Autonomous Underwater Vehicles for Ocean Research: Current Needs and State of the Art Technologies

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ABSTRACT

Research in the field of Autonomous Underwater Vehicles (AUVs) has been underway for the past three decades. Much of the original work was funded by the military, although the vehicles were built with payloads that could be used for science purposes. Recently over the last decade, many systems are now being purpose built for and operated by the science community. Because of the variety of science missions, the number of AUV types and configurations available today are numerous.

This paper gives a brief overview of the history of AUVs for science. Included are discussions of the applications that are suitable to AUVs. Highlighted are some important points a potential user might consider when selecting an AUV for a particular science application. The paper continues with a review of some of the AUVs available to science today and a look at the cross-section of capabilities offered. The discussion continues with the emerging requirements the technology community is envisioning for the near and long term future of AUVs. The paper also considers the state of the art and what is reasonable to expect from a system today. Finally the paper offers some insight to the lessons learned and how they might be applicable to a scientist considering AUVs as a technical solution to studying and answering today's most intriguing oceanographic science questions.

1. INTRODUCTION

The history of autonomous underwater vehicles (AUVs) can be traced back for more than 100 years. Many developers would include a host of systems in the category of autonomous platforms, such as early torpedoes and other untethered underwater vehicles developed long ago (Bucknell, 1889). Significant developments in key technical areas have had direct impact on the oceanographic community since then. Recent developments include a wide selection of autonomous systems, and each offers the potential user a variety of capabilities and choices to accomplish a specific application. Although there are many uses of AUVs, this paper focuses on systems specific to oceanographic research applications for science purposes.

Underwater vehicles with their own on-board power source, computing, controls, propulsion, and missions are considered autonomous. Opposite are remotely operated vehicles (ROVs), which are tethered to the support vessel. Similarly any towfish system is not considered an AUV. Each of those systems have specific capabilities to accomplish specified missions, and both have been proven many times to be extremely useful systems. Moored systems, either submerged or not, also do not meet the definition of autonomous underwater vehicles since they do not have the ability to apply motive force in a discretionary manner. Now that many systems have been eliminated there are several types of systems that do qualify as AUVs.

Gliders and Lagrangian platforms are just some of the devices that have the ability to partially or completely control direction based on a set of pre-defined conditions. One limitation of these systems is they are often at the whim of nature regarding successful completion of commanded condition. The forces within the ocean often overcome the platform, and it will stall or be taken off of the intended course. The payload space and available power is also limited for these platforms. The standard system when the term AUV is applied includes the ability to command position and control mission time, i.e. the system is given a mission and initialized at some point, and from there, the operator expects to meet the system at a predefined location at a specific time. These AUVs use propellers driven by electric motors, and they range in speed from one to five knots. How about some discussion of UUV vs AUV here? The general audience of the Marine Technology Society could benefit from such a discussion. A few sentences would suffice.

One of the first AUV systems to meet the outlined parameters (named SPURV) came from the University of Washington Applied Physics Lab. SPURV in an acronym for Self Propelled Underwater Research Vehicle that started as a concept in 1963 (Widditsch, 1973). SPURV demonstrated capabilities that are typical of what an AUV in 2004 is capable of, namely a 3600 meter depth rating with a 5.5 hour mission duration operating at about 2.5 knots. The two areas that have changed dramatically in all modern AUV systems are the electronics and the power sources. The electronics have become smaller and more efficient while also providing greater computing capability. The power sources have increased the safety and ease of recharging, but they are not advancing as fast as the computing industry which doubles processor speed and doubles storage capacity every 18 months (Moore’s Law).

SPURV’s electronic systems were constructed from discrete electronic components. These were state of the art and provided advances in functionality which dramatically increased reliability and the operational success of SPURV. Is there a reference for such a strong claim? Given the historical nature of the comment it might be nice for the interested reader to know where to go for more information on this “dramatic” success. The vehicle had a custom-built, single purpose computer greatly comprised of hardware elements with hard switches to make program changes. The advent of microelectronics and computing capability has changed all of this and allowed systems to use less power for hotel loads (loads that are non-propulsive) and to focus more energy on payload capabilities and support. AUVs no longer have custom boards hard wired for control purposes but use off the shelf components and software to command those elements. This also enables easy modification of commands and more complex command sets to accomplish a higher level of sophistication in autonomous operation. In today's AUV it is not uncommon, for example, to have Digital Signal Processing devices (DSP) allowing greater accuracy and data richness in acoustic devices by performing active state control and beam forming. Work that was previously hand done in the lab after the AUV was retrieved is now accomplished quickly at sea onboard the vehicle. With the capabilities of onboard processing, missions can be programmed to track frontal processes and upwelling events and to seek out hot vents.

Advances in battery technology have not been as rapid. Power density is still a large barrier to a variety of AUV missions, and numerous efforts have been made to get around this hurdle. Fuel cells (Størkersen, 2001) and thermal buoyancy engines (Eriksen, 2001) are two approaches to provide extended range while supporting two completely different payloads. SPURV employed Silver-Zinc technology, which allowed for the necessary dynamics in current draw while supplying a stable bus voltage to support the system. Today the common chemistries are Lithium based and come in a variety of forms that offer greater flexibility for the AUV user. Still the field of energy storage is widely recognized as a limiting technology for AUVs to make a dramatic advance in size reduction while increasing range and payload (Henderson, 2002).

Although AUV technology and applications have not been adopted as quickly as ROVs, in the past few years several new vehicles are permitting small science labs to go out on a ship of opportunity or even a dock and launch a mission. The vehicles are coming closer to turnkey systems where expert engineers are not needed for day-to-day operations. As long as the vehicle is a reasonably small size, large support equipment like specialized launch and recovery systems are not necessary. For example, REMUS (9” diameter) vehicles are small enough to be launched by two people from a rigid hull inflatable boat (RHIB). Obviously the military makes use of this scenario and actually funded the original vehicle development, but now science is taking advantage of it for low cost oceanographic research missions.

2. APPLICATIONS of AUVs

Certain types of underwater data collection missions are perfectly suited for AUVs, while others are not. The ocean research done quite well with AUVs today are mid-water transects, mid-ocean ridge surveys It is likely more accurate to say geophysical surveys? AUV data is supporting science in regions other than just the ridges, and physical oceanographic missions in the upper water column. Other means of collecting these data sets exist, but are expensive and labor intensive. Before AUVs were in operation, these data sets were acquired by other platforms. As AUVs become more capable, scientists are beginning to generate science mission requirements that call for immediate deployment of an instrument after an event occurs, like a volcanic eruption. When support ships and human operators are not available to deploy a vehicle, AUVs need to respond on their own and carry out a pre-programmed mission. This assumes that an AUV is already out at sea ready to run a mission. In ice-covered areas where ships cannot reach, AUVs are the only vehicles that scientists can deploy to collect spatial datasets. AUVs cannot replace all of the other oceanic platforms too soon because there will always be a need for fine manipulation and deployment of instruments that only ROVs can handle. AUVs also have many other limitations that will be discussed later.

In the interest of saving money, AUVs are being used to automate science missions that do not require manipulation. For example, high-powered ROVs are used today to perform mid-water video transects at MBARI (Robison, 1993), but the ROV's capabilities are underutilized. Even the pilots tend to lose focus because of the monotony during these transects. Automating these surveys would bring back the same data, perhaps in less time since AUVs are generally much faster than ROVs (3 knots vs. 1 knot typically), but they do impose technical challenges on an AUV. Since an ROV can provide thousands of Watts of power to a payload, high intensity lighting systems can be used. High definition video can be stored on large, 30-minute digital cassette tapes administered by a human. A transect payload on an AUV would require much energy storage for the lighting, and a compact way to store the video. Perhaps the mission could be accomplished with low-light cameras and high output LED lamps. The video could be compressed in real-time and stored onto a high-capacity hard drive. This science mission in particular and many others are driving the requirements of autonomous underwater vehicles.

Mid-ocean ridge (geophysical again?) surveys using multibeam, side-scan, and chirp sub-bottom sonars have been done in the past with towfish and hull-mounted units. In figure 1, multibeam sonar data is shown. On the left is data from a ship-mounted sonar, and on the right is a post-processed data set from a towfish. During the cruise, the operators had a difficult time keeping the towfish on the intended course and the navigation was not optimum. As the sonars become miniaturized and data processing needs are met by small DSPs, AUVs are the platforms of choice for these surveys. An AUV can cruise precisely at a specified altitude and a constant velocity. It is worth mentioning the elimination of surface wave/vessel influence when the tether is removed. Vehicles like the Hugin 3000 and the Autonomous Benthic Explorer (ABE) are used today to perform these surveys. As the multibeam sonars shrink in size and power requirements, smaller vehicles like the 21" diameter Dorado class AUVs are entering this survey realm. Since the surveys can cover a large site, energy again becomes the limiting factor for the length of each mission. For example, MBARI's seafloor mapping Dorado AUV is built to perform a 3x6 km box survey at an altitude of 150m in about 10 hours with a speed of 3 knots. This should be possible with a reasonably sized battery payload of about 6 kWhr. After analyzing the data from these missions, scientists are able to direct ROVs and Human Occupied Vehicles (HOVs) into interesting areas without wasting precious bottom time. The concept of AUVs and ROVs working in tandem has been demonstrated with ABE and Alvin, and the relationship proves to be extremely useful. This is a true statement but the reader unfamiliar with ocean technology might assume Alvin is an ROV. Really it is the concept of AUV and manually operated systems (HOV or ROV) that was proven by ABE/Alvin pairings.

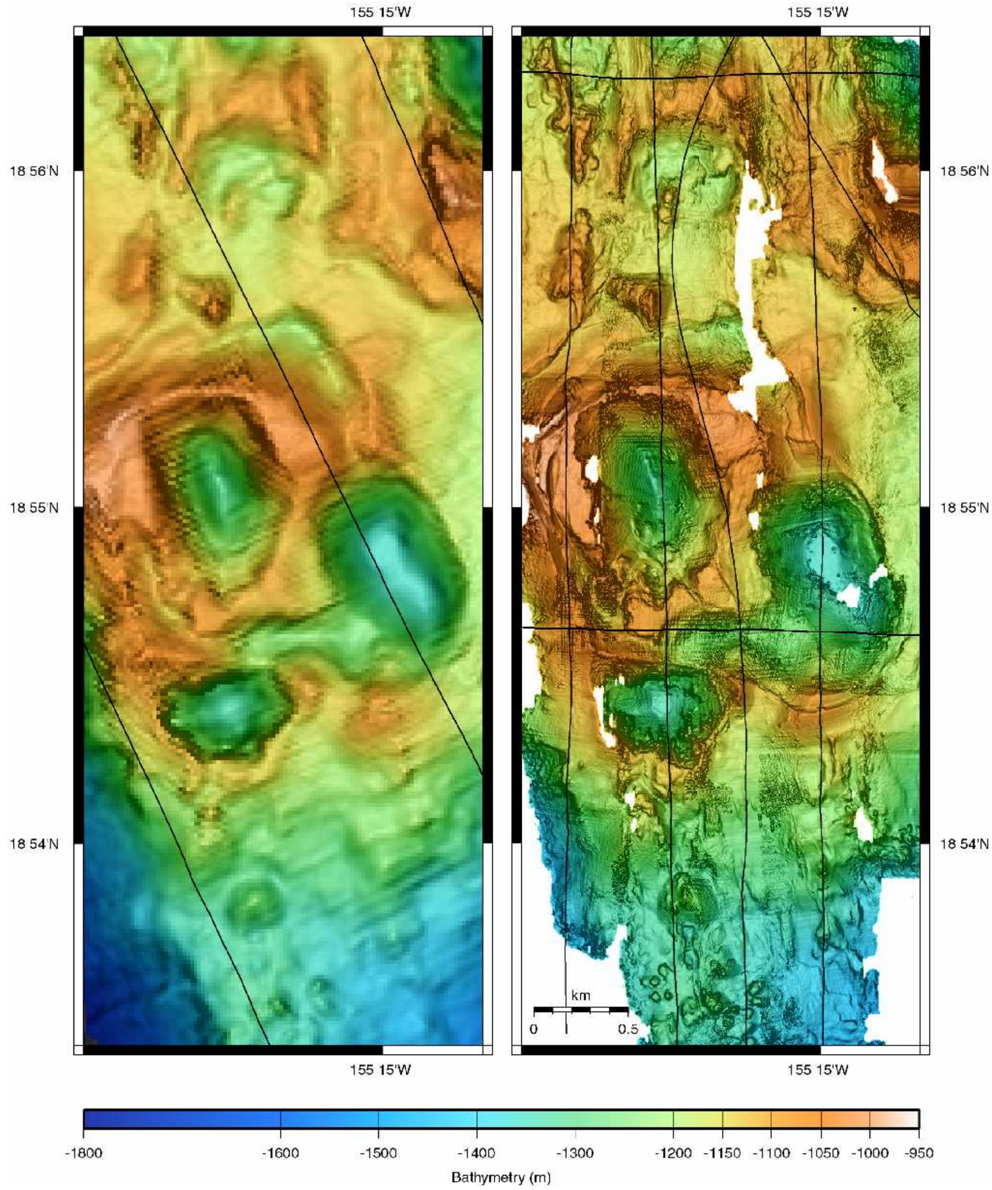


Figure 1: Multibeam data from a hull-mounted sonar (left) and a towfish (right) of the Loihi Seamount near Hawaii. Data courtesy of Professor Fred Duennebier,University of Hawaii. Figure courtesy of Dave Caress, MBARI.

At present most of the scientific missions run with propeller driven and glider type AUVs are physical oceanographic surveys in the upper water column. Large time-series datasets like the CalCOFI series (please explain, even if only in a footnote, what this acronym stands for and possibly the background of the experiment) are still being taken with ships and CTD casts.

AUVs can be used to perform most of the data collection for these series by using a payload consisting of CTD, dissolved O_2, fluorometry, optical backscatter, and nutrient sensing instruments. Ideally the AUV would be off performing its mission, while a support ship handled other activities like taking water samples. Eventually a network of docking stations and AUVs would perform all of the tasks necessary to meet the requirements of something like the CalCOFI time series, so no support ships would be needed, except for routine maintenance. Research is still ongoing to develop a water sampling system for AUVs that can completely replace ship based methods.

With high precision pressure sensors and fast rate instruments, thin layers can be studied in the water column from AUV surveys. Figure 2 shows such a data set gathered with an Odyssey vehicle. The ability of the AUV to dynamically follow density and salinity surfaces allowed precise mapping of a three-dimensional plume structure as it evolved in the Monterey Bay.

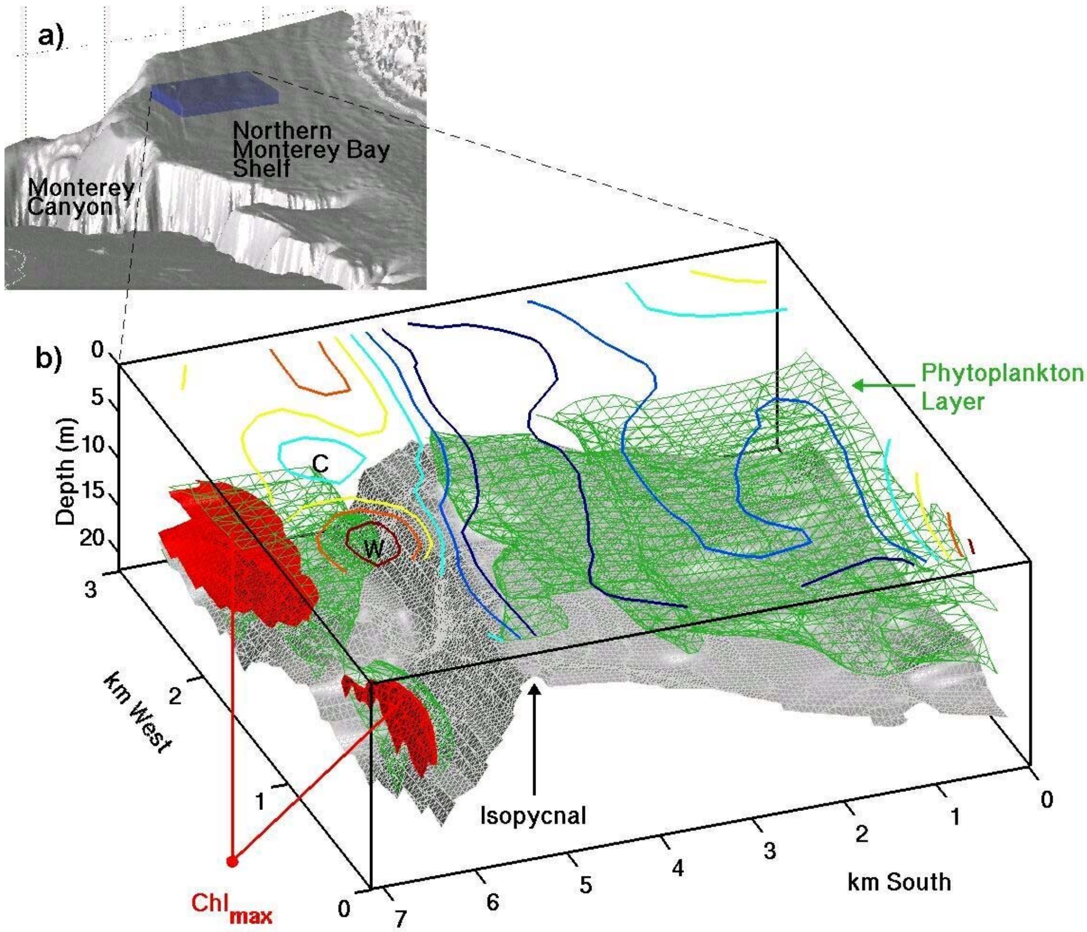


Figure 2: Data set from an Odyssey vehicle showing thin layers of phytoplankton and Chlorophyll in the Monterey Bay. Data and figure courtesy of John Ryan, MBARI.

For synoptic surveys of large volumes of water, the leading method of collecting the data is with multiple platforms deployed at the same time. In 2003 the Monterey Bay was the site of the Autonomous Ocean Sampling Network (AOSN2) (Bellingham, 2004). Over three dozen assets were deployed to cover 100s of km^3 of water. Twenty of those assets were AUVs made up of gliders, REMUS, and Dorado vehicles. Both shallow diving gliders (~200m) in a dense net close to shore and deep diving gliders (~500m) in a sparse net further offshore were responsible for measuring physical oceanographic data (temperature, salinity, depth, particle scattering, and fluorescence) during upwelling periods. The gliders exhibited a horizontal speed of about 0.5

knots. On the other hand relatively fast moving AUVs (~3.5 knots), Dorado and REMUS, were effective for filling up the voids created among the measurements of slow moving gliders, stationary moorings, weather-driven drifters, and ship-tracks. During the AOSN2 experiment Dorado and REMUS were equipped with a variety of science instruments such as CTD (temperature, salinity, depth), nutrient, bioluminescence, particle back scattering, fluorometer (chlorophyll), and dissolved oxygen.

Although this paper focuses mainly on scientific applications of AUVs, it is important to mention some of the uses in other sectors. As of 2001, more than half of the use of hydrographic survey AUVs was in the government and military sector (Danson, 2003). These vehicles also make use of multibeam echosounders, side-scan sonars, and sub-bottom profilers. General charting and mine detection are the two major uses in this sector. The oil and gas industry also makes up a large percentage of the users for AUVs with their surveys of oil fields. Comparing an AUV in the seafloor survey business to another method such as a towfish shows much greater return on investment and data quality when the survey goes as planned. As long as data quality can be checked in real-time while an AUV is underway, the survey time will be shorter than a ship-towed system. AUVs can change heading very quickly and do not require long run-in lines to get to depth, whereas towfish need special handling. While these statements are true, and possibly "common knowledge" in the AUV community, it would be good to offer a reference so that the more general reader can pursue this in more detail.

3. EMERGING REQUIREMENTS

In the past decade many researchers have done extensive research on various aspects of AUV design and development (Bellingham, 1993, 1996; Blidberg, 1995, 2001; Griffiths, 1999, 2003; Lane, 1995; Whitcomb, 1999; Yoerger, 1999; Yuh, 2000). From the application point of view there is a diverse array of requirements for AUVs. In the present demand scenario, a vast majority of the requirements are associated with the specific users such as military, oil and mining industries, marine scientists, and others.

Oceanographic science is a very broad application field for AUVs, and the type of AUVs in use depends upon the science missions. We can divide the missions into a variety of categories based on *water depth* – (1) upper water column, (2) midwater column, and (3) benthic operation; based on *region of operation* – (1) coastal, (2) offshore, (3) polar; and based on *mission type* – (1) synoptic snap-shot, (2) long time-series, and (3) geologic survey. This clearly indicates the complexity in determining a set of unique requirements for AUVs. The mission types could benefit from explanation. For example what is the difference between a synaptic snap-shot of the seafloor and a geologic survey? Is there a true difference in missions or just in sensors/data of interest? This in turn demands for several different types of vehicles, namely: small, medium and large size (what defines these ranges, length, diameter? How big is big?) vehicles. It is obvious that a small propeller driven vehicle is unable to carry a large payload and cannot be operated for an extended period (what qualifies at extended? Smaller AUVs are knocking on the door of 20+ hours endurance. As compared to just a few years ago this is extended. Please clarify here or elsewhere in the paper.) of time without recharging, however, it can be faster (how much faster and why does this matter?)and more agile. On the other hand, large AUVs are able to carry large payloads (perhaps an example of a large payload here) and can be operated for long durations without recharging, but they might have to sacrifice speed and/or maneuverability. Therefore, the requirements for AUVs will vary significantly to accommodate the demands from the users. For example, science missions like monitoring geological changes on the seafloor or surveying fine layers for physical oceanography require high precision navigation, but general routine surveys for detecting an "event" may not require very accurate navigation. Therefore, instead of providing a long list of requirements for different types of AUVs, common requirements are discussed in the forthcoming section.

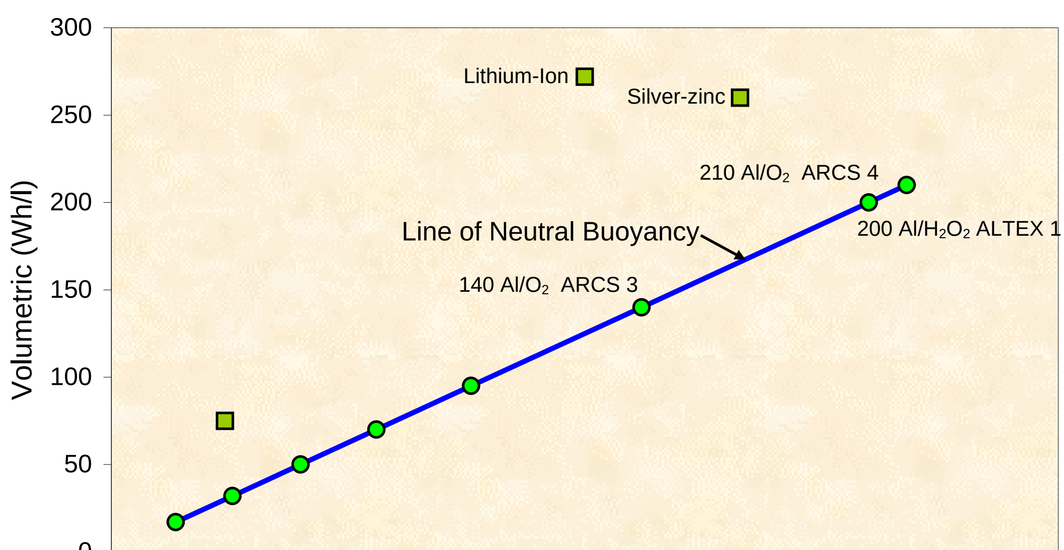
The common thread in all (this might be a bit strong, unless there is a reference to defend this, I suspect there is an emerging requirement that may diverge) the emerging requirements from the different levels of applications are: more autonomy (this may confuse the general audience, autonomy might mean more range or more reliability. I suspect the intention here is to call for more artificial intelligence or advanced behaviors), high-density energy storage, accurate navigation, increased payload carrying capacity, enhanced two-way communications for quality assurance, ability to maneuver in a range of water depths, 3D imaging (this is true but vague, does this mean acoustic or optical imaging and is this really an AUV requirement or a sensor requirement), increased reliability and maintainability, moving towards standardization of the product (or use of standard components) and cost effectiveness. From the scientific application point of view some additional requirements are: sustainable ocean presence, prompt response to episodic events, operation under ice, multi-vehicle coordinated operation for transient events, and intelligent operation. It is encouraging that researchers in different parts of the world have been working on these issues for the past three decades. Some progress has been made, but still many of the issues are open for active research.

The dynamic, uncertain, and unstructured underwater environment poses formidable challenges for autonomous operation of robotic vehicles in the ocean. The underwater exploration efforts are heavily constrained by many technical, environmental, and other issues. Some of the technical issues are: limited sensor capabilities (range, update rate, accuracy, and availability), poor signal to noise ratio (this is a sensor not a vehicle limitation, shouldn't this be in the sensor entry with range etc.?), dense medium (water), continuous change in physical parameters (temperature, conductivity, pressure, visibility, current, drag), high-density energy storage, and slow progress in underwater instrumentation development (size, weight, power consumption, cost, reliability). The main environmental problems are: biofouling, corrosion, salinity, hydrostatic pressure, high sea-state, and uncertainty (of what?). Some of the other compelling issues (for ocean science or AUV development or both this list is confusing without some definition) are: insufficient funding, lack of public awareness, sharing and conflicting deployment areas with fisheries and entertainment agencies. One of the other main issues with the development and operation of such a complex system is the prediction and assurance of the system reliability and maintainability. However, in the passage of research and development for the last three decades a tremendous success has been achieved. It is very encouraging to see a lot of research activities towards the improvement of AUVs' capability and affordability. I don't see the point of these last two sentences. They are true but don't tell the reader anything about what the "tremendous success" is/was. An example here might help, perhaps contrast SPURV to a current AUV.

4. STATE OF THE ART TECHNOLOGIES – SUBSYSTEMS OF AUVs

An AUV is composed of several main subsystems, they are: (1) energy storage unit, (2) propulsion unit, (3) navigational instruments, (4) communication system, (5) payload, and (6) control software.

Energy storage is one of the most serious bottlenecks in the expansion AUV technology for sustainable operation in a cost effective manner. Though several types of energy storage systems such as batteries (lead-acid, silver-zinc, alkaline, nickel-metal hydride, sodium-sulphur, lithium-ion, lithium-polymer), fuel-cells (proton exchange membrane, solid oxide), and closed-cycle diesel engines have been tried for AUVs, the rechargeable (secondary) batteries remain the dominating energy source. Recently, lithium-ion batteries have been used in AUVs such as REMUS, ABE, and Dorado. Although lithium-ion has an energy density of about 115-135 Wh/kg, making the whole package neutrally buoyant in a deep rated vehicle (6000m) forces the energy density down to a typical range between 50-95 Wh/kg. Life of this battery is limited by number of charging cycles 200-300 (depending on cut-off voltage), thus it makes the battery quite expensive for AUV operation. On the other hand, vehicles like Urashima, Hugin 3000, and ALTEX were powered with fuel cells, which provided a relatively high energy density and were less expensive but required maintenance and refueling when exhausted. The energy density of fuel cells is in the range of 200-290 Wh/kg in the neutrally buoyant condition for a deep rated vehicle. A comparison of different batteries and fuel cells is provided in Figure 3 and Table 1. The speed, range, and endurance of AUVs are severely constrained by the lack of inexpensive high-density power storage systems. However, power efficient AUV design and instrument development are evolving in terms of both propulsion and hotel load. Additionally, technology may be borrowed from the commercial electronics sector where power sources for hand-held consumer devices are rapidly advancing.



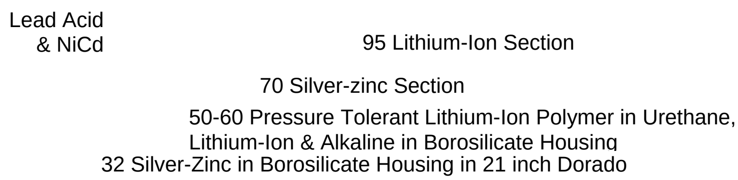


Figure 3: Volumetric vs. gravimetric comparison of batteries and fuel-cells. The line of neutral buoyancy is for a deep rated vehicle (>4000m).

Table 1: Comparison of commercially available batteries.

Battery Type	Specific Energy (Wh/kg)	Specific Power (W/kg)	Max. Charging Cycle
Lead-acid	35	100	700
Silver-zinc	170	400	50
Nickel-cadmium	30-55	100	1500
Nickel-metal hydride	50-70	145	1500
Sodium-sulphur	90-120	150	800
Lithium-ion	130		300

The *propulsion system* is the main moving part in all the AUVs and it inflicts several problems on the system during operation such as high power consumption, possible faults, limited life, noise, and vibration. However, the degrees-of-freedom in motion (or maneuverability in loose sense) of both the hovering and the non-hovering vehicles depends on the number and geometric position of actuators and thrusters in use. Apart from conventional fixed angle rotary thrusters, researchers are developing other kinds of propulsion systems like oscillating foil thrusters, flapping fin thrusters, etc. inspired by the biological systems mainly by the swimming techniques of fish (Triantafyllou *et al*., 2003). These novel propulsion methods offer high control in turbulent hydrodynamic settings. Recently, Biomimetic AUVs are attracting attention from engineering research labs.

Navigational instruments – An AUV's position with respect to a fixed (inertial/ world) coordinate system is required for underwater surveying. Especially, tracking of horizontal position (x-y position) is still quite challenging as compared to depth (z-position), which can easily and accurately be estimated using a pressure sensor. Accuracy of commercially available pressure sensors ranges from +/-0.015% to +/-0.5% and the maximum measurement can go as high as 15000psi. Various sensor packages are available for navigational purpose such as acoustic (LBL, USBL, SBL, DVL, altimeter), optical (video, laser), electro-magnetic induction, inertial system (IMU/INS), gyrocompass, along with aiding from GPS. Although within a well-developed LBL transponder net underwater navigation is a straightforward problem, outside of the network it is still a challenging task. The Doppler Velocity Log (DVL) can provide a reasonable solution if bottom lock is maintained. The addition of an INS can significantly reduce the navigation errors if used along with a DVL. Comparative figures of various navigational systems are given in Figure 4 and Table 2, with the increase in accuracy and precision the instrument becomes more expensive. For example, in the case of gyro heading performance, if we want to move bias stability and scale factor stability from 20deg/h and 800ppm to 0.015deg/h and 10ppm, the cost will increase by ~100 times (from <$10K to >$1000K). Can we have the reference for this? Such a large figure is likely to inspire readers to further investigation.

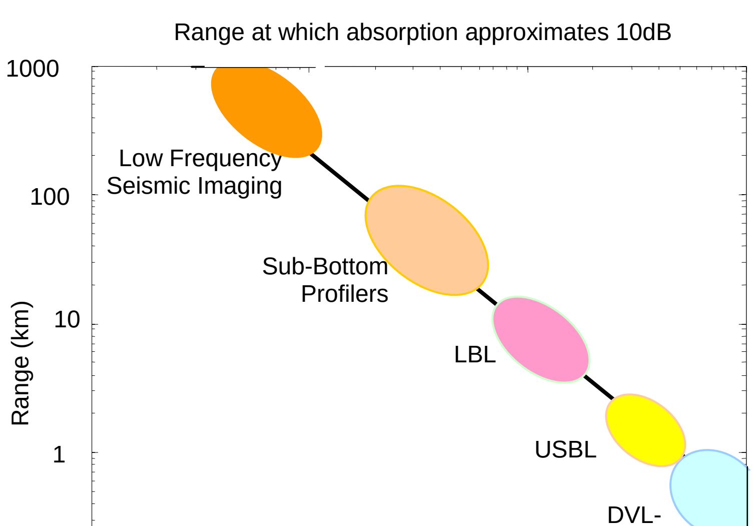


Table 2: Comparison of navigation systems.

Navigation System	Accuracy	Power Consumption	Major Constraint
GPS	1m-150m	O(1W)	Surface only
Doppler Velocity Log with magnetic AHRS	~1% of travel distance	25W	1m-500m Altitude
Correlation Velocity Log with magnetic AHRS	~1% of travel distance	25W	> 500m
LBL	5cm @ 100m, 3m @ 10km	O(5W)	Calibration and deployment
USBL	0.1%-10% of slant range	O(30W)	Telemetry from surface
INS	1 nm/h (RLG & Hi performance IFOG)	12-20W	Alignment
INS-DVL	0.05%-0.1% of travel distance	25-40W	Alignment

Communication unit – under some circumstances two-way communications are used during AUV operations. Some of those scenarios include monitoring of the quality of collected data (should not find all data as garbage at the end of the day), tracking some interesting events, and retrieving the vehicle's operating condition. Acoustic modems are commonly used for this type of communication, but they consume quite a bit of power. Acoustic modems available in the market today can have MFSK and PSK modulation schemes, operate in the 9-30kHz frequency bands (LF-MF-HF), have data transmission rates of 150-15000bps, and have power consumption around 25W. Data compression can help in both transmission time as well as power consumption. A reference again please, there is much to this subject and readers might like to know where to look.

Payload – depending on the mission, a variety of different sensors and instruments are required to be mounted on an AUV. For example, a common physical oceanographic mission in the upper water column would require instruments such as CTD, ADCP, fluorometer, optical back scattering instrument, dissolved O_2 sensor, ISUS (nutrient sensor), and pCO_2 sensor. For more detailed descriptions of payloads for various science missions see Podder *et al*., 2004. One asks, so what? There are many payload options beyond these. To discuss only one mission and not others offers little. Please either add more discussion of other payloads, sonars, cameras, etc. etc. or simply mention the large variety for many missions.

Software (dynamics and control) – the dynamics of AUVs are highly nonlinear, coupled, and time varying. Researchers have developed several modeling and system identification techniques for AUV dynamics (Fossen, 1994, 1995; Goheen, 1995). Controlling such a system in the presence of hydrodynamic uncertain environment with accuracy is a highly challenging task. Thus, it is desirable to have a control system that has self-tuning capability when the performance of the AUV degrades during its operation due to the change in the AUV dynamics and its environment. True but tell the reader when/if such a capability is available.

Fault-tolerant operation capability of AUVs is important in a truly autonomous regime. Any fault (in both hardware and software) that may occur during AUV operations ought to be detected, isolated, and accommodated (if possible) instead of simply aborting the mission. It is not always wise to abort a mission and let the vehicle float to the surface, as is the case for under ice operations. Subsystem or component redundancy may be incorporated into the system to increase the system reliability, but it is expensive in terms of space, power consumption and obviously monetary costs. Therefore, it is desirable that the software should be smart enough to perform the task up to the possible extent.

This entire section is so brief as to be unsatisfactory. Readers deserve better insights into the future technology needs for AUVs. Alternatively this section can be shortened further and probably conveyed in one or two paragraphs. As currently written it needs work.

5. LESSONS LEARNED

Since the first scientific AUV, SPURV, was built in the 1970's, reliability has been a major concern. The mean time between failures of underwater robotic systems has gradually been going up. The oceanographic community is not yet large enough to have the luxury of operating a commodity system. AUVs are largely one-off vehicles where each one is different than the other. Commercial companies are leading the way to a standard product, but the amount of vehicles built will never come close to something like in the automobile industry. Auto manufacturers have years of experience with defects and manufacturing processes, and cars still fail.

Since AUVs will never be 100% reliable, failure modes are detailed and prepared for before deployment. AUVs are nearly neutrally buoyant or slightly positively buoyant in water, so if a failure during a mission does occur, the vehicle can float back to the surface where it is generally easier to find with the help from satellites and beacons, unless the vehicle is under ice or in a cave. Some vehicles run into trouble while underway, and end up being slightly negatively buoyant, so they cannot float to the surface. The ability to autonomously drop a weight is useful in this scenario.

Much work has been done to correct problems with failure prone systems. For example, experience at MBARI and Southampton Oceanographic Centre has shown that the use of metal shell connectors, although much more expensive and heavier than rubber molded connectors, can increase reliability. The old adage, “you get what you pay for”, definitely applies here.

A lot of the problems encountered while an AUV is running a mission actually happen up front because of operator error. A pressure housing might not have been closed up properly, so a leaky seal would terminate a mission prematurely. Operators were notorious for making errors in the mission scripts for MBARI’s Dorado AUV in the first few years of running the vehicles in sea trials and science experiments. If missions are not simulated, the only way to know whether the waypoints and mission parameters entered are correct is to let the AUV run the mission out at sea. On more than one occasion, MBARI’s AUV had propelled itself in an unwanted direction because of a missed negative sign or misplaced decimal point in a mission script. While the authors should be applauded for this admission can they go on to explain how they have changed their approach to avoid such errors?

There are still plenty of problems with systems that have moving parts. Propulsion systems with propellers and linear actuators rely on shaft seals to keep sea water out of the motor windings, unless they use magnetic coupling. For deep-water applications, most of the propulsion systems use compensating oil to fill the voids in motor housings. Although these systems are designed to not leak, a small amount of oil usually weeps out of them, so operators need to perform maintenance and replace lost oil every few missions.

As extended missions come online, made possible with docking vehicles, high density batteries, and long-range gliders, maintenance periods will have to be few and far between. There is a need for software and electronics systems that identify faults when they occur. The best case is a fault tolerant vehicle that can accomplish its mission even if a problem occurs, such as a broken actuator. Since fault tolerance is usually costly to implement, the vehicles will simply need to recognize a fault and phone home for further instructions. Accelerated testing can also be done during the design stage to weed out the unreliable components. Pressure chambers are always used to test pressure vessels and pressure tolerant electronics before deployment at sea. Testing programs like these are necessary to increase the overall AUV reliability.

6. SUMMARY

In this paper, the motivations for using AUVs in ocean research were presented. A brief history of AUV development was given to show the progress in this research field. Some applications of AUV technology were presented to give an idea of the impact that an autonomous craft can make in a hostile environment. These applications were compared to other platforms such as ROVs and ship-towed instruments. Next the emerging requirements from these applications were discussed in detail, making it evident that many instruments are necessary to collect various data sets. The state of the art technologies were then listed under several sub-systems. Finally, some lessons learned from the authors' experiences deploying AUVs at sea were discussed.

Even though many companies and research institutes have built hundreds of different vehicles, there are still many problems. In the future the reliability of AUVs will go up as software gets more detailed and artificial intelligence becomes better. Ships are being built to accommodate AUVs, and ocean observatories are being installed with docking stations to provide data and power outlets for AUVs. As scientists get more concerned with global warming, under ice vehicles will be called upon to make transects in Arctic and Antarctic waters where it is difficult or impossible for ships to go. The technology providing energy and navigation capabilities to the autonomous systems will improve. With the help of commercial companies developing new batteries and navigation sensors for consumer industries and the military, AUVs will take advantage of the new capabilities as they are released to enable highly accurate, long-term, unattended operations.

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