mating, including both axial separation and axial misalignment. More than one circuit can be established, making possible the integration of power and data transfer into a single coupling. Finally, careful design can result in mating components which provide adequate inductive coupling while permitting passive mating in many dock designs. Passive mating obviates the design of a mechanism for inserting or mating the power transfer components. The disadvantages of this technique include the need for an inverter and

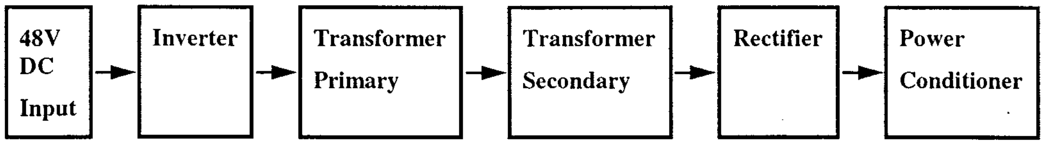

Fig. 10. The components of the power-transfer system.

a rectifier with attendant losses that these imply. This is a disadvantage that is likely to be shared with other transmission methods as mentioned above. Inverters may be designed which have very high efficiencies near their maximum power capacities, but switching losses and other losses limit the efficiency at lower power levels. Inductive transfer also has the disadvantage that the leakage inductance of the magnetic coupling is significantly greater than for a conventional transformer, and is a function of the separation of the transformer halves. The associated electronics must accommodate this variation and adapt to maintain efficient power transfer in the event of poor physical alignment. Poor alignment also results in crosstalk between power and data channels, particularly under conditions of high power transfer. For this reason, misalignment may limit the simultaneous transfer of power and data.

The perception that the inductive power/data transfer method solved a number of problems led us to choose this technique. In addition, the likelihood that the circuits could be established passively, or probably with an extremely simple mechanism was additional incentive as designing a dock to capture the Odyssey II vehicle in deep water on a mooring was deemed sufficiently difficult without additional mechanisms.

An inductive power-transfer system consists of the following components (Fig. 10): 1) An inverter to convert the dc power to ac which can pass through a coupling transformer, since only dc is ordinarily available at the dock. The inverter should adaptively maintain an efficient transfer as coupling parameters change; 2) A transformer having separable primary and secondary elements to accomplish the dock/AUV link; 3) A rectifier to convert the ac back to dc; and 4) A power conditioner to accommodate the large variations in output voltage of the rectifier, and supply a voltage/current characteristic required by the AUV battery charging/power management system. Each element of the power-transfer system entails unavoidable losses. Careful design was required to minimize the loss of each component and to achieve a high overall efficiency.

1) System Component Design: The first inverter converts the 48-V dc available at the dock to a high frequency ac which can efficiently pass through the coupling transformer.

Initially a square wave inverter was designed. This inverter had the advantage of good efficiency over a range of power levels, but harmonics of the square wave proved difficult to suppress. Snubbers were required to reduce switching transients which imposed electrical stress on the switching devices. These switching transients were aggravated by leakage inductance in the coupling transformer. This leakage inductance is inevitably higher than in a more conventional transformer design. Data transfer was generally impossible when power was being transferred. Attempts to convert the square wave into a sine wave using filters were not successful. We then designed two new sine wave inverters. The first synthesized a sine wave using eight switching devices each of which selected a tap on the primary of a transformer. The switching devices were switched in sequence to produce an output which was a stepwise approximation to a sine wave.

Several problems arose with this design. First, the switching transients still required snubbers as in the case of the square wave inverter. Second, this topology proved unable to accept the reactive components of output current produced by leakage inductance and the nonlinear load imposed by the rectifier. Third, the use of eight power switching devices produced at least eight times the switching losses than the case of the square wave inverter.

The final inverter used a push–pull resonant mode. Two power FETs drive a center tapped resonant circuit. An inductor connected to the center tap supplies dc power to the output devices while relieving the output stage of the switching harmonic currents. Since essentially no harmonic energy is generated, no snubbers are required. Full power efficiency is good. Low power efficiency suffers from losses in the resonator in addition to switching losses, however. The circuit employs a phase-locked loop configured to facilitate inverter startup, and to maintain the frequency of operation very close to the resonant frequency of the coupling transformer primary circuit.

A drawing of the coupling transformer is shown in Fig. 11. The transformer is composed primarily of encapsulated ferrite. The primary half has a conical ferrite section mounted on a ferrite disk. The secondary is the complementary shape designed to have a close fit with the primary. The power windings are located ont he conical surface of the primary half, and on the matching concave conical surface of the secondary half. Ancillary windings are included for full duplex 10-Mbs ethernet. An opening of about 2,5 in extendg through the center of both halves and may be used to accomodate a capture mechanism for certain docking configurations. Conductive and magnetically permeable materials may be used in this region since the magnetic fields do not normally extend into these areas.

The shunt inductance of the secondary power winding of the coupling transfer has an inductance which is very close to that of the primary. The secondary is resonated to the same frequency as the primary using an identical value of capacitance. Since the leakage inductance of the transformer is common to both halves, the resonant frequency of both halves is the same, regardless of the degree of mating misalignment. The secondary therefore resists the generation of harmonics by the nonlinearities of the rectifier circuit.

The rectifier circuit is a straightforward inductive input full wave bridge rectifier. High-voltage Shottky rectifiers were required to permit efficient operation at the relatively high frequency of operation, and to accommodate the relatively large

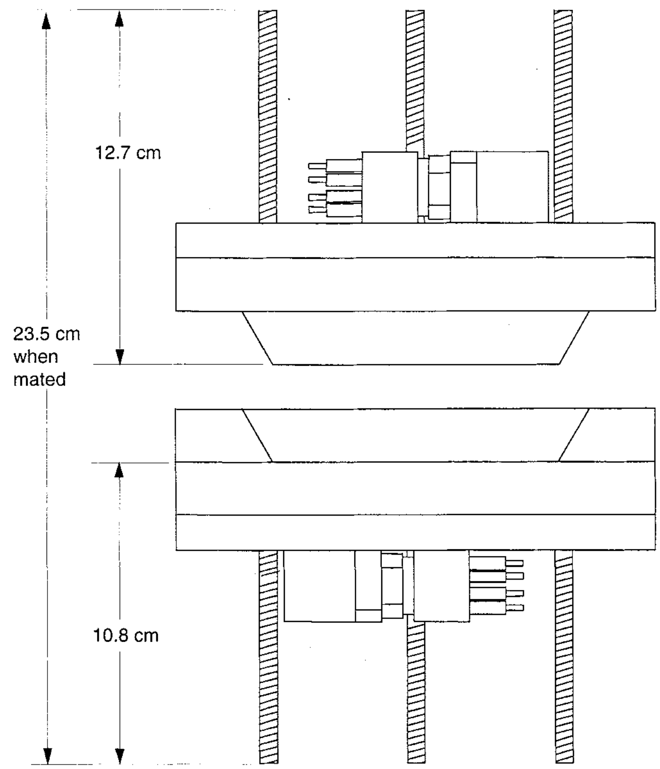

Fig. 11. The inductive cores used for data and power transfer. The male core (top) is mounted on the AUV while the female core (below) is mounted on the dock.

output voltage variations produced by the combination of dock power supply variations, variations transformer coupling, and variations in the AUV load. The power conditioner is a buck regulator whose output characteristics may be varied according to the requirements of the AUV.

2) System Efficiency: The maximum overall efficiency of the system varies between 79% and 83%, depending somewhat on the value of the input voltage, and the quality of mating of the coupling transformer. This peak efficiency occurs at a power output of 180–220 W. At lower output levels, the quiescent losses of 15–18 W limits the efficiency. At higher power levels, resistive losses increase disproportionately. When fully mated, the efficiency of the coupling transformer has been measured at about 97%. The efficiency of the other components has not been independently measured.

V. Conclusions

After a careful review of the available battery systems, we selected lithium–ion secondary cells as the most appropriate for use in an AUV in an AOSN context. They offer long cycle life, can operate in a sealed housing and have attractive energy densities approximating that of alkaline primary cells. We developed monitoring and control circuitry to enable us to combine many relatively small cells into multi-kilowatt battery packs appropriate for our AUVs. Li–ion technology is evolving rapidly and we can expect continual improvements in the next few years, but the basic cell characteristics seem stable. Cells that can be operated at ambient pressure will be the biggest improvement for the AUV community in the near future. As our packs grow and the energy contained increases, safety becomes a greater concern. Elimination of the pressure housing will reduce the impact of a possible pack failure. Our work on *in-situ* power transfer combined with our Li–ion battery system provides a solid basis for a power system suitable for long term, untended deployments at remote sites anywhere in the world oceans.

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