Design Considerations for Engineering Autonomous Underwater Vehicles

by

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B.S., The University of Texas at Austin, 2005

Submitted to the Joint Program in Applied Ocean Science & Engineering in partial
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Abstract

Autonomous Underwater Vehicles (AUVs) have been established as a viable tool for Oceanographic Sciences. Being untethered and independent, AUVs fill the gap in Ocean Exploration left by the existing manned submersible and remotely operated vehicles (ROV) technology. AUVs are attractive as cheaper and efficient alternatives to the older technologies and are breaking new ground in many applications. Designing an autonomous vehicle to work in the harsh environment of the deep ocean comes with its set of challenges. This paper discusses how the current engineering technologies can be adapted to the design of AUVs.

Recently, as the AUV technology has matured, we see AUVs being used in a variety of applications ranging from sub-surface sensing to sea-floor mapping. The design of the AUV, with its tight constraints, is very sensitive to the target application. Keeping this in mind, the goal of this thesis is to understand how some of the major issues affect the design of the AUV. This paper also addresses the mechanical and materials issues, power system design, computer architecture, navigation and communication systems, sensor considerations and long term docking aspects that affect AUV design.

With time, as the engineering sciences progress, the AUV design will have to change in order to optimize its performance. Thus, the fundamental issues discussed in this paper can assist in meeting the challenge of maintaining AUV design on par with modern technology.

Thesis Supervisor: Hanumant Singh
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List of Acronyms

ABE – Autonomous Benthic Explorer

ADCP – Acoustic Doppler Current Profiler

AUV – autonomous underwater vehicle

CCD – charge coupled device

DOF – degree of freedom

DR – dead-reckoning

DSL – Deep Submergence Lab

DVL – Doppler velocity log

FAU – Florida Atlantic University

FOG – fiber optic gyro

GPS – global positioning system

INS – inertial navigation system

PEFC - polymer electrolyte fuel cell

LBL – long baseline

MBARI - Monterey Bay Aquarium Research Institute

MIT – Massachusetts Institute of Technology

ROV – remotely operated vehicle

SLAM – simultaneous localization and mapping

USBL – ultra short baseline

WHOI – Woods Hole Oceanographic Institution

1 Introduction

The research in Autonomous Underwater Vehicles (AUV) has gained a lot of momentum in the recent past which has been fueled by the successful commercial implementation of AUV technology. This paper will explore the considerations in designing AUVs specific to their applications budgets. The first step is to understand a little history of Ocean Engineering and its development over the last century.

1.1 Brief History of Oceanographic Engineering

The ocean has always intrigued mankind. We can claim to know more about the surface of Mars than the ocean bottom on Earth, with much of the ocean still to be explored. The medium of water that separates us from the ocean bottom poses interesting challenges to scientists exploring the sea floor. The human race has been exploring the ocean for millennia. Most exploration since the 19th century involved sending some kind of trawl to gather samples that could be studied and analyzed later. The limited information obtained this way was interesting enough to keep the explorers busy for quite some time. Next came efforts by Otis Barton and William Beebe for humans to descend to the depths of the ocean. They used a tethered vessel to descend to unexplored depths in the 1930s [13]. This vessel technology enabled explorers to have a first hand experience of the deep ocean. Engineering technology advanced with untethered manned submersibles like ALVIN in the 1950's made possible by developments in electronics and engineering materials [3]. Alongside the manned submersibles in the1960's

Remotely Operated Vehicles (ROVs) were in early stages of development. Early ocean studies had been a qualitative science based on observations and random samples, but soon this would change into a more quantitative science as sensors improved, acoustic navigation became more accurate and computing power increased. The last quarter of the 20th century saw development of Autonomous Underwater Vehicles (AUVs) made possible with digital computers, efficient batteries and better materials. Since then AUVs have made a critical impact on marine research.

The manned submersibles were very successful in their missions and have proved their worth time and again. Since they are untethered they allow scientists control to explore the sea floor and put scientists in the midst of a unique experience of being in the "unexplored". This access comes with a cost. The fact that humans are involved means that extra precautions need to be taken to ensure the safety of the operators and scientific crew, which limits the capabilities and increases the costs of manned submersibles. Also, any mission that uses a manned submersible needs a large dedicated surface vessel for deployment and recovery, which means a lot more manpower, and limits the deployment of the submersible to good weather. All this means added costs.

Parallel to the manned submersibles was the development of the Remotely Operated Vehicles (ROVs). One of the biggest driving factors for ROV development was when the oil industry was reaching diver limits and needed alternatives. One of the main hurdles to initial ROV development was the cables that could carry data over kilometers of wire while being flexible to allow the submerged ROV to maneuver freely. The ROVs, which are typically powered by the surface ship, have much better power capabilities than their manned counterpart. This means that they could have better thrust, lighting and could be used on much longer missions. ROVs could be used with a smaller crew and possibly deployed from smaller ships than the manned submersible and their operations would not be too dependent on the weather, making them attractive alternatives to the manned submersibles. Other than the science goals, the ROVs quickly started being used in all possible underwater applications like the energy industry, transatlantic communication etc. Even with their advantages, the ROVs had some issues. The ROVs needed a ship around while they completed their missions. This presented a problem when working in areas covered with ice. The long tethers used with the ROVs in the deep water applications limited the mobility of the ROVs and affected their dynamics. There were still some gaps in the underwater technology that needed to be filled.

1.2 The Role of AUVs in the science fleet

In the early 1980's we started seeing development for Autonomous Underwater Vehicles (AUVs). Considering the issues with manned submersibles and ROVs, a need arose for an untethered vehicle that could be sent out to do missions; analogous to the remotely operated spacecrafts. There were a number of challenges in the underwater world that needed to be overcome before this could be worked out. In water, electro-magnetic waves (including light) attenuate very fast and so cannot be used to communicate with the vehicle. The other alternative which is acoustics, in the ideal scenario, has very limited bandwidth [31] and long delays making it impossible to do any real time control of the vehicle. Thus came the need for a completely Autonomous

Underwater Vehicle (AUV). One of the major enabling technologies for the AUV would have to be the microprocessor which made computing small enough to be put into a mobile vehicle with limited power capabilities. Also the syntactic foam that was developed in the 1960's made it possible to provide flotation without having huge pressure vessels, thus reducing the size of the vehicles.

The resulting AUVs were small vehicles that could be put over the sides of the ship, to complete their missions and be retrieved when done. AUV deployments could be done from smaller surface vessels that needed a small operations crew. In addition, while the AUV was busy doing its missions, the surface vessel could be used for other activities. AUVs became feasible and cheaper alternatives to other existing technologies for numerous applications. AUVs are very efficient at survey/mapping type applications that are too monotonous and tedious for human operators. Also, AUVs are able to work in places that might be too risky for manned submersibles and inconvenient for the tethered ROV, such as ice covered areas.

AUVs definitely had a lot of advantages over other technologies including their being inexpensive to deploy. Despite this, they would not completely replace the manned submersibles and ROVs. A successful science team would require all three for their unique advantages. For example, if the goal was to find hydrothermal vents; one would start with AUVs to map the area and find characteristic signature of vent sites. Once a particular vent site was located, one would go in with an ROV or a manned submersible to study the particulars of the site such as its ecology and other characteristics. Thus, AUVs have certain clear advantages which can be levered and used in conjunction with other technologies making them an important tool for scientists.

1.3 Types of AUVs

Most AUVs can be classified into the following categories:

1.3.1 Shallow Water Survey AUVs

Shallow Water Survey AUVs are rated up to 500m, and are used for performing oceanographic surveys from close to the surface. These are typically small in size since they don't have to bear a lot of water pressure, have a high thrust to drag ratio, and so are able to maneuver in areas with high currents. Also the typical surveys that these types of vehicles are done over a large scale with fairly low resolution, so their operating speeds are relatively high, on the order of a few knots / hr. Examples of mid-water AUVs include the REMUS, Iver etc. [5, 11].

1.3.2 Mid-water AUVs

These refer to the class of AUVs rated up to 2500m that are typically used for performing mid-water column surveys or seafloor surveys in shallower areas. These are typically bulky in order to handle the high pressure at depth, which in turn means they need more thrust and more power that also add to their size. Since there is not much current at these depths, this class of AUVs can have small thrust to drag ratio. Depending upon the application that a typical AUV of this class is being used for, its operating speeds can vary from less than one knot/hr for a photographic survey to a few knots / hr for a multibeam or sidescan survey. Examples of mid-water AUVs include SeaBED, REMUS etc. [11, 58].

1.3.3 Deep-water AUVs

Deep-water AUVs are the class of AUVs designed to be used at depths of more than 2500m. Due to the high oceanographic pressures that these vehicles need to be able to bear, the housings are large and bulky. Also, since diving to such depths takes a long time, one would like to get longer missions out of each dive which means that these vehicles need more power storage, again adding to their size. To keep their sizes small, and make them more power efficient, these vehicles have a low thrust to drag ratio. Since AUVs of this class are usually used close to the ocean bottom for high resolution surveys, they must be able to maneuver at low speeds. Their design cannot involve control surfaces for maneuvering which results in multi-hull designs with multiple thrusters. Examples of deep-water AUVs include ABE, SENTRY, JAGUAR etc. [1, 6, 35, 81, 82].

1.3.4 Gliders

Gliders refer to underwater vehicles that use changes in buoyancy and water temperature in conjunction with wings to convert vertical motion into forward motion. These buoyancy engines typically achieve much more efficiency than the conventional electric thrusters, greatly increasing their range to an order of thousands of kilometers. Typically these vehicles operate in the upper water column, and are usually rated for less than 1000 meters. Examples of gliders include Spray, Seaglider, Slocum etc. [26, 55, 71].

Table 1: AUV Navigation Accuracy vs. Coverage

	Power	Spatial Coverage	Temporal Coverage	Navigation accuracy
Survey AUV	O(100W)	O(10 km)	O(1day)	O(1m)
Glider	O(1W)	O(1000km)	O(100days)	O(100m)

For a more comprehensive list of applications and AUV development refer to [76, 77, 83]. Table 1 shows the variance in terms of power requirements, range and resolution between a survey AUV on one end of the spectrum and a glider on the other. Depending upon the type of application, AUVs can be designed to fit anywhere in this spectrum with the appropriate balance between range and resolution. The resulting designs can be drastically different from one another. This paper will discuss the variables that can be adjusted in designing AUVs to suit the appropriate application. Each subsequent section discusses a different aspect of AUV design and addresses the design solution in terms of the different types of AUVs.

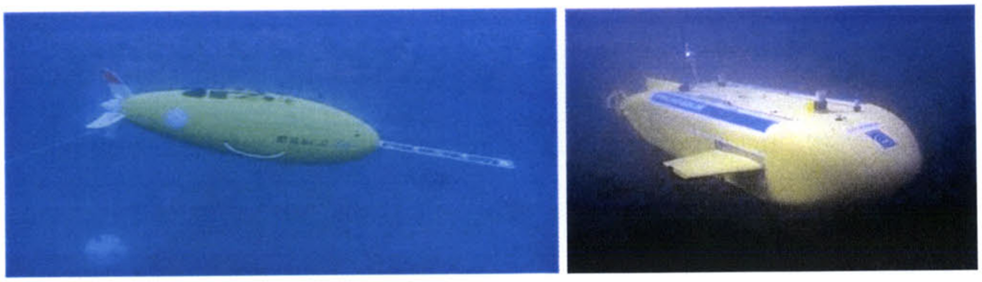
2 Mechanical and Materials Issues

The most basic characteristic about an AUV is its size and shape. The basic shape of the AUV is the very first step in its design and everything else must work around it. The shape of the AUV determines it application, efficiency and range. This section will discuss the issues that go into the mechanical design of the AUVs and how the resulting design affects the operation of the AUV in every way.

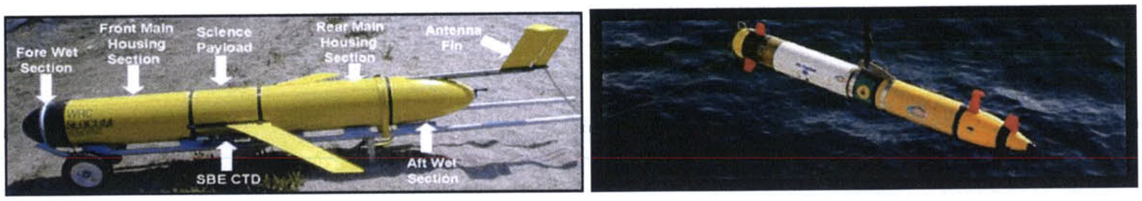
2.1 Torpedo vs. non-torpedo shape vehicles

Most AUVs used in science and industry today can be classified into torpedo shaped design and the non-torpedo shaped design independent of other characteristics. Figure 2-1 and Figure 2-2 below show some of the state of the art AUVs in the science community today.

This classification is important because it governs a lot of the characteristics of the AUV. A typical torpedo shaped or single hull AUV has less drag and can travel much faster than its non-torpedo shaped counterpart. A torpedo shaped AUV usually uses an aft thruster and fins to control its motion; thus these designs need some translational speed to keep full control of the vehicle. This class of AUVs in general has a much longer range and can work well in areas with moderate currents. They are appropriate for low resolution scalar surveys in larger areas, but are not suited for optical surveys or high resolution bathymetric surveys of a smaller area. These AUVs have six degrees of freedom, namely xyz translation, roll, pitch and heading, but these cannot be controlled independently, making the autonomous control of these AUVs relatively harder.

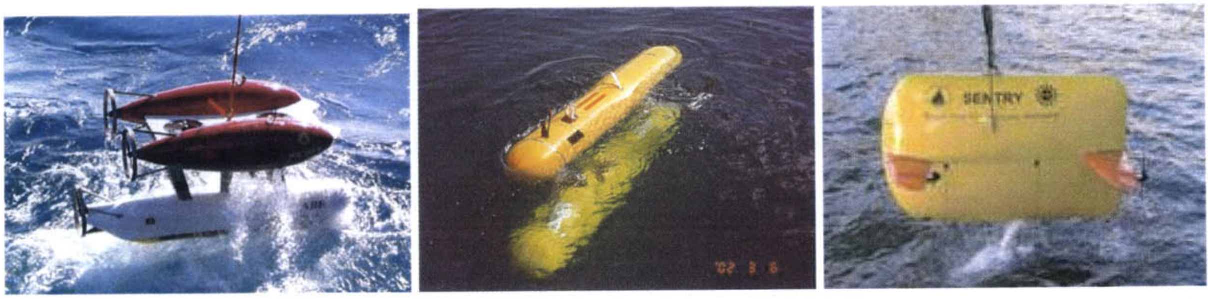


(a) Odyssey class AUV (b) Atlas Maridan M600


Fore Wet Section
Front Main Housing Section
Science Payload
Rear Main Housing Section
Antenna Fin
SBE CTD
Aft Wet Section

(c) Slocum Glider (d) REMUS AUV

Figure 2-1: Torpedo shaped AUVs



(a) ABE (b) SeaBED (c) SENTRY

Figure 2-2: Non-torpedo shaped AUVs

The non-torpedo shaped AUVs are typically designed to be completely controllable at much lower speeds. The multiple hull design makes these kinds of AUVs passively stable in pitch and roll, which means the other degrees of freedom can be independently controlled using multiple thrusters. A larger form factor for these vehicles means a higher drag, which makes their use difficult in areas with significant currents. The lower speeds and high maneuverability of this class of AUVs means higher navigational accuracy to follow very close tracklines. They are well suited for high resolution photographic surveys, multibeam mapping, and sidescan surveys.

The difference in the two classes of AUVs is analogous to that of the airplane and helicopter. The two have their own advantages and cater to different applications. The science community will always have these two kinds of AUVs co-exist to meet the complete set of requirements.

2.2 Materials Requirements

The water pressure on the AUVs is enormous where ocean depth can range up to 11000m. We can get an idea of how high these pressures are from the fact that at just 10m, the pressure is 406 kPa, which is twice the atmospheric pressure. Also the chemical environment of the open ocean is highly corrosive, making the selections of materials used in the ocean a critical issue. The materials that can be used need extremely high strength, rigidity and resistance to corrosion. The materials used for underwater vehicles can be classified into the following categories:

2.2.1 Housing Materials

Most AUV components are adopted from ones that are designed to be used at one atmosphere. In many cases the components might be pressure compensatable, they experience a uniform high pressure instead of a differential pressure. In such scenarios a simple oil filled enclosure can be used to keep the components dry. The advantage with this setup is that the enclosures are relatively light in water. The issue with such a setup is that dealing with oil is messy if the component needs to be serviced frequently. Also the oil filled housings need to be topped up with oil frequently, making them a bad choice for long term deployments.

Most electronic components need to be placed in housings at one atmosphere, such as batteries, computer electronics, sensors etc. The pressure housings need to be of extremely high strength since they bear a differential pressure between one atmosphere in the housing and the water pressure outside. The selection of the pressure housing materials becomes a critical issue for AUVs since the materials determine the weight of the AUV which in turn affects the size of the resulting vehicle. The properties of some commonly used materials are summarized in Table 2 below.

Table 2: Commonly used Pressure Housing Materials

Property	Steel Alloy	Aluminum Alloy	Titanium Alloy	C composite	Ceramic
Ultimate Strees (Kpsi)	60	73	125	300	100
Density (lb/in^3)	0.283	0.1	0.16	0.056	0.13
Fabrication	Excellent	Very Good	Good	Fair	Fair
Corrosion Resistance	Poor	Fair	Very Good	Excellent	Excellent
Magnetic Susceptibility	Very High	Medium	High	Very Low	Very Low
Relative Cost	Very Low	Very Low	High	Moderate	Moderate

The material selection for underwater vehicles is a little more complicated and non-intuitive. Nichols performed detailed analysis on materials selection for the SeaBED pressure housings, which can be found in [46]. Even though titanium alloy housing for a given depth rating weighs less in air, the Aluminum alloy (Al7075-T6) is a better choice in water because of the advantage in buoyancy. In spite of the fact that these alloys are quite corrosion resistant, the harsh environment of the ocean corrodes these materials.

Therefore, it is common to attach a sacrificial anode of a more galvanically active material like zinc, which would corrode preferentially before the housing [25].

2.2.2 Structural Materials

This refers to the materials used to make the structural members that hold the vehicle together like the struts, back plates etc. These components do not experience a differential pressure and have to be able to hold the weight of the vehicle in air and in water, so they are much thinner than those used on the housings. Usually a convenient choice for these is Aluminum alloys since they are light, cheap and easy to fabricate.

2.2.3 Flotation

Most of the flotation on the AUV is provided by syntactic foam. Syntactic foam is probably one of the most important technological developments making AUVs feasible. Before Syntactic foam, the housings would have to be made large enough to have the correct buoyancy, thus increasing the size of the vehicles. Syntactic foam is a high-strength low-density material. Foam is a deceptive word used to describe a composite material which has glass, ceramic, polymer, or even metal spheres suspended in an epoxy resin. There are various manufacturers that supply syntactic foam for underwater applications like Syntech Materials Inc. and Emerson & Cumming [8]. Syntactic foam rated up to 4800m is available in a moldable form and can be conveniently used in any desired shape on the AUV. The density of the 2000m moldable foam is about 593 kg/m^3. Deeper-rated foam is usually more dense and bulky. The 6100m rated Syntech foam has a density of 641 kg/m^3. Better density deeper-rated foam is available at the cost of moldability. Emerson & Cumming supplies a machinable 6000m rated foam with a density of 0.513kg/L. The machining makes its use limited to simpler shapes and increases the costs.

2.2.4 Other Materials

The other material requirements include the wet cables that go between the various housing to connect the sensors, electronics and batteries. Since the cables are compliant under pressure, they just need to be water tight. These cables are usually the standard cables covered in molded rubber. Other material requirements on the AUV include the hydrodynamic skins that are used to cover the interiors of the vehicle and reduce its drag. These are usually made of ABS or other plastic that are convenient because they are neutrally buoyant.

2.3 Mechanical Setup of SeaBED

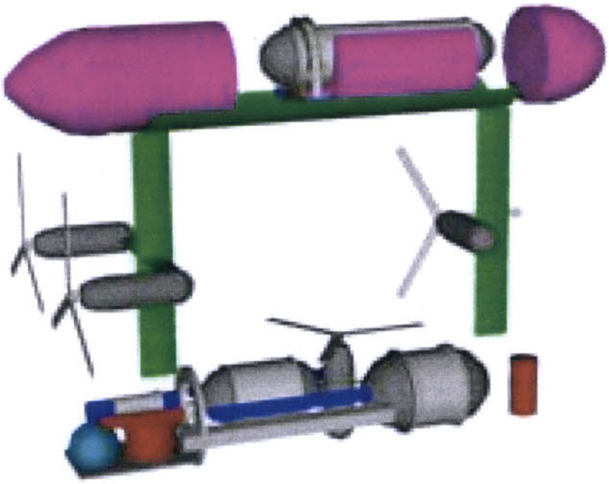


Figure 2-3: 3D Model of the SeaBED AUV

A typical mechanical setup for an AUV can be understood by studying the 2000m rated SeaBED AUV. The basic shape, as shown in Figure 2-3 above, is composed of two torpedo shaped hulls which are 1.9m in length, 0.34m in diameter and 1.1m apart. The overall weight is about 200m in air, and depending upon the mounted sensor suite, it is ballasted to be slightly positively buoyant in water as a safety measure. As an additional safety measure it carries a drop weight of about 10 lbs which is connected with a corrodible zinc link in case one of the housing floods or the vehicle gets entangled. The top hull carries the electronics housing which is positively buoyant and all of the flotation while the bottom carries all the heavy sensors and battery back. This design makes the center of gravity (CG) and center of buoyancy (CB) separation about 23 cms which is significantly more than any torpedo shaped AUV which has the CG-CB separation in the range of a few centimeters. Such a design is very conducive for imaging since it makes the vehicle stiff in two degrees of freedom namely pitch and roll. The other degrees of freedom can be controlled independently using the 3 thrusters.

The housings on the vehicle are made from Al7075-T6 alloy which seems to have the best trade off at the designed depths. The housings have hemispherical end-caps as opposed to flat ones because of the significant weight savings offered by the more stable shape for housings this wide in diameter. The flotation foam used is the moldable syntactic foam with a specific gravity of 0.4. The struts have an airfoil design to reduce the drag. Finally, both the hulls are enclosed in ABS plastic shells to reduce the hydrodynamic drag.

The thrusters on SeaBED use torque controlled brushed DC motors that are housed in a one atmosphere pressure vessel. The propeller shaft is driven from the motor using magnetic couplings avoiding the need for high pressure seals which have a lot of friction. SeaBED was designed to not have any oil filled components to make is viable for long term deployments in the future.

The SeaBED was expected to be used on science missions around the world; this placed one practical design constraint, which was to make it air-shippable. This meant that every piece on the vehicle had to fit the maximum dimensions that could be shipped by any standard carrier.

3 Power Systems

Unlike tethered vehicles, AUV operations are limited by the onboard power that they can carry. The power is probably the most important design characteristic on the AUV, since it determines the range and accordingly the mission characteristics of the AUV. The typical sources of power on the AUVs have been batteries, but there is some experimental work with using closed cycle engines and fuel cells. This section will discuss the characteristics of the AUV power system and elaborate on the various available alternatives.

The important design parameters of the power storage systems on the AUV include specific energy (energy storage / unit mass), energy density (energy storage / unit volume), charge / discharge voltage and current characteristics. In order to understand the power requirements of the AUV better, it is helpful to have a theoretical model. A good quantitative measure of the performance of the power system on the AUV is the range that it can provide the AUV. We can easily see that since this is a system traveling through water, the energy wasted in drag is proportional to the speed of the AUV and thus the range of the AUV will depend strongly on the speed at which it is operated. A simple analysis shows that this range is given by the equation below [59].

$$R = \left(\frac{E}{K_d}\right) u^{-2} \qquad \textbf{eq. 1}$$

Where:

R – Range in meters

E – Energy Available in Joules

K_d – Effective drag coefficient W s^3/m^3

u – Speed in m/s

Thus when all the energy is used for propulsion, the range is inversely proportional to the square of the velocity. In most vehicles the propulsion requires a lot more energy than the sensors and this can be a valid assumption. Thus one could say that the slower you travel the farther you can go. This is a good analysis for the typical torpedo-shaped AUV that is designed to be used between 5-10 knots/hr, but when we look at the hovering AUVs that operate at 0.5-2 knots / hr, we see that the propulsion is not the majority of power consumption now. We need to start looking at the hotel load which refers to the sensor suite on the vehicle. At low speeds the sensors are typically still using the same amount of power, but that of the propulsion is much lower. Adding this into the model we get the following result, where P_h refers to the hotel load [16].

$$R = \left(\frac{E}{K_d + \frac{P_h}{u^3}} \right) u^{-2} \qquad \textbf{eq. 2}$$

The resulting model shows that for a given power capacity and hotel load, the range of the vehicle has a maxima. The following figure shows the range as a function of velocity for different hotel loads on the ABE AUV.

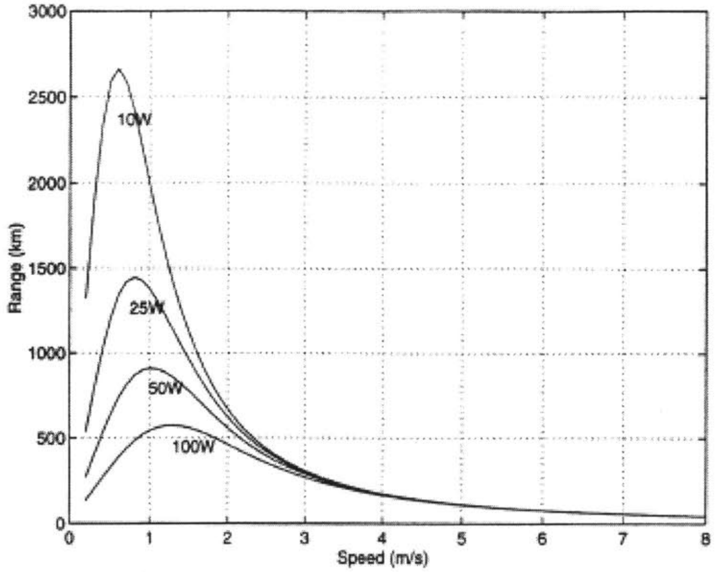


Figure 3-1: Range vs Speed for ABE [60]

The interesting point to note in this figure is that each curve has two asymptotes: the high speed asymptote represents the energy being lost in the turbulence, while the low speed asymptote shows the energy being lost in the hotel load before the vehicle can get too far.

The above analysis is more suitable for AUVs using batteries as the power source; for vehicles using other sources like engines, the analysis is further complicated by the losses associated with the engine itself. The AUV is only useful if it can effectively collect the data it is designed to collect, which means that the sensors should be able to work with good resolution at the operating speed of the AUV. As an example let's look at SeaBED as a platform for underwater photography. For high colored imagery it needs to travel at an altitude of 3-4 meters above the seafloor, and for good post processing of the images it needs about 50 percent overlap between consecutive images. Assuming the standard strobes can fire every 2.75 sec, the vehicle needs to travel at 0.3 m/s. On the other hand for black and white images, it can fly at 5 meters with a 30 percent overlap yielding an operating speed of 0.9 m/s. Figure 3-2 below details the possible choices of speed, altitude and strobe frequency. Thus the power system of the AUV should be adapted to the particular application for which the AUV is being designed [58].

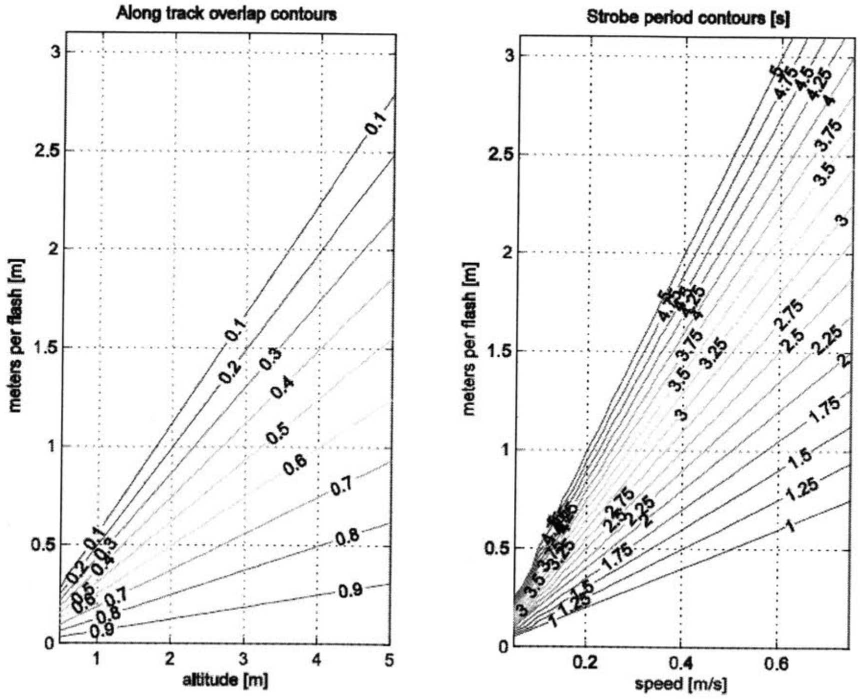


Figure 3-2: Visual coverage as a function of speed/altitude/strobe frequency

3.1 Closed Cycle Engines

For decades, the navy submarines have been trying to solve the problem of providing power underwater. This has prompted a lot of development in the field. All combustion based engines need oxygen for combustion which is a problem underwater where there is no atmospheric oxygen. Thus, such systems need some way of carrying around an oxygen source that can be used in combustion.

The first significant development was in Germany during the Second World War which involved using concentrated hydrogen peroxide as the source of oxygen underwater. The hydrogen peroxide was decomposed by a potassium permanganate catalyst to provide hydrogen and oxygen that would burn the diesel fuel to power steam turbines [78]. Next was the development of the Closed Cycle Diesel Engine (CCD), similar to the conventional engines that could operate normally on surface with the atmospheric oxygen, but when submerged would use an onboard supply of liquid oxygen. In order to control the combustion, the pure oxygen would be diluted with the exhaust gases. Another technology that followed was called the Closed Cycle Steam Turbine that used compressed oxygen and ethanol to produce steam to drive the turbo electric generators. Another successful technology has been the Stirling Cycle Engines, which power the closed cycle Stirling Engine with liquid oxygen and diesel fuel to produce energy [70].

The closed cycle engines have been fairly successful, but come with their share of problems like being combustible, unsafe, expensive and added complexity. Thus, because of the problems associated and better alternatives the closed cycle systems haven't been very popular for use with AUV programs. One of the few such AUVs was the Japanese AUV R-One Robot that was equipped with the Closed Cycle Diesel Engine [67].

3.2 Batteries

Batteries are by far the most commonly used power sources for AUVs. The advantages include the simplicity of the resulting system and commercial availability.

Battery technology is also very mature because of its innumerable applications in automobiles, portable electronics, etc. The AUV development has taken advantage of this development and adapted available batteries to the AUV use.

Table 3: AUVs in the US Science fleet and their power sources

Name	Size	Battery Chemistry	Depth
REMUS	1m	Lead Acid	150m
Odyssey	2m	Silver Zinc	4500m
ABE	2mx3 hulls	Lead Acid	5500m
FAU Explorer	2 m	Ni Cad	300m
Autosub	7m	Alkaline	300m
FAU Morpheus	1.5-3 m	Ni Cad	varies
SeaBED	2 m x 2 hulls	Li ion	1500m
Jaguar	2m x 2 hulls	Li ion	5000m

Table 3 shows the various batteries that were traditionally being used on some of the science AUVs. Most of these AUVs have now adopted the newer technologies like Lithium ion or Lithium polymer. The rest of this section is devoted to the characteristics of the various battery chemistries. Table 4 shows the important properties of some commonly used chemistries. The typical setup on an AUV involves packing the batteries into 1 atmosphere pressure housing or pressure compensated oil filled housings. Pressure compensated housings usually mean considerable weight savings on the AUV.

Table 4: Battery Characteristics [16]

Chemistry	Energy Density	Pressure Compensatable	Outgassing	Cycles	Comments
	(Whr/kg)	(Whr/kg)			
Alkaline	140	No	at higher temperatures	1	Cheap, easy to use
Li Primary	375	No		1	High energy density
Lead Acid	31.5	46	Yes, even when sealed	~100	Mature technology
Ni Cd	33	No	If Overcharged	~100	Flat discharge curve
Ni Zn	58.5	160	None	~500	Emerging technology
Li Ion	144	No	None	~500	Wide use in small packs
Silver zinc	100	No	Yes	~30	Can handle power spikes

3.2.1 Alkaline

Alkaline primary cells are probably the cheapest most easily available batteries. These have a very high energy density which is very conducive for AUV use [22]. These batteries are usually safe, but outgas if kept in a sealed housing for a long time. Their voltage drops by 50 percent over the battery life which is not a problem with the modern inverters that can operate over a wide range. Some other nuances with alkaline cells are that at higher discharge rates they are inefficient and they are not easily pressure compensatable. Also primary cells are quite inconvenient to use in typical AUV deployment scenarios and so lose to other secondary cells [39].

3.2.2 Lead Acid

Lead Acid batteries are the cheapest and most convenient secondary batteries to use. The lead acid cells have been used in cars for many years and their characteristics are well understood. These have a low power density, but that is made up for by the fact that they are pressure compensatable. A minor problem with the lead acid cells is that they release a little hydrogen at the end of the charge cycles which poses an explosion hazard, but some simple tricks can be used to overcome this problem. The REMUS and ABE AUVs have proved the success of the lead acid batteries on AUVs [11, 81].

3.2.3 Nickel Cadmium

Nickel Cadmium (NiCd) cells are also a mature technology and are well understood. The NiCd cells have a little advantage in terms of energy density, but their biggest problem is that they need one atmosphere housings. It is also hard to recognize when the NiCd packs are charged and they heat when overcharged. Despite these fallouts we see some use of NiCd cells in the FAU AUVs [63].

3.2.4 Lithium Ion

The Lithium Ion (Li-ion) cells have seen considerable development in the last decade, mainly due to their extensive use in portable electronics. These are very attractive for AUV use because of the high energy density and long cycle life. The only issue is that they are not pressure compensatable, but their high energy density makes up for this disadvantage. Until recently, the Li-ion cells were quite expensive, but now with widespread commercial use they are one of the top choices for AUVs. The SeaBED class AUVs have been successfully using Li-ion battery packs since 2001.

3.2.5 Lithium Polymer

Lithium Polymer cells refer to the Li-ion cells where the electrolyte is enclosed in some absorbing material. This makes these cells pressure compensatable. These cells are projected to provide a better energy density than the Li-ion cells. Bluefin Technologies has recently commercialized batteries with this technology [79]. Once they prove their success in the field, this will probably be the best chemistry for the AUV community.

3.3 Fuel Cells

Fuel cell technology has been the focus of attention as an alternative power source for automobiles. This has led to development that reduces fuel-cell technology costs and improves its efficiency. Fuels Cells may now be considered another viable alternative to power AUVs, having a high power density and thus making long range missions possible. Fuel cells are devices with no moving parts that basically convert the chemical energy of the reactants into electrical energy without, combustion along with the by-product which is water. The reactants in this process are the fuel (hydrogen) and the oxidant (oxygen). Unlike batteries that store their energy internally, fuel cells' energy is supplied externally from the reactants. The conventional fuel cells cannot be directly used on AUVs, since on AUVs they should be able to manage the by-products while having manageable size and weight. Of the various alternatives the Polymer Electrolyte Fuel Cell (PEFC) seems to be best suited for underwater applications. The PEFC operates at efficiencies above 50% at relatively low temperatures (80°C) and works well in confined spaces [66]. Hyakudome et al. have successfully demonstrated the first Fuel Cell propelled AUV URASHIMA a powered with the PEFC along with hydrogen and oxygen tanks. The designed range for this AUV is expected to be 300 km at about 3 knots [34]. Commercially, Alupower has also been developing various kinds of Aluminum based Fuel Cells for use with underwater vehicles [54].

3.4 Nuclear Power

Nuclear power has been used to power naval submarines. The technology has been matured and been used successfully for quite some time. The nuclear reactor produces heat which is then used to generate electricity to power the vehicle. As opposed to land-based nuclear power plants, the marine nuclear reactors are either pressurized water, liquid-metal-cooled, or boiling water so that they have a high power density in a small volume. Although nuclear power has been successfully used on naval submarines, it is not an economically viable option for commercial vessels. Also, the complexity that the nuclear power system adds to the AUV, along with the costs is not acceptable to most science-driven AUV projects. Thus this has not been seen on any of the AUVs, but could possibly be an option for long term deployments in the future [44].

3.5 Typical Power System Setup

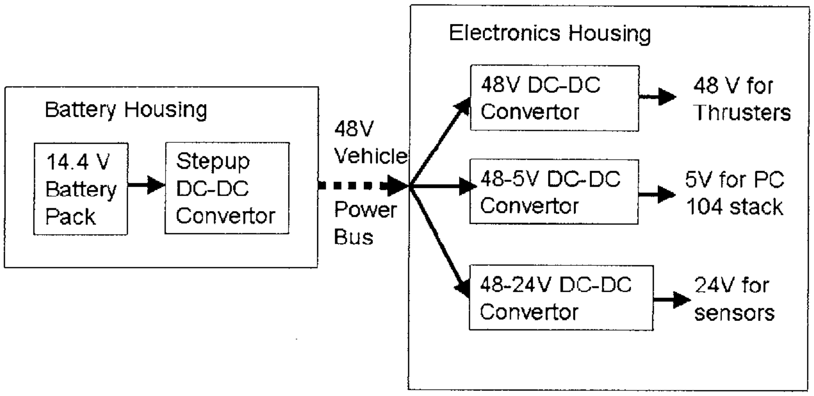

Battery Housing
14.4 V Battery Pack
Stepup DC-DC Convertor
48V Vehicle Power Bus
Electronics Housing
48V DC-DC Convertor
48 V for Thrusters
48-5V DC-DC Convertor
5V for PC 104 stack
48-24V DC-DC Convertor
24V for sensors

Figure 3-3: SeaBED Power Setup

In order to understand other design subtleties, we can study the power setup being used on the SeaBED AUV. The power source for the vehicle is a 2kWHr rechargeable Li-ion battery pack comprised of 20 Ocean Server batteries, each of which consists of 12

Li-ion cells, 3 stacks of 4 cells in parallel; thus resulting in a 14.4V output [7]. The output from the battery pack is then stepped up to 48V for the main vehicle bus, since the thrusters operate at 48V. The bus voltage is then stepped down to the various desired levels using isolated DC-DC convertors. Even though this might seem inefficient, it has the advantage of providing a cleaner power bus and supplying clean power at various voltages. On the AUV this is important since the various sensors are sensitive to the quality of the input power supply. This setup allows the operation of sensors in similar frequency range, asynchronously. The hotel load of SeaBED, including the main processor, navigation sensors (compass, gyro, depth and LBL) and motor controls is about 50 W. The main thrusters at 1 m/s represents a load of 100 W. Surveying sensors and navigation (camera, strobe, scanning sonar and doppler) represent another 50 W; thus resulting in a total power that is under 200 W. This results in a ten hour endurance and a theoretical range of 36 km with some room for additional sensors [52].

4 Computer Architecture

An AUV is after all a mobile robotic system. The performance and robustness of the AUV completely depends upon its computer hardware and software. The computer architecture on the AUV is the component that has seen the most development in the last decade.

4.1 Hardware

Any software can only perform as well as the hardware it is running on. The early AUVs used various different hardware setups depending upon their particular needs. These older AUVs have very different customized hardware which made it imperative to write AUV specific software. In the older systems, a limited processing power required parallel processing on multiple processors and an infrastructure for message passing, such as the Autosub AUV which used LONWorks that is a distributed computing environment based on the Neuron chip [42, 47]. Valavanis et al. have summarized the hardware and software setup on the early generation AUVs in great detail [68].

Today, the technological development has made powerful, low power consumptions microcontrollers easily available. The common choice for the modern AUVs are the standardized i386 based processors in different form factors, which can run standard operating systems like Linux, DOS, Windows etc. Lippert offers the Cool LiteRunner 2 which has a 366 Mhz processor, that is more than adequate for most AUV operations, using 0.9W of power which comes in a convenient PC-104 form factor and is passively cooled [2]. As opposed to the older systems, the modern AUVs with more powerful processors find it more convenient to use a central computer connected to all the sensors and actuators via an RS-232 or Ethernet type link, ex. Sentry, SeaBED, REMUS [11, 41, 52]. Such a standardized microprocessor also makes it possible to write standardized software independent of the operating system. Newman has developed MOOS for AUVs, a modular software that can be adopted to any platform [45].

4.2 Software

The standardization of hardware has brought along some standardization in the software platforms used on the AUVs. Commercial off the Shelf (COTS) software is the more common choice for most AUV designers for the operating systems of the AUV as predicted by Whitcomb [73]. Even with the standardized operating systems, there are some differences in the control software architecture of the different AUVs. Even though in many cases these differences in the architecture result in the same behavior of the AUV in similar scenarios [19], there is a philosophical difference in the way the different architectures approach the problem of AUV control. The following are the basic different approaches commonly found on AUVs.

4.2.1 Hierarchical Architecture

A hierarchical software system divides the system into different levels. The lower levels interact with the sensors and actuators and solve the problems of controlling simple behaviors: Maintaining a particular depth or heading. The higher level interacts with the lower levels to control the mission level goals. The resulting structure is linear where the data is only exchanged between two consecutive levels. The higher level can get data from the lower level and accordingly send it a command. This results in a robust system, which restricts the usable data to the functions that need them. The design and debugging of these systems is easy because each function is simple and can be easily tested. However, changing or adding functionality is complicated because the change has to propagate through all the levels. These systems work well in a more structured predictable environment and are not suited as well for dynamic ocean environments. Examples of hierarchical based system include the Autonomous Benthic Explorer and Ocean Voyager II [62, 80].

4.2.2 Heterarchical Architecture

Philosophically the opposite of hierarchical architecture is the heterarchical architecture. This is a system that has a parallel structure where each function can exchange data with every other function without intermediate levels. Such a structure results in a very computationally efficient system. The resulting system would also be quite modular and flexible. While the software is small it would be easier to manage, but as it gets larger the management and debugging of such software becomes more difficult. Also, since there is no supervision of the communication, the system is not as reliable and small bugs could bring down the entire system. The characteristics of the purely heterarchical system make it unsuitable for AUV use, though in a modified form such a system could be quite attractive.

4.2.3 Subsumption Architecture

The idea of subsumption, which was introduced by Brooks, can be applied to the world of AUVs [18]. The subsumption architecture consists of behaviors working in parallel independently. Each behavior consists of layers that communicate directly with sensors. The behaviors are prioritized and so while they run in parallel, a higher-level behavior could suppress a lower-level behavior. This architecture has data and control distributed through all the layers that process their own required information. This structure has characteristics similar to the heterarchical architecture like flexibility, robustness and computational efficiency. Even though, such systems result in a dynamic and reactive behavior, they are often unpredictable. Thus, in the typical applications of the AUV in the science community a purely subsumption based system is not desirable. An example that includes the subsumption idea is the Odyssey II AUV [14].

4.2.4 Hybrid Architecture

A hybrid architecture essentially draws the best qualities from all three of the above systems. The system is usually divided into a higher and a lower level system. The higher level draws its ideas from the hierarchal system in that it is abstracted from the lower level functions and just implements strategic mission level logic. The lower level is usually heterarchical based where the lower level functions can access all the sensors and actuators working in parallel. The idea of subsumption can still be used to define some vertically integrated behaviors which might be triggered in an emergency. The advantage of such a system is that it has the elegance of the hierarchical architecture with the flexibility of the heterarchical architecture, while having the dynamic response of subsumption. The resulting system is also modular where the lower level functions can be quickly changed to adapt to the particular sensor and vehicle, while maintaining the same mission level logic. This has been the more popular architecture on the science AUVs such as SeaBED, Autonomous Benthic Explorer, SENTRY, HROV etc. [41, 52, 80].

Having studied the philosophy of the various software architectures, the next step would be to understand their implementation of the various AUVs in use today.

4.2.5 REMUS

At the heart of the REMUS control architecture is a PC-104 based x86 computer. The computer uses eight 12-bit analog to digital channels and I/O ports to communicate with the sensors and actuators. They also run the control code from a flash drive as opposed to the hard-drive since it is much less likely to fail. On the software side, the REMUS team chose to use DOS as the operating system, since it is a real time operating system as opposed to Linux or Windows. The advantage of a real time system is that it gives a very tight control of the order in which the functions execute as opposed to a multithreaded system which lets you run many processes at the same time without being able to predict exactly when a process runs. Thus, using a real time systems lets one write their own multithreading algorithm giving a much better control of the software. The control code on the REMUS is written in C++ and is loosely based on the hybrid architecture described above.

4.2.6 Autonomous Benthic Explorer

The Autonomous Benthic Explorer (ABE) was originally designed as a distributed, hierarchical control architecture, based on two different layers with different computational capabilities. The hardware for this original setup consisted of 68HC11 microcontrollers at each node which were connected to its respective sensor or actuator. These nodes talked to each other using a SAIL bus. The major limitation of this bus was that the embedded PC could only talk to one sensor/actuator at a time which meant that their update frequencies were very low. The resulting top layer had low computation capability and thus very low power requirements, while the lower layer which consisted of a lot of nodes had large and expandable computational power and higher power requirements. This old system eventually became obsolete and was upgraded to a x86 based central computer with RS 232 interface for the sensors and actuators.

4.2.7 SeaBED

The SeaBED computer architecture involves 2 PC-104 stacks powered by a 300 Mhz Geode GX1 processor. The first stack is the control computer which has a 12-port RS 232 board which is used to talk to the various sensors and actuators. The second stack is mainly used to log images from the camera. All the sensors talk to the computers via RS-232 or Ethernet. The thrusters are closed loop servo controlled with their own micro-controller and also talk to the control computer via an RS-232 link. The computers run an open source implementation of Linux, Fedora Core 4 which is very robust and reliable. This operating system can be easily installed on any personal computer, making development very convenient.

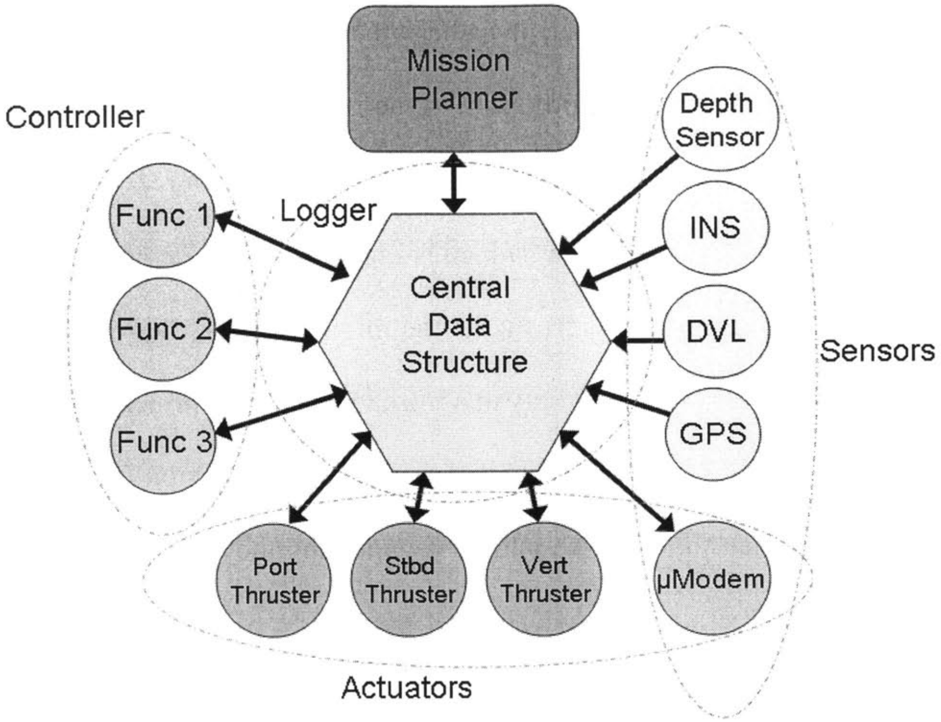

Mission Planner
Controller
Depth Sensor
Func 1
Logger
INS
Central Data Structure
Func 2
DVL
Sensors
Func 3
GPS
Port Thruster
Stbd Thruster
Vert Thruster
µModem
Actuators

Figure 4-1: SeaBED software architecture

The SeaBED control software is an elegantly implemented hybrid architecture. The Figure 4-1 shows a schematic of the SeaBED control code. At the heart of the system at the lowest level is the Logger which is implemented in C. The Logger manages a data structure that keeps track of all the sensor data and commands which can be accessed by individual sensors and actuators. The Logger also manages individual sensor and actuator threads. A sensor thread basically queries the serial line periodically for new data, which is sent to the central data structure with a time stamp. The actuator thread periodically checks for updated commands that need to be sent to the actuator and sends the appropriate command whenever there is a change.

Running in parallel with the Logger is the Controller which is also implemented in C. The controller periodically queries the Logger data structure for changes in the current goal. When it sees a particular goal, it gathers the sensor data from the Logger and calculates the commands that need to be sent to the actuator and sends them back to the Logger. It also updates the Logger when a particular goal has been reached.

The top level is the Mission Planner, which is implemented in Perl. Perl is a scripting language which makes it much easier to write the mission files. The Mission Planner is also written in a different language to stay in accordance with the principle of 'Separation Between Church and State'. This essentially means that the Mission Planner makes the strategic decision of what the AUV should do by updating the goal in the Logger, but it doesn't have routine access to particular sensor data. The Mission Planner then hands over the responsibility of meeting these goals to the Controller. Once a particular goal is met, the Mission Planner decides the next step and accordingly keeps the Logger updated with the goals.

One safety feature in the SeaBED implementation is the watchdog thread. This thread runs independently of the control code and keeps checking if the code has stopped execution. If because of some problem, the control software hangs up, the watch dog reboots the vehicle and goes into emergency mode.

4.2.8 SENTRY/NEREUS

The Deep Submergence Lab at WHOI has been testing their AUV Sentry which would be replacing ABE. SENTRY shares its software suite with the NEREUS hybrid remotely operated vehicle (HROV) that is based on the original Jason Talk control system which was used on the Jason ROV [43]. The hardware for these systems consists of an x86 type central processor in a PC104 setup. The software architecture is a multiple layered hybrid architecture called the Mission Controller [41]. This Mission Controller meets the extra challenge offered by the HROV that can operate either as a tethered ROV or an untethered AUV. This setup also caters to the requirements for manual control and thus is distributed over a number of computers.

5 Navigation & Communications

Once an AUV is deployed it drives around gathering different kinds of sensor measurements. In order to make any sense of these measurements, the AUV has to be able to keep a track of where the measurements were made. Also to make a successful survey it is necessary to be able to direct the vehicle to a particular location and keep track of where it has been with respect to the earth's axis so that we can associate the data gathered by the AUV to a particular X-Y location. This issue is a little easier to deal with if we have high quality sensor maps of the area apriori. In such a case the problem is reduced to just locating the AUV in the map. In almost any typical application of the AUV we do not have the convenience of such a map, and even if the area is familiar, the quality of the a priori survey done from a surface vessel would be limited. In some cases, near oil wells etc. where an AUV is frequently deployed we might be able to get decent maps or insert artificial clues in the area to enable accurate navigation. But this forms a very small portion of the typical applications seen by the science community.

This leads to the next type of navigation, which involves starting from a known point, building a map while using it to navigate and at the same time updating the map using the new sensor data available. This chicken-and-egg problem of navigating using an inexact map and updating it with inexact sensor information is referred to in the Robotics community as the Simultaneous Localization and Mapping (SLAM) problem or the Concurrent Mapping and Localization (CML). Much work has been done in this field using the typical sensor data available on surface like laser range finders, optical images, GPS, acoustics etc.

In the underwater environment the navigation problem is further complicated by the fact that EM waves attenuate very quickly, thus rendering the optical sensors quite useless. Even in optimal conditions the optical data would be limited to a few meters. This section details some methods that are used to solve the navigation problem underwater.

Table 5: Typical AUV Navigation Sensors [72]

Instrument	Variable	Internal	Update Rate	Precision	Range	Drift
Acoustic Altimeter	Z - Altitude	yes	varies: 0.1 - 10Hz	0.01-1.0 m	varies	-
Pressure Sensor	Z - Depth	yes	medium: 1 Hz	0.01-1.0 m	full-ocean	-
12 kHz LBL	XYZ - Position	no	varies: 0.1 - 1Hz	0.01-10m	5-10 Km	-
300 kHz LBL	XYZ - Position	no	1.0 - 5.0 Hz	+/-0.002 m	100 m	-
Bottom-Lock Doppler (1.2 MHz)	XYZ - Velocity	yes	fast:1-5Hz	+/-0.2% cm/sec	30 m	-
Inclinometer	Roll and Pitch	yes	fast:1-10Hz	0.1°-1°	+/- 45°	-
Magnetic Compass	Heading	yes	medium: 1-2 Hz	1-10°	360°	-
Gyro Compass	Heading	yes	fast:1-10Hz	0.1°	360°	10°/hour
Ring-Laser Gyro	Heading	yes	fast: 1-1600Hz	0.0018°	360°	0.44°/hour

5.1 Dead Reckoning

In order to navigate underwater, the first option is to simply keep a track of where the AUV is traveling or 'dead reckoning'. This would mean keeping track of the AUV in the 3D co-ordinates by integrating the velocities measured using appropriate sensors. One advantage underwater is that we can easily fix the z-coordinate of the vehicle by using accurate depth sensors, which are commercially available. This reduces the problem to 2 dimensions but even this basic dead reckoning is a difficult problem to solve since it is quite hard to measure the velocities of the vehicle which is floating in a medium without reference to the stationary world.

There are a few sensors that are available to overcome these issues. Over the past few decades acoustic doppler systems have been developed that can calculate the relative velocity with respect to the water column by measuring the acoustic waves scattered by the particles suspended in water. The issue with using the instruments in such a mode is that since these are relative measurements, if there are significant currents in the area, the navigation errors are high enough to make such systems quite inaccurate. A typical operation can see currents of 2-3 knots/hour with the AUV traveling at 5-6 knots/hour rendering the navigation information useless [38]. To overcome these issues another possibility is to use the acoustic dopplers in the Doppler Velocity Log (DVL) mode [10, 53]. In this method of operation the Doppler locks to the bottom of the seafloor and measures the velocities with respect to that. This results in much more accurate navigation but will only work when the vehicle is operating close enough to the bottom of the ocean. Alternatively, one can also use accelerometers to keep track of accelerations seen by the vehicle and integrate those twice to calculate its positions. This is possible using commercially available Inertial Navigation Systems (INS. Such systems tend to be quite expensive and power hungry making them undesirable for small AUV operations.

Another important measurement required to navigate in a dead-reckoning mode is to keep a track of the heading of the vehicle at all times. This is more critical than the translation velocities because a small error in heading translates into a much larger error in position when traveling long distances. Typical sensors used for heading information include magnetic compasses, mechanical gyroscopes, ring-laser gyroscopes and fiber-optic gyroscopes. The magnetic compass can't provide high enough accuracies (O (1°)) and is also affected by the local magnetic fluctuations of the region, plus other magnetic fields generated in the vehicle itself. The mechanical gyroscopes are more accurate (O(0.1°)) but have the problem of drifting over time. The other alternatives, which are the ring-las Design Considerations for Engineering Autonomous Underwater Vehicles er and fiber-optic gyroscopes, are much more accurate (O(0.001°)) and have a similar drifting problem that is much less than in their mechanical counter parts. These ring-laser and fiber-optic gyros are extremely expensive and would probably not fit the budget constraints of a small AUV operation; as the technology matures we might see this technology being more affordable.

Even with highly accurate sensors, the navigation errors are unbounded since they grow with the length of the mission. Sometimes this problem can be overcome by surfacing the AUV and getting GPS fixes which can be used to bound the navigation errors; but this might not be possible for deep missions since submerging and resurfacing could take on the order of hours and the drift while doing so might make the GPS fixes not usable. Thus, in most AUV operations dead reckoning on its own is not a very viable method, but can be used to supplement other methods.

5.2 Long Base Line Navigation

Long Base Line or LBL navigation is the traditional method for navigating underwater and has proved its success and robustness over time. This method is analogous to the GPS systems that we have on land. The basic idea of the LBL method is to use the slant range of the vehicle from two or more fixed points along with its accurately known depth to correlate its position in the 3D space.

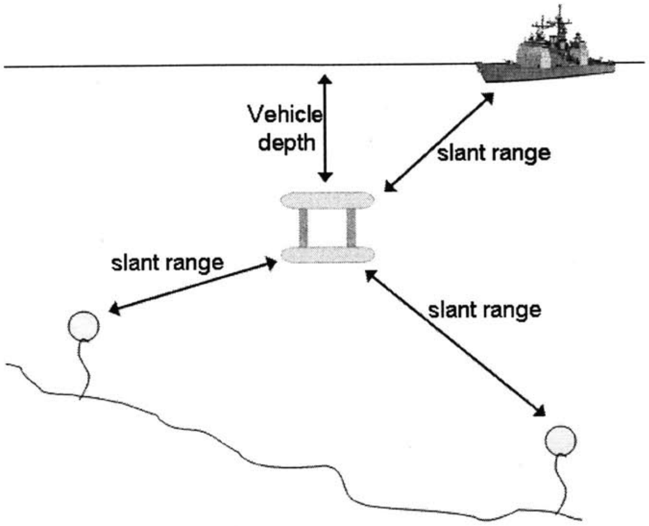


Figure 5-1: A Typical LBL setup

A typical LBL setup includes the following steps:

a. Transponder Deployment: Before setting up the LBL system in a site of interest, a bathymetric survey is performed to understand the topology of the area. After studying the area, the optimal locations are determined for the acoustic transponders, which are then deployed at the site of interest with appropriate tether lengths so as to optimize the geometry of the survey and minimize the error bounds. The transponders are simple devices that typically listen at a particular frequency and on receiving a ping respond at another fixed frequency. By measuring the round trip time of the pings the distance from the transducer can be calculated.

b. Transponder Survey: The next step in the setup is to drive the surface ship around the transponders, while pinging them and logging the round trip travel times along with the GPS coordinates of the ship so as to fix the transponder XYZ positions in the earth co-ordinate system. By using accurate GPS measurements, this can fix the transponders positions with an accuracy of a few meters.

c. AUV Navigation: Once the locations of the transponders are fixed, the AUV can be deployed. While performing the survey, the AUV interrogates the transponders and calculates the slant ranges from the round trip travel times of the pings. Using the slant ranges and an accurate depth sensor onboard, the AUV can fix its position relative to the two transponders and thus in the earth's coordinate system.

The LBL setup under optimal condition can provide highly accurate position fixes for the AUV which means it can accurately keep a track of the AUV during the survey. The limitation of the LBL navigation is that acoustic waves have a significant travel time in water which means that the frequency of the LBL fixes is highly limited (depending upon the geometry it can vary between 0.1 – 1 Hz)[75]. Also another problem with these systems is the false returns received by the transducers when the acoustic waves bounce off the surface, seafloor or other reflecting thermal layers. Even though LBL systems can be very efficient for doing detailed surveys of a small area, it requires a lot of ship time to setup and deploy which makes it inconvenient and expensive for large area surveys.

5.3 LBL-DVL

As we have seen above, the LBL system is highly accurate and drift-free over long deployments but has a lower update rate, while dead reckoning with good sensors is quite accurate for smaller periods of time. So the obvious next step to having more accurate navigation is to use the LBL in conjunction with the DVL [36, 72, 74]. The problem with the LBL system is the false hits, which generate high frequency noise and the problem with the dead reckoning is the low frequency drift in the error. Thus we can take advantage of both the systems by using a low-pass filtering the LBL data and high-pass filtering the DVL data. This essentially means that the AUV primarily uses the LBL fixes to navigate, but between fixes it uses DVL navigation [75]. By navigating in this way the error of the dead reckoning data is bounded by the LBL fixes while still having a high update rate from the DVL system. Now at these update rates the XY navigation problem can be solved using closed-loop control, which gives a much better accuracy in the resulting AUV motion. Instead of just knowing where the AUV is at a given time, it can control where it goes and thus perform the survey in a much more efficient way. Figure 5-2 shows a comparison of the navigation accuracy when using just LBL vs. using LBL-DVL for navigation.

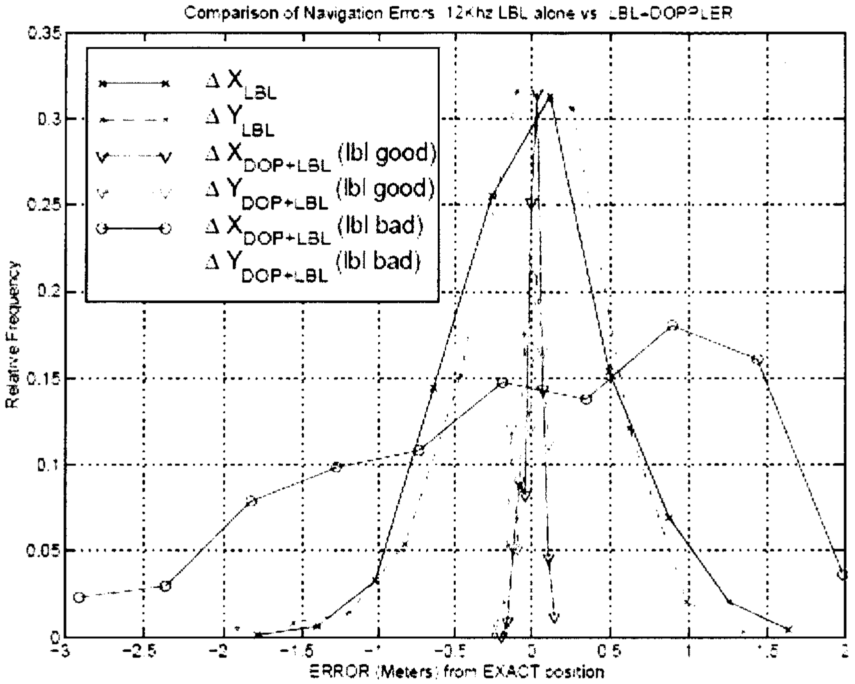


Figure 5-2: Comparison of LBL and LBL+DVL nav on Jason [75]

5.4 Ultra Short Baseline

An Ultra Short Baseline (USBL) system measures acoustic pings on transducer arrays. From the difference in the time of arrival between the accurately calibrated transducers, it calculates the range and bearing of the submerged vehicle. In an AUV mounted configuration, the AUV can navigate off a surface mounted transponder which makes deployment very easy. The USBL systems can be used with a reasonable level of accuracy, but nowhere near to that of the LBL systems. Other disadvantages of the USBL system are that they need to be calibrated well to get a reasonable accuracy and the USBL system relies on data from other sensors like the gyro and depth sensor to get a reliable absolute positioning [69]. Though USBL systems are not very accurate on their own, they can be used along with dead reckoning to provide reasonably high accuracy [40]. Thus, we see that the USBL systems can be used for basic navigation of the AUV, but do not meet the requirements for the high accuracy needs of the surveying AUVs. Many surveying AUVs still use a ship-based USBL system like the TrackLink that is completely independent of the vehicle power and electronics to keep a track of the AUV underwater as a safety measure [4].

5.5 Communications

One of the reasons that AUVs exist is that wireless communication is extremely difficult underwater, thus making it difficult to control untethered vehicles underwater. In water the electromagnetic waves attenuate very quickly rendering radio waves useless for communication. Communication with the AUV can be useful to keep track of its mission, to be able to modify the mission on the fly, monitor some observations that the AUV is making etc. There are some tricks commonly used for communicating with AUVs, ex. Gliders that are deployed over long missions commonly surface periodically and communicate with the servers via satellite phones to report mission updates and download mission changes. But this is not a convenient option for most of the typical AUV missions.

The only reliable solution for communicating underwater is using the acoustic waves. Due to recent advances in technology there are a few off-the-shelf options available for acoustic modems like the WHOI micro-modem developed by the Acoustic Communications group at the Woods Hole Oceanographic Institution (WHOI) [31] and the acoustic modems developed by Link Quest [9]. Even in the most optimal situations these acoustic modems have a very limited data rate, ex. typical modems with modulating frequency in the range of 1-50 kHz provide peak data rates of up to 4800 bits/sec over tens of kilometers. At this data rate it is impossible to have any real-time control of the AUV. Such communication can just be used to relay essential information about the AUV back to the surface vessel or important mission changes to the AUV. As we will see in the next section, these modems can be used to send the ship's GPS coordinates to the AUV to use the ship as a LBL transponder for navigation [61].

5.6 Recent Advances in Navigation

A lot of work has been done in the field of underwater navigation recently. The traditional LBL setup requires transponders to be deployed in the area of interest which can be on the order of 5-10 kms. If the area to be surveyed is bigger than that, it means having to re-deploy the transponders and calibrating them, all of which translates into more ship time and thus costs. Leonard and his group at the Massachusetts Institute of Technology have been working with using autonomous surface crafts equipped with the WHOI micro-modem and GPS sensors to address these problems [23]. When the AUV queries the surface crafts, they respond with their GPS locations and using those along with the travel times and depth, the AUV can calculate it 3D coordinates.

Another problem with traditional LBL systems is that they are designed to be used with single vehicle deployment. As AUVs become more popular we would see multiple vehicles being deployed in the same area to perform different kinds of surveys which would need a more elaborate setup. Once again the acoustic modems can be used with interesting algorithms to be able to use multiple underwater vehicles at the same time and even use each of their respective pinging to get better navigation [12, 32]. Another interesting concept is to use successive ranges from a single transponder along with its dead reckoning data to create a 'Virtual Long Baseline' for navigation, thus reducing the ship time or creating a redundancy in the standard deployment .

Recently, Eustice et al. have successfully experimented with using the acoustic modem with a highly accurate clock and on board sensors to navigate accurately without any LBL transponders [30]. This setup uses the acoustic modem to send the ship navigation data time stamped with a synchronous clock to the AUV which can calculate its slant range and coupled with the dead reckoning information to navigate with high precision. Also, other methods include using dead reckoning sensors along with overlapping visual images as drift free measurements to constrain the errors in navigation, which yields a robust system over long deployments [28, 29]. One other trick to improve the navigation is to use the discrepancy in the bathymetry map created by the ships versus that created by the AUV to get rid of the low frequency drift in the dead reckoning measurements [27]. Also Roman shows that the bathymetric information coupled with dead reckoning navigation information can provide both better maps and much improved navigation accuracy [51]. These are a few of the recent developments in the underwater navigation; there are many more projects that involve creative solutions for improving navigation to the required accuracy.

6 Sensors

AUVs are platforms for surveying and measuring. Sensors are what make AUVs work and the reasons why AUVs are made. Some basic sensors like the depth, DVL, heading sensors etc are needed to navigate and control the AUV, while the other set of payload sensors like multibeam sonars, sidescan sonars, digital cameras etc. are the driving factor for AUV development. In this section we will see how the characteristics of such sensors governs the dynamics and hence the design of AUVs. Figure 6-1 depicts how a typical sensor setup on the SeaBED AUV interacts with its environment. Podder et al. have described in detail the various sensors used by the scientific community [50]. The basic navigational sensors are described in detail in chapter 5 above.

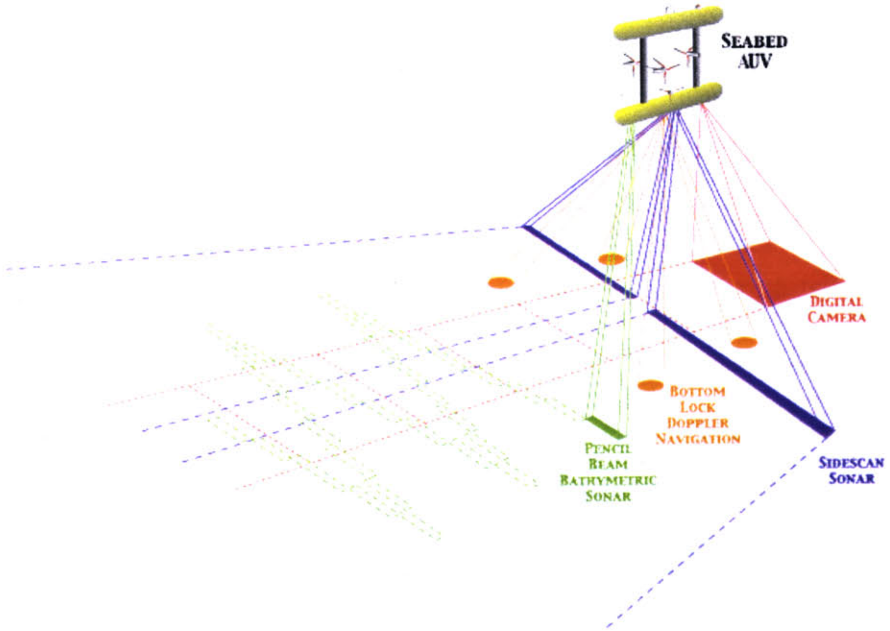

SEABED AUV
DIGITAL CAMERA
BOTTOM LOCK DOPPLER NAVIGATION
PENCIL BEAM BATHYMETRIC SONAR
SIDESCAN SONAR

Figure 6-1: Different types of sensors on a typical survey AUV [29]

6.1 Scalar Sensors

Scalar sensors refer to the types of basic sensors that make scalar measurements. Some examples of this kind of sensor include the depth sensor, salinity sensor, depth sounder etc. These sensors usually report the data measured from some transducer or other electromechanical device usually without much processing. They are important because they make water column measurements that are not possible from the surface vessel. They are generally very easy to use and can easily interface with the vehicle electronics using standard RS-232 links.

6.2 Vector Sensors

Vector Sensors refer to sensors that need position and orientation information to make sense of their measurements. Examples of this kind of sensors include the multibeam sonar, sidescan sonar, magneto meter etc. These sensors usually transmit data in a sequential manner and the interpretation of the data needs navigational information. Thus the quality of the data is highly dependent on the accuracy of navigational sensors on the AUV. Sensors like the multibeam and sidescan sonar send out acoustic pings and record the signal on an array of transducers [51]. This signal information needs to be preprocessed before it can be useful. Thus these sensors usually are more complex and power hungry compared to the scalar sensors. Though the multibeam and sidescan measurements can be made from the surface vessels, using higher powered and more sophisticated versions of these sensors, the resulting accuracy in the deep ocean is very limited because of the noise and acoustic attenuation. The AUV makes these measurements much closer to the seafloor and thus provides much better resolution and accuracy. The data provided by such sensors is more extensive and needs more intense communication links than a simple RS 232. Now, with the standardization of computers, these sensors can usually be linked using Ethernet connections.

6.3 Underwater Imaging

Visual surveys of the sea-floor bottom can provide scientists with high level of detail. In many cases using optical images is essential for studying archeological sites, analyzing airplane and shipwrecks, evaluating coral habitats etc. The rapid attenuation of light underwater and excessive back scatter limit the use of optical images to a few meters in a conducive environment, usually about 3-5 meters. Figure 6-2 shows the optical back-scatter from an underwater image [57]. Also, because of the high attenuation of light, there is almost no light below few meters from the surface so the underwater vehicle has to carry its own source of light. The matter is further complicated by the fact that the AUV is power limited and so the light source has to be very energy efficient. To conserve power, most AUVs use a strobe light to illuminate the floor. The practical problem with strobes is that you are limited by the frequency at which they can be fired. One solution to reduce the backscatter problem is to have a high separation between the light source and the camera. But this is not very easy to do on highly constrained small AUVs.

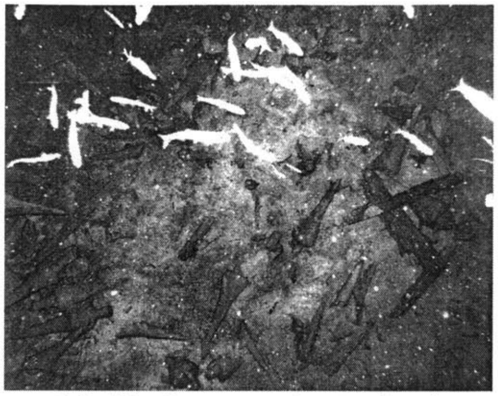


Figure 6-2: Underwater image backscatter

The characteristics of light underwater limit the area that can be captured in an image to about $10m^2$. This area can hardly provide useful information in most applications. It is very inconvenient to look at such small images and extract useful information out of them. This brings up the idea of photomosaics which involves stitching a large number of smaller images together to generate a bigger view of the scene. The basic idea methodology to make a photomosaic is to register features between overlapping images to find an orientation in which the images can be stitched together. This is much easier to do with images taken on land with ambient lighting. The poor lighting source carried on the AUVs make this a harder problem to solve. The typical strobe is not a uniform source of light making the image much brighter at the center than towards the edges. Hence, the features in consequent images appear in differently lit sections of the pictures, making registration harder. Thus, before using the images they need to be corrected for brightness, typically using a radiometric correction as described in [49].

Another issue with underwater imaging is that water doesn't absorb light uniformly. In water the low energy frequencies are absorbed more than the high frequencies in a non-linear manner, thus the resulting underwater images look bluish-green. In order to make the images more conducive to the human eyes, they also need to be corrected for the colors. These images taken underwater tend to be of a low contrast, and the standard 8-bit are often times insufficient to provide high quality images. To extract more information, often times higher dynamic range (12-16bit) Charge Coupled Device (CCD) Cameras are used. After applying the corrections for color and brightness, the images are ready for photomosaicing. Figure 6-3 shows an underwater image of a shipwreck before and after color-correction. There is some ongoing effort at the Deep Submergence Lab (DSL) of WHOI to improve the lighting source. Custom built LED arrays can be used to provide uniform lighting by varying the geometry of the LEDs on the array. These arrays can also be built using multiple colored LEDs to overcome the non-uniform frequency based attenuation. Also these LED arrays would have the added advantage of power efficiency over the conventional strobes and they would also be capable of firing at a much faster rate, making it possible to survey at higher speeds.

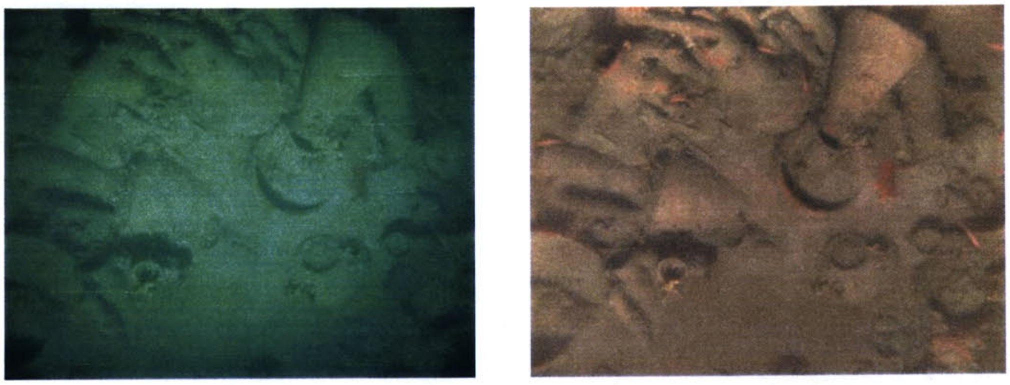


Figure 6-3: Raw underwater image and color corrected image

The next step in the photomosaic process is to register features between consecutive images. In order to do this successfully there needs to be a significant overlap between the images, about 30 percent for black and white images and 50 percent for colored images; a discussion of how this affects the AUV design is presented in chapter 3. Figure 6-4 shows connective images taken from ABE at the Chios shipwreck site.

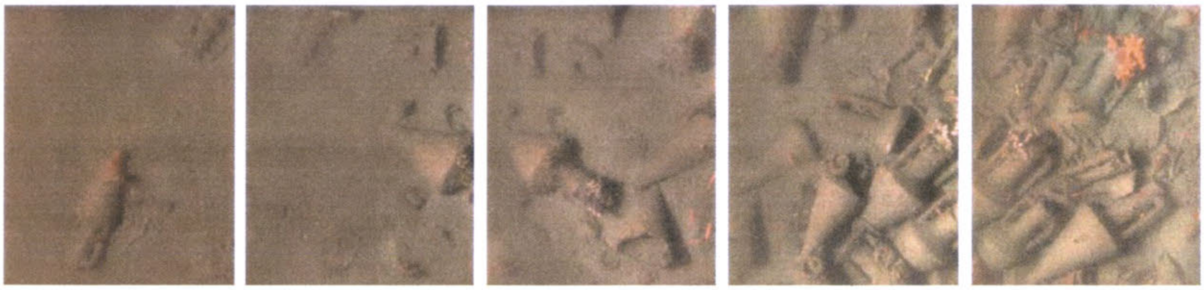


Figure 6-4: Consecutive Images collected by the AUV

The images taken on the AUV are usually taken in a lawn mowing with significant overlap between successive images and reasonable overlap between neighboring track lines. The images are first assembled into long strips from each leg using image registration tricks [57]. Though having navigational information of the images can improve the quality of the mosaic, this is not necessary as the images themselves are a zero-drift measurement. This property can actually be used to enhance the navigation accuracy of the AUV [29]. For the next step the photomosaic is assembled from neighboring images using similar image registration methods.

shows a photomosaic assembled from hundreds of images.

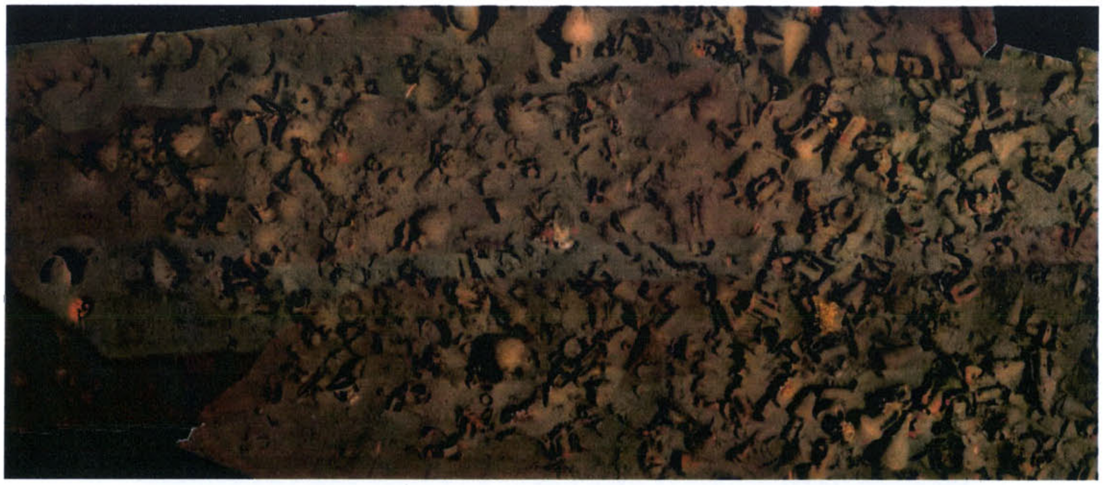


Figure 6-5: Photo-mosaic of a 4th century B.C. wreck at Chios

The assembled photomosaic presents a coherent picture of the site making it possible to perform quantitative and qualitative analyses. The above described method works relatively well in an area with a relative flat geometry with a lot of features which is characteristic of most areas of interest underwater. In order to visualize areas that have a lot of height variability like a large shipwreck, these methods fail since the same features may look very different in different images making it difficult to construct a coherent photomosaic. Pizarro et al. have done some work to solve this problem using algorithms for 3D image reconstruction which generates a 3D view of the site which can be projected to a 2D image [48].

6.4 Adaptive Sampling

Until recently most AUV missions have involved well defined paths for the AUV to follow in a prescribed fashion. As the AUV technology develops further the vehicles can be employed in a more autonomous fashion. One of the major undertakings is the problem of finding hydrothermal vents under the arctic ice using AUVs. Typically these vents are characterized by change in chemical composition, rise in temperatures, change in the optical back scatter etc. One critical sensor that would make this possible is the NEREUS mass spectrometer developed by Camilli at the Deep Submergence Lab of WHOI [21]. The NEREUS class mass spectrometer enables in-situ chemical sensing on the AUVs making it possible to detect very small changes in the chemical compositions.

The ideal way to approach the problem of finding these vents would be to have the AUV start by surveying a larger area O(10km^2) and note interesting conditions that might indicate the presence of hydrothermal vents. Once the larger survey is done, the AUV would fly to the site of interest and perform another smaller scale survey O(1km^2) and again note peaks in sensor data. After such a survey is done, go back for a much finer optical or multibeam survey O(100m^2). This is what is referred to as adaptive sampling. Even though this method seems simple, it involves a lot of development. One issue that needs to be solved is that the sensor data is often unreliable and can get false outliers; though humans can easily interpret this data, having an AUV autonomously filter it might be tricky. Another issue is autonomously deciding the sites of interest. The AUV has multiple sensors which generate an array of measurements that could indicate the presence of vents generating a multi-dimensional space; thus it is not just a problem of finding a peak but a more interesting point in a multi-dimensional space. There has been ongoing work at the DSL to overcome these issues which is summarized in [20].

6.5 Typical Sensor Suite on a Surveying AUV

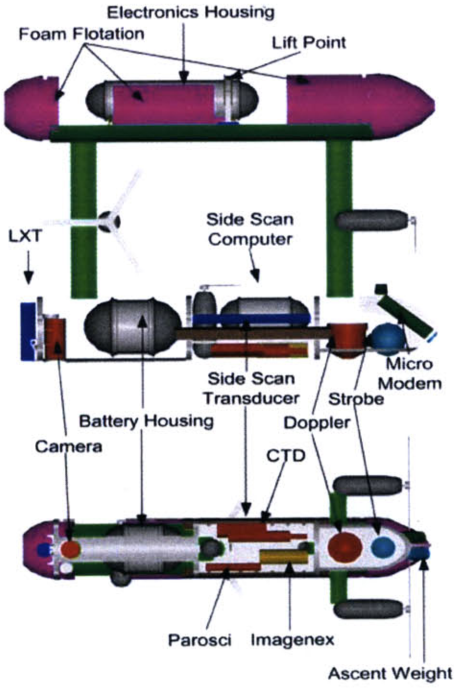

Electronics Housing
Foam Flotation
Lift Point
LXT
Side Scan Computer
Micro Modem
Side Scan Transducer
Strobe
Battery Housing
Doppler
Camera
CTD
Parosci
Imagenex
Ascent Weight

Figure 6-6: Sensor Suite on the SeaBED AUV

In order to understand a typical AUV sensor setup, we can look at the sensors on the SeaBED AUV.

Navigational Sensors: The first essential set of sensors is the navigational suite, which is standard to the AUV on all missions, required for its navigation and control.

- Optical encoders on the thrusters which provide propeller speeds.
- Paroscientific pressure sensor provides depth with 0.01 % accuracy
- WHOI Micromodem which provides LBL navigation and an acoustic link to the surface vessel
- 300 kHz RDI navigator - DVL -which provides altitude and translational velocities relative to the sea floor bottom
- IXSEA Octans - Fiber Optic Gyroscope which provides true north heading with a resolution of 0.01°
- TrackLink USBL Transponder

Payload Sensors: This set includes sensors that are more specific to the mission. The AUV can be loaded with the required set of sensors depending upon the science goal it is catering to. These are easily swappable as the connect to the main electronics using a standard RS 232 or Ethernet link.

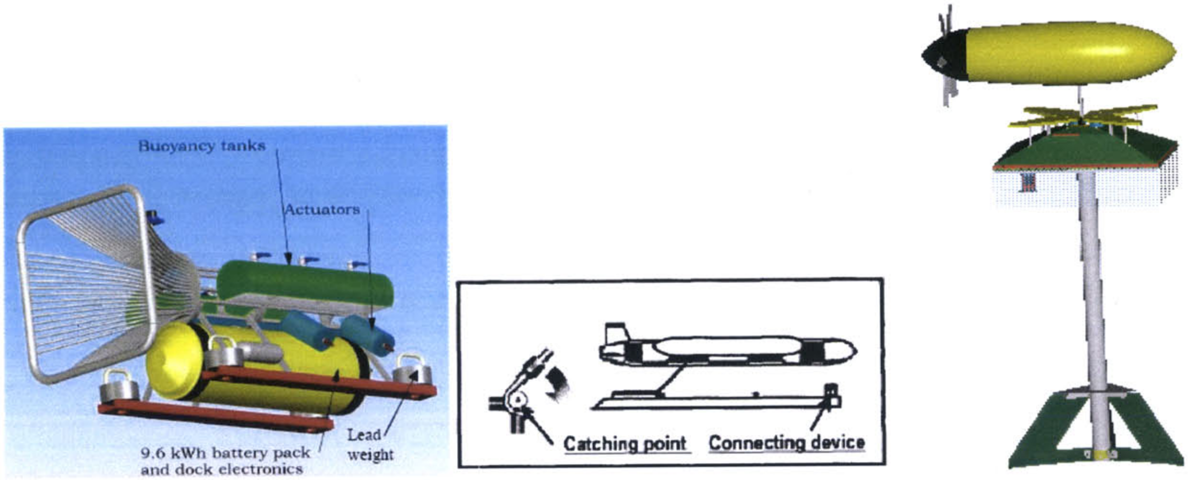
- MST 300kHz Sidescan
- Imagenex 675 kHz pencil beam Sonar
- Imagenex Delta T multi-beam Sonar
- Seabird CTD – conductivity, temperature, salinity
- Gemini Mass Spectrometer
- Prosilica GE 1.3 Mega pixel 12 bit digital camera
- EH Sensor
- Methane Sensor
- Fluorometer

- Optode Oxygen Sensor
- Optical Backscatter Sensor
- Magnetometer

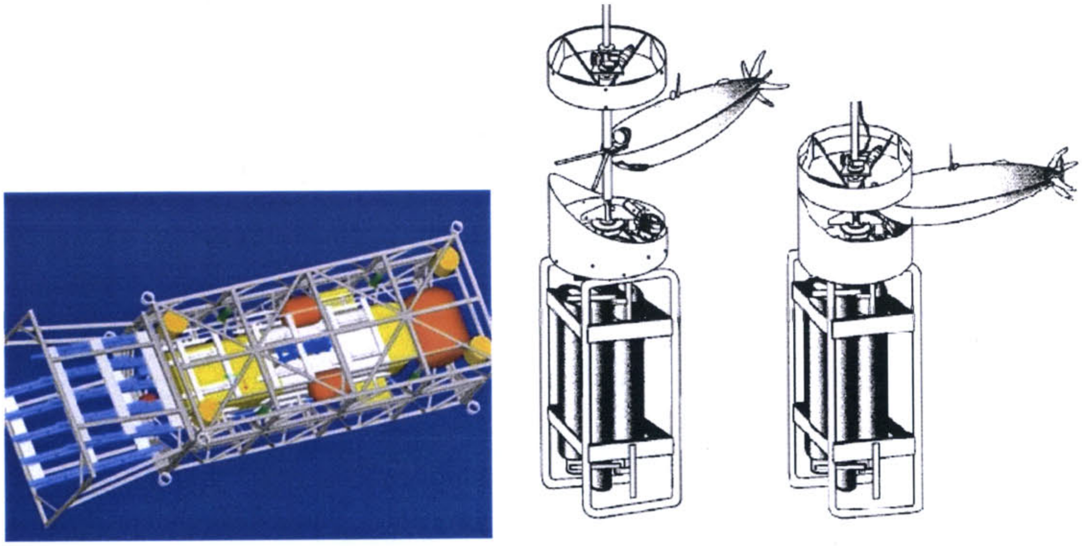
7 Docking Systems for AUVs

Now that AUVs have established themselves as successful platforms for oceanographic exploration, the next step is to exploit the advantages of the autonomous nature of these systems. This brings up the issue of long term deployment of AUVs over periods of weeks or even months. In a typical AUV mission the most expensive and tedious part is the deployment and recovery since it involves a lot of ship time, personnel costs and weather dependency. Leaving AUVs out in the areas of interest would enable us to bring these costs down, plus get good surveys in the most interesting environments like hurricanes when it is very difficult to deploy the AUVs. A lot of oceanographic surveys would benefit from such long term deployments eg. periodic benthic surveys of a potential tsunami site. Podder et al. have a very comprehensive list of science applications that can benefit from such long term deployments [50]. In order to make such long term deployments possible, we need to have some way of stowing the AUV when it is not on a mission and transferring power and data to and from the AUV. This section of the thesis will talk about various issues that would have to be considered for designing such a docking system for AUVs.

Quite a few of the AUV projects around the world have designed docking systems to go with their AUVs; a few of these have also had good repeatable success for their design. Notable among these are the WHOI-MIT-AOSN dock [15], EURO-DOCKER [17], REMUS dock [64, 65] and the Kawasaki Docking System [33]. All these systems have been quite successful and employ different ideas to deal with the problem of docking. A significant amount of work in this field was also done in the Autonomous Oceanographic Sampling Network project [24]. We will frequently refer to these as we discuss the various issues of the docking problem.


Buoyancy tanks
Actuators
Lead weight
9.6 kWh battery pack and dock electronics
Catching point
Connecting device

(a)REMUS docking system **(b) Marine Bird docking concept** **(c) FAU dock**



(d) Eurodocker **(e) MIT-AOSN Dock**

Figure 7-1: Docking Mechanisms

A next step in considering docking systems would be to identify all the requirements that a docking system would need to fulfill, which can be used to evaluate the design.

1. First and foremost the dock should be able to latch mechanically, electrically and computationally with the AUVs for physical storage, power transfer and data transfer.
2. The dock should have enough power and data storage to sustain deployment long enough to meet the science goals.
3. The dock must be able to communicate with remote scientists to enable quick mission changes to respond to nearby events.
4. The system must be able to adapt to near surface or benthic applications; especially in deep ocean this becomes important as the dive time of the AUVs can be in the order of hours. It would also be advantageous if the dock can be adopted to mount below ships, on towed sleds etc.
5. The station should be able to dock with various different kinds of AUVs. Also, as each type of AUV performs better at different scales, or might be outfitted with different kinds of sensors, the dock should be able to handle multiple AUVs.
6. Another basic requirement is that it should be able to withstand the natural biofouling in the adverse conditions of the ocean, this might be one of the biggest challenges of long term deployment.
7. Lastly, the use of the dock should require minimal modification on the existing AUVs, so that even the smaller AUVs can be efficiently used.

This should be our guide in designing an appropriate docking system for the AUV. The problem of docking can be broken down into a number of parts which can be approached quite independently.

7.1 Mechanical Locking

This refers to the issue of physically locking the AUV into place, preventing it from drifting. This in turn affects the options you can use for data and power transfer. So let's start by looking at a few different approaches.

7.1.1 Cone / Cage type dock

This refers to a type of system where the AUV gets completely enclosed into the dock. This can be seen in the Remus and Eurodocker systems [17, 65]. This method provides good physical protection for the AUV and leaves a lot of options open for power and data transfer. The possible problem with such an arrangement is that it tends to be more vulnerable to bio-fouling. Also, it is a uni-directional system, which means that the AUV would need precise navigation. There might be possible problems because of cross currents, but the dock can be made to always swivel around downstream, so that the AUV has more control while docking. The biggest issues with this setup would be the fact, it would not easily fit AUVs of different shapes, especially dual-hulled vehicles.

7.1.2 Bar Latch type dock

This refers to a mechanism involving a pole to which the AUV locks one degree of freedom following which another mechanism can constrain the AUV. This is seen in the WHO-MIT-AOSN dock for their Odyssey class AUVs [15]. This style of a system is simple and elegant. It lets the AUV have omni-directional approach, which means that the navigation on the AUV doesn't have to be too sophisticated. With a little modification this design would be able to accept various different types of AUVs. Also, it would be easy to use this near the surface or close to the floor. The only issue is that it imposes some design restrictions on the design of the AUV, in that it cannot have open thrusters that can be damaged during approach. If we can live with that, it is one of the more elegant designs.

7.1.3 Cable Latch type docks

This refers to the docks which involve latching a hook onto a cable like that on an aircraft carrier. The Kawasaki docking system and FAU-Morpheus docking system use this kind of a mechanism [33, 37]. Once again the success of this kind of system is more dependent on the navigating capacity of the AUV. If the dock is used in an area that has a lot of currents it would make it much harder for the AUVs to dock. Also, this kind of a design cannot be easily adapted for mid-water column and near surface application. Though, the design is elegant, it comes with limited applicability.

7.2 Power Transfer

For this discussion we will only discuss the AUVs that use rechargeable batteries, which is almost all the AUVs in the world. Given the smaller size of the AUVs, it has a limited power capacity and so we would like to have a setup where the dock has much more power storage to facilitate long term deployment. This power would have to be transferred to the AUV every once in a while. A discussion of the options that are available follows.

7.2.1 Inductive Methods

This refers to a noncontact method of power transfer where direct contact is not needed between two units. The nice thing about such a setup is that no conductor is exposed to the sea water which makes it more durable and less prone to failure. On the other hand efficiency of the power transfer is very sensitive to the alignment of the cores. Even though, less efficient power transfer might be possible with slightly misaligned cores, it still affects the reliability of the system.

7.2.2 Direct Methods

The other option is to have a system that basically aligns conductors to establish contact between the dock and the AUV. Such a setup would require a complicated design to insulate the conducting surface from the sea-water. Once again the alignment would have to be accurate to ensure power transfer, but misalignments might be easier to detect in this case. Finally, typical direct conductor systems would be vulnerable to bio-fouling.

7.3 Data Transfer

Almost all of the AUVs, especially ones that would be used for long term deployment are surveying AUVs. Which means that they essentially drive around and collect data on their appropriate sensor suite. To make any use of the data, and because of the limited data storage on the AUV, this data has to be transferred to the docking station for storage or transmission. Here is a discussion of the various options available to us.

7.3.1 Inductive Methods

Refer to the section 7.2.1 for inductive power transfer above.

7.3.2 Direct Methods

Refer to the section 7.2.2 for direct power transfer above.

7.3.3 Optical Methods

This refers to systems that would use LED's and optical sensors to setup communication between the dock and the AUV. The elegance of these systems is that they require minimal additions to the AUV and can provide high data rates. For these systems the physical alignment is not as critical and they can even work over a short distance (order of centimeters). One of the issues is that the efficiency of communication is easily affected by the quality of water in the area. Also if some kind of optically opaque material is stuck between the sensors, it would render the system completely useless.

7.3.4 Electromagnetic Methods

Even though electromagnetic waves decay very quickly in water, they are transmitted fairly well over short distances. Thus the standard wireless communication methods can be adapted with a little modification to cater to these underwater applications. Such systems would require minimal setup on the AUV and make it possible to use existing off-the-shelf components and protocols. Quite a high rate of data transfer can be made possible by using these methods. The only constraint is that one needs to make sure that the sensors are in close proximity to each other and that there isn't too much electromagnetic noise in the area.

7.4 Homing Systems

Most AUVs designed to be used with docking stations can be expected to have reasonable navigation capabilities. Thus when the AUV goes out it can keep track of where the dock is in the general area, but as the missions get longer in terms of time and spatial range, the dead reckoning errors start to become significant and make it impossible for the AUV to return completely on its own. Thus the dock would need some kind of a homing system by which the AUV can find its way back and perform the docking task. The following is a list of the more popular ways to home AUVs to the dock.

7.4.1 Acoustic Methods

This set of method includes systems that use acoustic waves to calculate the one way travel times and get navigation information from that. Acoustics can be used many different ways, but the more common ones are the long base line (LBL) and the ultra short base line (USBL) systems. The LBL system is more accurate and can also be used for navigation in the surrounding area, but needs a little more setup and convenient geometry. The USBL system on the other hand is easier to setup but you compromise on the accuracy when away from the dock. Given that acoustic waves travel the furthest, underwater, these systems can operate over quite a long range. The drawbacks in these systems come from limited update rates because of the fact that the acoustic characteristics of the water column can cause delayed pings, false bounces etc so the channels need to be clear of acoustic noise before sending the next signal. Another issue with these systems is that once you are too close to the dock, the travel time of the sound decreases, increasing the error in the navigation.

7.4.2 Optical Methods

This refers to systems that use some kind of flashing beacons or optical imagery to home in to the docks. When they are working correctly, such systems can provide a very high update rate and home in quite accurately. But since the visible light attenuates quickly underwater, these systems have very limited range. Also the system would be dependent on the quality of water on a given day affecting its reliability.

7.4.3 Electromagnetic Methods

These are methods that would use inductive electromagnetic properties to bring home the AUV. These systems provide a high update rate and are quite robust under most oceanic conditions. These systems can home accurately even when close to the dock. Some of the issues with this system include the fact that it is bulky and that the system is sensitive to magnetic anomalies in the area or quick salinity changes.

After studying these methods we can see that a much more efficient system can be easily composed by coupling two of these systems together. If we used a USBL system to get into visible range of the dock and then a flashing beacon to home in the rest of the way, we can come up with a well-rounded system.

7.5 Universal Docking Problem

We have seen that various kinds of applications call for drastically different designs of AUVs. In the future we can expect science missions to use different types of AUVs working together to completely satisfy the goals. In such a scenario it would be inconvenient to have different docks for the various AUVs. This calls for the design of a Universal Docking station that can lock multiple AUVs of different sizes, shapes and capacities. Singh et al. at the Applied Ocean Physics and Engineering Department at WHOI have been working to solve this problem [56]. Their conceptual design is illustrated in the following figures.

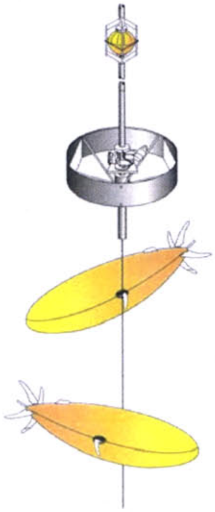


Figure 7-2: An artist's rendering of a universal docking concept

The Figure 7-2 shows a simple universal docking mechanism. The idea is that an AUV would approach the cable and latch onto it, thus constraining one degree of motion. It would then be able to spiral up the wire with its own propulsion and lock into place to make the power and data connections. Figure 7-3 demonstrates how this design can be used to accommodate AUVs of varying sizes by appropriately placing the power/data connectors on the AUV.

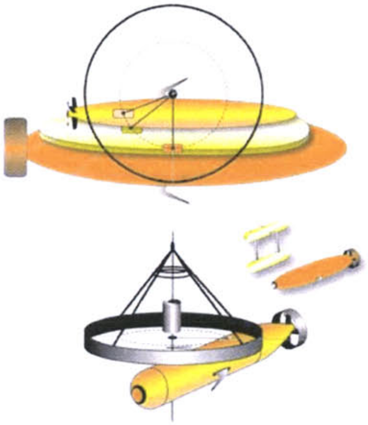


Figure 7-3: Universal dock accommodating different types of AUVs

The above design also has other advantages in that it can be setup on the sea floor or suspended from a buoy at the surface. Since it does not have a preferred orientation, the vehicle can approach the dock from any direction depending on the currents, making the control system on the vehicle side easier. Also the setup can be modified to accommodate multiple AUVs on the same dock, making it much more convenient. This design is undergoing further review and development.

8 Conclusion

This thesis has summarized the major issues that go into designing AUVs. As with any design problem, there is no one correct answer for the most optimal design. The best AUV for one application may be completely useless for another. The design for each AUV has to be customized to the application for which it is intended. Also, as technology progresses, the design of the AUV would have to change to adapt to it. As we get better higher resolution sensors and cameras the AUVs can become faster. As better power sources become available, the size of the AUVs can become smaller, the range of the AUVs can improve, and they can carry better high-power sensors. Development for the materials would again lead to smaller and lighter vehicles. As these components of the AUVs change, the optimal design for the AUV would change. Thus getting the most out of an AUV that is on the cutting edge of technology will always be a challenge, and hopefully, the issues discussed in this paper can help with this challenge.

References

1. *ABE/ Sentry*. [cited 2007; Woods Hole Oceanographic Institution]. Available from: http://www.whoi.edu/page.do?pid=8458.
2. *Cool LiteRunner 2*. [cited 2007; Lippert]. Available from: http://www.lippert-at.com/index.php?id=378.
3. *Human Occupied Vehicle Alvin*. [cited 2007; Woods Hole Oceanographic Institution]. Available from: http://www.whoi.edu/page.do?pid=8422.
4. *Integrated USBL Acoustic Tracking and Communication Systems*. [cited 2007; LinkQuest Inc.]. Available from: http://www.link-quest.com/html/intro2.htm.
5. *Iver AUV*. [cited 2007; Ocean Server]. Available from: http://www.iver-auv.com/.
6. *Jaguar*. [cited 2007; Woods Hole Oceanographic Institution]. Available from: http://www.whoi.edu/page.do?pid=11397.
7. *OceanServer Standard Lithium Ion Smart Packs*. [cited 2007; OceanServer]. Available from: http://www.ocean-server.com/battery_packs.html.
8. *Standard Buoyancy Foams*. [cited 2007; Syntech Materials Inc.]. Available from: http://www.syntechmaterials.com/standard.nxg.
9. *Underwater Acoustic Modems*. [cited 2007; LinkQuest Inc.]. Available from: http://www.link-quest.com/html/intro1.htm.
10. *Workhorse Navigator Doppler Velocity Log*. 2007 [cited; R. D. Instruements]. Available from: http://www.rdinstruments.com/navigator.html.
11. Allen, B., et al. *REMUS: a small, low cost AUV; system description, field trials and performance results*. 1997, p.994-1000 vol.2.
12. Baccou, P., et al. *Cooperative positioning and navigation for multiple AUV operations*. in *MTS/IEEE Conference and Exhibition OCEANS*. 2001, p.1816-1821.
13. Beebe, W., *Half Mile Down*. 1934: Duell, Sloane and Pearce.
14. Bellingham, J.G. and J.J. Leonard, *Task Configuration with Layered Control*, in *Autonomous Underwater Vehicles Laboratory Report MITSG*. 1994, MIT Sea Grant College Program: The MIT Press, Cambridge, MA,. p. 94-245.
15. Bowen, M.F. and D.B. Peters, *A Deep Sea Docking Station for Odyssey Class Autonoumous Underwater Vehicles*, in *WHOI-98-11*. June, 1998, Woods Hole Oceanographic Institution: Woods Hole, MA.
16. Bradley, A.M., et al., *Power systems for autonomous underwater vehicles*. Oceanic Engineering, IEEE Journal of, 2001. **26**(4): p. 526-538.
17. Brighenti, A., et al. *EURODOCKER-a universal docking-downloading recharging system for AUVs: conceptual design results*. 1998, p.1463-1467 vol.3.
18. Brooks, R.A. *A Robust Layered Control System For A Mobile Robot*. in *IEEE Journal Of Robotics And Automation*. 1986, p.14-23.

19. Byrnes, R.B., et al. *An experimental comparison of hierarchical and subsumption software architectures for control of an autonomous underwater vehicle.* in *Symposium on Autonomous Underwater Vehicle Technology.* 1992, p.135-141.
20. Camilli, R., et al. *Integrating in-situ chemical sampling with AUV control systems.* in *MTS/IEEE OCEANS.* 2004, p.101-109.
21. Camilli, R. and H.F. Hemond, *NEREUS/Kemonaut a mobile autonomous underwater mass spectrometer.* Trends in Analytical Chemistry, 2004. **4**(23): p. 307-313.
22. Collar, P.G. and S.D. McPhail, *Autosub: an autonomous unmanned submersible for ocean data collection.* Electronics & Communication Engineering Journal, 1995. **7**(3): p. 105-114.
23. Curcio, J., et al. *Experiments in moving baseline navigation using autonomous surface craft.* in *Proceedings of MTS/IEEE OCEANS.* 2005, p.730-735.
24. Curtin, T.B., et al., *Autonomous Ocenographic Sampling Networks.* Oceanography, 1993. **6**(3): p. 86-94.
25. Dexter, S.C., *Handbook of Oceanographic Engineering Materials.* 1979, New York: John Wiley & Sons, Inc.
26. Eriksen, C.C., et al., *Seaglider: a long-range autonomous underwater vehicle for oceanographic research.* Oceanic Engineering, IEEE Journal of, 2001. **26**(4): p. 424-436.
27. Eustice, R., R. Camilli, and H. Singh. *Towards bathymetry-optimized Doppler re-navigation for AUVs.* 2005, p.1430-1436 Vol. 2.
28. Eustice, R., O. Pizarro, and H. Singh. *Visually augmented navigation in an unstructured environment using a delayed state history.* in *International Conference on Robotics and Automation.* 2004, p.25-32.
29. Eustice, R.M., *Large-Area Visually Augmented Navigaiion for Autonomous Underwater Vehicles*, in *Mechanical Engineering.* 2005, Massachusetts Institute of Technology & Woods Hole Oceanographic Institution: Woods Hole, MA.
30. Eustice, R.M., et al. *Recent Advances in Synchronous-Clock One-Way-Travel-Time Acoustic Navigation.* 2006, p.1-6.
31. Freitag, L., et al. *The WHOI micro-modem: an acoustic communications and navigation system for multiple platforms.* 2005, p.1086-1092 Vol. 2.
32. Freitag, L., et al. *Integrated acoustic communication and navigation for multiple UUVs.* in *MTS/IEEE Conference and Exhibition OCEANS.* 2001, p.2065-2070 vol.4.
33. Fukasawa, T., et al. *"MARINE BIRD", a new experimental AUV with underwater docking and recharging system.* 2003, p.2195-2200 Vol.4.
34. Hyakudome, T., et al. *Key technologies for AUV "URASHIMA".* in *MTS/IEEE OCEANS.* 2002, p.162-166.
35. Jakuba, M.V., *Modeling and Control of an Autonomous Underwater Vehicle with Combined Foil/Thruster Actuators.* 2003, Massachusetts Institute of Technology: Cambridge, MA.
36. Kinsey, J. and L.L. Whitcomb. *Preliminary Field Experience with the DVLNAV Integrated Navigation System for Manned and Unmanned Submersibles. In: .* in

Proceedings of the 1st IFAC Workshop on Guidance and Control of Underwater Vehicles, GCUV '03,. 2003, p.83–88. Newport, South Wales, UK.

37. Lambiotte, J.C., et al. *Results from mechanical docking tests of a Morpheus class AUV with a dock designed for an OEX class AUV.* 2002, p.260-265 vol.1.
38. Leonard, J.J., et al., *Autonomous Underwater Vehicle Navigation*, in *IEEE ICRA Workshop on Navigation of Outdoor Autonomous Vehicles.* 1998: Leuven, Belgium.
39. Linden, D., *Handbook of Batteries.* 1994, New York: McGraw-Hill Inc.
40. Mandt, M., K. Gade, and B. Jalving. *Integrating DGPS-USBL positioning measurements with inertial navigation in the HUGIN 3000 AUV.* in *8th Saint Petersburg International Conference on Integrated Navigation Systems.* 2001.Saint Petersburg, Russia.
41. Martin, S.C., et al. *A Mission Controller for High Level Control of Autonomous and Semi-Autonomous Underwater Vehicles.* in *OCEANS.* 2006, p.1-6.
42. McPhail, S.D. and M. Pebody. *Autosub-1. A distributed approach to navigation and control of an autonomous underwater vehicle.* in *Seventh International Conference on Electronic Engineering in Oceanography.* 1997, p.16-22.
43. Mindell, D.A., et al. *JasonTalk: A standard ROV vehicle control system.* in *Proceedings of IEEE/MTS OCEANS.* 1993, p.253-258.Victoria, BC, Canada.
44. Moltz, J.C. *Global Submarine Proliferation: Emerging Trends and Problems.* 2006 [cited 2007; Monterey Institute of International Studies]. Available from: http://www.nti.org/e_research/e3_74.html#fn31.
45. Newman, P., *MOOS - A Mission Oriented Operating Suite*, in *Department of Ocean Engieneering.* 2002, Massachusetts Institute of Technology, Tech. Rep.
46. Nichols, N., *What It Takes To Upgrade The SeaBED AUV Depth Capability.* 2002, WHOI: Woods Hole, MA.
47. Perrett, J.R. and M. Pebody. *Autosub-1. Implicatons of using distributed system architectures in AUV development.* in *Seventh International Conference on Electronic Engineering in Oceanography.* 1997, p.9-15.
48. Pizarro, O., R. Eustice, and H. Singh. *Large area 3D reconstructions from underwater surveys.* in *MTS/IEEE OCEANS.* 2004, p.678-687.
49. Pizarro, O. and H. Singh, *Toward large-area mosaicing for underwater scientific applications.* Oceanic Engineering, IEEE Journal of, 2003. **28**(4): p. 651-672.
50. Podder, T., M. Sibenac, and J. Bellingham. *AUV docking system for sustainable science missions.* 2004, p.4478-4484 Vol.5.
51. Roman, C., *Self Consistent Bathymetric Mapping from Robotic Vehicles in the Deep Ocean*, in *Mechanical Engineering*, Massachusetts Institute of Technology & Woods Hole Oceanographic Institution: Woods Hole, MA.
52. Roman, C., et al. *A new autonomous underwater vehicle for imaging research.* in *MTS/IEEE OCEANS.* 2000, p.153-156.
53. Romeo, J. and G. Lester, *Navigation is Key to AUV Missions.* Sea Technology, 2001. **42**(12): p. 24-29.

54. Scamans, G.M., et al. *Aluminum fuel cell power sources for long range unmanned underwater vehicles.* in *Symposium on Autonomous Underwater Vehicle Technology.* 1994, p.179-186.
55. Sherman, J., et al., *The autonomous underwater glider "Spray".* Oceanic Engineering, IEEE Journal of, 2001. **26**(4): p. 437-446.
56. Singh, H. *A Universal Docking Mechanism for Multiple AUVs With Differing Geometries.* in *American Geophysical Union, Fall Meeting.* 2004.
57. Singh, H., et al., *Imaging Underwater for Archaeology.* Journal of Field Archaeology, 2000. **27**(3): p. 319-328.
58. Singh, H., et al., *Imaging Coral I: Imaging Coral Habitats with the SeaBED AUV.* Subsurface Sensing Technologies and Applications, 2004. **5**(1): p. 25-42.
59. Singh, H., D. Yoerger, and A. Bradley. *Issues in AUV design and deployment for oceanographic research.* in *IEEE International Conference on Robotics and Automation.* 1997, p.1857-1862.
60. Singh, H., et al. *Sonar mapping with the autonomous benthic explorer (ABE).* in *9th Int. Symp. Unmanned Untethered Submersible Technology.* 1995.Durham, NH.
61. Singh, S., et al. *Underwater Acoustic Navigation with the WHOI Micro-Modem.* in *OCEANS 2006.* 2006, p.1-4.
62. Smith, S.M. *An Approach to Intelligent Distributed Control for Autonomous Underwater Vehicles.* in *Proceedings of the 1994 Symposium on Autonomous Underwater Vehicle Technology.* 1994, p.105-111.Cambridge, MA.
63. Smith, S.M., et al., *The Morpheus ultramodular autonomous underwater vehicle.* Oceanic Engineering, IEEE Journal of, 2001. **26**(4): p. 453-465.
64. Stokey, R., et al., *Enabling technologies for REMUS docking: an integral component of an autonomous ocean-sampling network.* Oceanic Engineering, IEEE Journal of, 2001. **26**(4): p. 487-497.
65. Stokey, R., et al. *A docking system for REMUS, an autonomous underwater vehicle.* 1997, p.1132-1136 vol.2.
66. Tamura, K., et al. *The development of the AUV-Urashima.* in *MTS/IEEE Conference and Exhibition OCEANS.* 2000, p.139-146 vol.1.
67. Ura, T. and T. Obara. *Twelve hour operation of cruising type AUV 'R-One Robot' equipped with a closed cycle diesel engine system.* in *MTS/IEEE OCEANS.* 1999, p.1188-1193.
68. Valavanis, K.P., et al., *Control architectures for autonomous underwater vehicles.* Control Systems Magazine, IEEE, 1997. **17**(6): p. 48-64.
69. Vickery, K. *Acoustic positioning systems. A practical overview of current systems.* in *Workshop on Autonomous Underwater Vehicles.* 1998, p.5-17.
70. Walsh, D. *Air-Independent Propulsion: An Idea Whose Time Has Come?* [cited 2007; Navy League]. Available from: http://www.navyleague.org/seapower/aip_alternative.htm.
71. Webb, D.C., P.J. Simonetti, and C.P. Jones, *SLOCUM: an underwater glider propelled by environmental energy.* Oceanic Engineering, IEEE Journal of, 2001. **26**(4): p. 447-452.

72. Whitcomb, L., D. Yoerger, and H. Singh. *Advances in Doppler-based navigation of underwater robotic vehicles.* in *IEEE International Conference on Robotics and Automation.* 1999, p.399-406.

73. Whitcomb, L.L. *Underwater robotics: out of the research laboratory and into the field.* in *IEEE International Conference on Robotics and Automation.* 2000, p.709-716.

74. Whitcomb, L.L., D.R. Yoerger, and H. Singh, *Combined Doppler/LBL Based Navigation of Underwater Vehicles*, in *Proc. Int. Symp. on Unmanned Untethered Submersible Technology.* 1999.

75. Whitcomb, L.L., et al. *Towards Precision Robotic Maneuvering, Survey, and Manipulation in Unstructured Undersea Environments.* in *Robotics Research - The Eighth International Symposium.* 1998.Springer-Verlag, London.

76. White, D.G., *Autonomous Undersea Vehicles Part 1: The Test Bed AUVs.* Ocean News and Technology, 1999. **July/August**: p. 30-32.

77. White, D.G., *Autonomous Undersea Vehicles Part 2: AUVs for Search and Survey.* Ocean News and Technology, 1999. **September/October**: p. 30-32.

78. Whitman, E.C. *Air-Independent Propulsion: AIP Technology Creates a New Undersea Threat.* [cited 2007; Undersea Warfare]. Available from: http://www.chinfo.navy.mil/navpalib/cno/n87/usw/issue_13/propulsion.htm.

79. Wilson, R.A. and J.W. Bales. *Development and Experience of a Practical, Pressure-Tolerant, Lithium Battery for Underwater Use.* in *OCEANS 2006.* 2006, p.1-5.

80. Yoerger, D.R., A.M. Bradley, and B. Walden. *System Testing of the Autonomous Benthic Explorer.* in *Proceedings of the IARP 2nd Workshop on: Mobile Robots for Subsea Environments.* 1994, p.159-170.

81. Yoerger, D.R., A.M. Bradley, and B.B. Walden, *The Autonomous Benthic Explorer.* Unmanned Systems, 1991. **9**(2): p. 17-23.

82. Yoerger, D.R., A.M. Bradley, and B.B. Walden, *Autonomous Benthic Explorer, Deep Ocean Scientific AUV for Seafloor Exploration: Untethered, On Station One Year Without Support Ship*, in *Sea Technology.* 1992. p. 50-54.

83. Yuh, J., *Design and Control of Autonomous Underwater Robots: A Survey.* Autonomous Robots. **8**: p. 7-24.