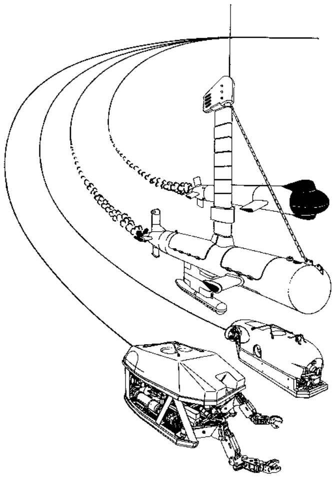

ISE WEB BASED AUV DESIGNINFO

EXPLORER

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TABLE OF CONTENTS

1 MEETING YOUR REQUIREMENT

In the development of an AUV, there is really only one requirement: ensuring that the AUV meets the needs of your mission.

As AUV technology matures, a large number of applications will be found for these vehicles – just as was the case with the ROV. Because the attributes of these missions will vary, a range of vehicles with different payload configurations, depth ratings and endurances will be needed. No single design – small, medium or large - will be capable of meeting these diverse requirements.

The key to meeting this range of requirements lies not in finding a universal design but rather in configuring modular vehicle designs from the bottom up. This calls for modular designs which permit rapid and economical reconfiguration of a vehicle for different applications, modular hardware which can be used through the range of small to large vehicles, and modular software which is easily configurable by the operator.

Our Explorer series of AUVs have been developed along these lines. While maintaining modularity as a design priority, we have also placed emphasis on power efficiency, weight reduction, reliability and safety.

In the following series of notes, the Explorer design approach is presented. ISE is registered to the ISO 9001 for AUV design, development and support and all of the design effort under the Explorer AUV is conducted to this standard.

2 SYSTEM DESIGN

The key issues that determine the characteristics of the AUV and guide the system design are:

What sensors or other hardware must the AUV carry as payload?
At what depth will the AUV operate?
At what speed will the AUV operate?
For how long will the AUV operate?

To a large extent, the payload sensor configuration determines how the vehicle is going to be operated. In the design of the vehicle, it dictates how items in the free flooding sections are arranged as well as the volume that must be allocated within pressure compartments (at atmospheric pressure) for associated equipment. Finally, the power consumed by the payload is an important factor in assessing energy requirements to complete the mission.

The depth rating of the vehicle determines the thickness and construction of the pressure compartments as well as the depth rating for underwater equipment which is placed outside these compartments. Depth rating has much to do with overall vehicle weight and vehicle size. As the depth rating increases, the proportion of vehicle weight that is allocated to structure increases, thus reducing the amount of weight which can be allocated to the energy source.

The total power demand is the sum of the payload power, the power to operate vehicle equipment and power required for propulsion. The minimum *energy* required on-board is the product of the average power consumption and the time it takes to complete the mission. The faster an AUV goes, the more propulsive power is required to overcome drag. On the other hand, the higher the speed, the less time it takes to complete the mission. There is always some optimum speed where the energy required is the lowest.

This optimum speed does not always correspond with what is most economical from an operator point of view. Faster mission completion times are generally desirable. In the QuickDesign© process we have assumed a mission speed of 2 metres per second (3.9 nautical miles per hour) which, in our experience, offers reasonable mission times but is typically less than the maximum speed at which the sensors are capable of collecting data. For each of the designs however, a graph is provided to determine the endurance at a variety of speeds.

With the payload, depth, range and speed requirements defined, there is enough information to produce a general configuration and layout of the vehicle. A second set of questions refines the size, weight and the power requirements of the AUV. These include:

What positional and navigational accuracy is required?
Is there a need for an obstacle avoidance sonar?
Are external communications needed?
What emergency and locator equipment is needed?

In order to keep the QuickDesign© process relatively straightforward, these factors are not treated as entry variables, but as options to the completed design.

In the following sections of this introduction to AUV design, we discuss briefly the following specific aspects:

- Payload Sensors
- Pressure Hull
- Hull Form
- Ballasting
- Propulsion
- Hydroplane Control
- Electric Power Distribution
- Energy
- Vehicle Control
- Navigation and Positioning
- Obstacle Avoidance
- Communications
- Locator and Emergency Equipment

3 PAYLOAD SENSORS

AUVs have many applications and consequently, the number of payloads which can potentially be carried is extensive. In this first version of QuickDesign©, we have offered some of today's more popular acoustic payload sensors. There are, however, many other acoustic and non acoustic payloads which span a range of applications from measuring water qualities to laying submarine cable.

The sensors featured in QuickDesign© are: the multibeam sonar, the sidescan sonar, and the sub-bottom profiler. Where any of these acoustic sensors are used in the AUV, we have also included a Conductivity Temperature and Depth (CTD) sensor as standard to the design.

The multibeam sonar, also known as a "swathe bathymetry sonar", is a hydrographic survey tool consisting of a Mills Cross transducer array that produces multiple across-track beams as the intersection of one transmit beam (fan shaped across the survey track) with numerous receive beams (each fan shaped along the track). This allows the sounder to provide continuous swath bathymetry over a 120° to 150° sector.

The multibeam sonar market has traditionally focused on shipboard systems and has been segmented on the basis of the water depth. Deep-water, high altitude systems utilise low acoustic frequencies (~12kHz) and have large, heavy transducer arrays to achieve the necessary range. Shallow-water, low-altitude systems can exploit the reduced acoustic range by increasing the operating frequency (~ 200 to 300 kHz) to increase the spatial resolution. At the same, the physical size and weight of the transducer arrays is reduced. The marriage of an AUV to low-altitude multi-beam sonar provides a seafloor survey capability that is unmatched.

In addition to better resolution there are two other significant advantages that accompany the AUV survey. The first is the ability to provide constant spatial resolution and swath width over the course of an entire survey through the use of bottom tracking. In the case of a shipboard system the swath width and footprints of the sonar beams varies as the water depth varies. In terms of resolution this means that not all regions can be surveyed with the same precision. With an AUV mounted sonar, however, the desired resolution can be chosen at the start of a survey on the basis of operating altitude and then sustained by maintaining a constant vehicle height along the survey path.

By maintaining constant vehicle altitude, the survey swath width also remains constant. For shipboard systems the swath width fluctuates with water depth and therefore complicates the task of selecting survey track spacing. The use of bottom-track or constant altitude with an AUV can substantially improve both survey efficiency and overall coverage.

A potential disadvantage of bottom-track in maintaining a constant altitude above the seafloor results from the vehicle pitching up and down to follow the terrain. ISE's AUV designs solve this problem through the use of both tail and forward hydroplanes which limit pitch, roll, and yaw to less than 1° at 1°/s angular rates. All survey are therefore actively motion compensated by the AUV itself during both fixed altitude and fixed depth survey modes.

Simrad SM2000 Multibeam Sonar

To be suitable for use in an AUV, the multibeam sonar array must be rated to the operating depth of the vehicle, and the system should be reasonably compact. Ideally, power consumption should be minimized and functions within the sounder which are not required in the AUV should not be powered. Several manufacturers have developed equipment along these lines. These include Kongsberg Simrad Ltd. of Norway (EM3000, EM2000); Kongsberg Simrad Mesotech Ltd. of Canada (SM2000); and Reson A/S of Denmark (Seabat ™ 8101).

With the exception of the EM3000, which is limited to 1500 metres, all of these sensors can be operated to depths of 6000 metres. Both the EM2000 and the SM2000 use the same wet end transducer array, and differ only in the dry end processing and the price. QuickDesign© offers the EM and SM2000, as well as the Reson Seabat 8101.

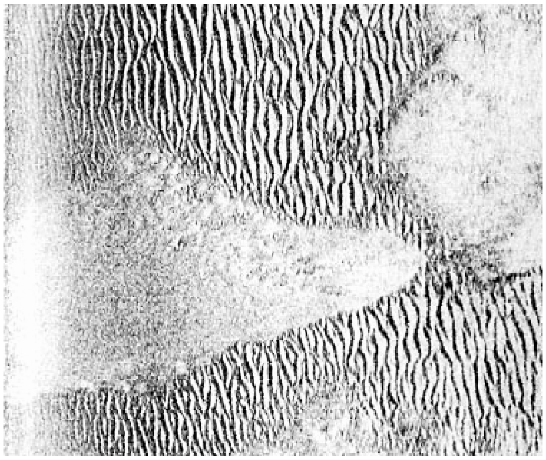
The Simrad multibeam sonars operate at a frequency of 200 kHz while the Reson Seabat ™ operates at 240 kHz. All units have a 120° to 150° swath coverage with 1.5° beam spacing. All have roughly the same weight, volume and power consumption, except that the Reson Seabat ™ wet end transducer is heavier than the Simrad unit. Generally speaking, the performance in terms of swath coverage will be roughly the same for all of these systems. The area coverage rate will be determined by the AUV's height off the bottom (altitude) and by its speed.

The multibeam sonar is comprised of a wet end and a dry end. The wet end consists of the transmit and receive transducer arrays together with any closely associated electronics. It is mounted within the flooded section of the AUV and an acoustic window is provided to contain them within the outer dimensions of the vehicle hull minimizing risk to the sensors during launch and recovery. The dry end, which is mounted inside the pressure hull, consists of the sonar processing electronics and any additional equipment required for sonar control and data logging

In operation the AUV controller monitors the sonar and provides navigation and motion sensing data for synchronous internal logging with the multi-beam data. This permits the system to integrate all data relevant to multi-beam/ post-processing directly into the sonar data files. The sonar also provides quality assurance ("check") and sub-sampled bathymetry data to the AUV controller for transmission to the surface over the acoustic communication link. In the event that sonar-operating parameters must be changed, the operator can do so on-the-fly from the surface.

After a survey mission has been completed, the logged sonar data is retrieved from the vehicle through a fast Ethernet link (100Mbits/s) that is accessible without opening the pressure hull. The data is downloaded to a post-processing computer where survey results are analyzed and images are generated. A variety of post-processing systems exists for this – one popular source being Triton Elics International Inc. who offer Bathy Pro™ and Delph Map®.

The side scan sonar is one of the most accurate sensors for imaging large areas of the ocean floor. The side scan sonar transmits beams of acoustic energy from the side of the towfish and across the seabed. For these reasons, it is normally towed from ships. Unlike a ship, the AUV can operate close to the seabed, and consequently, the sonar transducers are mounted on the hull rather than towed.



Imagery from a Klein Associates, Inc
500 kHz Side Scan Sonar

Typically, a side scan acoustic beam is very narrow in the horizontal dimension (~ .1 degree) and much wider (40-60 degrees) in the vertical dimension. The sonar transmits one pulse at a time and waits for the sound to be reflected back. The imaging range is determined by how long the sonar waits before transmitting the next acoustic pulse. The image is thus built up one line of data at a time.

The roughness of the floor of the ocean and any objects on it, reflect some of the incident sound energy back in the direction of the sonar. Hard objects which reflect the most energy produce a dark signal on the display, while soft objects that do not reflect energy as well show up lighter. The absence of reflected sound, such as in shadows behind objects, appears as white areas on a sonar image.

High frequencies on the order of 500 kHz provide excellent resolution but short ranges on the order of 125 metres. Lower frequencies in the 100kHz range have a greater swath ranges to 400 or 500 metres, but less resolution. In terms of AUV integration, the lower the frequency of the side scan sonar, the larger and heavier the array will be. Lower frequency systems will also draw more power as they ensonify a larger volume of water.

Five companies have, or are now in the process of developing side scan sonars for AUVs. These companies are Benthos, Inc. formerly Datasonics, EdgeTech Klein Associates, Inc, Marine Sonic Technology, Ltd and Sonatech, Inc, all of the USA. Of these, Klein and EdgeTech offer dual (low and high) frequency systems. Benthos offers only single, low frequency systems (100 and 200 kHz) and Marine Sonic offers several single, high frequency systems. QuickDesign© features the EdgeTech dual frequency system operating at 120 and 410 kHz, and the Marine Sonic Technology 600 kHz Sea Scan ® sonar

The components of the side scan sonar are the port and starboard sonar transducers and cabling, and the dry electronics including data logging equipment which is fitted within the pressure hull. Placement of the side scan transducers within the AUV hull is critical to data quality and is guided by several criteria. These criteria include minimizing the probability of acoustic interference from other sensors, and minimizing turbulent flow over the transducers. To that end, the side scan transducers are partially recessed into the vehicle hull, and are mounted forward of the control surfaces and away from other acoustic devices.

Marine Sonic Sea Scan®
600 kHz Transducers

Bottom following during side scan operation is a very important capability since the side scan swath width and image resolution on the seafloor can be approximately maintained if the vehicle altitude can be held constant. The hydroplanes are placed to provide minimal pitch angle during bottom following side scan imaging operations.

A final step taken to maximise data integrity is the synchronisation of acoustic transmissions from the sidescan sonar and other acoustic devices which come with the vehicle or which are subsequently added. All acoustic instruments will ideally include the capability for external ping triggering. In the case of the Marine Sonic sonar, this is not possible and consequently, the Sea Scan® sonar is set as the master and other transmissions are sequenced to it.

Operation of the side scan is controlled via an interface (such as RS232) to the AUV computer. Sonar data will available to the AUV computer over an Ethernet connection. During an AUV mission, data will be recorded in image data files on a hard drive or other storage device. The size of each file is determined by the side scan sonar data storage parameters. Again, a variety of post-processing software exists for developing images from the logged data such as ISIS® and Delph Map® from Triton Elics International, Inc.

EdgeTech 2-16 kHz Sub-Bottom Profiler

The sub-bottom profiler is a shallow geophysical sonar designed to provide higher resolution profiles below the seabed but with less penetration than lower frequency seismic equipment such as air guns and sparkers. Unlike these seismic devices which must tow separate hydrophone arrays for transmitting and receiving, the sub-bottom profiler is often self-contained in a single small towbody.

Because the resolution and the penetration of the sub-bottom profiler depend in its proximity to the seabed, sub-bottom profilers are often towed from surface ships. With the AUV, the same benefits can be obtained by mounting the equipment in the vehicle, rather than towing it.

Two types of sub-bottom profiler are manufactured. These are “chirp” and active (pulsed) continuous wave systems. Chirp sub-bottom profilers offer greater bottom penetration than continuous wave systems and are superior to seismic systems in terms of range resolution and reduced ensonification. For example, a chirp SBP mounted on an AUV can typically provide seafloor penetration of 5-100 metres, depending on bottom type, and a 10 cm range resolution while ensonifying an area less than 18 metres in diameter from an altitude of 50 metres.

Sub-bottom profiler images are made up of backscatter from the seafloor strata. The first boundary is at the seabed, between the water and the seafloor itself. As layers of clay, sand and various other sediments succeed each other, they reflect sound at their interfaces. It is this reflected energy that the system uses to build the image.

Chirp sub-bottom profilers operate by transmitting a long pulse swept over a wide frequency range. They then use digital signal processing to perform match filtering in the receiver. The long pulse and FM chirp combined with the match filtering provide increased receive signal power over conventional pulsed continuous wave systems and does not sacrifice range resolution. Thus the chirp systems offer high-resolution sub-bottom profiling and better seafloor penetration for a variety of bottom types.

Sub-bottom profilers have been normally manufactured for hull mounted or towfish deployment. Neither of these deployments requires special considerations for weight, power consumption, or data storage. In fact, towfish operations depend on a heavy sensor to maintain depth. Consequently, typical sub-bottom profilers are difficult to integrate into an AUV. However, manufacturers are beginning to develop sub-bottom profiler equipment that is more suited to the AUV application.

The chirp sub-bottom profiler market is primarily served by three manufacturers: EdgeTech, and Benthos, Inc. (formerly Datasonics) both of the US, as well as GeoAcoustics Ltd. of the UK. Of these, both EdgeTech and Datasonics offer systems designed for operation aboard an AUV to depths of 6000 metres. GeoAcoustics has systems available with depth ratings to 2000 metres. Recently, Klein Associates, Inc. of the US have also produced a sub-bottom profiler for AUV applications with a depth rating of up to 6000 metres. QuickDesign© features 2 sub-bottom profilers from EdgeTech, a 1 to 6 kHz system and a smaller 2 to 16 kHz system.

The chirp sub-bottom profiling sonar is installed on the AUV in two parts; a wet end and a dry end. The wet end consists of the transmit and receive transducer arrays and will be mounted within a flooded section of the AUV. The transducers must be located well away from any vehicle and sensor pressure housings. The dry end consists of the sub-bottom profiler's processing and data logging electronics which are mounted inside the AUV pressure hull.

During data collection, the AUV controls the SBP and ensures that the sonar data and vehicle motion sensor data are logged simultaneously with common time stamps. These transmissions can also be synchronized with multibeam and sidescan sonar in order to avoid acoustic interference between the devices. The sub-bottom profiler also provides sub-sampled output data to the AUV controller for transmission to the surface over the acoustic communication link. Although the communication link is not essential for survey operation, the sub-sampled data sent to the surface will allow an operator to confirm that the profiler is collecting useful data. It is also useful in the event that sonar-operating parameters must be changed; the operator will be able to do so on-the-fly from the surface.

After a survey mission has been completed, the logged data is retrieved through an externally accessible Ethernet port on the pressure hull. The recorded data is downloading to a post-processing and display computer. Post-processing in the topside computer may include integration with motion sensing and navigation data. TEI's Delph Seismic™ is an example of a package which will collect up to 24 channels of seismic data in standard SEG-Y format and then merge navigation and attitude data in post-processing.

Sea-Bird SBE 19 SEACAT CTD Probe

A **CTD Probe** measures conductivity, temperature, and depth of the water. A large number of seawater parameters including salinity, density, and sound velocity can be computed from CTD data. QuickDesign© provides the SBE 19 SEACAT CTD, manufactured by Sea-Bird Electronics Inc. of the USA as standard equipment with all configurations except vehicles with "No Payload". The SEACAT Profiler sensors consist of an internal-field, glass conductivity cell with platinum electrodes, an aged, pressure-protected thermistor temperature sensor; and a mechanical strain gauge pressure sensor with stainless steel or titanium elements depending on sensor range. Plastic, aluminum and titanium housings allow operations at depths to 10,000 metres.

Because the AUV speed is relatively slow and the CTD is contained within the AUVs free-flooding space, a Sea-Bird SBE 5T pump is provided to flush water through the conductivity cell. This improves dynamic accuracy.

4 Pressure Hull

The pressure to which the AUV is subjected is directly proportional to depth. At 300 metres below the surface, the pressure about 30 times atmospheric pressure. At 5000 metres, the pressure increases to over 490 atmospheres or 3.6 tons per square inch.

In all AUVs, some form of pressure hull must be provided for equipment that needs to work in a dry, atmospheric environment. This pressure hull must be weight-efficient and it must also contribute to the design of a vehicle hull form that is low drag. Packaging must also be considered. Internal items must be accessible, maintainable, and arranged so that the payload sensor operation is not compromised. Additionally, the internal distribution of the various subsystems must leave the vehicle in proper trim.

Finally, the hull must provide reliable and cost-effective service over its life. Since different sensors and a wide variety of missions can be envisioned for the future, the vehicles must also be designed with modularity in mind to accommodate growth in the form of new payloads, and larger or possibly alternative energy sources.

The depth rating of an AUV will strongly influence its the size and range. To go deeper, the pressure hull must be thicker and heavier, leaving less residual buoyancy to support batteries or payload. To increase battery or payload capacity, the pressure hull can be made larger so that it is more buoyant. However, the in-air weight increases as well. Selecting a deep-rated design tends to reduce range or payload capacity, and to increase size and weight. To maximize the battery capacity and range while carrying a given payload, the shallowest depth rating possible for the mission should be chosen.

Although, a spherical form provides the best structural efficiency, it is difficult to use the internal volume efficiently. Off-the-shelf electronics packages and batteries are rectangular in shape and fit better into cylinders. When several spheres are used together, the spaces left between them on the outside are difficult to utilize at all.

Hull Joint – ISE Theseus AUV

In the ISE Explorer vehicles, electronics and batteries are housed together in a cylindrical pressure hull made of modular sections with a hemispherical dome at each end to provide a good balance between structural, weight and packing efficiency. The pressure hull provides most of the buoyancy for the vehicle and all the necessary space for dry components. It is made up of a series of machined aluminum sections joined together at circumferential joints that incorporate the stiffening rings and o-ring seals. By splitting the hull at one or more of the joints and moving sections apart, it is easy to access the inside of the hull when required.

This configuration has a number of attractive features starting with a generous volumetric capacity. Cylinder sections are relatively inexpensive to manufacture. Since all of the dry components are housed in the same space, fewer underwater cables and connectors are required than in configurations where components are in separate housings. Modular pressure hull and free-flooding sections can be added or removed as required for payload and to vary the size of the battery.

The lighter hull is, the better, and consequently, stronger and lighter materials are preferable. However, they must also be corrosion resistant and cost effective. Currently, ISE uses high yield strength aluminum and titanium in the fabrication of its pressure hulls.

The use of ceramics as a pressure hull material in the future appears promising. The US Navy has been advancing this technology and has conducted extensive cyclic testing of 65-cm diameter alumina-ceramic pressure vessels to depths of 6000 metres. Development of larger diameter ceramic pressure hulls has started and the continuing development of ceramics should be monitored. We are also currently conducting research on the use of Boralyn TM, another alumina-ceramic, as an alternative.

5 Hull Form

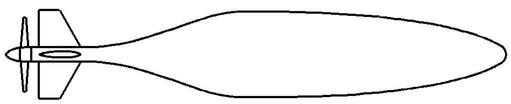
The hydrodynamic form of the AUV determines the propulsion energy required, as well as the stability and maneuverability at various operating speeds. A hull form may also impose limitations on vehicle access, launch and recovery, and maintenance.

The speed regime for the Explorer AUVs is between 1 and 2.5 metres per second. The hull lengths vary from 5 to 7 metres with diameters ranging from 0.46 to 1.14 metres. In most applications, the vehicle will maintain a steady speed throughout the mission. The following considerations drive the selection of the hull form:

- minimization of overall vehicle drag;

- minimization of flow separation , especially for efficient propulsion near the tail;
- stability as a sensor platform at 2 to 2.5 metres per second;
- stability and maneuverability at lower speeds on the order of 1 metre per second

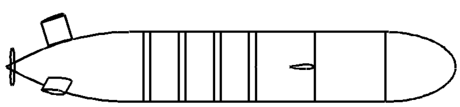
Skin friction and form drag contribute to overall vehicle drag. Friction drag varies with speed and the exposed surface area so smaller hulls with less surface area have less friction drag. Form drag is a function of the how well the hull shape minimizes flow separation. Longer, more slender shapes tend to be better in this respect. Test results show that streamlined forms with length to diameter ratios between 5 and 7 are best for minimizing drag.



Example of Laminar Flow Hull

From the simple perspective of drag reduction, a form which promotes laminar flow within the boundary layer is the best choice. The Carmichael hull, developed and tested by Dr. Bruce Carmichael of Rockwell International in the 1970's is a good example of such a hull form.In laminar flow, fluid particles move in laminae or layers. Skin friction drag is much lower than in a turbulent boundary layer where the fluid particles move more erratically resulting in higher shear stresses between layers and at the surface.

To sustain laminar flow, a hull is designed such that the diameter increases gradually from the nose to create a favorable pressure gradient over the forward 60-70% of the hull. In this area, the surface must be smooth and as hydrodynamically 'clean' as possible. Forward-mounted hydroplanes cannot be fitted as they could destabilize the laminar flow. Consequently, all hydroplanes are mounted on a tailboom. Acoustic payload, communication and navigation transducers must be located as far aft as possible so that the resulting openings or protuberances also do not disturb the laminar flow. Unfortunately, the unique shape of the laminar flow body does not readily permit lengthening (or shortening) the vehicle, thus limiting the possibility of modular expansion.



Torpedo Body of the Explorer Vehicle

A simpler alternative to the laminar flow form is commonly called the 'torpedo body'. The torpedo body has a nose cap followed by a parallel mid-section and a tapered tail section. As suggested by its name, it has been the form of choice for torpedo developers for over a century.

Since the torpedo body is not a laminar flow vehicle, drag can be expected to be approximately 30% greater than with the laminar flow hull. While lacking the hydrodynamic efficiency of the laminar flow hull, the torpedo body drag is relatively insensitive to manufacturing imperfections or damage that may occur. The packing density for payload and power source is also better in the torpedo hull than in the laminar flow body. Furthermore, the long parallel mid-section allows the vehicle length to be extended for future growth.

In a general sense, the hydrodynamic drag of the Explorer AUV will require approximately half of the total power requirement. Rather than try to reduce this component of the power requirement, ISE has chosen the torpedo hull form because of its advantages in other areas. These include:

- modularity;
- ease in launch and recovery;
- flexibility in the arrangement of wet end transducers; and
- low speed stability.

6 BALLASTING

For efficient operation, AUVs are generally designed to operate at neutral or near-neutral buoyancy and are ballasted such that the hull remains near horizontal when submerged. To achieve this, AUVs have fixed ballast consisting of lead and buoyant foam, which can be arranged to achieve the proper trim condition before the mission. As vehicle components or payload are changed for future missions, the trim lead and foam are adjusted accordingly. All Explorer AUV designs include such a fixed ballast arrangement with lead weights in the nose and tail.

During a typical mission, changes in ballast may be desired to aid in ascent or descent or to compensate for payload deployment. In some cases, salinity changes or compressibility effects additionally cause minor variations in displacement or weight. On-board variable ballast tanks are often used in conjunction with pumps or compressed air systems to fill and empty the tanks with water. However, at deep depths where pressures are high, pumps or compressed air systems become less practical because of their large size and their considerable power draw. The change in buoyancy between the surface and the maximum operating depth is minor and well within the control capabilities of the vehicle's hydroplanes

In addition to a fixed ballast system, the Explorer AUVs are equipped with an emergency drop weight system. If AUV propulsion or the control system fails, this weight is released to give the vehicle positive buoyancy to bring it rapidly to the surface. Before, the next mission the weight is replaced.

7 PROPULSION

When an AUV is moving at constant speed, the thrust produced by the propeller is equal to the drag of the vehicle. That is,

$$\text{Thrust} = \text{Drag} = \frac{1}{2}\rho V^2 A C_D$$

where:

ρ	= water density	A	= reference area (often the projected frontal area)
V	= speed	C_D	= drag coefficient (propelled)

The power required for propulsion is the product of thrust and speed. Since, by the above equation, thrust is proportional to the spee*d squared* (assuming that C_D remains more or less constant), power becomes proportional to speed *cubed*, that is,

$$\text{Thrust Power} = \text{Thrust} \times V = \frac{1}{2}\rho V^3 A C_D$$

Thrust power increases very quickly with speed. Doubling the speed requires eight times more power. However, our experience to date has been that cruising speeds of more than 2 m/s are not often required. The Explorer AUVs are designed for a nominal cruise speed of 2.0 m/s and a design maximum speed of 2.5 m/s. Greater speeds can be achieved if required at the expense of larger and heavier thruster components.

Because the amount of energy the AUV can carry on-board is limited, the efficiency of the propulsion system is critical to minimize the amount of electrical power consumed. The total efficiency is a function, not only of the propeller and its installation, but also of the electrical efficiency of the motor and associated mechanical losses from windage and friction in seals, bearings, and gearing.

For optimum efficiency, the Explorer AUVs are equipped with a single, two-bladed propeller mounted at the tail on the centerline. Propeller momentum theory establishes this as inherently more effective than two smaller thrusters used side-by-side.

ISE has had extensive experience with propulsion thrusters using brushless dc motors. Our thrusters are designed by integrating brushless dc motors from third party vendors into oil-filled pressure-compensated housings. To maximize reliability, electronics associated with the motor controller are located separately within the pressure hull rather than inside the motor housing. For the Explorer AUV, ISE has selected a direct drive thruster with no reduction gearing. This has resulted in a propulsion system that is light, efficient and acoustically quiet.

8 HYDROPLANE CONTROL

Most AUVs maneuver by means of deflecting control surfaces (hydroplanes), thrusters or a combination of both. On the Explorer AUVs, five independently actuated deflecting hydroplanes provide attitude control. Lateral or vertical thrusters are not normally used, as they are less effective when lengthy transits at a constant “cruise” speed are required and a low-speed hovering capability is not. If hovering is required as part of the mission, lateral or vertical thrusters can be integrated into the Explorer design.

On the Explorer AUVs, three hydroplanes are mounted in an inverted ‘Y’ configuration on the tail and two are mounted horizontally and forward on the hull. This arrangement provides independent control of pitch angle and depth unlike designs in which the hydroplanes are mounted on the tail only.

The vehicle computer uses the hydroplanes on the Explorer vehicle for the closed-loop control of heading, pitch, roll and depth. The control system is designed such that, in the event of a hydroplane failure, the remaining ones can be re-tasked to compensate and the mission can be completed. This fault tolerant design, proven on the *Theseus* and *ARCs* AUVs greatly enhances the overall reliability of the system.

The hydroplane actuators utilize brushless DC motors in oil-filled, pressure compensated housings. Both the actuator drives and the hydroplane foils are designed to be robust and easily removable for transportation, repair or replacement.

9 ELECTRIC POWER DISTRIBUTION

In the development of the electrical power distribution system, we have used designs from our previous AUVs. These proven methods emphasize reliability and safety for equipment and personnel.

A number of cells are connected in series to form battery banks. Generally, these form two or more banks which are connected in parallel. Each bank connects to the main bus through a power diode to ensure an even discharge of the banks and prevent the flow of current from one bank to another. The batteries are switched onto the main bus through a contactor that is controlled by a manual, oil-compensated switch mounted outside the pressure hull. An umbilical connection outside the pressure hull can be used to power the vehicle when on deck to conserve battery power during system checkout and pre-dive preparations.

Fuses protect each battery bank from excessive current resulting from accidental shorting or equipment malfunction. A breaker individually protects each power supply so that in the event of a power overload, only one device will be affected. A ground fault monitoring system is used to monitor the individual power supply outputs and main bus for isolation from the hull. If the isolation falls below a pre-set value a fault is generated. The faults are sensed by the vehicle computer which can take fault action if programmed to do so.

The current drawn from each battery bank and the main bus voltage are monitored. Using this data the vehicle calculates the energy used and estimates the energy remaining. The vehicle controller then determines if the energy draw is as expected and if the mission can be completed. If not, the vehicle can automatically take corrective action by shutting down unnecessary equipment or by slowing to a more efficient speed.

All electrical systems are completely isolated from the vehicle hull, reducing the potential for hull corrosion. Sacrificial anodes are also attached to the hull for extra protection. Each device within the AUV is powered through its own isolated supply. Because the failure of one device or power supply will not affect other systems, reliability is increased.

10 ENERGY

Many factors must be considered in the selection of an energy system for an underwater vehicle. These include mission endurance, speed requirements, vehicle size and weight constraints, non-propulsive or auxiliary power requirements, and energy reserve requirements. From these parameters, the total power and energy requirement can be determined. Two additional parameters useful in evaluating candidate systems, energy to weight ratio (specific energy) and energy to volume ratio (energy density).

To provide a basis for estimating the energy density and specific energy of power sources for a specific mission requirement, other subsystem weights and volumes must be included in the analysis. A major aspect in this regard is the weight and volume of the pressure hull required to contain the power source. Other evaluation factors that need to be considered in selecting an underwater power source are its reliability, its simplicity and ease of operation, and finally, any safety concerns that arise through its use.

In the past 30 years of AUV development, there has been a tendency to use low cost, low energy density batteries such as lead acid and nickel cadmium for system testing and trials and to turn to higher energy density batteries only for operational missions.

Long a mainstay for undersea vehicle programs, the lead acid battery has been used because of its low cost, known performance, reliability and reasonable cycle life. Its principal disadvantages are low specific energy (30 Wh/kg) and energy density (65 Wh/litre), loss of capacity at low temperatures and the production of hydrogen gas during charges as well as high rate discharges. Nickel cadmium batteries have a specific energy (30 Wh/kg) and energy density (75 Wh/litre) that are comparable to lead acid. Their cost, performance, reliability and cycle life are also comparable. Unlike lead acid batteries, however, cold temperatures do not degrade their performance significantly. A major limitation of the nickel cadmium battery is memory effect, requiring more stringent battery management.

Until recently, the silver-zinc battery has been the battery of choice for long range missions. Silver-zinc batteries are available off-the-shelf and have a higher specific energy (130 Wh/kg) and density (240 Wh/litre) than most other commonly available secondary batteries. High cost, limited cycle and shelf life, and a long recharging process reduce its overall attraction. While at normal discharge rates, 40 to 50 cycles can be expected from the battery, this reduces to 10 or 15 at high discharge rates. Cycle life is also reduced if the battery is discharged below 80% of rated capacity and thus, a 20% reserve is required at the end of the mission. Silver-zinc batteries have been used extensively in AUVs and their performance is reliable and documented. Their high cost and short life have, however, prompted consideration of alternative technologies.

Traditionally, the development of new power source technology was an expensive consideration for the sponsors of underwater vehicle programs. Fortunately, the emerging requirement for an electric car over the past decade has begun to absorb part of the cost of this research. Development in the space and computer industries is also helping to advance new power source technology. As a result, a number of new alternative power sources are emerging as candidates for underwater vehicles.

The two most promising in terms of AUV development are the Lithium Ion and the Lithium Polymer batteries.

Lithion products Inc.
35 Ah Lithium Ion Cell

Developed principally for the electric car market, the lithium polymer cell has specific energy (130 Wh/kg) and energy density (300 Wh/litre), both which compare well with silver zinc technology. It is solid state and can operate in ambient pressure. Because of this, it does not have to be contained inside a pressure hull. Other advantages include a high cell voltage (3.8 VDC), a long endurance with over 600 cycles, and a battery life of over 5 years. A North American developer has estimated the cost of a 40 kWh battery to be $6000 in production. Unfortunately, the technology is not fully mature, with 5-7 years of development remaining.

Like lithium solid polymer, the rechargeable lithium ion battery is a potential energy source for the electric car. Saft of France and Lithion products, Inc., a division of Yardney Technical Products, Inc. of the USA are now producing cells for the underwater market and other battery manufacturers plan to follow shortly. While energy densities are slightly poorer that silver zinc and the cost is currently about 50% higher, the battery has very long service life (1000 discharge cycles), can be used for 6 to 8 years and requires no maintenance. From the perspective of life cycle cost, it is very attractive. A second feature is that it is hermetically sealed and can charged in the AUV without opening the pressure hull.

In the Explorer series of AUVs, ISE has chosen to use lithium ion batteries as the energy source. Should a smaller capacity battery be required, it can be provided from nickel cadmium cells on request.

In estimating the total power requirement, the propulsion, payload and vehicle equipment requirements must all be taken into account. The following equation determines the energy capacity required to complete a mission of a given survey range, speed and depth:

$$e_t = \frac{(p + p_p + p_v)r}{3600v}$$

where:

e_t	= energy carried in kWh	p_v	= vehicle equipment power in Watts
p	= propulsion power in Watts	r	= survey range in km
p_p	= survey sensor power in Watts	v	= velocity in metres per second

To estimate the survey range given an energy capacity for different combinations of survey instruments the above equation can be solved for *r*, resulting in

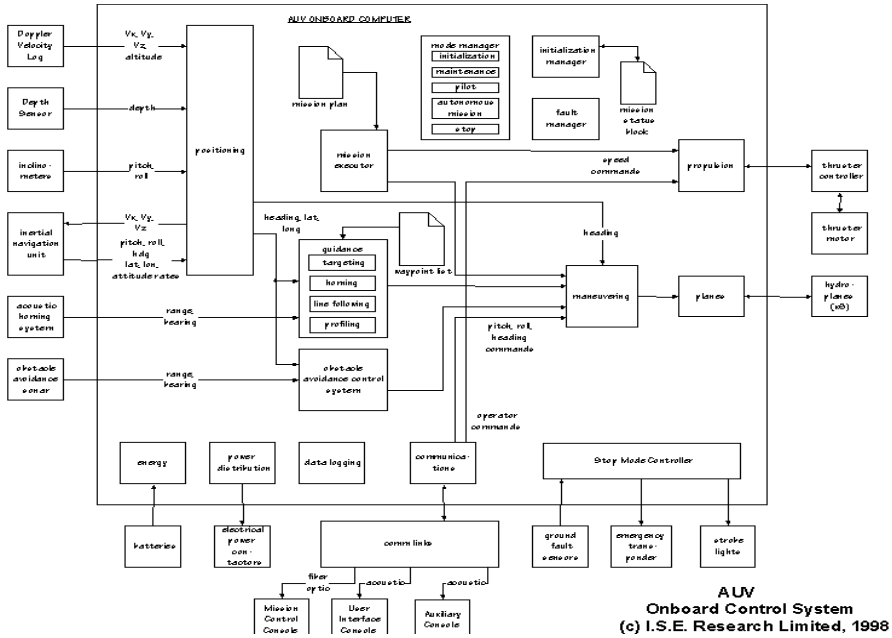
$$r = \frac{3600 e_t v}{p + p_p + p_v}$$

11 Vehicle Control

We have designed and implemented software controllers for AUV, ROV, and autonomous robotic applications for more than twenty years. The Explorer AUV will have a controller that incorporates experience gained in our other AUVs. The following are considerations in developing an AUV controller:

- full autonomy
- easy configuration of mission plans
- reliability
- easy modification
- configurable fault responses
- ease of operation

In the AUV the Vehicle Control Computer provides guidance and control using both AUV sensors and actuators. The Vehicle Control Computer supports a well-defined communication protocol for interface with various payload computers. An Ethernet network connects components onboard the AUV and a connection to this network is provided in the umbilical cable for use when the AUV is on deck. On the surface ship a network of computers can provide AUV mission planning, monitoring, data analysis and access to shipboard positioning sensors.



ISE AUV Controller

ISE vehicle controllers have been run on several different hardware platforms. CompactPCI has been chosen for the Explorer vehicle because of its rugged standard format and the availability of low power processors and I/O components. The vehicle hardware is made up of a Pentium processor, digital and analog I/O boards, DeviceNet™, serial I/O, and Ethernet. A solid state hard drive will store software executables, mission plans, and vehicle data log files. All critical vehicle mission information (pitch, roll, position, speed, heading, depth, etc.) is logged to the hard drive during operation.

Our standard software environment is the Automated Control Engine (ACE). ACE is a stable, easily upgradable software system designed around simple components which are connected together with events. Systems, such as the vehicle controller, are drawn using the schematic layout package Protel. Standard and custom ACE components are documented in a standard format and bound into a configuration programmer's manual. ACE and accompanying documentation is managed under a company wide Configuration Management system using Mortice Kern System's Source Integrity. Archived and documented ACE upgrade releases are produced bi-annually or more frequently as required.

A strength of the software architecture is the ease with which it can be modified. The controllers are based on simple, modular, and reusable software component libraries written in the C++ programming language. Software components are interconnected graphically or in ASCII text files without writing software code and without the need to recompile existing software. The graphical and textual configuration completely defines the control of the vehicle. This means that the support of a software engineer is not required to make modifications to the vehicle controller.

Surface operations and control of the AUV are straightforward and are conducted using a custom designed graphic user interface (GUI). This system runs on a Pentium II PC or on any unit of comparable capability.

12 Navigation and Positioning

The navigation and positioning accuracy required in an AUV will be determined by the mission requirements. Positional accuracy is the error which the AUV makes in determining its geographic position. Navigation accuracy is the precision with which the AUV can guide itself from one geographical point to another.

A very basic navigational error model for AUV navigation uses the following terms:

ε_p = initial vehicle position error δV = along-track velocity error

ϕ_O = initial heading error δV_O = cross-track velocity error

ϕ_{DI} = sensor heading misalignment

The values for these terms are combined to give a root-sum-square estimate (1σ) of vehicle position error as a function of distance traveled (D). All of these error contributions are independent of vehicle speed and higher order terms such as heading drift rate are not included.

$$\text{Total error } (1\sigma) = \sqrt{\varepsilon_p{}^2 + (D\sin\phi_O)^2 + (D\sin\phi_{DI})^2 + (D\cdot\delta V_O)^2 + (D\cdot\delta V_A)^2}$$

It should be stressed that this is a worst case scenario as it assumes the vehicle is on a constant heading throughout the mission. In many operations, the vehicle changes or reverses heading frequently, and in these cases, other error models are used to account for cancellation of navigational errors.

Watson Industries
AHRS–E303 Unit

In the QuickDesign© standard options, we offer two navigation sensor packages. One is a low cost system which offers a basic navigation capability. The other is a survey grade system providing high levels of accuracy over extended periods without positional updates.

The lower cost standard system consists of:

Watson Industries, Inc (USA) BA303 Attitude Heading Reference System (AHRS)
SonTek Argonaut Doppler Velocity Log
OMEGA PX5500LI strain gauge depth transducer

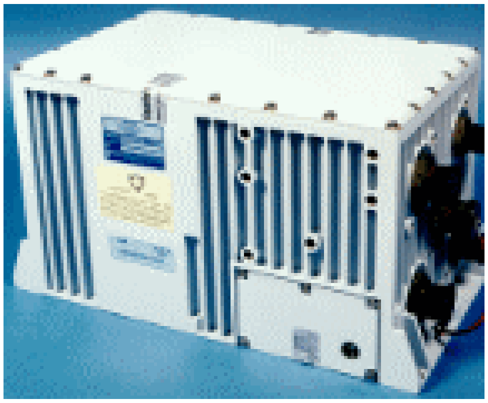
An AHRS transforms and integrates signals from three solid state angular rate sensors to determine the attitude and heading of the AUV. A velocity input from the Doppler Log compensates for errors within the unit, to improve overall stability and accuracy. The Doppler Velocity Log transmits two separate beams downward from the AUV to measure the speed along the AUV track and across it. The AUV controller then integrates the heading, attitude and velocity into a dead-reckoned position estimate.

For highest accuracy, the DVL must be in contact with the seabed, and consequently, lower frequency units can operate at higher altitudes above the seafloor. Typically, a 300 kHz system can operate at altitudes of up to 200 metres, while a 1200 kHz system will be limited to altitudes on the order of 30 metres. Finally, the Paroscientific strain gauge depth transducer measures the depth of the AUV from the surface.

The survey grade precision system consists of:

Kearfott Guidance and Navigation Corp. (USA) SEANAV Inertial Navigation Unit
RD Instruments (USA) Workhorse Doppler Velocity Log
Paroscientific, Inc. Digiquartz ® Strain guage depth transducer

Very basically, the Inertial Navigation Unit consists of an Inertial Measurement Unit (IMU) and a Kalman Filter. The IMU is comprised of 3 sensors which measure acceleration and angular velocity and integrate them to determine heading and speed. In the Kearfott SEANAV INU, three ring laser gyros are used for this.



Kearfott 5000 INU

A Kalman filter is a digital data processing algorithm which takes inputs from other sensors and based on the knowledge of the dynamics of these systems, generates an overall best estimate of position. In its standard configuration, the Kearfott SEANAV INU is capable of accepting inputs from Global Positioning System (GPS) receivers, Doppler Velocity Logs as well as propeller rpm.

A sophisticated analysis of this system has demonstrated that when it is used to survey a rectangular area such that the AUV reverses its heading frequently, navigational accuracy's of ±15 metres can be maintained for periods of up to 10 hours without position update.

As part of our ongoing research, we are presently examining the benefits of fiber optic gyro (FOG) technology as a replacement for the ring laser technology used in our current INU.

Both GPS and acoustic positioning systems can be used to assist in determining AUV position. DGPS positions accurate to 1-2 metres are obtained on the surface. When the vehicle has dived, position has to be obtained acoustically. There are several methods for this including:

- Ultra short baseline system (USBL)
- Short baseline systems (SBL)
- Long Baseline Systems (LBL)

Although ultrashort and short baseline systems do not require additional equipment to be deployed in the water or on the seafloor, they do require careful shipboard calibration. In the case of a short baseline system, two transducers need to be installed on the ship's hull as far apart as possible. The ultrashort baseline system on the other hand requires only one transducer to be installed. This makes the ultrashort baseline system more portable and consequently the preferred approach in instances where a variety of surface ships may be used.

ORCA Inverted LBL – GIB System

Ultrashort baseline systems can provide excellent positional accuracy. In order to achieve these results, it is necessary to provide high quality motion sensing instrumentation on the support ship. This can include a Vertical Reference Unit and a gyro. The ultrashort baseline system must be also be accurately calibrated to the motion sensing reference. Another option is to invert the USBL and place the transceiver in the AUV. This enables the AUV to position itself with respect to a hull-mounted transducer or to "home" on transducers that are placed on the seabed.

In the past, long baseline systems have also required careful calibration and the deployment of equipment on the seafloor. However, an inverted LBL system, in which GPS receivers are used on the ocean surface, does not require any shipboard system calibration. Although equipment must be deployed in the water, there is no need for special shipboard motion sensing equipment. Thus, an inverted LBL system may be utilized with a ship of opportunity.

In QuickDesign©, we offer the Sonardyne International Ltd (UK) combined USBL/LBL AUV transponders (models 7656 and 7866 depending on depth) as well as the ORE 4326A. These can be used with a variety of Long and USBL systems as well as Simrad HPR systems. We also offer the ORCA Instrumentation (France) Inverted Long Baseline System known as GPS Intelligent Buoy or GIB.

In the case of the inverted long baseline GIB system, a basic model to assess the positional accuracy is given by:

$$\varepsilon_{ILBL}^2 = \varepsilon_Z{}^2 + (\varepsilon_p + \varepsilon_{clk})^2 + \frac{N \cdot \varepsilon_{GPS}^2}{2}$$

where:

ε_{ILBL}	= total positioning error	N	= number of buoys
ε_Z	= pressure sensor depth error	ε_{GPS}	= GPS error
$\varepsilon_p + \varepsilon_{clk}$	= acoustic range error and clock drift		

This error is depth independent. For a USBL system, a basic model to assess the positional accuracy is given by:

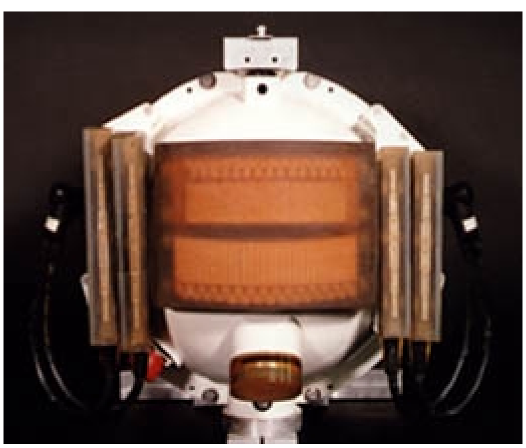
$$\varepsilon_{USBL}^2 = (R\varepsilon_\theta)^2 + (R\varepsilon_{Gyro})^2 + (R\varepsilon_\phi)^2 + (R\varepsilon_{VRU})^2 + \varepsilon_R^2 + \varepsilon_{GPS}^2$$

where:

ε_{USBL}	= total positioning error	ε_{VRU}	= VRU angular error
ε_θ	= USBL azimuth measurement error	ε_R	= USBL range error estimate
ε_{Gyro}	= gyro angular error	ε_{GPS}	= GPS error
ε_ϕ	= USBL elevation angle measurement error	R	= Range

With I/LBL, the dominant error is GPS. With USBL, the dominant error is GPS at short slant ranges and USBL system errors at longer ranges. Note that unlike the I/LBL, the positioning error is a function of the operating range and it increases with depth.

13 Obstacle Avoidance



Sonatech Inc. STA 013 Obstacle Avoidance Sonar

Generally, an AUV will require some means of detecting obstacles in its path, and a capability of maneuvering to avoid them. A variety of acoustic systems have been developed for this requirement over the past 20 years. These range from simple, single beam echo sounders which look ahead of the vehicle to more sophisticated multibeam sonars which can detect, track and classify an obstacle and then carry out one or more pre-programmed avoidance maneuvers.

ISE has had experience with a number of these systems. In the ‘80s with Kongsberg Simrad Mesotech Ltd, we developed and tested an 8 beam system using Simrad Model 1071 echo sounders in our ARCS vehicle. This system was very successful and demonstrated the capability to detect and classify an obstacle and then perform a simple avoidance maneuver. This system was later upgraded to provide the ability to track objects including depth contours at a preset range. We also conducted experiments with fewer beams (transducers), and demonstrated that a fundamental capability could be met with much fewer beams. In the '90s, we integrated a Sonatech, Inc. 20 beam obstacle avoidance sonar which provided the vehicle with sufficient information to undertake sophisticated maneuvers.

The level of sophistication required by an AUV will be determined by the mission, and more specifically by both the frequency of encounter with obstacles and potential complexity of the situation. In QuickDesign©, a relatively simple 2 beam system is featured. This system is developed by ISE and has the capability of detecting obstacles in the path of the AUV and performing simple avoidance maneuvers. ISE can also offer it's 8 beam system with an optional tracking capability or a more sophisticated system from Sonatech, Inc.

14 COMMUNICATIONS

Even though an AUV is capable of fully autonomous operation, a well-designed system provides the operator with communications links to the vehicle whenever possible. At a minimum, a link is needed to start the mission after the AUV has been launched. This contact confirms that all systems are ready and allows the operator to command the start with knowledge that the AUV is fully functional.

During the mission it is often possible for the support ship to maintain contact to allow for occasional vehicle health checks. Contact also allows the support ship sufficient data transmission to confirm that the payload is logging worthwhile information.

The communications link for most of the mission will need to be acoustic although, in exceptional circumstances, a fiber-optic link may be available. Radio contact is possible only at the start and completion of a run when the AUV is on the surface. At this time radio contact is also critical because the acoustic system is not functional. Finally, some form of high speed, hardwire link is an asset for working with the vehicle on deck.

Acoustic Telemetry ISE's experience has been that 150 bps should provide sufficient bandwidth to monitor the vehicle periodically, and to send it high-level commands. The amount of data that may be required to oversee the quality of the survey record depends on the nature of the survey equipment used. A 2400 bps link will provide a capacity to handle vehicle traffic and provide basic support for the survey quality control function. Higher data rates will enable more detailed quality control activities.

A telemetry transducer with a narrow vertical beam is desirable for reliable communications in deep water because it increases the Signal to Noise Ratio (SNR) and reduces the acoustic power required. This will result in lower electrical energy consumption from the acoustic telemetry. However, the narrower the beam of the acoustic telemetry transducer, the smaller the tolerance for positioning the support ship. This becomes especially critical in shallow water. Since these characteristics conflict, a system must strike a balance between reliability and operating conditions imposed on the support vessel.

LinkQuest, Inc. UMW4000
Acoustic Telemetry System

The duty cycle of the telemetry system can also have a significant impact on AUV energy requirements or endurance. In shallow water, the power requirements are modest. In 5000 metres water depth, however, 75 watts or more may be required and if the system is used continuously, it may noticeably reduce the range of the AUV.

The acoustic telemetry market has traditionally been served by two manufacturers – Benthos, Inc (formerly Datasonics) of the USA and ORCA Instrumentation of France. A third company, LinkQuest , Inc has also recently started manufacturing similar equipment. All use frequency shift or spread spectrum techniques for transmission. For deep water, transmission rates between 4800 and 9600 bps are claimed, however, under operational circumstances, lower rates may be inevitable at some times. All companies can provide either directional or omni-directional transducers. In QuickDesign©, we feature the Benthos ATM series of acoustic telemetry systems, using a 15 to 20 kHz transducer with a 60º beamwidth for shallow water operations above 1000 metres and a 35º beamwidth transducer for deeper work.

Radio Telemetry: The Explorer vehicle is fitted with a radio telemetry system for moderately high speed communication with the surface ship while the AUV is on the surface. For this link, a 400 MHz UHF 9600-baud radio manufactured by Dataradio, Inc is used. A range of 2 - 3 km is easily achievable with the vehicle on the surface. We have found the radio telemetry link to be valuable for two phases of AUV operations.

Communicating with the vehicle at the end of a mission is very important. At this point the acoustic system doesn't function because the top mounted transducer is out of the water. It is important, however, to be able to assure that the AUV is safely shut down before recovery and this link allows that to be verified or to be accomplished. Also, given favorable sea conditions, it is helpful to be able to pilot the AUV into position for recovery. Under these conditions, the link can also be used to pilot the vehicle at the start of the mission.

The Explorer AUV has a single, short fixed antenna mounted to the top of the hull. The radio and duplexer are inside the electronics compartment. Power demand is not a concern since the system is switched off when the AUV is submerged. The shipboard end of the system is located in the control console with the antenna situated as high as convenient on the superstructure of the ship.

Hardwired Telemetry: A hardwired 100 Mbits/s Ethernet link is for use while the AUV is on the deck of the support ship. This umbilical connection is used for vehicle systems monitoring and pre-dive checks. It is also be used to download mission plans and modifications to the fault response tables as well as data following the mission. A connector external to the pressure hull will allow this link to be enabled without opening the vehicle.

15 Locator and Emergency Equipment

Novatech Designs Ltd. ST-400AR Xenon Flasher

At the end of a mission when the AUV returns to the surface, it must be located by the host surface ship (or other platform) and recovered. Because of waves, weather or darkness, it is prudent to equip the AUV with devices that make the task of locating it simple. To that end, all Explorer AUVs are equipped with a GPS receiver so that the exact position off the vehicle when at the surface can be transmitted to the host vessel or platform over the radio telemetry link. In addition, each Explorer vehicle is equipped with a xenon flasher (strobe) and radio beacon built by Novatech Designs Ltd. which activate automatically when at the surface. These are independently powered by batteries.

To locate a vehicle underwater, acoustic devices must generally be relied upon. The simplest device is a pinger. Essentially an underwater beacon, this device provides a regular sequence of acoustic pings that can be detected by a hydrophone. As it is a passive device, the pinger signal can only provide bearing information to the surface. Transponders and responders, on the other hand, also emit acoustic pulses but are triggered by an acoustic pulse in the case of the transponder or through a hard-wire command in the case of the responder. Because they are interrogated or triggered, transponders/responders can provide both bearing and range information. Thus these systems provide a more efficient way to locate an AUV underwater. Consequently, all Explorer vehicles are equipped with a transponder.

To assist in bringing a disabled vehicle to the surface, Explorer AUVs are equipped with a lead weight which can be released by operator command through the acoustic telemetry system or if desired, automatically as a response to a pre-defined fault condition. The drop weight is located such that the vehicle attains a bow up attitude during ascent when the weight is released.