Extending our Reach Beyond Neptune Nodes: Autonomous Underwater Vehicles and Acoustic Communications

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Introduction

Autonomous underwater vehicles (AUVs) are rapidly approaching maturity. Like ROVs in the early 1980s, the vehicles are becoming more reliable, are proving themselves in a variety of applications, and their specific capabilities for scientific work are becoming clear. On the downside, some expectations may exceed our capabilities. Over the lifetime of NEPTUNE, we can anticipate continuous improvements in endurance, sensing capabilities, navigational infrastructure, communications, and intelligent control. In this document, we will attempt to anticipate those developments and place them in the context of existing vehicles.

In addition to scientific interest, AUVs are receiving considerable attention from the military and industry. While the military has been behind much AUV development in the past, the US Navy has recently shifted its focus from large, tactical vehicles to smaller vehicles that will also be appropriate for scientific work. At the same time, they seem to be losing interest in deep water. In the commercial sphere, survey companies working in the offshore oil and gas industry are positioning themselves as major players in AUVs and are especially interested in their application to deep water problems.

Acoustic communication will become a key element of AUV systems, so we have included it in this white paper. The ability of an AUV to communicate to a Neptune node can add key capabilities during both routine survey and event response. If fully integrated from the beginning, acoustic comms would use much of the same on-vehicle infrastructure required for other necessary subsystems such as acoustic navigation, so the additional capabilities come at little additional cost or complexity. Finally, an acoustic communication infrastructure could provide communications to and from self-powered instrument packages placed near the nodes, allowing each node to be expanded quickly and inexpensively either from ships or possibly from aircraft without intervention by ROV.

The goal of this document is to aid the science groups as they prioritize their scientific needs and map their needs to AUVs. Hopefully, we will learn to maximize the scientific return by exploiting existing capabilities and stimulating new developments.

AUV Capabilities and Scientific Needs

Our final report should contain a framework for AUV requirements generated by scientific needs. AUV engineers would benefit from a scientific checklist of needed measurements, including their spatial and temporal scales. Ideally, these would be ranked in order of importance, so tradeoffs can be made when economic or operational realities manifest themselves. Like most measurements for Neptune, we may benefit from considering two kinds of measurements: routine measurements and measurements made during events.

The following subsections describe information that would enable AUV systems to be generated from scientific needs. In particular, they will allow AUV designers to consider vehicle range, speed, payload, and required intelligence or mission flexiblity. We are certain that these sections are incomplete, but hope that they push discussions in the right direction.

Required measurements and samples

The required sensors payload could be an important driver on AUV size, range, etc. For any given type of survey or event response, we should assemble a list of the required measurements, drawing examples from commercially available sensors when available. We can also make projections about how *in-situ* sensing capabilities will evolve. Especially during event response, sampling may also be required when *in-situ* sensors are unavailable. As the AUVs may remain docked subsea for prolonged periods, sensor calibration issues could be extremely important.

Some types of data (such as video and some kinds of sonar data) completely dominate sensor payload in terms of data storage (and later transmission). Even the simplest video system, such as the video snapshot system on ABE, can rival propulsion in an AUV power budget due to lighting requirements. Video also requires a vehicle that can manuever close to the bottom and has sufficient size to provide the required camera-to-light separation.

Expected distance from the nearest node

How far would an AUV likely be required to travel to and from the survey area? If we can count on AUVs with long range, we could extend the reach of each node, either providing better coverage or reduced cost.

Spatial character of phenomena

After reaching the desired area, how far must an AUV travel to obtain sufficient coverage? Does the sensing scheme place any restrictions on vehicle speed? Is the desired survey pattern primarily horizontal, vertical, or a mix? Will the vehicle have to cope with difficult terrain or will it travel a safe distance from the seafloor?

Temporal character of phenomena

How often do we need to repeat a time series? How quickly do we need to survey a transient event? How long does the event last and how often should AUVs survey it. Would a transient event be captured better by multiple, coordinated vehicles that can make simultaneous observations from different locations? Would a rechargable vehicle of limited range be able to capture the event despite the necessity to return to the node for recharging, or would a longer range vehicle (either rechargable or one-time use) be better?

Apriori knowledge of phenomena

Based on data from other sources within Neptune, could a vehicle mission be completely planned just before the vehicle is launched? Would incremental data transmitted from the vehicle in real-time be needed to redirect the vehicle? Or could the vehicle require on-board intelligence to sufficiently capture the needed data? Would either real-time data or on-board intelligence allow surveys to be conducted more efficiently even if they were not strictly necessary?

Typical AUV Characteristics

Present AUVs come in a variety of shapes and sizes, which translate into characteristics such as range, maneuverability, and depth capability. We will restrict our discussion to AUVs capable of working at depths corresponding to the JdF ridge or greater. We will also focus on vehicles in the medium to small size range (< 1000 lb).

The majority of AUVs are built around low-drag bodies of revolution (i.e. MIT's Odyssey [3,4], WHOI's REMUS[4,5]). They feature a single propulsor (thruster) at the stern. Fins at the stern provide the ability to turn and control pitch. Depth control is achieved by changing pitch, which couples into depth control through body lift.

Such vehicles can be very efficient and provide excellent stability when extreme maneuvers are not required. They can make "toyo" style surveys very efficiently, as long as the desired vertical speed lies within their capabilities. They have also been used for bottom survey in flat to moderate terrain. They must maintain forward speed to maintain controllability, so they can't stop or backup.

A vehicle such as the Autonomous Benthic Explorer (ABE [6]) can maneuver much more generally. Using 7 thrusters, ABE has demonstrated that it can hover, back up, and follow the bottom in rugged terrain at sites like the Juan de Fuca (Floc) and the Southern East Pacific Rise. The vehicle is also an extremely stable sensor platform at all speeds. Overall drag is higher, however, so range is reduced over a comparable single-body fin-controlled vehicle.

We are currently building a next generation version of ABE, which will retain the ability to stop, hover, maneuver at slow speeds, and follow the bottom in difficult terrain. The new vehicle will have significantly longer range and will be able to perform large depth excursions efficiently. It will be explained in a bit more detail in a later section.

Typical AUV Missions

An AUV fully integrated into NEPTUNE will be stationed for long periods of time at a subsea node, maintaining communications and in most cases obtaining power through the cable between missions. Our community has done engineering demonstrations of docking (including power and data transfer), but we are just beginning to attempt deployments of any length. Clearly, the long-duration docked AUV will be getting much attention in the near future, and we can anticipate that these capabilities will continue to mature.

We have lots of work to do, especially in the area of long-term reliability. The leap from an AUV serviced after every mission (which we do now) to one that could perform many missions with no human attention is significant. We see no show-stopping basic engineering issues, rather a long list of details to conquer. Tests at existing and near-term observatories such as LEO-15 and MBARI's COMB would enable us to move forward directly to a NEPTUNE capability. At either of these sites, we could test systems for prolonged periods while retaining easy access from shore, COMB is particularly interesting in that it will provide substantial water depth and would hopefully be free from shallow-water biofouling problems.

If we had one or more AUVs docked to NEPTUNE nodes, how would we use them?

Initially, we may be forced to consider the AUVs to be valuable, somewhat fragile assets. Depending on the number of vehicles at our disposal, we might not use all the AUVs to make routine, repeated surveys, but would save some of them for an event-response role (what if an eruption occurred and all the AUVs were broken or had been lost?). Or perhaps an occasional run with the AUV (one/month?) would be required to assess its condition and might even enhance its reliability. We won't be able to make judgements about these matters without more experience. A site like COMB would be very useful for building up this knowledge.

With time, we will have enough cheap, reliable AUVs that we will be able to send them off at will, perhaps keeping a few in reserve to respond to unexpected events. We will have a mix of vehicles with different capabilities and costs. We will be able to repeat observations on almost any schedule desired. In principal, a rechargeable AUV would be available about half the time (see later discussion on power). Of course, our present operational experience does not support near-continuous operation, and we would have to justify such a massive data set on scientific grounds.

How would we best use AUVs to capture specific oceanographic phenomena? This is an area where close collaboration between scientists and engineers is essential. Bellingham and his group at MIT have developed a methodology for adaptive sampling that takes into account the spatial and temporal variability of the phenomenon, the speed/range capabilities of the AUVs, their sensing capabilities, and the number of vehicles employed. The technique is helpful both in vehicle design and in planning missions with existing vehicles, both on single and multiple vehicle deployments. We've attached a paper about the concept with this white paper.

Range, Power, Recharging

Current AUVs are generally restricted in range, however this situation is improving rapidly for several reasons. First, vehicle designs are evolving to use power very efficiently, both in terms of propulsion and "hotel" loads. Second, batteries are advancing rapidly due to the demands of other sectors (i.e. cell phones, video equipment, and notebook computers).

Maximizing the range of an AUV requires careful attention to power. In particular, any AUV has a tradeoff between range and speed. Analysis will quickly show that the maximum range (in the absence of currents) is achieved when the propulsion load and "hotel" loads are matched. If the vehicle goes slower than this ideal speed, nonlinear drag effects reduce the range, if the vehicle goes slower than the ideal speed, the hotel load burns off power. Some papers on this subject are included in the attachments.

In general, range increases approximately linearly with vehicle length (battery capacity increases by L^3, drag by L^2). We will revisit the subject of vehicle size when we consider conceptual vehicle designs.

We can illustrate some interesting points about power using ABE as an example.

The current version of ABE uses lead-acid batteries carried inside its main pressure housing at one-atmosphere pressure. Using these batteries, ABE has executed 12 km bottom tracks at 2500 meters depth at 1.5 knots. By simply substituting an equivalent volume of lithium ion batteries (which are well-suited to frequent recharging), we could extend this range by a factor of 3.5. Lithium polymer batteries are not currently available for this purpose (current production is aimed at the cell phone market, so they're building cells about the size of AA batteries), but we anticipate that they will be available in the proper size in the next few years. Although lithium polymer cells can provide slightly less energy than lithium ion cells, preliminary tests show that they may work well at pressure, increasingly their performance by an addtional factor of 2.5 based on in-water weight. By substituting lithium primary cells in the one-atmosphere volume, we would increase ABE's range 10 fold over the lead-acid version, but at a cost of ~$10K/run.

The version of ABE currently under development will move the batteries from the one-atmosphere volume to a pressure-compensated space, and the vehicle will have significantly lower drag. Using pressure-tolerant lead-acid batteries similar to those used on the submersible Alvin, the new vehicle should achieve ranges well over 100 km at a speed of about 1 m/s. If lithium polymer batteries suitable for operation at pressure become available (strongly possible), this range would probably exceed 500 km.

While we have achieved power transfer to an Odyssey using an inductive coupling suited to long-term deployments, battery charging represents additional challenges. Batteries typically evolve hydrogen during both charge, discharge, or both, and the prospect of building up an explosive gas mixture in a pressure housing is not very attractive. If the batteries are pressure-compensated, the problem might be easier to deal with. Regardless of the battery technology we employ, this problem requires careful engineering.

The availability of a rechargeable AUV would be critical to its performance during event response. Many modern battery technologies permit rapid charging (on the order of 1-2 hours). Unfortunately, if we recharge inductively the capacity of the inductive link will be the operative limit. For the Odyssey inductive system, the capacity is approximately 200 watts, and to make the system more capable would increase the weight significantly. This power level is approximately 1/3 higher than the expected total power drain of a typical AUV (see later section on conceptual designs). Given limited recharge and conversion efficiencies, the vehicle will take about the same amount of time to recharge as for an entire run. So, 50% maximum vehicle availability will be a good rule of thumb.

Navigation

Within the confines of a standard deep-ocean long-baseline transponder net, AUV navigation is a solved problem. By buoying the transponders at several hundred meters above the seafloor, we can range off the transponders out to nearly 10 km if we have line-of-sight. We achieve repeatability on the order of a few meters, which allows us to fly tracklines on spacings as dense as 15 meters. You can see many examples of navigation tracks and resulting bathymetric maps (made with a scanning sonar) in the attached report from our recent ABE cruise at 17 South (Cormier et. al).

How would an AUV navigate outside the confines of an LBL net? A doppler navigation log (DVL) provides a good solution, provided the DVL maintains acoustic bottom lock (within about 100 meters from the bottom for a 300 khz RDI Workhorse, for example). Compass performance drives the error budget for a navigation suite consisting of a DVL and a flux-gate compass, not the DVL (depending on whether repeatability or accuracy is most important).

We routinely run a 1200 khz DVL on Jason, and we've bookkept its performance relative to our standard LBL and high-precision transponder systems. Unquestionably, the flux gate/DVL combination would allow an AUV to leave the net, perform a survey with useful accuracy (building up navigation errors of a few 10s of meters/hour), and find its way back to the LBL net without difficulty.

The addition of an INS would reduce navigation errors by perhaps an order of magnitude over the DVL alone, but at considerable cost and power (note that the INS is not very effective without the DVL). A new generation of compact, medium-accuracy INS units are nearing completion that should sell for well under $100K and draw around 25 watts. Due to the cost and power usage, we wouldn't want to put these on all of our vehicles, but they would be available when needed (perhaps on a long-range event response vehicle).

For absolute acoustic positioning, we will soon be able to move well beyond our present, somewhat crude transponder navigation capabilities. Engineers at WHOI are developing low-power acoustic modems that can also perform navigation

(LBL, USBL) using coding schemes that should improve performance considerably. These units draw very little power (100 milliwatts while receiving). Their range will be comparable to a conventional transponder net.

A navigation network based on the fixed cable of the NEPTUNE project allows simple and reliable long-baseline navigation with an accuracy better than the traditional deep-ocean transponder system because the navigation beacons could be synchronized via the cable and only one-way time of arrival or time-difference of arrival measurements are needed (depending on the clock accuracy available within a particular vehicle). In addition to improved accuracy, use of synchronized one-way travel time signals would permit an unlimited number of vehicles to use the net simultaneously. Active ping capability from autonomous vehicles to the transponders could still be supported and in combination with GPS-timed broadcasts from the beacons, both position and centralized timing could be available to vehicles or fixed, independent sensors within the net.

For acoustic navigation at longer ranges, we could build on the SOFAR and RAFOS float systems in use since the 70's. Systems using 250 Hz, 700 Hz and 1500 Hz have been deployed in support of various projects. In the NEPTUNE context, beacons (sound sources with spread spectrum coding) would be moored near the cable and receive power and timing from it, creating a GPS-like navigation net over a very wide area. Proven ranges (near the thermocline) are 1000 km, 300 km and 100 km for the three frequencies. Bandwidth limitations of the transmitting transducer limit the range resolution to 1000m, 300m and 100m respectively. (Over these ranges ray paths must be considered when evaluating coverage) Digital correlation receivers for these signals are well developed and typically require under 10 mw.

While these low frequency techniques provide insufficient accuracy for detailed on-site surveys, they would be useful to allow the AUV to make a long transit to an eruption site where it could then drop a traditional transponder for the local survey. Using this local transponder augmented with INS and DVL, it could perform its survey, then use the long-range system to return to the nearest cable node to report. This capability might be especially important for an event response vehicle.

In reality, the navigation transponders described above conceptually as stand-alone modules are simply part of an integrated communications and positioning system which provides both command down-link broadcasts to vehicles and status uplink to shore. The operation of the integrated navigation and communications system is described in the following section.

Communications

In Neptune, underwater acoustic communication could be used for retrieving data from AUVs or remote instruments and providing them control signals to alter their behavior. Requirements for uplink fall into two categories:

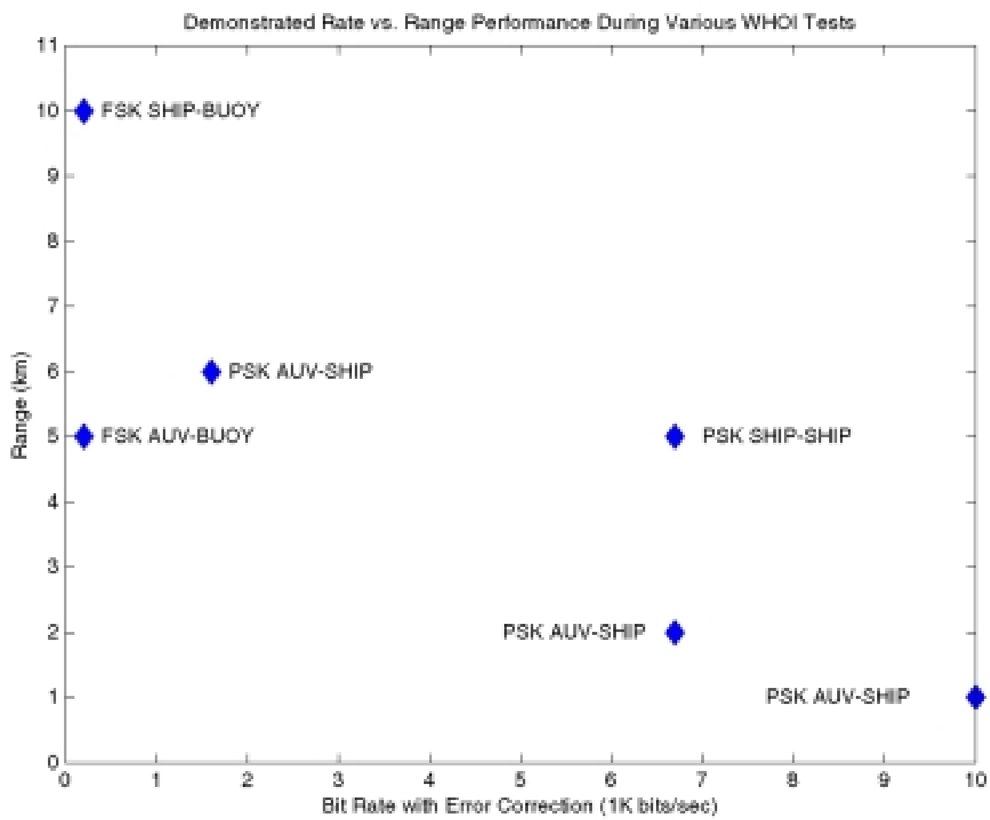
1. low-rate, very high reliability status transmissions as to the health of the vehicle and its basic sensor readings
2. higher rate transmissions with specific data of interest to observers on shore.

Down-link to the vehicle is also relatively low-rate, with high-reliability and positive acknowledgement by the AUV important factors.

Reliable, low-rate (20-200 bps) acoustic communication is now available on a number of commercial and custom-built modems and while range depends on propagation conditions and transmitter power, recent low-rate tests in deep and shallow water have demonstrated robust communications at 5-10 km.

While low-rate communications will suffice for simple status information that informs engineers on shore as to the health, position and basic sensor readings of the vehicles, higher-rate data uplink is desirable for certain types of information. However, even though high-rate (5-10 kilobits per second) bidirectional communications have been demonstrated with underwater vehicles, in general this requires high source levels or short ranges. In a recent test in the Bahamas, compressed still video images were transmitted in near real-time from the Ocean Explorer vehicle to a nearby surface vessel [Freitag, Oceans 98]. Each short packet of information consisted of an image "thumbnail" useful for quick-look evaluation of bottom type, but insufficient for scientific interpretation. Images with more detail could be transmitted, but even at the higher rates available via an acoustic link the time to transmit a rich image (such as one from an electronic still camera) is quite long.

Furthermore, underwater vehicles have power limitations which argue against continuous high-power acoustic transmission. An efficient messaging system would transmit short status packets most of the time, reserving high-power, high-rate transmissions for specific items requested from shore. In addition, high-rate data upload can be achieved by orbiting the vehicle within 100 to 200 meters of a fixed node using modest power levels. Conservative numbers for upload in this manner are 1 kbyte per second at less than 20 W. While reasonably large time series of routine survey data can be uploaded using this strategy, imagery such as sidescan and video are still problematic unless highly compressed. By further extension of the same concepts, we could park a vehicle within a few meters of a node and use carrier frequencies greater than 100 kHz to achieve another factor of ten in data transfer speed. Such links are being considered for other applications and should be evaluated and compared with inductive links (which are yet again 10 times faster) that require more precise docking to the fixed node. Such a "soft docking" capability combined with primary batteries with high energy density could have an interesting niche.



Performance results for acoustic communication links during at-sea tests with both FSK and PSK signaling using various versions of Woods Hole modems. The FSK links have been tested on the Odyssey vehicle using the Utility Acoustic Modem, while the PSK tests have been done using a very similar but larger prototype modem. While much longer ranges have been achieved using high-power projectors and large arrays, these results are realistic and representative of achievable performance on AUVs with limited transmit power and small or single-element receivers.

Integrated Navigation and Communications

The addition of a simple and reliable acoustic communication capability to a standard transponder navigation system would provide a significant improvement in flexibility for underwater positioning systems. Indeed, the Global Positioning System makes use of low-rate communication signals (50 bps) modulated with broadband pseudo-noise (PN) codes to disseminate satellite ephemeris information and other data required by GPS receivers to provide accurate positioning for terrestrial and airborne platforms. The extremely robust, low-rate communications links described in the previous section are now ready for use in underwater positioning systems in order to offer similar capability to GPS.

The main centrally-cabled NEPTUNE transponders could send commands to vehicles or instrument packages within the network, offering reprogramming capability directly from shore. All of these signals will be relatively low-rate in order to offer maximum reliable range.

In addition to communication via the navigation beacons, we could add one or more large vertical arrays that could maintain communications to vehicles or fixed instruments over larger ranges and at higher data rates. Conceptually, these arrays could act much like cellular phone towers, potentially allowing vehicles to maintain contact as they move from one sector to another. Additionally, the potentially high receiving gain of a large vertical array could increase the capability of self-powered instruments placed around the nodes to communicate large amounts of data using minimal power. Signals from the array could be transmitted back to shore at full bandwidth, providing a general purpose VLA for a variety of purposes including acoustic tomography

The navigation signal broadcasts would be intermittent to allow windows of opportunity for data uplink from remote units to the wired nodes (which will be single-duplex, i.e. unable to listen while transmitting). Acoustic access is thus coarsely time-division multiplexed, though it can be either single-access or provide multi-user access via code-division techniques. Bandwidth limitations of inexpensive transducers which operate in the 5 to 20 kHz band limit the number of users and their data rates, but preliminary tests of various methods for simultaneous multi-user access have been successful [Freitag et al, Oceans 99].

While some of the technology discussed above has been tested and is ready for use in new applications, the combined navigation and communications system is a work in progress for the ONR shallow-water MCM program. This work is well underway, and initial demonstrations will be performed in calendar 2000 and 2001. In addition, a prototype of the deep-ocean transponder with built in telemetry capability will be tested in 2000. A moderate scale test of a complete deep-water system could be performed in calendar 2002 and 2003.

Conceptual Vehicle Designs

Due to the wide range of scientific needs and their impact on the details of AUV design, the needs of Neptune will be best served by a mix of AUV capabilities. Rather than building one type of vehicle to try to accomodate all needs, we could combine subsytems or capabilities in a variety of ways to build specialized vehicles to perform different functions with varying price tags. At the extreme, a routine survey vehicle might be fully loaded (and expensive). A large number of inexpensive “one shot” vehicles might be desireable for event response.

Common subsystems

All vehicles would contain as many common systems as possible. Likely candidate subsystems include the integrated navigation/communications suite and the control architecture (or at least the corresponding communications protocols). While all vehicles might not have the docking/inductive comms and recharge capability, we would choose only one standard setup for this purpose.

For discussion purposes, we can consider several basic vehicle shapes and sizes. These will include a vehicle resembling an MIT Odyssey and another vehicle resembling the new version of the WHOI ABE vehicle.

“Strawperson” vehicle: Odyssey-like

For water column survey or bottom survey in gentle terrain, a shape similar to an MIT Odyssey II vehicle would be appropriate. While these vehicles would be completely reengineered for a Neptune effort, they represent a good starting point for a deep-water survey vehicle (we had considered using REMUS, but extrapolating its 100 meter operating depth design is too much of a stretch). The Odyssey vehicles are approximately 1.6 meters long, weigh 165 kg. in air.

By gathering a number of our own experimental data points, we can project the performance of an Odyssey-like vehicle if proper attention was paid to hydrodynamics, propulsion, and power management. To travel at 5 km/hour, such a vehicle would require approximately 100 watts for propulsion (extrapolated from Fast Fish hydrodynamic tests and ABE propulsor

Range of an Odyssey-type vehicle with a 30kg battery pack

Chemistry	Type	wet/dry	energy density	total energy	range at 5km/hr
Lead acid	secondary	dry	31 Wh/kg	0.93kWh	31 km
Lead acid	secondary	wet	40 Wh/kg	1.2kWh	40 km
Lithium Polymer	secondary	dry	82 Wh/kg	2.4kWh	82 km
Silver Zinc	secondary	dry	105Wh/kg	3.1kWh	105 km
Lithium Ion	secondary	dry	110 Wh/kg	3.3kWh	110 km
Lithium Polymer	secondary	wet	219 Wh/kg	6.6kWh	219 km
Lithium Th. Cl.	primary	dry	380 Wh/kg	11kWh	380 km

This table shows how far an Odyssey type vehicle could travel with a 30 kg battery pack. For the batteries contained in the dry volume, the results are shown for 30 kg air weight. For the batteries contained in the wet volume, the results shows are for 30 kg in-water weight.

results). If we add 14 watts for a carefully designed "hotel" load (from ABE), add another 20 watts for fin actuators (estimate), add 15 watts for a basic science payload, we arrive at a total load of 150 watts. Assuming a battery pack weighing 30 kg (either in air or in water, depending on whether the battery is in the dry one-atmosphere volume or run at pressure in the wet volume) and depending on the battery type chosen, we obtain the range capabilities found in the accompanying table.

Not surprisingly, we obtain the maximum range using primary lithium cells running at one atmosphere. The table also shows the dramatic improvement achieved if we can assemble pressure-tolerant lithium-polymer packs (preliminary tests are encouraging). As lead-acid batteries are much more dense, the gains obtained by running at pressure are less dramatic. The prospects of recharging silver-zinc batteries autonomously appear dim, but the lithium polymer or lithium ion cells make this a moot point.

We need to keep in mind that the ability to recharge at depth is somewhat speculative. No one has accomplished this yet, although we certainly will succeed. But we need to be cautious about the number of recharges as well as the reliability we will be able to achieve. Again, this is an area where we can expect considerable evolution over time.

"Strawperson" vehicle: ABE2-like

For repeated surveys in difficult terrain, we will require a vehicle that can move more generally and over a wider speed range than a tail-controlled vehicle can achieve. ABE2 (currently under construction at WHOI) will retain much of the manueverability of the original ABE, but will drop the open "Starship Enterprise" type design. ABE2 will feature a single, very streamlined hull approximately 2.2 meters long, 1.5 meters tall, and 0.9 meters wide (I will try to include a sketch in the final draft of this paper). Unlike an Odyssey, ABE2 will manuever with a combination of control surfaces and thrusters that will tilt together to provide thrust either fwd/aft or up/down in any combination. Combined with the static attitude stability inherent in its shape, ABE2 will be able to stop, back up, and climb steep cliffs like the original ABE. ABE2 will be optimized for survey at slower speeds (3.5km/hr), when it will draw roughly the same propulsion load as the Odyssey at 5 km/hr. ABE2 will be much larger (> 600 kg air weight) and it will have a much larger battery payload (approximately 200 kg). This translates into ranges roughly 4.5 times those listed for the Odyssey-like example. ABE2 will have the battery capacity to carry power-intensive sensors such as snapshot video systems as well as the controllability to carry them into tight places.

Several variations on the ABE2 type design could be useful. Assuming we are successful with the rechargeable, pressure-tolerant lithium polymer batteries, we could build a rechargeable ABE2-like vehicle of smaller size that would have several hundred kilometers range. The current ABE2 is a one-of-a-kind vehicle designed to withstand the rigors of daily launch and recoveries. A variation designed to be left at depth could use less expensive buoyancy (glass spheres instead of syntactic foam) and could be made less expensive to manufacture in multiple copies.

Conclusion

In this paper, we have presented a framework describing potential capabilities of AUVs and acoustic communications. We have asked questions about the phenomena to be surveyed that would help define tradeoffs in an AUV design. Current capabilities in vehicles and acoustic communications have been summarized, and an integrated approach to acoustic comms and navigation is presented. Finally, we present some "strawperson" vehicle designs and show how various power options could influence their performance.

List of Attachments

A. A. Bradley, Power usage papers
B. Wilcox, Bellingham, Bagerroer (in preparation)
C. J. Bellingham et. al., Adaptive Sampling
D. H. Singh, Docking.
E. L. Whitcomb, Doppler navigation performance
F. M. Tivey, Magnetics mapping paper
G M. Cormier, ABE SEPR Cruise Report.
H. Freitag et. al, Oceans 98 paper
I. Freitag et. al, Oceans 99 paper

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