Energy Systems for FAU AUVs

Ed Henderson, Tom Pantelakis, Edgar An
Department of Ocean Engineering
SeaTech Campus
Florida Atlantic University
Dania Beach, FL 33004
Contact: ean@oe.fau.edu

Introduction

AUV technology is rapidly maturing, and is revolutionizing the field of experimental and tactical oceanography [4,6,7,19]. This is evidenced in many recent military and commercial demonstrations of hydrographic survey and mine reconnaissance [15,17]. By capitalizing on the off-the-shelf commercial sector, AUVs are much smaller in size and weight, thereby substantially reducing the operational cost and constraints. This improvement is epspecially critical for military fleet battle experiments that require the vehicles to be of low surface observability, and transported with small support vessels [15,17].

While small AUVs provide advantages such as low capital and operational costs, there is less room onboard for storage of energy sources, and thus mission endurance performance can be compromized. Common techniques that can address such an issue include: 1) a better streamlined body in order to reduce vehicle drag, 2) better mission optimization to increase the throughput efficiency, 3) a better energy source that leads to more energy capacity available, and 4) a docking station available for remote power transfer during time critical missions. It is conceivable that any combination of these techniques can be used in order to maximize the utility of the vehicle for search and survey operations. Although there are many different energy systems available to AUV's today (batteries, fuel cells, and even combustion engines), batteries are typically preferred because the technology is relatively inexpensive and straightforward to be implemented on small AUVs. In [3,5,14] different primary and secondary battery chemistries were compared and their applications to AUVs discussed. Regardless of the technology used, the AUV energy system must satisfy design constraints that govern AUV systems. Size, weight, reliability, and safety are at the top of the list. The AUV research program at Florida Atlantic University has focused its design efforts on battery powered AUVs, developing both the battery packs and power distribution systems that provide a robust energy system for the AUV. This paper focuses on the development of our energy systems on our 3 AUVs (Ocean Voyager II, Ocean Explorer and Morpheus) in terms of battery pack arrangements and power distribution systems.

Ocean Voyager II

Three generations of vehicles, the Ocean Voyager, Ocean Explorer, and Morpheus have been developed. With each generation came advancements in the battery system and refinements in the power distribution system as well. The key philosophies in recent development have been modularity, multiple redundant packs, in-situ charging, expandability, and safety.

The Ocean Voyager II was the first generation vehicle developed [8]. The energy system is simply five 12V 12Ahr lead-acid gel cell batteries in series. This comprises the basic battery pack, with energy of 720 WHrs, which delivers a 60V (50V-72V) bulk voltage to all other systems onboard. The vehicle design allows for a maximum of two battery packs to be installed, which are parallel wired.

The power distribution is simply daisy chained wiring to all sub-systems of the AUV through a master circuit breaker (on/off switch). The battery packs have no monitor or control circuits. The vehicle monitors the bus voltage and aborts the mission on a low voltage condition. Charging is accomplished by removing the battery packs from the vehicle, opening the pressure vessels, and connecting 12V chargers to each cell. Although this system is very simple, it provides a useful energy system for the vehicle.

Ocean Explorer

Many shortcomings of the Ocean Voyager's energy system were identified and new ideas were implemented in the design of the Ocean Explorer (OEX). Modularity, a key development concept of the

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OEX series AUV [16], in the energy system is made possible by the use of the multiple battery pack modules, each in it's own pressure vessel. These packs are connected to the "battery bus" (see Figure 1), supplying current in parallel. The bus carries a 48V (42V-60V) bulk voltage to the system as well as a two wire LonTalk network. All vehicle loads, including the payload, are connected to the "load bus", also carrying power and LonTalk. The two buses are connected together through a circuit breaker located in the control box. The control box also contains a LonTalk node that allows battery packs to be turned on and off electronically. The current battery bus allows for up to 31 battery packs to be connected.

An intelligent battery pack designed for the OEX uses 42 1.2V 5Ahr Ni-Cd D cells in series. The Ni-Cd battery pack, with energy of 250 WHrs, was chosen because of the increased energy density (50% more than a similarly sized lead-acid cell) and the maturity of the battery chemistry (most of today's high energy cells were still in the development stage). Ni-Cd batteries also perform well over the wide range of discharge rates normally seen in an operational setting (transit, survey, standby, etc). This enabled rapid development of the energy system used on the OEX.

Each NiCd pack has an independent battery controller board. The controller, a microprocessor with a connection to the LonTalk network used throughout the OEX, monitors and controls the battery. Control circuitry for the pack includes an electronic on/off switch, electronic circuit breaker, 1A constant current source for charging, and low voltage diode for paralleling multiple packs. Monitor circuits include voltage monitoring of every 6 cells in the 42 cell series string, discharge battery current sense, pack temperature, and bus voltage. A fuse and thermal fuse are safety features incorporated into the pack. The microprocessor controls the various functions of the pack from command messages sent via the LonTalk network. Health and status messages are also sent via the network.

Battery packs are charged in-situ by applying a higher voltage, from an external power supply, to the battery bus via the control box. The processor monitors the progress and condition of the charge cycle and controls a simple protocol that allows up to eight battery packs to be charged simultaneously. The charge is at a 0.2C rate, allowing for a charge time of about 5 hours. The microprocessor also implements a simple gas gauge function providing energy status to the host system. The gas gauge assumes a constant charge rate, and does not provide any compensation for effects of temperaure and discharge rate variations. In addition, it does not account for the self-discharge of the batteries. Although simple, this function can be critical for accurate mission planning.

The OEX energy system is extremely modular and expandable. Different types of battery packs can be connected to the bus as long as all are capable of operating in parallel. Several types of primary cell packs have been developed for specialized missions. A 37 D cell Alkaline pack, with energy of 830 WHrs, has been developed and used for long endurance missions. A 42 D cell Lithium-Manganese Dioxide pack, with energy of 1000 Whrs, has also been developed.

Morpheus

The development of the Morpheus vehicle brought about many changes [15]. The basic vehicle concept (see Figure 2) has three parallel buses (battery bus, load bus, and communications bus) that connect to all pressure vessels. This concept allows true modularity. All vessels may contain vehicle loads and/or battery packs. All battery packs connect to the "battery bus", providing power in parallel. All loads are connected to the "load bus". The "battery bus" and "load bus" are connected together through a circuit breaker in the Fin vessel. A new control panel was also developed to electronically turn battery packs on and off, as well as monitor the status of each pack in the vehicle.

Due to size and weight restrictions of the Morpheus (each module was designed to be neutrally buoyant and trim), a new battery pack was needed that provided a better energy density than Ni-Cd. Several battery chemistries were studied to determine the best fit. Lithium-Ion, having almost the best energy density at the time, was unavailable commercially for underwater applications. Polymer batteries were also in their infancy. The Ni-MH family of batteries proved to be the best choice. Their energy density is nearly twice that of Ni-Cd and the technology is fairly mature. The similarities to Ni-Cd also helped speed up the development process. Preliminary bench test results using 6 NiMH cells in series confirmed their capacities at their specified discharge rate (see Figure 3).

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A new intelligent pack with 42 1.2V 3.8Ahr Ni-MH in series was developed. This pack, with 190 Whrs energy, also has an independent battery controller board. Each pack is independently controlled. Three battery packs fit within one Morpheus pressure vessel, for a total of 570 WHrs. Other vessels many also incorporate battery packs to further enhance the energy carrying capability of the vehicle.

Several enhancements in the battery controller were made for the Ni-MH battery packs (see Figure 3). A new bi-directional current controller allows the charge and discharge currents to be controlled. During the charge process, the external power source can be either higher or lower than the battery voltage while maintaining the proper charging current. This allows a single external power supply to both power the vehicle and charge the batteries.

The control circuitry includes electronic on/off switch with soft start for heavily capacitive loads on the battery bus commonly found in AUV systems, software circuit breaker, programmable 0 – 8A current limit with time out, programmable 0 – 4A constant current source for charging, and low voltage diode for paralleling multiple packs.

Monitoring circuitry includes voltage monitoring of every 4 cells in the 42 cell series string which allows a more precise estimation of end of discharge/charge conditions[§], charge/discharge current sensing for accurate gas gauge calculations, multiple temperature sensors throughout the pack, and battery bus and load bus monitoring. Safety features include fuse, redundant thermal fuses, pressure sensor, and pressure relief port. All control and status messages are sent via a LonTalk network wired throughout the vehicle.

The gas gauge has also been enhanced to provide much more accuracy over the varying conditions the battery is exposed to. Temperature effects, charge, and discharge efficiencies and self-discharge characteristics have been incorporated. Pack cycle life is also monitored to assist in maintenance of the packs. The controller has also been designed with very low power consumption to allow for a long-term sleep or standby operation.

[§] For both NiCad and NiMH batteries, there is a negative drop in voltage and positive rise in temperature at the end of a charging cycle.

Conclusion

The current energy systems in operation on the three AUV systems developed at Florida Atlantic University have proven both useful and reliable. Countless hours of at-sea operations as well as extensive laboratory testing have shown this. As new battery technologies mature, they will be incorporated into the vehicles energy systems. The modularity of the OEX and Morpheus vehicles enable new battery packs to be developed and implemented in the vehicle easily. Table 1 lists various data of commercially available cells of different battery chemistries, which show the electrical and physical properties one may use when selecting a particular battery technology. Many factors are considered when designing a particular battery pack such as weight, volume, energy storage, voltage, vehicle turn around time, operational discharge rate, and others.

Although certain chemistries have much higher energy densities than others, these may also require more complex monitoring and control circuitry. This, in effect, lowers the total system energy density. It is also worthwhile to note that the available energy in a particular cell is dependent on the discharge rate. The packing factors associated with different cell packages will also affect system energy density.

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	Manufacture Part Number	Chemistry	Voltage (V)	Capacity (AHr)	Capacity (Hr rate)	Weight (gm)	Volume (cm^3)	Energy (WHrs)	Energy Density (WHr/kg)	Energy Density (WHr/L)
Primary	Duracell MX1300	Zn/MnO_2	1.5	-	212	147	56.4	21.2	144	376
	Ultralife U3360HCES	Li/MnO_2	3.0	11	5.5	117	52.7	33	282	626
Secondary	Hawker Cyclon 0810	Sealed Lead Acid	2.0	2.5	10	178	56.5	5	28	88
	Moltech (OEX-B) EC-5000D	Sealed Ni-Cd	1.2	5	5	140	46.5	6	43	129
	Panasonic (Morpheus) HHR380A	Sealed Ni-MH	1.2	3.8	5	53	15.2	4.6	87	303
	Moli-Energy ICR-18650G	Li-Ion	3.75	1.8	5	45.5	16.9	7.5	165	444
	Sanyo (OEX-C) HR-4/3FAUX	Sealed Ni-MH	1.2	4.1	5	62	17.2	4.9	79	285
	Ultralife UBC44106102	Li Polymer	3.8	3.8	5	108	47.6	14.4	134	303

Table 1: A comparison of different battery chemistries (ref [9,10,11,12,13,18])

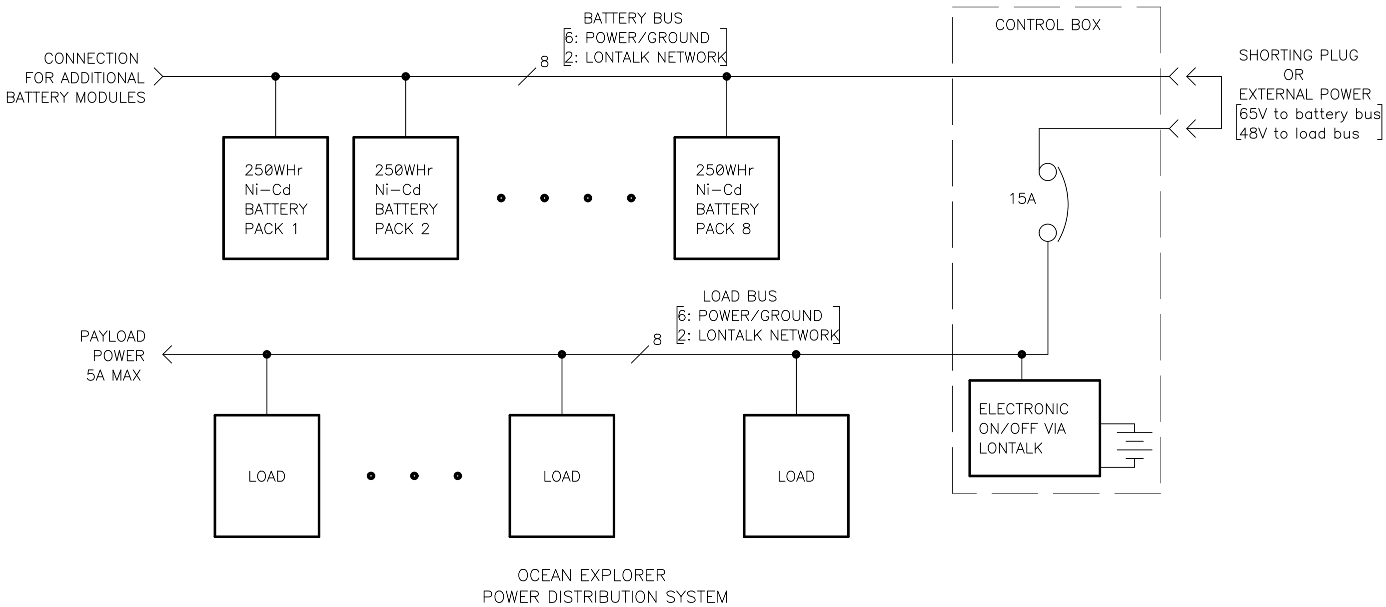

Figure 1: A power distribution system for Ocean Explorer

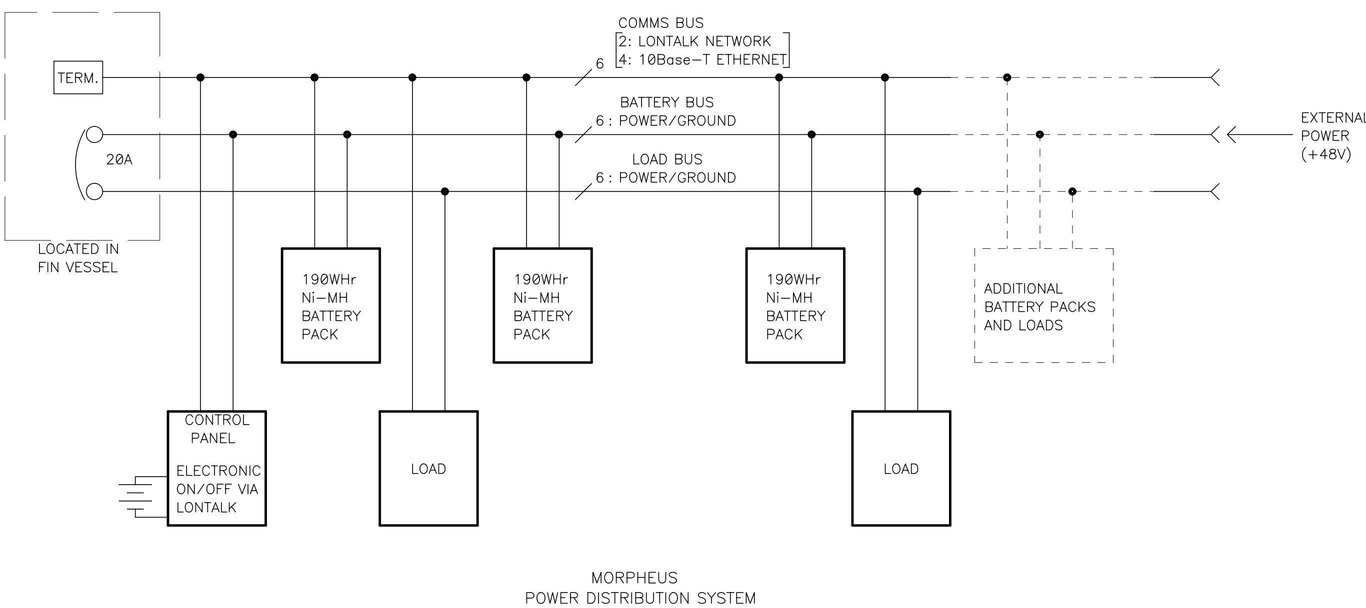

Figure 2: A power distribution system for Morpheus

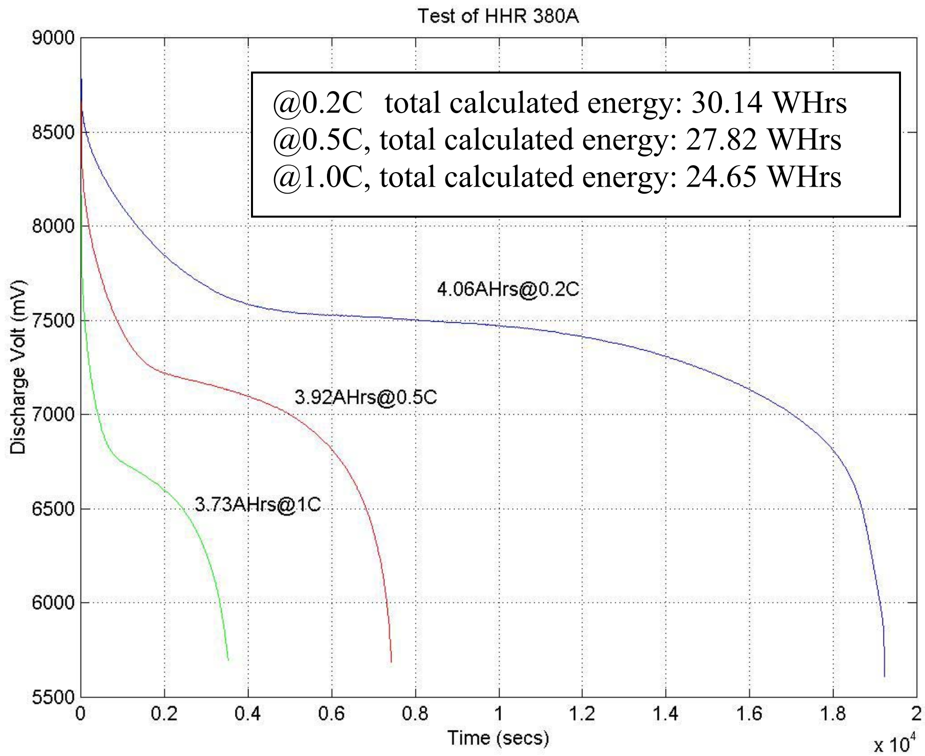

Figure 3: Bench test results at different discharge rate using 6 Panasonic HHR380A NiMH cells in series. The nominal cell voltage is 1.2V.

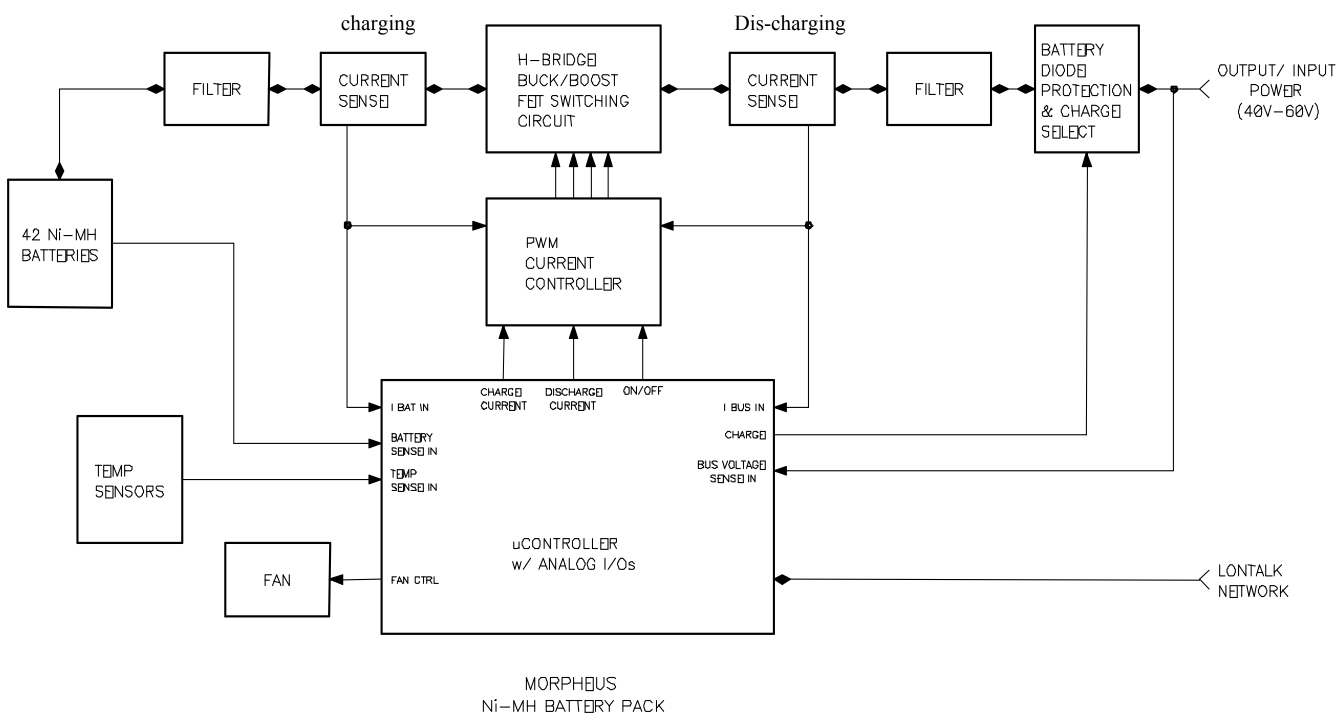

Figure 4: Morpheus monitoring and control mechanism