AUVSI Foundation and ONR

Engineering Primer Document
for
RoboSub Competitions

Association for
Unmanned Vehicle Systems International (AUVSI) Foundation

US Navy Office of Naval Research (ONR)

FOREWORD

The Association for Unmanned Vehicle Systems International (AUVSI) Foundation and the Office of Naval Research (ONR) sponsored the development of this primer document. It is intended for students who are considering participation in the annual AUVSI Foundation/ONR RoboSub Competition. The document provides an overview of engineering and organizational considerations for designing, building, and operating a vehicle for this event. Development of an underwater system requires knowledge of multiple engineering disciplines, as well as good organizational and execution skills. This primer provides a brief overview of these topics to acquaint readers with the subjects, knowledge, and skills important to competitive teams. The document also includes practical tips and advice based on experience developing and operating AUVs. The primer authors include past AUV competition participants who have shared their experience.

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Rafael.R.Rodriguez 9/14/06 3:20 PM
Comment [1]: Regularly required statement when releasing Navy documents to public domain

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1 INTRODUCTION

1.1 Engineering and RoboSub Competition

Engineering design, fabrication and testing requires a team of individuals working together to accomplish a common goal. The RoboSub competition provides a unique challenge every year to groups of individuals who choose to make meeting that challenge their engineering goal. The RoboSub Missions are designed to integrate topics relevant to underwater vehicle operations and to promote innovative design and operation of future underwater vehicles.

Typical Tasking Requirements

The exact requirements of the RoboSub Competition vary from year to year. For example, the 2006 RoboSub Competition (formerly known as AUVSI AUV competition) consisted of three primary tasks:

1. Rendezvous with a docking station.
2. Inspect and mark an area on a pipeline.
3. Breech within a marked zone.

These tasks were to be accomplished by sensing a flashing beacon on the docking station, making a visual inspection of the pipeline, releasing a marker, and conducting acoustic sensing of a homing beacon located within the breech zone.

A vehicle designed to meet tasks such as these will need to be equipped with specific hardware designed to sense optical and acoustic signals. In addition to having these sensors, the vehicle will need to be able to "interpret" sensory input and respond as required. Therefore, with the varied sensor and performance capabilities necessary to complete the RoboSub mission, each team will need to integrate several different engineering areas into their final design. For example, the following engineering areas will be significant in developing a successful platform:

- **Vehicle Hydrodynamics**: ballasting, buoyancy, drag
- **Underwater Propulsion**: momentum, thrusters
- **Underwater sensing**: visual, acoustic, direction
- **Mechanical systems:** release mechanisms for the markers
- **Power Systems**: types of batteries for the propulsion system and onboard equipment, power distribution
- **Systems engineering**: system integration and testing

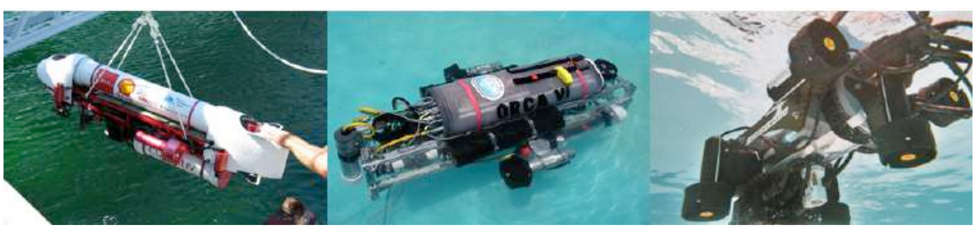

Figure 1-1. Underwater vehicle design requires several areas of engineering.

Signe A Redfield 9/14/06 3:20 PM
Comment [2]: Should be either "2007" or "consisted of" followed by past tense throughout following paragraph

Rafael.R.Rodriguez 9/14/06 3:20 PM
Comment [3]: To avoid appearance of endorsing a commercial UUV system, recommend replacing picture of BPAUV with this composite of the winning entries from the last three AUV competitions

Considering the complex mission tasks, a systems engineering approach will be critical to a successful vehicle design. Systems engineering is a coincident design methodology, which considers the integrated mission requirements and final system performance. It is the application of solutions to the complete problem in its operational environment by systematic assembly and matching of parts.

AUV Vehicle Dimension Requirements

The vehicle is required to fit within a 6 foot by 3 foot by 3 foot box, be battery powered, weigh less than 140 pounds and carry two markers (1.5 inches x 1.5 inches x 6 inches maximum) each not more than 1.5 pounds.

Rafael.R.Rodriguez 1/24/07 4:51 PM
Comment [4]: Need a better quality AUVSI logo here & on cover page

1.2 Teaming

The RoboSub Competition is an opportunity for motivated individuals to challenge themselves and work together to accomplish a unique and rewarding goal. Organizing a team to complete any project requires collecting a group of individuals with diverse capabilities, each person contributing to the overall success of the mission. The team will require individuals capable of mechanical, electronic, and control system design, individuals who can integrate and test underwater systems, and individuals who can work together, compromising where necessary to accomplish their mission.

A team is a group of people bonded with a common goal. The primary measure of a team's success is not the size of the team but the capabilities represented in that team and the team's ability to get the best out of each individual.

Figure 1-2. Teams are comprised of individuals with different types of capabilities working together to accomplish a common goal.

1.2.1 Team Structure

Each team must structure itself to allow for decision-making within individual areas of expertise as well as the overall project. For example, a team may be structured with an overall Project Manager with five Assistant Managers each in charge of the Propulsion System, Control System, HM&E (Hull, Mechanical and Electrical) System, AUV Integration, and Programmatic and Financial Administration as shown in Figure 1-3. A team's structure may be different, but it should be organized to define specific responsibilities, relationships, and a decision process.

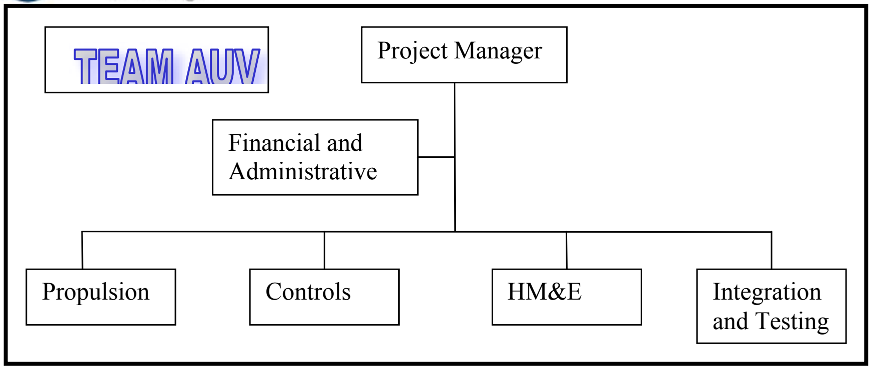

Figure 1-3. Team Organization Chart based on a systems approach.

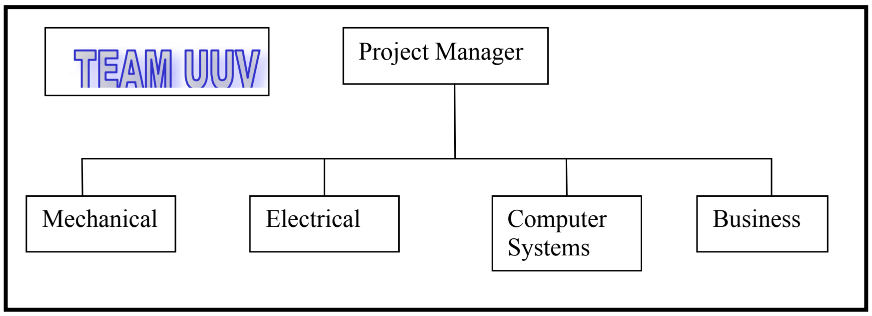

Figure 1-4. Team structure based on a business focus.

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Comment [5]: Captions are too close to image boxes on figures 1-4 and 1-5; captions are hard to read

1.2.2 Teaming References

http://www.managementhelp.org/grp_skll/teams/teams.htm
http://www.teambuildinginc.com/index.html
http://www.teambuildinginc.com/tps/index.html

1.3 Financial Considerations

Successful engineering projects at any organization require not only detailed design but also careful financial and costing considerations. For this competition, fundraising and sponsorships will be essential to provide each team with the means necessary to build, assemble, and test the vehicles they design. Fundraising provides each team with some minimal capital to purchase hardware and software components for vehicle integration and development. Fundraising activities can vary from holding car washes to providing community service. In addition, teams often get multiple sponsors, each contributing either financial donations or hardware donations needed for the AUV. Hard-to-find or expensive hardware donations could be the most useful type of donation that a team may get. Sponsors may be manufacturers of AUV sensors, connectors, and/or underwater thrusters, or they could represent other major industrial concerns in your vicinity.

1.3.1 Fundraising References

http://www.fasttrackfundraising.com/
http://www.fundraiserhelp.com/articles.htm

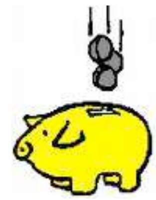

Figure 1-5. Fundraising is essential to support the building of your AUV.

1.4 Summary

The RoboSub Competition is an opportunity for students to work together on a unique engineering problem. The competition requires an integrated engineering solution as well as a practical industrial approach to production of a vehicle satisfying mission requirements. The following chapters will provide an introduction to a systems engineering approach used to develop an unmanned underwater vehicle, a review of the engineering areas relevant to accomplishing the RoboSub mission, examples of previous AUVs and lessons learned from previous competitions, and references for hardware, sponsors, and previous engineering reports.

2 DESIGN PROCESS

2.1 Design Approach

The following steps may assist in initiating, affecting, and carrying to a successful conclusion the design of an AUV that is capable of competing in the RoboSub Competition.

1. Define the problem: Each year, the problem is defined on the AUVSI Foundation web site. Teams must interpret the information about the mission statement provided. If teams have questions about the problem statement, these questions should be addressed prior to designing your solution vehicle by contacting the Technical Director, working within your team, or contacting your NEST representative.

2. Determine the requirements: Requirements can be categorized into two primary bins: mission requirements and vehicle requirements.

   a. *Mission requirements:* These are determined through interpretation of the defined problem, above. For example, in RoboSub's Mission Arena section, a series of operations (i.e. docking, breaching, dropping a marker) are described in general terms. These operations are then further defined and described in later sections, which has direct bearing on the design process. It is important to understand all the details of the operations needed to complete the mission. All requirements should be well documented for guidance with respect to design decisions.

   b. *Vehicle requirements:* A number of vehicle requirements are defined by AUVSI Foundation (i.e. AUV weight and physical size constraints), whereas others are to be defined by each team (i.e., flooded or water-tight fuselage, thruster types, battery types, sensor types and specifications, navigation method, control methods and requirements). These requirements should be documented for guidance with respect to design decisions. Further, performance specifications can result from considering how the vehicle will accomplish the mission (i.e. minimum required speed, maneuverability, sensing capabilities, etc.).

   Note that any requirements determined by the design team can be revisited in the course of the project. However, changing individual parameters often has ripple effects on other aspects of the vehicle design. These effects should be considered prior to altering the design plan.

   Along with these requirements, it is helpful to determine goals that may exceed the defined requirements. For example, AUVSI Foundation has limited the size of the vehicle by requiring it to fit in a six-foot long by three-foot high by three-foot wide box. This would be defined as a requirement; however, a team may decide that their design is better served with smaller dimensions. Thus, they may set a different goal for size.

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Comment [6]: What does this mean? "Processed" It sounds like you need to feed them into an Eniac. I'm guessing this should be something more like "Information provided on the web site should be interpreted, and associated questions generated by the interpretation should be answered either within the team or by contacting AUVSI."

GazagnaireJ 9/14/06 3:20 PM
Comment [7]: Should these be more functions that need to be performed to complete the mission (sense, navigate, locate etc.? These seem to be more of design options. [SAR] I agree. Maybe could be more like "speed, sensory capabilities, maneuverability"

3. Identify Options: After definition of the problem and determination of the requirements and goals, the next step in the design process is to identify options for solutions. This can be accomplished through research into previous solutions to similar problems as well as brainstorming ideas for novel or improved approaches.

4. Examine tradeoffs & develop conceptual design(s): Once the options are considered, tradeoff studies and feasibilities need to be assessed to determine the possibility of success for a given idea. Once the best candidate is determined, the development of a notional concept and design specifications can be started. The notional concept is a high-level design study of the major components within the design to determine basic functionality. Pieces of the design to consider here may include: power components, navigational hardware, propulsion, basic hydrostatics and dynamics, and major structural components. Concurrent with notional design development, component specifications are initiated (i.e., required propulsor power, battery container size, and high-level hydro requirements). Specifications are further developed throughout the spiral development process.

5. Perform cost analysis: A high-level cost analysis for the major components should be considered to determine budget requirements. Along with the cost analysis, the project plan and timeline should be assessed.

6. Select concept option & design: Once the concept option is selected it needs to be matured through a final fabrication design. The design process is an iterative one, requiring give and take between the various disciplines. Typically the design spiral process is followed allowing the team to evaluate decisions made along the way with respect to their effect on other design aspects. Figure 2-1 is a sample design spiral sketch. Throughout the process attention to detail needs to be maintained, particularly for weights and ballast purposes, so that negative surprises and unplanned events are avoided. Essentially, the idea is to continuously revisit design aspects throughout the project. By developing a detailed design schedule with stepped tasks and timelines, the overall design can be achieved and tested by competition time. The project manager's job is to make sure everyone stays on schedule.

Signe A Redfield 9/14/06 3:20 PM
Comment [8]: Should say "Figure 2-1 shows" not "Below" since it's on the next page and not technically "below" the paragraph…

GazagnaireJ 9/14/06 3:20 PM
Comment [9]: We should emphasize that once a concept and preliminary design is in place a detailed schedule with a description of what needs to be done (task), who is responsible for the task and how long they have to do it. It is the project managers job to make sure everyone stays on schedule.

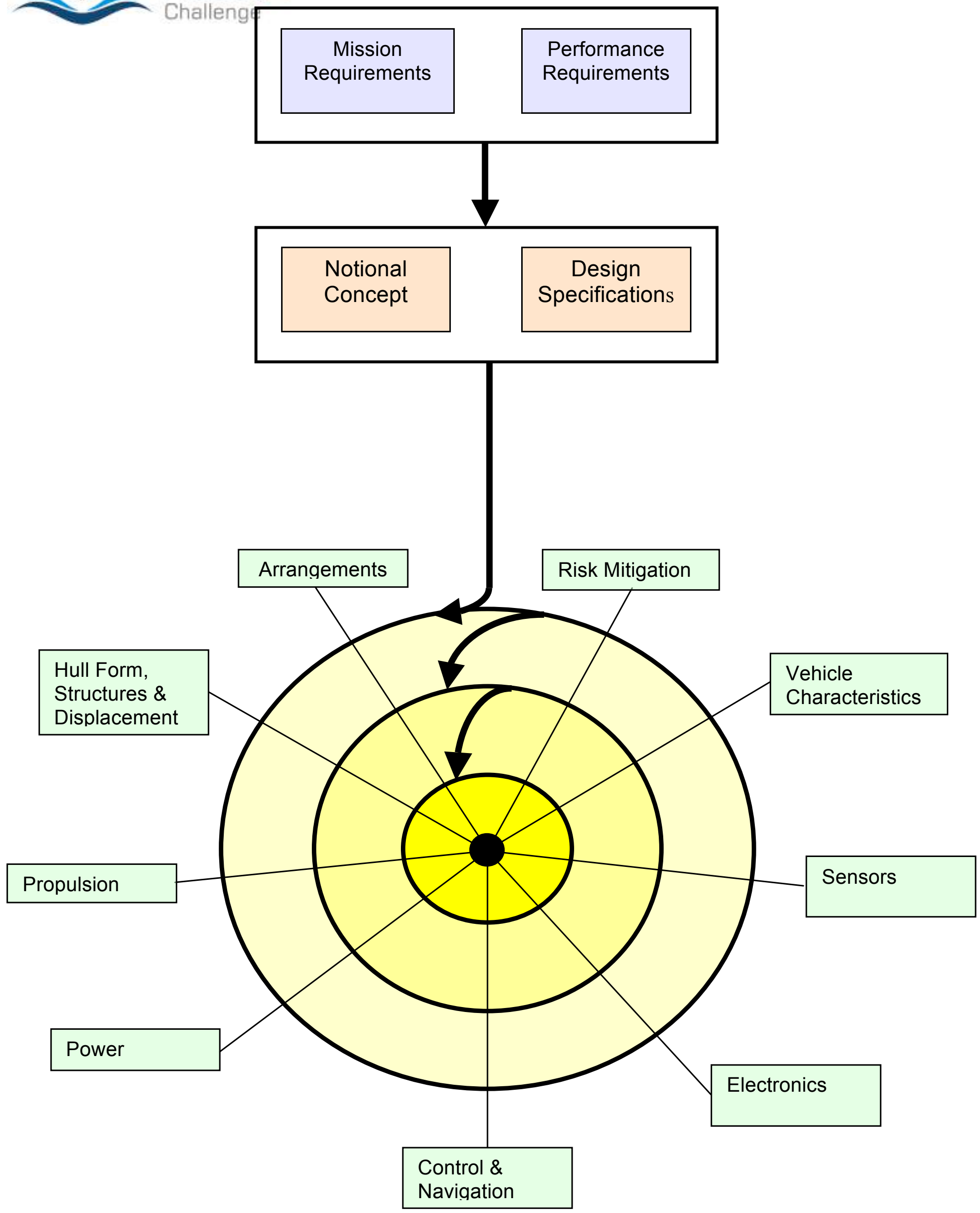

Figure 2-1. Systems engineering design spiral

Signe A Redfield 9/14/06 3:20 PM
Comment [10]: Problem with graphic; mine says "Design Specificatio" in the box, and there are two "Sensors and Electronics" boxes on the circle. Still not fixed! Maybe it's just my version of the document (older version of Word), but at least the two "Sensors and Electronics" circles should be taken care of…

Rafael.R.Rodriguez 9/14/06 3:20 PM
Comment [11]: Recommend adding caption for consistency

2.2 Peer Reviews

Periodic peer reviews allow for interjection of fresh perspectives on the design or project plan. Often, peers not directly associated with the project will observe or discover potential issues that the involved design team might miss due to its goal-oriented perspective. Peer reviews tend to allow a chance to step back and assess decisions, designs, and plans, and assure that the probability for success remains high. Reviews need not be formal; however, they need to be informative in order to take full advantage of peer perspectives.

2.3 Testing

The value of testing cannot be emphasized enough. Testing of components and the system as a whole is essential to the success of the design and fabrication. The emphasis should be to get the vehicle as a whole into the water as soon as possible, conducting component and sub-system testing along the way. These in-water tests will provide insight and experience, as they exercise the components in an appropriate environment, while also exposing potential design improvements and allowing practice in competition-like operations. By employing in-water testing early, problems can be identified and solved and design improvements can be implemented prior to the competition. Below are possible tests that may be conducted to ensure successful operations:

- Hull integrity
- Leak tests
- Structural tests
- Drives
- Integration
- Friction
- Slop
- Endurance
- Propulsor(s)
- Input signal vs. output RPM
- Electronics
- Sensor output noise/signal
- Circuit noise
- Integration checks
- Software
- Response to input
- Fail-safe checks
- Control
- Perturbation response
- Error signal response
- Integration
- Component assembly
- Vehicle assembly
- Ballasting check

- In-air operations
- In-water operations (static and free running)
- Operational tests (In-Water)
- Control checks
- Mission simulation checks
- Practice runs

Prior to testing, test readiness reviews are highly recommended. A test readiness review will provide a chance to assure the tester(s) that the system is prepared for the test, thus avoiding potential problems due to a forgotten procedure, installation, and/or action. This will greatly reduce the chance of equipment damage or safety issues. A typical test readiness review will have a checklist of items that need to be completed prior to actual test performance. Upon completion of the items on the checklist, the system should be ready for testing or operations.

3 THEORETICAL BACKGROUND

3.1 Introduction

Designing an AUV to satisfy a particular mission requires the careful consideration of each system component and the determination of the effect of each component on the overall vehicle and other onboard systems. For example, the vehicle hull form influences the amount of drag occurring on the vehicle and will therefore require a specific amount of thrust to be generated to make it move through the water. The amount of thrust required will influence the propulsion system design, and the propulsion system will influence the onboard power requirements and power system design. The power system will affect the onboard sensors and the computer that will be able to be supported. To understand the relationships between these systems, each team will require some fundamental background in each of the engineering areas mentioned previously. This section presents a fundamental discussion of:

- Hydrodynamics
- Propulsion
- Power
- Underwater sensing
- Navigation
- Controls
- Underwater components (connectors, seals)

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Comment [12]: Autonomy section moved to Chapter 4

Note that a brief discussion on **Safety** is included to identify specific areas where care should be taken when dealing with battery-powered AUVs.

This general overview of each topic contains fundamental information of benefit to all team members. Some topics provide more detailed information for the team member assigned that area. References are included along with website locations which provide helpful information.

3.2 Fluid Dynamics

3.2.1 Hydrostatics

3.2.1.1 Buoyancy

The buoyant force F_B is the net upward force acting on an object caused by the surrounding fluid (water, in this case):

$$F_B = \rho g \mathbf{V}, \qquad (3.2\text{-}1)$$

where ρ is the density of water, g is the gravitational acceleration, and $\mathbf{V}$ is the volume of the object. In other words,

The buoyant force is equal to the weight of the displaced fluid.

The net buoyancy is equal to the difference between the buoyant force and the weight of the vehicle hull and its components.

$$NetBuoyancy = F_B - W_{hull} - W_{components} \tag{3.2-2}$$

If an object is neutrally buoyant, it can be considered weightless when it is submerged. In order to achieve this, it must displace an amount of water equivalent to its weight. Neutral buoyancy is often the goal of underwater vehicles. This is achieved by adjusting the weight of the vehicle by adding or removing ballast. Submarines use tanks that are flooded or evacuated to adjust buoyancy as necessary.

3.2.1.2 Stability

The Center of Buoyancy (CB) is the point at which the buoyant force F_B can be considered to act. This occurs at the centroid of the displaced volume, and remains in the same place as the vehicle operates fully submerged. Once it begins to surface, however, the CB will begin to migrate. The vehicle's weight (W) acts at the Center of Gravity (CG), which does not change position during operation unless mass is shifted within the vehicle.

In a stable condition F_B and W produce a couple that tends to right the vehicle, known as the righting or restoring moment. For a submerged vehicle, hydrostatic stability exists when CG is below CB as shown in Figure 3-1. The distance between the two determines the righting moment and therefore dictates the stability characteristics of the vehicle. In an unstable condition, the moment will prevent the vehicle from returning to its proper roll orientation as shown in Figure 3-2. The practical issue is determining the minimum distance required to provide sufficient righting moment. In a static condition, the righting moment should be large enough such that movement of internal components does not lead to an unstable condition. The distance between CB and CG also provides an effective spring stiffness term to the equations of motion in the vertical plane, causing a resistance to pitching. While increasing this distance will increase the vehicle stability, a tradeoff must be made with carrying an impractical amount of ballast.

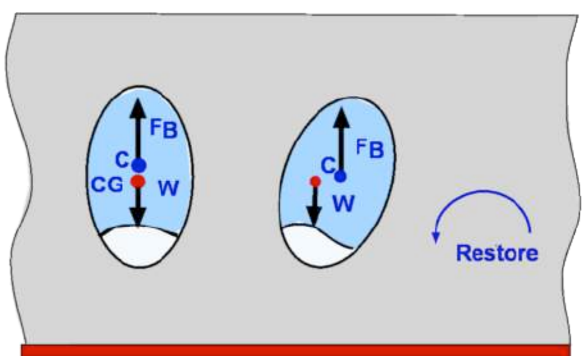

Figure 3-1. Schematic of an immersed body that is stable in roll.
(From http://www.aeromech.usyd.edu.au/aero/fprops/statics/node24.html)

Julia Gazagnaire 9/14/06 3:20 PM
Comment [13]: Do you mean as the vehicle reduces its depth or if the vehicle is only partially submerged as opposed to fully submerged as mentioned in the previous paragraph?

Julia Gazagnaire 9/14/06 3:20 PM
Comment [14]: Vertical distance?

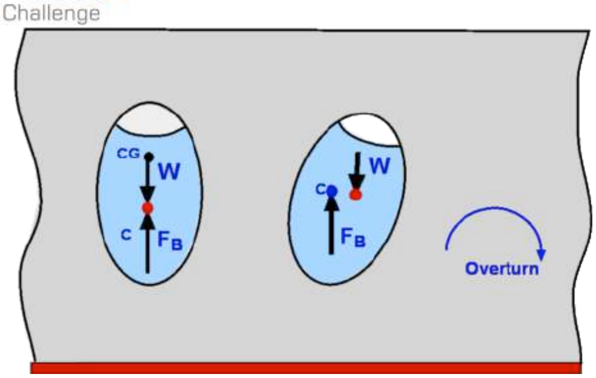

Figure 3-2. Schematic of an immersed body that is unstable in roll.
(From http://www.aeromech.usyd.edu.au/aero/fprops/statics/node24.html)

Ballast can be described as *fixed* or *variable*. Fixed ballast includes any internal components, as well as weights and/or positive buoyancy chambers to bring the vehicle to the desired buoyancy. Ballast is also used to cause the longitudinal positions of CG and CB to be coincident (pitch stability), as shown in Figure 3-3, and to adjust the vertical distance between CG and CB (pitch and roll stability). If a cylindrical hull shape is used, the CB will be close to the cylinder axis, and fixed negative ballast placed low in the hull will pull the CG below CB. Tubular frames can be used to gain buoyancy; however, careful consideration must be given to strength and chance for impact damage.

Variable ballast is used to adjust the buoyancy to accommodate a change in weight (due to decreased payload, for example) or to change depth (surface or submerge). Variable ballast systems can consist of soft or rigid tanks. Soft tanks have the disadvantage of changing volume as the vehicle changes depth. A system that floods and empties a rigid tank is relatively simple to implement. Opening a valve allows water to enter the tank; a pump or piston can be used to force water out. Ballast systems including tanks, motors, pistons, and switches are commercially available.

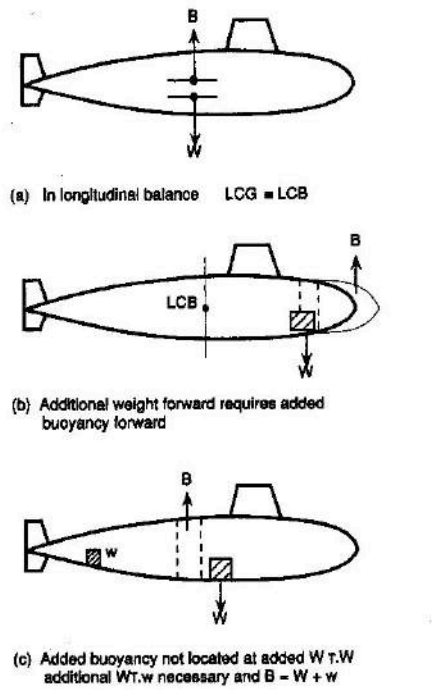

Figure 3-3. Various conditions of longitudinal stability.
(From *Concepts in Submarine Design*)

3.2.1.3 References

http://en.wikipedia.org/wiki/Bouyancy
http://www.aeromech.usyd.edu.au/aero/fprops/statics/node2.html
Fox, R.W. and McDonald, A.T., *Introduction to Fluid Mechanics*, John Wiley & Sons, New York, 1994.
Burcher, R. and Rydill, L., *Concepts in Submarine Design*, Cambridge University Press, New York, 1999.
Roberson, J. A. and Crowe, C.T., *Engineering Fluid Mechanics, 3rd ed.*, Houghton-Mifflin, Boston, 1985.

3.2.2 Hydrodynamics

3.2.2.1 Control Volume Formulation

A control volume can be thought of as a region in space that is defined to help solve a problem, and the control surface is the surface surrounding the control volume. A control volume formulation is particularly useful for hydrodynamics problems because it focuses the analysis on a region in space through which fluid flows, rather than trying to follow the same mass of fluid through time. This approach makes it easier to study the effect of fluid motion on a device or structure. For example, a control volume can be defined such that it surrounds a vehicle and travels with it:

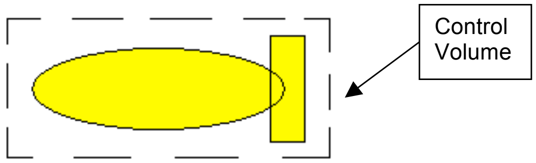

Figure 3-4. Control volume

For a given control volume *CV*, shown in Figure 3-4, with associated control surface *CS*, the rate of change of any extensive property *N* (related to the mass of the system) is governed by:

$$\left.\frac{dN}{dt}\right|_{system} = \frac{\partial}{\partial t}\int_{CV} \eta\rho d\forall + \int_{CS} \eta\rho\vec{V} \bullet d\vec{A}, \qquad (3.2\text{-}3)$$

where t is time, $\eta = N$ per unit mass, ρ is the fluid density, $d\forall$ is an element of volume in the *CV*, $\vec{V}$ is the velocity vector and $d\vec{A}$ is the area vector. Vector $d\vec{A}$ has a magnitude equal to the element of the area dA and its direction is the outward normal from the control surface. The left hand side of the equation is the total rate of change of N, and is equal to the sum of the time rate of change of N within the control volume and the net rate of flux of N through the control surface. An example of a one-dimensional control volume is given in Figure 3-5.

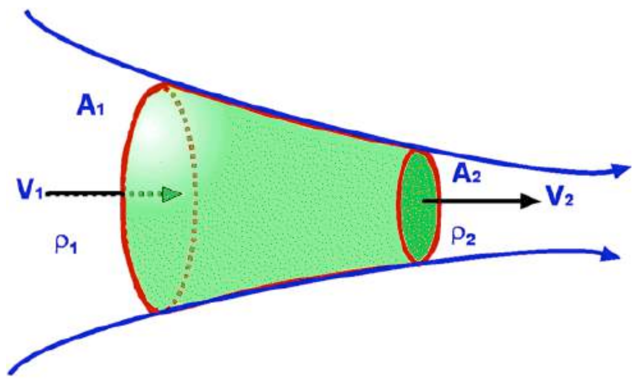

Figure 3-5. Control volume for one-dimensional flow.
(From http://www.aeromech.usyd.edu.au/aero/fprops/cvanalysis/node24.html)

Equation 3.2-3 can be applied to the quantities mass and momentum to obtain two relations relevant to hydrodynamics.

3.2.2.2 Continuity Equation (Conservation of mass)

Conservation of mass states that mass cannot be created or destroyed. Applying this concept to a *CV* yields:

$$\left.\frac{dM}{dt}\right|_{system} = 0 = \frac{\partial}{\partial t}\int_{CV}\rho d\forall + \int_{CS}\rho\vec{V}\bullet d\vec{A} \qquad (3.2\text{-}4)$$

In other words, the net flux rate of mass out through the control surface equals the rate of change of mass inside the control volume.

This equation can be simplified in special cases. For incompressible flow, which is a common assumption for water, density is not a function of space or time. Equation 3.2-4 can be simplified to:

$$0 = \frac{\partial\forall}{\partial t} + \int_{CS}\vec{V}\bullet d\vec{A} \qquad (3.2\text{-}5)$$

For a non-deformable control volume, $\forall$ is constant and the conservation of mass equation becomes:

$$0 = \int_{CS}\vec{V}\bullet d\vec{A} \qquad (3.2\text{-}6)$$

Note that this equation applies to steady or unsteady flow. The integral quantity in Equation 3.2-6 is commonly called the volume flow rate. Note that the sign of the dot product depends on the direction of the velocity vector relative to the area vector. Therefore $\vec{V}\bullet d\vec{A}$ is negative when fluid flows in through the control surface and positive when it flows out. In many applications, the assumption of uniform flow at a section (constant velocity across the entire area) is adequate. For the simple CV shown in Figure 3-5, the conservation of mass equation simplifies to:

$$V_1A_1 = V_2A_2, \qquad (3.2\text{-}7)$$

assuming incompressible flow and uniform flow at A_1 and A_2.

3.2.2.3 Momentum Equation (Conservation of Momentum)

Applying Newton's second law to a particle of water yields the momentum equation. It simply states that the sum of all external forces acting on a system is equal to the time rate of change of linear momentum $\vec{P}$ of the system. The control volume formulation for a non-accelerating *CV* can be written:

$$\left.\frac{d\vec{P}}{dt}\right|_{system} = \vec{F}_S + \vec{F}_B = \frac{\partial}{\partial t}\int_{CV}\vec{V}\rho d\forall + \int_{CS}\vec{V}\rho\vec{V}\bullet d\vec{A}, \qquad (3.2\text{-}8)$$

where $\vec{F}_S$ includes all surface forces acting on the *CS* and $\vec{F}_B$ includes all body forces acting on the *CV*.

In other words, the time rate of change of the linear momentum of the system = time rate of change of the linear momentum of the contents of the control volume + net rate of flow of linear momentum through the control surface.

Julia Gazagnaire 9/14/06 3:20 PM
Comment [15]: This eqn number should be updated

Julia Gazagnaire 9/14/06 3:20 PM
Comment [16]: Update figure number

Examples of body forces are gravitational and electromagnetic; examples of surface forces are shear stress (drag) and pressure. Equation 3.2-8 is a vector equation that can be broken into three scalar component equations relative to the defined coordinate system. Careful selection of the coordinate system and control volume boundaries can simplify the analysis.

A simple form of the momentum equation has been developed for the case of steady, incompressible, frictionless flow along a streamline, known as the Bernoulli equation. In this case, $\frac{\partial}{\partial t} = 0$, ρ = constant, and $\vec{F}_S$ is due to pressure forces only. In addition, if the CV is bounded by streamlines, the only flow occurs across the end sections. Considering Figure 3-5 in this context, the blue arrows would be streamlines that define two surfaces of the control volume, and areas A_1 and A_2 would define the other two surfaces, through which uniform flow is assumed to pass. With these assumptions, and using the continuity equation, the momentum equation reduces to:

$$\frac{p}{\rho} + \frac{V^2}{2} + gz = \text{constant}, \tag{3.2-9}$$

where p is the average pressure, V is the uniform velocity, and z is the elevation of the section. Note that it can be shown that the Bernoulli equation is also valid between two points in any steady, incompressible, frictionless, and *irrotational* flow.

This type of analysis can also be applied to the first (conservation of energy) and second laws of thermodynamics to obtain integral equations.

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Comment [17]: Are the integral equations going to be used in this section?

3.2.2.4 Drag

One type of surface force encountered by any object traveling through water is drag force. The total drag on a body is due to a combination of pressure forces (form drag) and shear forces (skin friction drag). The form drag is driven by the shape of the vehicle, with long, thin bodies typically having lower form drag. The skin-friction drag is driven by the surface area of the body that is in contact with the fluid. Therefore, an optimum body shape exists that will result in the minimum total drag. Figure 3-6 shows the relative contributions of form and skin-friction drag as the ratio of vehicle length to diameter increases. However, deviations from the ideal shape may be required to improve manufacturability or to accommodate internal equipment. Also, discontinuities, control surfaces, and other appendages will increase the total drag. Making the surface as smooth as possible and fairing appendages, i.e., creating a smooth transition into the main body, will minimize their contribution to the total drag.

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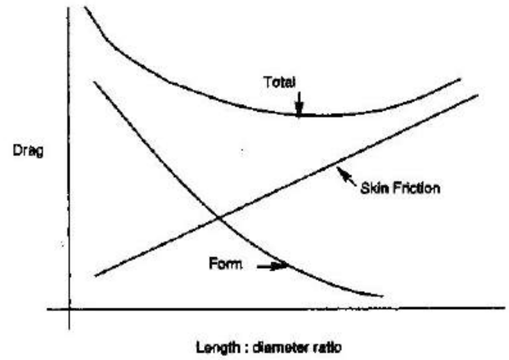

Figure 3-6. Relative contributions to total drag as a function of L/d. (From *Concepts in Submarine Design*)

The skin friction drag force is calculated by:

$$D_{SF} = \frac{1}{2}\rho C_D A_s V^2, \tag{3.2-10}$$

where C_D is the drag coefficient of the vehicle, which can be estimated or calculated from a measured drag force. The area A_s is the total surface area exposed to the flow and V is the vehicle velocity. The equation for form drag is the same, but the drag coefficient values are based on the frontal, or projected, area normal to the flow direction. Typical values of drag coefficient can be found in the references below, or any standard fluids textbook.

3.2.2.5 References

http://www.aeromech.usyd.edu.au/aero/fprops/cvanalysis/node3.html

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3.3 Propulsion

Every underwater vehicle has a mechanism for moving it through the water. This mechanism creates thrust by moving water at a certain velocity. Thrust is governed by the following equation:

$$T = \dot{m}(u_e - u)$$

where T is the thrust produced, $\dot{m}$ is the fluid flow rate through the propulsion device, u_e is the exit velocity and u is the inlet velocity.

Considerations in choosing which propulsion device to be used should include size, cost, power required, efficiency of the propulsor, and thrust produced. Below are a variety of propulsors used in underwater applications which might prove useful for vehicle designs.

3.3.1 Propellers

3.3.1.1 Concept

A propeller is connected to a shaft which penetrates the hull and is connected to an engine. The blades of the propeller can be designed in many ways (see below), but they all create thrust by moving water past the blades and creating vortices behind them. The propeller loading equation is useful in determining power requirements:

$$Loading = \left(\frac{K_T}{J^4}\right)^{1/4}$$

The Thrust Coefficient (K_T) equation is:

$$K_T = \frac{T}{\rho n^2 D^4}$$

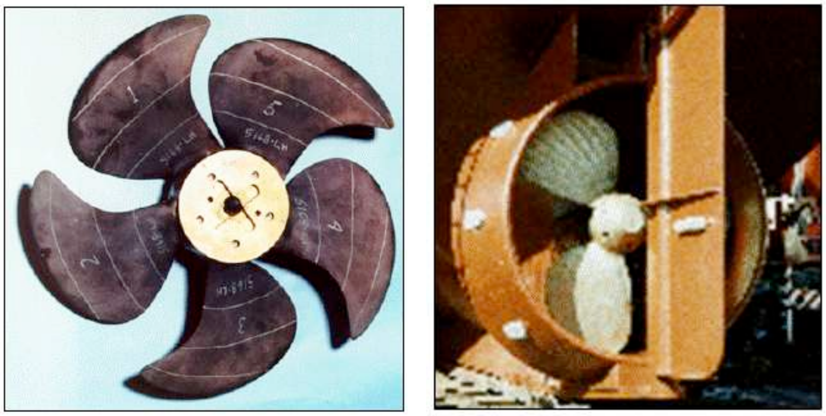
where ρ is the density of water, n is the speed of the propeller and D is the diameter of the propeller.

The Advance Coefficient (J) equation is:

$$J = \frac{V_A}{nD}$$

where V_A is the speed of advance of the propeller through the water.

Below are some propeller examples:



Source: U.S. Navy (David Taylor Model Basin)   Source: Kort Propulsion

(a) Skewed, fixed-pitch propeller   (b) Nozzle/ducted propeller

Figure 3-7. Propeller examples

The propeller in Figure 3-7(b) has a shroud around it (thrusters and other propulsion devices can also have shrouds). Shrouds minimize energy and thrust losses by keeping the water displaced by the propeller flowing in the direction of desired thrust. For the AUVSI competition, shrouds are also required for safety reasons.

3.3.1.2 Types

- Fixed: A fixed propeller's blades cannot be adjusted.
- Variable Pitch: The blades on the hub can be rotated to assume a different pitch, which changes the angle of attack of the blades.
- Contra-rotating: In this design, there are two sets of blades on one axis. These blades rotate in opposite directions so that the aft propeller can recover some of the rotational energy imparted to the water by the forward propeller, making it more efficient than just one prop. In addition, two sets of blades allows smaller propeller diameter.

3.3.1.3 Propeller Pros and Cons

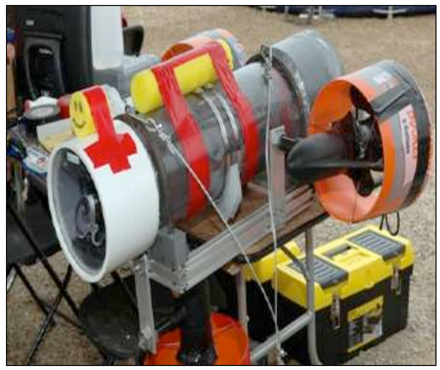
Advantages	Disadvantages
Very Efficient	Need rudder for maneuvering
	No redundancy
	Cavitation
	High Drag

3.3.2 Podded Propulsors

3.3.2.1 Concept

A podded propulsor uses a propeller for thrust production, but the propeller is behind a pod which allows smooth fluid flow over its body. A pod (see Figure 3-8) is a smooth cylindrical encasement which contains the motors for the propeller behind it. This extra housing allows more flexibility in arrangements and more space in the hull for other machinery. The pod can be attached to the main vehicle hull with a fixed or azimuthing wing/bar.
Below are some examples of pods:

(a) Podded propulsor on a ship



(b) Previous AUVSI competition thruster

Figure 3-8. Podded propulsors

3.3.2.2 Podded Propulsor Pros and Cons

Advantages	Disadvantages
Azimuthing: Excellent maneuvering capabilities	Loads: design issue with bearings to turn pods under large loads
Simplified plant & automation w/all electric ship	Cost: More than traditional propulsion devices
Low noise / vibration due to an almost uniform wake field	Power losses due to electric propulsion
Fuel savings through good hydrodynamic efficiency	
Arrangements: less ship space taken up by shafting and motors since motor is outside of ship in pod	

3.3.3 Jets

3.3.3.1 Concept

A jet also creates thrust by moving water, but it moves the water internally to the hull by using intakes at the side or front of the hull and then running the intake water through ducts. The water passes through a turbine inside the hull and is pushed out the aft end of the vehicle. Jets can also help in maneuvering if they have "buckets" at the vehicle exit. Buckets are similar in shape to pipe elbows which channel the exhaust water in different directions according to how they are moved. Figure 3-9 shows an example of a water jet with buckets.

Figure 3-9. Jet propulsion system with buckets

3.3.3.2 Types

- Water jet
- Pump jet

3.3.3.3 Jet Pros and Cons

Advantages	Disadvantages
Powerful	Less efficient than a propeller
Can run in shallow water	More vulnerable to debris
Less drag	Can be noisy

3.4 Power

Battery powered underwater vehicles are power limited, which means that the available onboard power has a limited value available over a finite time. The amount of power required for a vehicle can be estimated by the range and speed defined by the mission for which the vehicle is designed.

Power is defined as force times velocity.

$$P = F * v \,, \tag{3.3-5}$$

where P is the power, F is the force and v is the velocity of the vehicle. Therefore, as an initial estimate, the required propulsive power can be evaluated from the drag of the vehicle (D) and the speed at which the vehicle is traveling. From the hydrodynamics of the vehicle, the drag is proportional to the velocity of the vehicle squared. Therefore, the required power is:

$$P = D * v = C_D * A * \frac{1}{2} \rho v^2 * v, \tag{3.3-6}$$

where C_D is the drag coefficient of the vehicle previously defined in the hydrodynamics section. Also, the amount of energy used is defined as the force acting on the vehicle times the distance, or range, over which the vehicle has traveled. Therefore, the amount of energy that must be stored on the vehicle can be estimated as:

$$E = F * d = D * d = C_D * A * \frac{1}{2} \rho v^2 * R \,, \tag{3.3-7}$$

where E is the energy available. The generic term d (distance) can be equated to R, which is the range of the vehicle.

To estimate the range achievable by a vehicle with a given battery pack, the above relationship is rearranged to resolve range, R.

$$R = \frac{E}{C_D * A * \frac{1}{2} \rho v^2} \tag{3.3-8}$$

Other sensors onboard also use power from the battery pack. To include the effect of the power used by the onboard equipment on the range achievable by the AUV, the range equation can be augmented to include the "hotel power," or the power needed to maintain the onboard functions of the vehicle. Referring to the definition of power above, an equivalent force acting on the system can be estimated from the required hotel power:

$$P_H = F_H * v \quad \text{or} \quad F_H = \frac{P_H}{v} \tag{3.3-9}$$

Then, using the energy equation, the total energy required to travel a distance R is:

$$E = (D + F_H) * R \tag{3.3-10}$$

Rearranging to evaluate the range achievable:

$$R = \frac{E}{D + F_H} = \frac{E}{C_D * A * \frac{1}{2}\rho v^2 + \frac{P_H}{v}} \qquad (3.3\text{-}11)$$

Therefore, when selecting the batteries for an AUV, the mission must be well established and defined in order to select and size the required power pack. Table 3-1 gives examples of potential batteries for use in an AUV.

Table 3-1. Battery Characteristics

Battery Type	Energy Density (Whr/kg)	Cycles	Transportation and Storage	Comments
Alkaline	140	1	Simple storage and can be air freighted	Inexpensive, easy to use
Lithium Polymer	190	100's	**CAUTION** MUST CHARGE WITH PROPER CHARGER. **EXPLOSION HAZARD!**	Small size, use with caution
Nickel Cadmium	33	100's	Simple storage and can be air freighted	Good performer – even discharge; Memory effects
Lead Acid	30	10's	Specialized packaging for shipping.	Well known performance
Nickel Metal Hydride	50	100's	Simple storage and can be air freighted.	Similar discharge characteristics to NiCad

Table 3-2. Characteristics of Commonly Used Rechargeable Batteries.

	NiCd	NiMH	Lead Acid	Li-ion	Li-ion polymer	Reusable Alkaline
Gravimetric Energy Density (Wh/kg)	45-80	60-120	30-50	110-160	100-130	80 (initial)
Internal Resistance (includes peripheral circuits) in mW	100 to 200[1] 6V pack	200 to 300[1] 6V pack	<100[1] 12V pack	150 to 250[1] 7.2V pack	200 to 300[1] 7.2V pack	200 to 2000[1] 6V pack
Cycle Life (to 80% of initial capacity)	1500[2]	300 to 500[2,3]	200 to 300[2]	500 to 1000[3]	300 to 500	50[3] (to 50%)
Fast Charge Time	1h typical	2-4h	8-16h	2-4h	2-4h	2-3h
Overcharge Tolerance	moderate	low	high	very low	low	moderate
Self-discharge / Month (room temperature)	20%[4]	30%[4]	5%	10%[5]	~10%[5]	0.3%
Cell Voltage (nominal)	1.25V[6]	1.25V[6]	2V	3.6V	3.6V	1.5V
Load Current - peak - best result	20C 1C	5C 0.5C or lower	5C[7] 0.2C	>2C 1C or lower	>2C 1C or lower	0.5C 0.2C or lower
Operating Temperature (discharge only)	-40 to 60°C	-20 to 60°C	-20 to 60°C	-20 to 60°C	0 to 60°C	0 to 65°C
Maintenance Requirement	30 to 60 days	60 to 90 days	3 to 6 months[9]	not req.	not req.	not req.
Typical Battery Cost (US$, reference only)	$50 (7.2V)	$60 (7.2V)	$25 (6V)	$100 (7.2V)	$100 (7.2V)	$5 (9V)
Cost per Cycle (US$)[11]	$0.04	$0.12	$0.10	$0.14	$0.29	$0.10-0.50
Commercial use since	1950	1990	1970	1991	1999	1992

(from http://batteryuniversity.com/partone-3.htm)

Note: Data based on average ratings of batteries available commercially at the time of publication; experimental batteries with above average ratings are not included (Ref. http://www.buchmann.ca/default.asp)

3.4.1.1 Power Systems Primary and Secondary

Power system design may be divided into two subsystems. For example, a primary system may be used to power the propulsion system and a secondary system may be used to power sensors and on-board computers. Using subsystems may prove advantageous when trying to provide sensors, computers, and other components with a non-noisy power source.

Power Management: examples may be found at the following web address:
http://www.batterypoweronline.com/eprints/free/tisept05.pdf

3.4.1.2 References

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Nickel metal hydride:
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Alkaline:
http://en.wikipedia.org/wiki/Alkaline_battery
http://es.epa.gov/techinfo/facts/pro-act5.html

NiCad:
www.megabatteries.com
www.microbattery.com

Batteries overview:
http://ibet.asttbc.org/batterys.htm

3.5 Navigation

We define *navigation* as the accurate determination of position, velocity, and orientation relative to a known reference. Our discussion of this topic shall be limited to the problem of underwater vehicle navigation with organic instruments. Accordingly, we will not address navigation solutions that require underwater beacons or *a priori* maps. We shall discuss two traditional approaches to underwater navigation, the deduced reckoning, or "dead reckoning" (DR) technique, and inertial-based navigation. A relatively new approach known as Concurrent Mapping and Localization (CML) will also be described briefly. The report by Leonard *et al* (1998a, see references in section 3.4.5) provides a more detailed overview of underwater vehicle navigation technology.

3.5.1 Dead-Reckoning Navigation

DR relies on measuring the vehicle's speed and direction of travel. If the initial vehicle position is known, it can be updated by integrating the velocity measurement along each reference frame axis. If V(k) and ψ(k) denote, respectively, the vehicle's speed and heading at discrete time k, the DR position (X_N, Y_E) in north and east coordinates is computed as follows:

$$X_N(k+1) = X_N(k) + V(k)\cos[\psi(k)], \text{ k=0,1,2, …, XN(0) = X0} \tag{3.4-1}$$
$$Y_E(k+1) = Y_E(k) + V(k)\sin[\psi(k)], \text{ k=0,1, 2, …, YE(0) = Y0} \tag{3.4-2}$$

Underwater vehicle velocity is frequently measured with a Doppler Velocity Log (DVL) sensor. Other devices like a paddle wheel or a propulsion shaft speed counter can be used, too, although these are less accurate. Vehicle heading can be measured with a magnetic compass, or with instruments like a gyrocompass for increased accuracy. The initial position (X_0,Y_0) can be determined with a GPS fix while the vehicle is on the surface.

A simple geometric analysis of the DR algorithm shows the nominal relationship between navigation instrument errors and position estimation error. With a DVL sensor, the measured vehicle speed, $\tilde{V}$ is,

$$\tilde{V} = (1+\alpha)V, \tag{3.4-3}$$

where α is the DVL scale factor error and V is the true speed. The measured heading, $\tilde{\psi}$ is,

$$\tilde{\psi} = \psi + \Delta\psi. \tag{3.4-4}$$

Here ψ is the true vehicle heading and $\Delta\psi$ is the heading measurement error. With DR, vehicle position is estimated by integrating the north and east components of velocity,

$$\tilde{V}_N = \tilde{V}\cos(\tilde{\psi}) = (1+\alpha)V\cos(\psi+\Delta\psi), \tag{3.4-5}$$
$$\tilde{V}_E = \tilde{V}\sin(\tilde{\psi}) = (1+\alpha)V\sin(\psi+\Delta\psi). \tag{3.4-6}$$

Figure 3-10 shows the effect of a speed scale factor and heading bias error. These combine to produce a radial position error. If heading error is zero, the speed scale factor causes the navigation algorithm to over-predict or under-predict the displacement by ΔN, depending on the sign of α. If the scale factor is zero, a small heading error results (approximately) in a lateral position displacement ΔE.

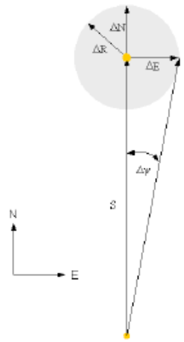

Figure 3-10. DR Position Estimation Error

The position error of an underwater navigation system is commonly expressed as a percent of distance traveled. Given an apparent travel distance S, the percent distance traveled error, D is defined as,

$$D = \frac{\Delta R}{S} \times 100 , \tag{3.4-7}$$

where the radial error, ΔR is a function of the north and east position deviations. For small heading error, the north and east position errors are,

$$\Delta N = (1+\alpha)S - S , \tag{3.4-8}$$

$$\Delta E \approx S \times \Delta\psi . \tag{3.4-9}$$

Therefore,

$$D = \frac{\sqrt{\Delta N^2 + \Delta E^2}}{S} \times 100 = \sqrt{\alpha^2 + (1+\alpha)^2 \Delta\psi^2} \times 100 . \tag{3.4-10}$$

For example, if $\alpha = 0.004$ and $\Delta\psi = 1°$, then D=1.8%. Therefore, on a 100-meter travel path, the final position error would be about 1.8 meters. This error is in addition to the measurement error in the initial position fix.

3.5.1.1 Magnetic Compass

A magnetic compass is frequently chosen for measuring vehicle heading. The compass measures heading relative to the horizontal component of the local earth magnetic field vector. If the orientation of the local field with respect to north is known, the compass measurement can be converted to a true north value.

Modern compasses are generally made from fluxgate or magneto-resistive devices. The fluxgate compass consists of an orthogonal triad of fluxgate magnetometers that measure the local magnetic field in three dimensions. If the vehicle attitude (roll and pitch angle) is known, the fluxgate readings can be translated to the horizontal plan to compute a magnetic heading measurement. A magneto-resistive sensor is an electronic component made of *permalloy* (nickel-iron magnetic strips) that changes electrical resistance with the applied magnetic field (Caruso 2003). An orthogonal triad of these sensors can measure the magnetic field like a fluxgate compass.

Magnetic compasses are relatively inexpensive and rugged, which makes them an attractive choice for small vehicle underwater navigation. However, the compass is sensitive to significant sources of measurement error that must be understood and managed. Healy (1998), Yun (1998) and Bourgeois (1999) discuss practical experience with compass errors in underwater vehicles.

Local Magnetic Field. To convert the compass reading to a true north measurement, the orientation of the local magnetic field must be known. The local magnetic deviation (the orientation of the horizontal magnetic field with respect to north) is usually obtained from nautical charts or a magnetic deviation calculation utility. Local magnetic deviation values originate from the World Magnetic Model (WMM) (McMillan 2000), a truncated spherical harmonic model of the earth's main magnetic field. The accuracy of magnetic deviation based on this model is about 1° root-mean-square (NOAA 2005). This limitation should be accounted for when analyzing the navigation position estimation accuracy, as discussed previously.

In addition, the WMM accounts only for the main component of the earth field, and not for temporal or spatial variations. Local anomalies can alter significantly the earth magnetic field, thus requiring a different magnetic deviation correction than the one predicted by the WMM. In particular, the user must take into account the effect of nearby man-made structures. For example, the structural steel beams and rebar on a dock can distort the magnetic field.

The user should be aware that magnetic deviation changes geographically. Therefore, a correction valid at one location might be incorrect after the system travels a few kilometers to a different location.

Finally, it should be noted that the parameters of the WMM are updated every five years. The user should verify that the magnetic deviation value has been calculated with the latest WMM coefficient set (currently, the year 2005 parameters).

Vehicle Magnetic Field. Like local anomalies, the vehicle's own magnetic signature can alter the local earth field. However, the vehicle-induced distortion results in a sinusoidal, heading-dependent error, instead of a bias error. This error is known as the *permanent magnet*, *hard-iron*, or *one-cycle* error (Navy 1969; Bowditch 1995; Healy *et al* 1998; KVH 2003).

The vehicle's permanent magnet field is formed from magnetized materials and components. The orientation relative to north of this magnetic vector follows vehicle heading. Therefore, the change in local magnetic deviation caused by the permanent magnet vector will be zero when the vehicle's field is parallel to the local earth field and maximum in magnitude when the vehicle's field is orthogonal to the earth's field. This results in a heading-dependent alteration of the magnetic net local vector. Figure 3-11 illustrates the problem. In the figure, X-Y represent the vehicle's reference axes, and N-E the north-east reference frame. The angle ψ is the true vehicle heading. **H** denotes the earth's magnetic field vector with magnetic deviation ψ_H relative to north. **P** is the vehicle's permanent magnet vector, which is oriented at an angle ψ_P relative to X. **M** = **H** + **P**, is the net local magnetic field sensed by the compass. Therefore, the compass measures the heading angle $\tilde{\psi}$, which must be corrected by the angle $\Delta\psi$ (rather than ψ_H) to calculate vehicle heading relative to north.

From Figure 3-11, it is simple to derive an expression relating the true and measured heading in terms of the earth's field and the permanent magnet vector. Define the angle $\theta \equiv \Delta\psi - \psi_H$. Then, according to the Law of Sines,

$$\frac{\sin(\theta)}{|\mathbf{P}|} = \frac{\sin(\Delta\psi - \psi_H)}{|\mathbf{P}|} = \frac{\sin(\psi + \psi_P)}{|\mathbf{H}|} . \qquad (3.4\text{-}11)$$

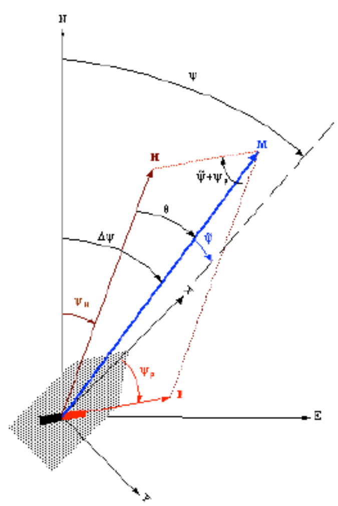

Figure 3-11. Compass Measurement Error Due to Hard Iron and Magnetic Deviation

Solving this equation for $\Delta\psi$ yields,

$$\Delta\psi = \psi_H + \sin^{-1}\left(\frac{|\mathbf{P}|}{|\mathbf{H}|}\sin(\tilde{\psi} + \psi_P)\right). \qquad (3.4\text{-}12)$$

If $|\mathbf{P}| << |\mathbf{H}|$, the previous equation simplifies to,

$$\Delta\psi \approx \psi_H + \frac{|\mathbf{P}|}{|\mathbf{H}|}\sin(\tilde{\psi} + \psi_P). \qquad (3.4\text{-}13)$$

Therefore, the heading error induced by the vehicle's permanent magnet vector is a sinusoidal error with amplitude equal to the ratio of the magnitudes of **P** and **H**, and phase angle ψ_P. The true heading is given by,

$$\psi \approx \tilde{\psi} + \psi_H + \frac{|\mathbf{P}|}{|\mathbf{H}|}\sin(\tilde{\psi} + \psi_P). \qquad (3.4\text{-}14)$$

<u>Compass Calibration</u>. If **P** and **H** are known, the last equation can be used to correct the measured heading, yielding the true vehicle heading with respect to north. Therefore, compass calibration involves determining these two vectors. In principle, **H** can be obtained from WMM, and **P** can be determined by conducting a one-time calibration of the system. When the vehicle moves to a new area, the local value of **H** from WMM can be used to determine ψ_H and the new ratio $|\mathbf{P}|/|\mathbf{H}|$. This eliminates the need to calibrate the system in each operating area.*

In practice, determining **P** can be difficult. The part of **P** due to hard iron materials can be measured in the lab. However, electrical currents also contribute to the net **P** vector. These can only be measured accurately while the vehicle is running in normal operating conditions. Therefore, it is preferable to calibrate the compass in water to determine ψ_H, the ratio $|\mathbf{P}|/|\mathbf{H}|$ and ψ_P.

Note that compass manufacturers provide utilities to calibrate the compass on land. The process consists in setting the vehicle to several known headings to allow the sensor to calculate internally the parameters of the heading correction equation. As discussed above, this approach ignores the change in **P** that occurs when the vehicle is in the water, so it may yield a less accurate calibration.

Healy *et al* (1998) demonstrated a real-time compass calibration procedure for a small AUV using an extended Kalman filter to estimate compass error. Another in-water calibration approach is to compare the navigation position estimated with the DR algorithm (which is affected by the compass error) to GPS fixes collected when the vehicle surfaces. If the submerged tracks are long enough and have varying orientation, the effect of compass error is observable as a difference between the GPS and DR position solutions. From these differences,

* Gebre-Egziabher *et al* (2001) developed an alternative algorithm for calibrating the compass in the magnetic field domain instead of the heading domain as done here. That algorithm relies also on the WMM.

the error model parameters may be estimated by numerical methods like non-linear least squares estimation.

Other Compass Errors. *Soft-iron* or *induced magnetism* error is another heading-dependent compass error (Navy 1969, KVH 2003). This error, also known as the *two-cycle* error, is similar to the permanent magnet error but is caused by ferromagnetic materials whose magnetic moment change depending on the orientation relative to the earth's field. In this case, the sinusoidal error goes through two full cycles as heading changes through one full turn. Typically, the amplitude of the two-cycle error is lower than the one-cycle error and can often be ignored.

System Integration. Every effort should be made to place the magnetic compass as far as possible from magnetic sources within the vehicle. Some obviously undesirable sources include the propulsion motor, thrusters and actuators, and power distribution systems. The magnetic signature of power distribution cables can be minimized by twisting (braiding) the positive and negative wires together. Another mitigation strategy is to use non-magnetic materials (plastics, composites, or fiberglass) for the fabrication of the vehicle hull and internal structures. In a small vehicle, finding a magnetically "clean" area for installing the compass can be difficult. Laboratory experiments in which the compass is placed at different locations within the vehicle can help identify the spot with the least amount of magnetic interference.

3.5.2 Inertial Navigation

Another traditional underwater navigation method is inertial-based navigation. This technique uses an orthogonal triad of inertial accelerometers to sense vehicle accelerations along each reference frame axis. The functional elements of an Inertial Navigation System (INS) are shown in Figure 3-12. The accelerometer data must be corrected to account for the effect of gravity. Rate gyroscope data is processed to estimate vehicle attitude (roll, pitch, and heading). These outputs are used to translate the accelerometer readings from the strapdown instrument frame to the navigation frame. The transformed signals are then integrated to determine velocity and position along each navigation frame axis.

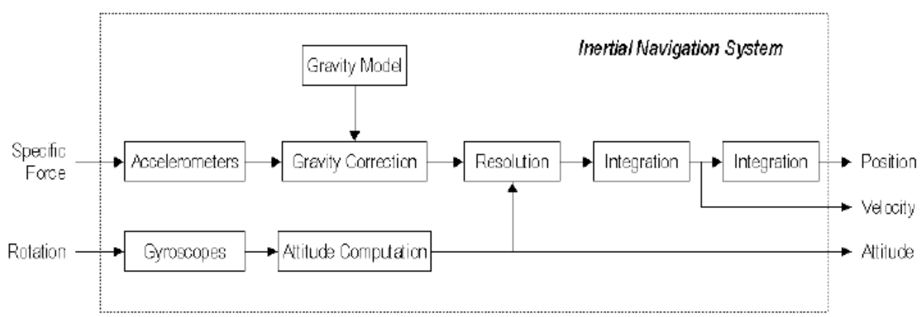

Figure 3-12. Functional Components of an Inertial Navigation System (Titterton and Weston, 1997)

The core element of an INS is the Inertial Measurement Unit (IMU), which contains the accelerometer and rate gyro orthogonal triads. The outputs of a modern IMU are changes in velocity and attitude angle ($\Delta V, \Delta\theta$) at some fixed sampling rate. Modern IMUs are strapdown devices in which the accelerometers and rate gyros maintain their orientation relative to the vehicle's axes.* A navigation-grade rate gyro is usually a ring-laser or fiber-optic design with bias (drift rate) of about 0.01 degrees/hour. In recent years, Micro-electromechanical Systems (MEMS)-based accelerometers and gyros have improved in quality and are being used for navigation applications (Lawrence 1998, Barbour 1998).

INS data contains errors due to measurement biases in the accelerometers and attitude computation errors. Although the bias may be small, the double integration of an acceleration error results in a position drift proportional to the square of time. Therefore, no matter how small a bias is, at some point in time the induced position error will be significant. A typical navigation-grade INS has stand-alone position error drift of about 1.5 kilometers per hour, which is too large for most small underwater vehicle applications.

INS data can be combined with other navigation instruments to reduce position drift. For organic applications, the common solution is to blend the INS data with a DVL and GPS (for initialization and periodic position resets). The data is combined with an extended Kalman filter that estimates the error in the INS outputs by comparing the data to the DVL and GPS measurements. The error estimates are removed from the INS data to yield measurements with significantly lower drift rate. With good-quality INS and DVL, it is possible to reduce the position drift from 1.5 kilometers/hour (INS alone) to 5 meters/hour (INS-DVL).

Kelly (1994), Titterton and Weston (1995), and Farrell and Bart (1999) provide good practical introductions to the subject of inertial navigation systems, including aided INS. A more thorough treatment of the subject is given by Chatfield (1997).

Practical Considerations. An aided INS can provide accurate underwater navigation without the difficulty of magnetic error calibration discussed earlier. While a well-calibrated compass may achieve measurement errors of about 0.5° to 1°, an aided INS can measure heading with an accuracy of 0.1° or better. The primary drawback of an INS is cost, which ranges from $90,000 to $100,000 for a navigation-grade instrument. With a DVL and GPS receiver, the cost may increase to $120,000 to $150,000. In addition, an INS weighs more and consumes more volume and power, which are critical factors for small underwater vehicles.

Another practical consideration is the alignment process. The INS must be initialized each time it powers up to determine its orientation relative to the navigation axes. This process requires the system to be nearly stationary or moving slowly, and have access to GPS. Alignment may take from 5 to 40 minutes, depending on INS model and desired navigation accuracy.

3.5.3 Attitude and Heading Reference System

An alternative use of an IMU is the Attitude and Heading Reference System (AHRS). In this application, the IMU is used only to measure vehicle attitude (roll, pitch, and possibly heading). Sensors like a pendulum pot measure roll and pitch, but have a relatively narrow response

* In older IMUs the accelerometers are installed on a platform that is mechanically rotated to maintain its orientation relative to the navigation (north-east-down) reference frame. These are known as *gimballed* IMUs.

bandwidth. If the navigation application requires higher attitude bandwidth, an AHRS may be the best solution.

A rate gyro can be used to estimate attitude by integrating the measured angular rate. However, the gyro bias will cause the estimated angle to drift over time. Filtering the signal with a high-pass filter to remove the bias also removes the true low-frequency vehicle motion, which may be unacceptable. The AHRS solves this problem by using the accelerometers as a low-frequency attitude sensor. The measured horizontal components of the gravity vector are indicators of vehicle roll and pitch. The AHRS numerically integrates a high-pass filtered rate gyro signal and blends it with a low-pass filtered attitude signal from the accelerometer to produce an estimate of roll or pitch over the entire frequency response bandwidth.

Figure 3-13 is a block diagram of the AHRS filter structure for single angle estimation. The parameters ζ and ω_n are filter parameters that determine the high- and low-pass filter frequency response. The "angle from acceleration" signal is the low-frequency angle estimate. For pitch, the angle from acceleration is $\theta = \sin^{-1}(a_X)$, where a_X is the axial accelerometer measurement. For roll, $\phi = \sin^{-1}(a_Y)$, where a_Y is the lateral accelerometer reading. Comparison of the estimated angle to the angle derived from acceleration measurements allows the filter to estimate the rate bias, which is removed from the angular rate measurement prior to integration.

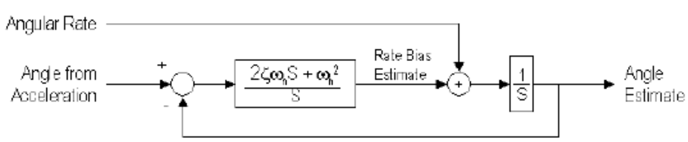

Figure 3-13. AHRS Attitude Estimation Filter Structure

The AHRS filter structure is known as a *complementary* filter. From Figure 3-13, the transfer function from acceleration-derived angle (a_G) to the output angle estimate, φ (roll or pitch), is a second order low-pass filter given by:

$$H_l(s) = \frac{\varphi}{a_G} = \frac{2\varsigma\omega_n s + \omega_n^2}{s^2 + 2\varsigma\omega_n s + \omega_n^2}. \tag{3.4-15}$$

At the same time, the transfer function from the measured angular rate to the output angle is a second order high-pass filter given by:

$$H_h(s) = \frac{\varphi}{\dot{\varphi}} = \frac{s^2}{s^2 + 2\varsigma\omega_n s + \omega_n^2}. \tag{3.4-16}$$

Notice that $H_l(s) + H_h(s) = 1$. Therefore, the two filters complement each other.

Gravity measurements are not useful to estimate heading. For this angle, the low-frequency acceleration reference can be replaced by a magnetic compass. Of course, doing so carries the burden of compass calibration discussed earlier.

Yun *et al* (1997) describe the use of a complementary filter approach for underwater navigation. In addition, it is interesting to note that under certain conditions a steady-state navigation Kalman filter behaves like a complementary filter (Maybeck, 1979).

3.5.4 Concurrent Mapping and Localization

Concurrent Mapping and Localization (CML)* is a relatively new approach to underwater navigation. The goal of this method is to build a map of the environment and simultaneously use this map to assist in navigation. With CML, the vehicle constructs a map by sensing landmarks with an on-board sensor like a forward-look sonar (FLS). Each re-observation of a mapped landmark provides information about the navigation position drift. Due to the need for landmarks, CML is better suited for navigation in areas with a relatively large, uniform contact density, where the likelihood of encountering landmarks frequently is high.

One approach to CML is known as the *stochastic map*. In this method, the position coordinates of each contact are elements of extended Kalman filter state vector. The filter state tracks landmarks as well as the estimated vehicle position. As new landmarks are detected, the state vector is augmented with the new landmark coordinates.

Some of the technical challenges that must be overcome with CML are:

- Contact Management: With each sonar return, the on-board system must decide whether the contact is real or a spurious sensor measurement. If the contact is deemed real, the system must then decide whether it is a new contact or a re-observation of an existing landmark (data association problem). Since the position coordinates of each contact must be tracked, each new landmark increases geometrically the computational load.

- Filter Divergence: If the CML algorithm associates a new sonar return with the incorrect landmark in multiple cycles, the estimation filter will be updated with incorrect information. This can lead to a condition in which the filter trusts its own state estimate more than the new measurements even though the filter state is wrong (filter divergence).

In spite of these and other difficulties, CML is an attractive concept because it enables the possibility of long-term submerged navigation without the need for frequent GPS fixes to keep the navigation position error bounded.

Leonard *et al* (1998b) describe a simulation analysis of CML based on stochastic maps, while Feder *et al* (1998) have proposed a hybrid estimation approach to CML. Carpenter (1998) reported the application of the stochastic map method using actual FLS data, while Hwang *et al* (2004) have applied Carpenter's work to a small underwater vehicle. The application of CML with side-scan sonar data has been investigated by Tena-Ruiz *et al* (2004).

* Also known as Simultaneous Localization and Mapping (SLAM).

3.5.5 References

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3.6 Control Systems

Closed loop, or feedback automatic control systems are a standard element of autonomous and semi-autonomous underwater vehicles. For example, a control loop enables the vehicle to follow and maintain an ordered heading, or a desired depth or altitude above the bottom. The closed loop control system generates an actuator command signal for the rudder, stern plane, or thruster that enables the vehicle to follow the external command. In these examples, the external command (ordered heading, depth, or altitude), originates from a higher level in the vehicle's autonomous intelligence architecture, like a pre-loaded sortie plan, reactive obstacle avoidance guidance, or a homing algorithm.

Figure 3-14 illustrates the elements of a closed-loop control system. The figure describes a single-input, single-output system, but similar principles apply to multi-variable systems. The system being controlled is commonly known as the *plant*. If the plant behaves like a linear, time-invariant system, it can be represented by a Laplace transform transfer function, G(s). The controlled signal, *y*, is one of the states of the plant, for example heading or depth. The actuator signal – rudder, stern plane, or thruster – is represented by δ. The signal *c* denotes the external desired value for *y*, such as the heading or depth command.

The control system is made up of a pre-filter function, P(s), and a feedback compensator, K(s). These elements can be a constant or a more complex function. The compensator compares the filtered command setting to the measured value of the output and adjusts the actuation signal to force the output to follow the command.

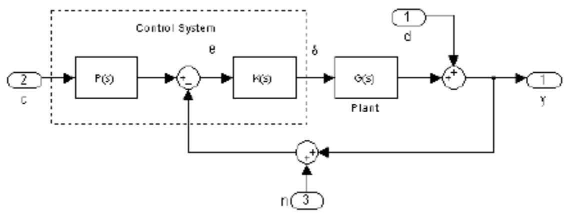

Figure 3-14. General Feedback Control System

The measured output signal is usually corrupted by sensor noise, *n*, which limits the control system's ability to regulate the output precisely. The system may also be affected by an external disturbance, *d*, like an ocean current or wave, which disrupts the output signal.

From , we can derive the following fundamental relationships of feedback control design:

$$\mathrm{T(s)} = \frac{\mathrm{G(s)K(s)}}{1 + \mathrm{G(s)K(s)}}, \tag{3.5-1}$$

$$y = \mathrm{T(s)P(s)}c - \mathrm{T(s)}n + \left[1 - \mathrm{T(s)}\right]d. \tag{3.5-2}$$

The function T(s) is known as the closed loop transfer function. Some key attributes and trade-offs in control system design can be inferred from equations 3.5-1 and 3.5-2 as described below:

- Equation (3.5-1) shows that if the compensator function is large such that G(s)K(s) >> 1, then T(s) ≈ 1, independent of the plant. Therefore, by properly designing K(s) the control system allows the output signal to follow the command even if the plant dynamics do not behave exactly as the model, G(s). This reduced sensitivity or robustness to modeling error is the key advantage of feedback control.
- From Equation (3.5-2), making T(s) ≈ 1 also allows the control system to reject an external disturbance. In practice it is not possible to achieve this across all frequencies, but it may be done in the frequency band where the disturbance occurs.

- Making the closed loop system insensitive to modeling error implies that the measurement noise is also allowed to disrupt the output. Therefore, there is a fundamental trade-off between making the control system robust and insensitive to disturbances, and rejecting measurement noise.

Another important factor is the practical limit of control energy. Making K(s) large may require the actuator device to exceed its position limit or maximum motion rate. Hence, there is a trade-off between large control gain and limited control energy. This trade-off exists regardless of which control design technique is used.

3.6.1 Control Design Methods

The control design process consists of selecting K(s) and P(s) so that the system follows the command signal as closely as possible while accounting for the trade-off in disturbance rejection, noise rejection, and limited control energy. There are many control design methods and the discussion of each approach is beyond the scope of this document. We shall mention a few techniques demonstrated in underwater vehicle applications and provide references, but limit detailed discussion to the classical control method.

3.6.1.1 Classical Control Design

This is a frequency domain design technique suitable for linear, time-invariant plants. The classical method selects the compensator parameters to shape the closed loop transfer function as needed to achieve desired control attributes like fast response (large bandwidth), band-limited disturbance rejection, measurement noise rejection, or modeling robustness (stability margins). A classical control autopilot consists of a proportional-integral-differential (PID) control rule of the form,

$$\delta = K_p e + K_i \int e \, dt + K_d \dot{e}, \tag{3.5-3}$$

where K_p, K_i, and K_d are, respectively, the proportional, integral, and differential gains (design parameters), and *e* is the feedback error. Classical control design methods are discussed by D'Azzo and Houpis (1981), and Ogata (1987). The MATLAB® control design toolbox contains many easy-to-use classical design functions, including the interactive sisotool() function for single-input, single-output systems.

3.6.1.2 Sliding-Mode Control

This technique has been used for controlling both hydrodynamically-shaped autonomous underwater vehicles and slow-moving remotely-operated vehicles (ROVs), for which hydrodynamic forces are more difficult to predict. The sliding mode controller has a linear part that may be designed using any classical or modern method, and a nonlinear part that depends on the magnitude of uncertainty in the plant model. This feature yields increased robustness for controlling systems that are nonlinear or poorly modeled. The application of Sliding Mode control to hydrodynamically-shaped underwater vehicles is discussed by Cristi and Healy (1990), Healy and Leinard (1993), Willy (1994), and Fossen (2002). For ROVs, the work of Yoerger and Slotine (1985), Yoerger, Cooke and Slotine (1991), or Slotine and Li (1991) may be consulted.

3.6.1.3 Fuzzy Logic Control

This technique consists of using logical (if-then-else) rules to adapt the control system parameters or architecture to changing plant conditions, like the variation in vehicle dynamic response as a function of speed. The decision rules are blended by means of weighting factors proportional to the degree that the conditions of each rule is satisfied ("membership function"). Thus, the controller output is a weighted combination of all the rules that fire at any given instant. Kanakakis *et al* (2004) provide one example of the application of this technique to free-swimming underwater vehicles, and the application to ROVs is discussed by Farbrother and Stacey (1991), and Wang and George Lee (2003) among many others.

3.6.2 Plant Modeling

To support control system development, a model of the plant, G(s) is needed. The model does not have to be very accurate to be useful. As explained above, feedback control systems provide some insensitivity to modeling errors. A system model allows the designer to develop a preliminary design of the control parameters that can later be tuned based on in-water performance. This approach generally is more efficient and safer than tuning the control parameters in water by trial-and-error. In addition, a system model is very useful as a tool to test and debug the software that implements the controller. A system simulation based on G(s) can generate simulated feedback inputs for the control software. In turn, the control outputs can be fed into the vehicle simulation model to close the loop. Debugging and testing software in a simulation environment is a lot easier and faster than with the vehicle in the water.

References like Prestero (2001) and Fossen (2002) explain how to derive mathematical models of underwater vehicles from hydrodynamic principles. These models are relatively complex, but can be linearized to make them suitable for control design. Vahedipour *et al* (1991) discuss a simpler modeling technique for the ship steering control design that is also applicable to underwater systems, as discussed next.

3.6.3 Lateral Dynamics

A simple model for the lateral dynamics of an underwater vehicle is given by the transfer function,

$$G(s) = \frac{\psi}{\delta} = \frac{K}{s(\tau s + 1)}, \tag{3.5-4}$$

where ψ is the vehicle heading and δ is the rudder angle. The parameter τ is the dominant system time constant, while K is the steady state relation between rudder angle and heading rate. These parameters can be estimated by running the vehicle in water, issuing rudder commands, and measuring the heading rate response. **Error! Reference source not found.Error! Reference source not found.** and Figure 3-16 show a diagram of the system model and the hypothetical response to a 5-degree rudder command. The ratio of the steady state heading rate to rudder angle is K. The time it takes heading rate to reach 95% of its steady state value is approximately 3τ. From the data in the figure, $K \approx 6.33/5 = 1.27$ (radian/second)/radian and $\tau \approx 4.45/3 = 1.48$ sec/rad. Note that in general K and τ vary with vehicle speed. Similar models can be developed for the vertical plane equations.

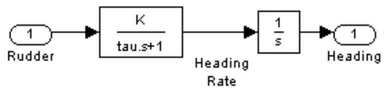

Figure 3-15. Heading Dynamics Model

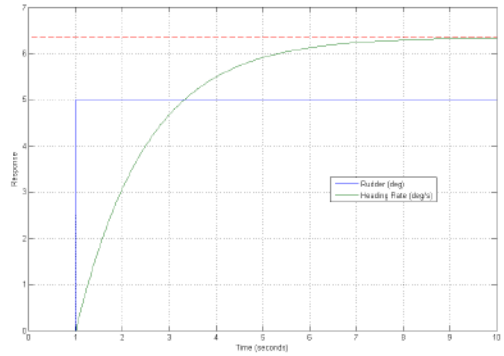

Figure 3-16. Heading Rate Response to Step Rudder Input

3.6.4 Control System Development Example

We now turn to the task of designing a heading control system for the plant of Equation (3.5-4). Using the classical control method, the task is broken into two subtasks. First, a control system is designed for the plant's heading rate output. This control loop computes a rudder angle to follow a desired heading rate command. Second, a heading control loop is designed that calculates a heading rate command as a function of a commanded heading angle. The output of this outer loop becomes the input to the inner rate control loop as shown in Figure 3-17. This control structure is known as nested loop architecture.

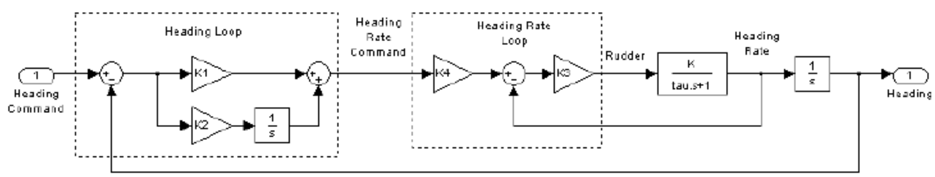

Figure 3-17. Heading Control System in Nested Loop Architecture

It is easy to show that the control structure in Figure 3-17 is equivalent to the following equation:

$$\delta = -K_3\dot{\psi} + K_3K_4K_1(\psi_{com} - \psi) + K_3K_4K_2\int(\psi_{com} - \psi)dt \,. \qquad (3.5\text{-}5)$$

Comparing Equation (3.5-5) to (3.5-3), $K_d = -K_3$, $K_p = K_3K_4K_1$, and $K_i = K_3K_4K_2$. Therefore, the heading control system of Figure 3-17 is a PID autopilot.

3.6.5 Heading Rate Loop

Comparing Figures 3-15 and 3-17, it can be seen that in the heading rate loop $P(s) = K_4$ and $K(s) = K_3$. Then, using Equation (3.5-1), the closed loop heading rate transfer function is,

$$T(s) = \frac{\dot{\psi}}{\dot{\psi}_{\text{command}}} = \frac{KK_3}{\tau s + 1 + KK_3}. \qquad (3.5\text{-}6)$$

The rate feedback gain moves the stability root from $s = -1/\tau$ to $s = -(1+KK_3)/\tau$. Hence, we can choose K_3 to alter the heading rate dynamic response, for example to accelerate the speed of response. Assume that $K = 1.27$ (rad/sec)/rad and $\tau = 1.48$ sec/rad, as in the previous section. Selecting $K_3 = 1$ rad/(rad/sec) moves the root from $s = -0.667$ to $s = -1.513$. Therefore, the closed loop time constant is 0.66 sec/rad or twice as short as the original, which implies a faster system response. The pre-filter gain is set to $K_4 = (1+KK_3)/(KK_3) = 1.787$ (rad/sec)/rad so that the steady state heading rate matches the command.

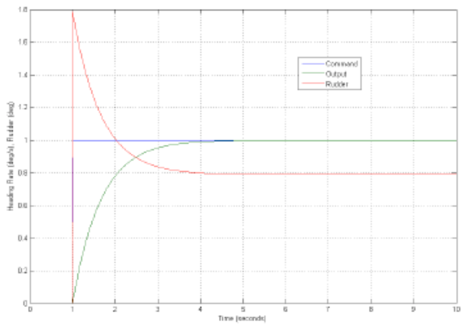

Figure 3-18. Response of the Heading Rate Loop to a Step Command

Figure 3-18 shows the closed loop heading rate system response to a 1°/sec step heading rate command. The figure shows that for this command the required rudder angle is relatively small and therefore, practical. Larger heading rate commands will require proportionally larger peak rudder angles that may exceed the maximum actuator deflection.

3.6.6 Heading Loop

With the inner heading rate loop tuned, the process is repeated for the outer heading control loop. A comparison of Figures 3-15 and 3-17 shows that in the heading control loop $P(s) = 1$ and $K(s) = K_1 + K_2/s$. The closed loop heading rate system becomes part of the new plant:

$$G(s) = \frac{\psi}{\dot{\psi}_{\text{command}}} = \frac{1+KK_3}{KK_3} \times \frac{KK_3}{\tau s + 1 + KK_3} \times \frac{1}{s} = \frac{1+KK_3}{s(\tau s + 1 + KK_3)} = \frac{Q}{s(\tau s + Q)}, \qquad (3.5\text{-}7)$$

where $Q \equiv 1 + KK_3$. Therefore, the heading closed loop transfer function is,

$$T(s) = \frac{QK_1 s + QK_2}{\tau s^3 + s^2 + QK_1 s + QK_2}. \qquad (3.5\text{-}8)$$

The heading control gains provide two degrees of freedom to shape the dynamic response of the system. Setting $K_1 = 0.5$ rad/(rad-sec) and $K_2 = 0.05\ \text{sec}^{-2}$, the closed loop system response to a 10-degree heading command is as shown in Figure 3-19.

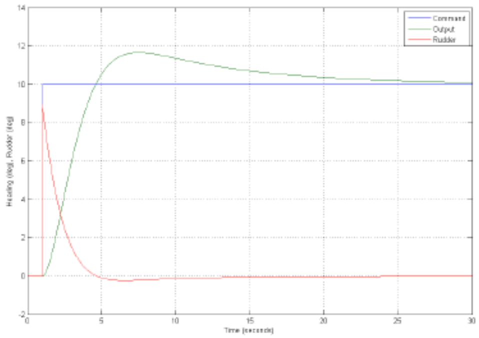

Figure 3-19. Heading Response to a Step Command

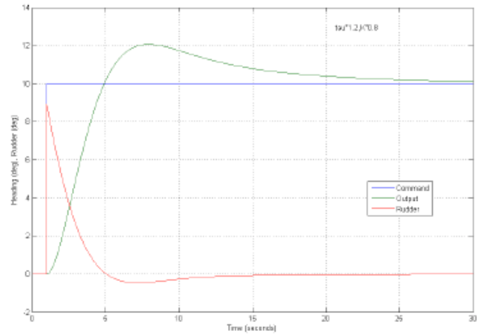

Figure 3-20. Heading Response to a Step Command With 20% Plant Parameter Variation

Consider now a change in plant parameters. If the time constant τ is 20% longer and the plant gain K is 20% smaller, the actual control system responds as shown in Figure 3-20. The heading response has slightly larger overshoot, but still follows the command even though the control parameters were tuned with the incorrect plant model. This example illustrates the inherent robustness of a feedback control system to modeling error.

Development of a control system for the vertical vehicle plane (depth or altitude control) can be done using a similar nested loop architecture, with pitch and pitch rate replacing heading and heading rate, respectively. However, in this case a third loop is needed to calculate a pitch command as a function of depth or altitude position error.

3.6.7 Practical Considerations

3.6.7.1 Actuator Limits

The example presented in the previous section assumed that the dynamic response of the rudder actuator or thruster differential response is very fast relative to the vehicle dynamics and can be ignored. In practice, an actuator may not respond as fast as desired, especially if it uses a DC motor or stepper motor, each of which has relatively large inertia. If the actuator responds slowly, its dynamics should be incorporated into the plant dynamics. This will limit the range of control gain values and generally will result in a slower control response. Ignoring slow actuator dynamics can lead to an unstable or oscillatory control response.

Even if the actuator response bandwidth is large relative to the vehicle, it will have a maximum motion rate (slew rate) and maximum position limit. These nonlinearities come into play when the actuator input commands are large. Large magnitude control gains tend to operate the actuator at the maximum rate or position limit and can result in poor or oscillatory control response. A simulation model of the vehicle and actuator can be used to evaluate the end-to-end control system and if necessary, tune the control parameters.

In addition, it should be noted that practical control fins stall (lose ability to generate lift force) at 15° to 20° deflection. This is a nonlinear hydrodynamic effect not captured by the linear model used for control design. Therefore, a control system that requires 20° to 30° deflections to perform well may not work at all in the water.

Finally, the effect of sensor noise must be considered in tuning the control parameters. Figure 3-18 shows that a control system requires about 2° of rudder angle to respond to a 1°/sec command. It follows that a noisy heading rate sensor with measurement error on the order of ±1 deg/sec will induce rudder commands on the order of ±2°, which can potentially overwhelm the actuator system and even cause mechanical failure. Again, a simulation model can be used to evaluate these effects and tune the control gains, if required.

3.6.7.2 Measurement Filtering

One way to mitigate the effect of sensor error on control system response is by filtering the feedback signals to reduce measurement noise. However, real-time filtering introduces some lag (phase distortion) into the signal, which can destabilize the control response. If a filter is used, it should be included as part of the plant model to ensure that its bandwidth is compatible with the control parameters.

3.6.7.3 Digital Control

The standard practice is to implement the control system equations in a general-purpose digital computer. The sampling required to convert continuous-time signals into discrete ones introduces a destabilizing lag inversely proportional to sampling rate. Therefore, the sampling rate should be as fast as possible, and compatible with the desired response bandwidth. For underwater vehicles, the plant bandwidth typically ranges from 0.1 Hz to 2 Hz, depending on the state (depth, pitch, angular rate, etc.). The minimum control sample rate should be five to ten times faster than the bandwidth to minimize the sampling distortion effect. If this is not possible because the computer is not fast enough, then the control gains must be reduced (i.e., the control response must be slowed down) to make the control system compatible with the sampling rate. The down side of this mitigation approach is that the vehicle reacts more sluggishly and may not be able to maneuver adequately in certain operating conditions.

If the control system includes filters or other high-order compensating transfer functions designed in the continuous-time domain, these will have to be converted to equivalent discrete functions for implementation in software. One commonly used discretization method is the bilinear (Tustin) transformation (Ogata 1987). This technique yields a discrete transfer function at the selected sampling rate that approximates the original continuous transfer function by a means of a trapezoidal numerical integration.

3.6.7.4 Integral Control

Integral feedback is required in any condition where the steady state actuator position needed to achieve the command is not zero. For underwater vehicles, integral feedback is generally required in the depth or altitude control loop. Unless the vehicle is ballasted perfectly at every depth, the control system will require a non-zero stern plane (or thruster force) in order to maintain the ordered depth. Without integral feedback, the stern plane command will be zero once the vehicle reaches the commanded depth. Then, the trim imbalance will force the vehicle to rise or sink. As the control system detects the depth deviation, it issues a non-zero stern plane command to return the vehicle to the ordered depth, and the cycle repeats. Thus, without integral feedback (K_i=0) the depth control response will tend to oscillate about the depth command.

Integral feedback allows the control to "learn" the required stern plane angle to keep the vehicle at depth. The integral term builds up to the steady state stern plane angle that balances the ballast condition.

In the lateral plane, integral feedback is required to counter the effect of water currents while the vehicle travels along a track. In this case the integral term builds up to a value that causes the vehicle to develop a side-slip (crab) angle, which in turn produces enough body lift force in the lateral plane to counter the cross-track water current.

3.6.8 Guidance

We define guidance as the generation of heading commands to achieve some mission objective. As discussed earlier, the commanded heading originates outside the control system function. However, because of its close relation to control, we will discuss briefly three basic guidance functions used frequently with underwater vehicles: Waypoint guidance, Track-following guidance, and Loiter.

3.6.8.1 Waypoint Guidance

This guidance method allows the vehicle to travel to a waypoint, or geodetic location. The waypoint is defined by its coordinates, (X_p,Y_p) in the local navigation reference frame (X pointing north and Y pointing east). Assume that the distance from the current vehicle location (X,Y) to waypoint is short so that the curvature of the earth is not a significant factor. Then, the heading command, ψ_{com} to travel to the waypoint is,

$$\psi_{com} = \tan^{-1}[(X_p-X)/(Y_p-Y)], \qquad (3.5\text{-}9)$$

where the inverse tangent function must be defined in the four quadrants to yield ψ_{com} values in the range ±180°. When the waypoint location is far, the heading command can be computed using spherical trigonometry relations, also known as *great circle sailings* (Maloney 1985).

3.6.8.2 Track-Following Guidance

This guidance method forces a vehicle to travel along a track defined by a pair of start and end points, (X_s,Y_s) and (X_e,Y_e) as shown in Figure 3-19. The track heading is, $\psi_T = \tan^{-1}[(X_e-X_s)/(Y_e-Y_s)]$. The off-track position, Δ of the vehicle relative to the track is,

$$\Delta = (Y-Y_s)\cos(\psi_T) - (X-X_s)\sin(\psi_T). \qquad (3.5\text{-}10)$$

Define a "chase" point at a distance D down track from closest point of approach. The track-relative heading, ψ_C from the vehicle to this point is,

$$\psi_C = \tan^{-1}[\Delta/D]. \qquad (3.5\text{-}11)$$

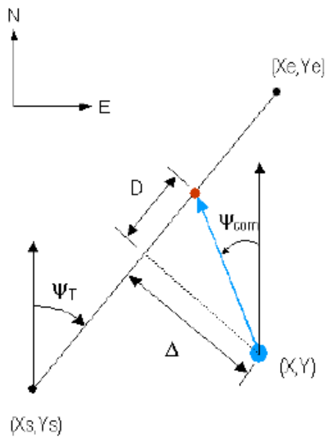

Figure 3-19. Track-Following Guidance

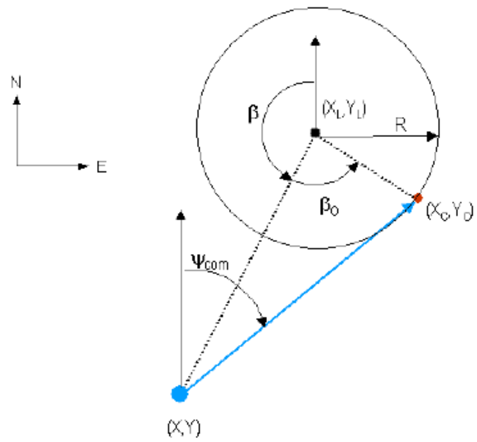

Figure 3-20. Loiter Guidance

Therefore, the heading command with respect to north is $\psi_{com} = \psi_C - \psi_T$. Every heading calculation must use the four-quadrant inverse tangent function.

As the vehicle moves closer to track, the chase point always stays ahead of the vehicle a distance D along track. Thus, the vehicle is commanded to a point that it cannot reach. The process of chasing this point forces the vehicle to capture and move along the desired track.

Notice that if the "look-ahead" distance is large relative to off-track error, the track-relative heading command is approximately, $\psi_C \approx [\Delta/D]$. Thus, the heading command is a feedback of the off-track error, and the look-ahead distance is like a control gain, 1/D. Therefore, D can be designed as a proportional control gain to achieve some desired control characteristics. Large D will result in a smooth but slow track-keeping process. Small D will produce aggressive track keeping, with possibly oscillatory response.

3.6.8.3 Loiter Guidance

This guidance method allows the vehicle to circle (loiter) around a given point (X_L,Y_L) at a radial distance R (Figure 3-20). The idea is similar to the track-keeping guidance. However, instead of chasing a point along a track, the vehicle chases a point located an angle β_0 ("look-ahead" angle) along the loiter circle. The intersection angle, β of the vector from the center of the circle to the vehicle is,

$$\beta = \tan^{-1}[(X-X_L)/(Y-Y_L)]. \qquad (3.5\text{-}12)$$

The coordinates of the chase point are,

$$X_C = R\cos(\beta+\beta_0) + X_L,\ \ Y_C = R\sin(\beta+\beta_0) + Y_L \qquad (3.5\text{-}13)$$

Therefore, the heading command is $\psi_{com} = \tan^{-1}[(X_C-X)/(Y_C-Y)]$.

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3.7 Underwater Acoustics and Sonar

3.7.1 Introduction

This section will attempt to summarize the theory applicable to underwater acoustics and SONAR (SOund NAvigation and Ranging) systems. These areas have been the subject of countless research efforts and an exhaustive tutorial is beyond the scope of this primer. However, there are a few basic principles that one should be aware of when choosing a sonar to perform a function and when trying to predict the performance of that hardware in a particular underwater environment. This brief overview will begin with a summary of the basic principals of underwater acoustic theory, emphasizing the key physics applicable to the expected operating conditions for this competition. There is a brief discussion of sonar systems. This is followed by an introduction to the Sonar Equation and how it is used to understand the expected performance of the sonar system. There is a discussion of signal processing. This will cover typical signal processing techniques that can be used to detect signals of interest. Given the brevity of this primer, the hope is that if nothing else it will inform the reader of areas that should be considered and encourage further study.

3.7.2 Theory

3.7.2.1 Refraction

Sound or pressure waves propagate at the speed of sound, c, for the medium. There are empirical formulas for calculating the exact sound speed. Typically c is 1500 m/s in seawater and 1435 m/s in fresh water. In air c is 340 m/s. These can change as temperature, salinity (for water), and density vary. For gradual changes in these parameters, c changes and the sound wave is bent or refracted. This causes the propagation path to change direction. The propagating pressure wave will bend toward the decreasing sound speed. The refraction angle is calculated, assuming a plane wave and small changes in sound speed, using a form of Snell's Law [1]. This is important to consider if operating in an environment, such as littoral regions of the ocean, where the temperature could change over the course of a day, or in areas near a fresh water outlet where there may be large changes in salinity. However, in the pond where the competition will be held, the sound velocity profile (SVP) is not expected to change appreciably, and can be considered as constant.

3.7.2.2 Reflection

The specific acoustic impedance, z, is defined as the ratio of the acoustic pressure, p, in a medium to the associated particle speed, u, [1]:

$$z = p/u \tag{3.6-1}$$

Assuming a plane wave, this reduces to the characteristic impedance:

$$z = \rho c \tag{3.6-2}$$

where ρ is the density of the medium and c is the sound speed.

If there is a discontinuity in the characteristic impedance, a portion of the pressure/sound wave will be reflected and a portion will be transmitted. The amount transmitted and the amount reflected is dependent upon the relative sound speeds of the two mediums and the incident angle [1]. An example of such a discontinuity would be at the air-water interface or water – seafloor interface. Sound generated at the source will travel through the water, hit the boundary and be reflected, and continue propagating through the medium. The ideal situation would be to receive the direct transmission from the source. However, in a small enclosed area, such as a pool, it is likely that a reflected signal will also be received. As will be explained below, the reflected sound waves can interfere with the receipt of the desired signal. The smaller the bounded area and/or more intense the sound source, the more reflections there will be.

3.7.2.3 Sonar Equation

There are basically two types of sonar systems, active and passive. Active sonar involves both a projector transducer and a receiver transducer. They can either be coincident, monostatic, or separated by some distance, bistatic. Both the projector and receiver are typically constructed from crystalline material that exhibits piezoelectric properties. That is, a charge is developed on the opposite face of the crystal due to an imposed pressure. The projector transducer converts an electrical input into a sound pressure wave that is transmitted into the water column. This electrical input can be a continuous signal or a short burst, or pulse, of constant or varying frequency. The acoustic wave propagates through the medium. It is reflected by the target of interest and returns to the receiver transducer. The receiver or hydrophone receives the signal reflected by a target and transforms the sound pressure into electric signals, which can be recorded. The passive sonar consists of just a receiver transducer and is used to 'listen' to the sound pressure waves generated by the target of interest.

When analyzing the performance of the sonar system in the underwater environment there are several factors that need to be considered, such as the environment, the hardware and the signal processing techniques. The problem can quickly become very complicated. The sonar equation was developed in an effort to simplify the process of evaluating the performance of a sonar system. Each of the parameters in the sonar equation is in dB scale, allowing for a wide range of values to be handled. Below are the sonar equations for both the active and passive sonar systems [2].

$$SL - 2TL + TS = NL - DI + DT \qquad \text{active, noise limited} \tag{3.6-3}$$

$$SL - 2TL + TS = RL + DT \qquad \text{active, reverberation limited} \tag{3.6-4}$$

$$SL - TL = NIL - DI + DT \qquad \text{passive} \qquad (3.6\text{-}5)$$

Where, SL = Source Level
TL = Transmission Loss
TS = Target Strength
NL = Noise Level (background)
RL = Reverberation Level
NIL = Noise Level + Interference (reverberation) Level
DI = Directivity Index (of source and hydrophone in the active case)
And DT = Detection Threshold

For this competition the underwater vehicle will be required to locate an acoustic pinger. This can be accomplished using a passive sonar system that consists of one or more hydrophones. Therefore, the emphasis of this primer will be on passive sonar, Equation 3.6-5. A brief description of each term is given below.

In the passive sonar case, the source level, SL, would be the expected source level of the target of interest, or the acoustic pinger, as measured one meter from the transducer. This is given by:

$$SL = 10 \log (I/I_{Ref}) \qquad (3.6\text{-}6)$$

where, I is the intensity 1 meter from the source and IRef is the reference intensity (typically IRef = re 1μ Pa). This definition assumes that the acoustic energy spreads omni directionally away from the source. However, most acoustic sources are designed to focus the acoustic energy into a narrower beam in order to improve efficiency. This effect is accounted for in the sonar equations by the directivity index (DI), a measure of focusing, which is discussed below.

The transmission loss, TL, is the loss in source level intensity as the sound pressure wave travels through the medium. It is a function of spreading and attenuation. Spreading is geometrical. Two simple approximations used to describe how sound level decreases as a sound wave propagates away from a source are spherical and cylindrical spreading. While these approximations do not provide an exact measure of the spreading loss, taking into account reflections and refraction, spherical and cylindrical spreading can be used to obtain an estimate of sound levels around a source without doing complex computer calculations. These are given by:

$$\mathrm{TL}_{sp} = 20 \log\left(\frac{\mathrm{r}}{\mathrm{r}_{ref}}\right) \quad \text{Spherical - Free field} \qquad (3.6\text{-}7)$$

$$TL_{cyl} = 10 \log\left(\frac{r}{r_{ref}}\right) \quad \text{Cylindrical - Between Plates} \qquad (3.6\text{-}8)$$

Where r is the range or distance from the source in meters and r_{ref} = 1 meter. In the passive case, transmission loss occurs in one direction. Spherical spreading describes the decrease in level when a sound wave propagates away from a source uniformly in all directions. This situation occurs for a sound source at mid-depth in the ocean, for example. Cylindrical spreading is a simple approximation for spreading loss in a medium with upper and lower boundaries. Sound generated by a source in mid-ocean cannot continue to spread uniformly in all directions once it reaches the sea surface or sea floor. Once the sound is trapped between the top and bottom of the ocean it gradually begins to spread cylindrically, with sound radiating horizontally away from the source. Sound levels decrease more slowly as sound spreads from a cylinder compared with the rate of decrease for spherical spreading.

The attenuation is a function of absorption, scattering and leakage. For the purpose of this application, due to the short distances that the sound will be traveling, spreading losses will dominate the transmission loss and attenuation can be ignored.

The received signal can be masked by several other sources of noise. Typically when predicting the performance of sonar systems using the Sonar Equation, only the predominant noise source is considered. Noise is usually placed in one of two categories: in-band noise, NL, or reverberation, RL. There are two main sources of in-band noise, ambient and host platform self-noise. The ambient noise can consist of wind, breaking waves, biological activity, and shipping. This background noise can generally be considered as steady-state and isotropic (equal in all directions). The self-noise is produced by on-board machinery, electronics or the water moving around the receiver. All of these combine to give the noise level (NL). Noise can be attenuated through filtering out the frequency band of interest. The concern is then with the noise that occurs within the band of interest.

The reverberation level (RL) refers to the echoes received from the incident signal scattered from the sea surface, the seafloor, the sea volume and other objects which contaminate the received signal. For the passive sonar case, the reverberation noise level would be the result of the signal traveling along many paths to the receiver, which is known as multi-path (Figure 3-21). It is important to be aware that the sonar may detect the interfering multi-path signals. If these paths are mistakenly assumed to be direct paths then the signal processing may miscalculate the location of the acoustic pinger. The Noise and Interference Ratio (NIL) refers to the contribution from both the in-band ambient noise and interference due to multi-path.

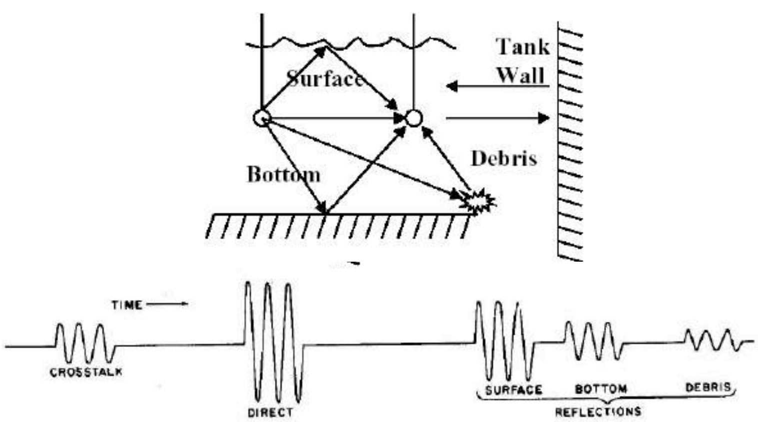

Figure 3-21. Oscillogram showing sequence of pulses at hydrophone position. [3]

The directivity index, DI, is the sum of the array processing gain and the signal processing gain. These will be explained in more detail below. Putting all of these components together, the passive sonar equation is given as:

$$DT \leq SNIR = SL + DI - TL - NIL \qquad (3.6\text{-}9)$$

The detection threshold, DT, is the minimum Signal-to-Noise and Interference Ratio, SNIR, needed at the receiver in order to be able to determine that the target is present.

3.7.3 Signal And Array Processing

One of the main functions of a sonar system is to detect and locate targets. Proper signal and array processing techniques are essential to achieve such functions. The following will discuss these signal processing techniques and concepts, including matched filtering, directivity, array shading and beam steering. It should be noted that this is not intended to provide all of the details needed to implement these processing techniques but to inform and encourage further investigation.

3.7.4 Signal Processing

3.7.4.1 Sampling Theorem

Because the signal processing will most likely be done digitally, the analog signal received at the hydrophone will have to be sampled. This is typically done with an analog to digital (A/D) converter. The A/D converts the impulse voltage into an integer number. Theoretically, when a real signal is sampled, copies of its spectrum (the frequency representation of the signal) occur at multiples of the sampling frequency, Fs. If the signal is not band limited or if the sampling frequency is too low, there will be insufficient separation between the two spectra. The result will be interference, which is termed aliasing. The Nyquist Sampling Theorem defines conditions under which the sampled signal represents no loss of information. It states that a continuous band limited signal of ±F is completely defined by the time-domain samples taken at intervals of $T_N= 1/(2F)$. F is the Nyquist frequency or the highest frequency of interest in the spectra. The Nyquist Sampling Rate is defined as $f_N=2F$. The theorem gives a lower bound on the sampling frequency to assure an unambiguous representation of the signal. To ensure against aliasing it is advisable to pass the received data through low-pass filter prior to processing. A low-pass filter is a filter that passes low frequencies well, but attenuates (or reduces) frequencies higher than the cutoff frequency. Note that the ideal low pass filter is not realizable. In other words, all filters have a transition region and the low pass filter will not stop all frequencies precisely at f_N. It is therefore, recommended that the data be sampled at a frequency greater than two times the highest frequency of interest or $f_N \geq 2F$.

3.7.4.2 Matched Filtering

The Signal to Noise Ratio (SNR) can be improved when the signal received at the hydrophone is matched filtered to the transmitted signal [4]. That is, the received signal is compared to the original emitted pulse. The matched filtering process involves determining the cross-correlation between the received signal and the original transmitted pulse [5], in order to quantify the similarity of these signals. This will, in-effect, remove any uncorrelated noise, hopefully allowing a clear determination of the desired signal.

The cross-correlation, R, of p and s is determined using a convolution integral. This can be effectively evaluated by taking the product of the Fourier transform of s and the conjugate of the Fourier transform of p for the cross spectrum, the frequency domain representation, and then evaluating the inverse Fourier transform. Time shifts in the data at the location of the peak in the correlation are directly proportional to the distance traveled. This is useful, for example, to determine if the vehicle is traveling toward the target from successive pings.

3.7.4.3 Beamforming

Both the projector and hydrophone transducers have a specific beam pattern associated with them. The beam pattern is dependent upon the configuration of the transducer and is given by the Pattern Function, *G(w)*. The transmitted acoustic energy propagates with spherical wave fronts in the shape of the transducer beam pattern. Likewise, the hydrophone receives acoustic energy propagating toward it within its beam pattern.

The angular response of a line hydrophone array to a plane wave arriving at an angle ψ (Figure 3-22) is considered. The hydrophone is aligned with the x-axis. Let the received signal at the origin be p(t). The signal at any point along the hydrophone is given by:

$$p(t,x) = p\left(t + \frac{x\sin\psi}{c}\right) \tag{3.6-10}$$

The total output resulting from a plane wave at angle, ψ , is:

$$p_0(t,\psi) = \int_{-\infty}^{+\infty} g(x)p\left(t + \frac{x\sin\psi}{c}\right)dx \tag{3.6-11}$$

Where, g(x) or the aperture function is the hydrophone response to a unit signal at x.

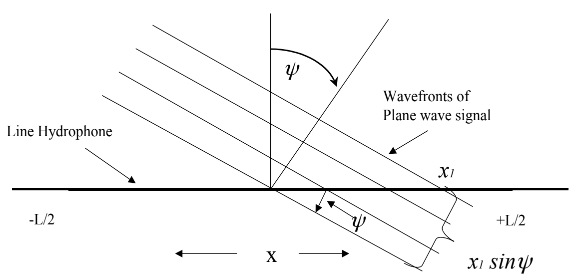

Figure 3-22. Plane wave signal incident on a line hydrophone [5].

The output of the line array can be calculated from the Fourier transform of the aperture function, g(x) and the Fourier transform of the time shifted array response, p(t,x), [5].

$$p_0(t,\psi) = \int_{-\infty}^{+\infty} P(f) G(f,\psi) e^{j2\pi ft} df \tag{3.6-12}$$

For a line hydrophone array comprised of several equally spaced discrete elements the aperture function, g(t) can be considered as a sampled version of the continuous aperture function [4]:

$$g(x) = \frac{d}{L} \sum_{n=-\infty}^{+\infty} \delta(x - nd)\, rect\left(\frac{x}{L}\right) \tag{3.6-13}$$

3.7.4.4 Directivity

The Array Gain (AG) gives an indication of the quality of a spatial filter and is defined as the ratio of the noise power out of an omni-directional receiver to the noise power out of the array receiver. In effect it indicates the improved SNR (Signal to Noise Ratio) over an omni-directional array. For a coherent signal in an isotropic noise field the AG reduces to the Directivity Index (DI). DI can be approximated for a line array as 10log(n), where n is the number of elements in the array spaced at $\lambda/2$.

To determine the location of the acoustic pinger relative to the vehicle, it is required that plane waves arriving from different directions be distinguishable, and that the direction of arrival be discernable. These requirements are similar to frequency-domain filtering used to process narrow-band data. An array sensor is a spatial filter [5] analogous in operation to a frequency-domain filtering operation. This is demonstrated in Figure 3-23.

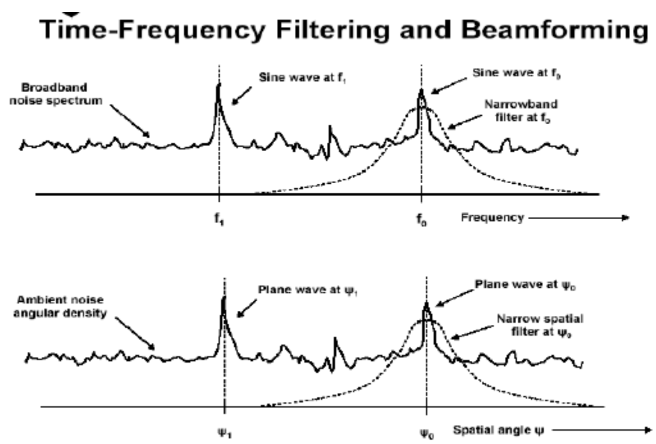

Figure 3-23. Comparison of Time-Frequency and Spatial filtering [5]

The goal of a spatial filter is to enhance the SNR for a particular direction. The SNR for the spatial filter is basically the ratio of the signal intensity density to the noise intensity density. Both are a function of spatial angle. This ratio is then multiplied by the aperture, ψ_B, of the spatial filter response. The aperture is a function of the number of elements in the line array, the spacing of the elements and the frequency. The Fourier transform of the aperture function g(x) is termed the pattern function, *G(w)*, and defines the shape of the spatial filter response provided by the line hydrophone at the frequency of interest, f_0. If the noise field can be considered as constant and isotropic then SNR is inversely proportional to the array aperture.

The ability of a system to distinguish between closely spaced targets and the accuracy of determining the direction of a target is inversely proportional to the aperture. That is, the length of the array contributes to the systems ability to determine the direction of a target. As the length of the array, Nd, increases, the width of the main lobe, ψ_b , decreases. N is the number of elements and d is the element spacing. The optimal spacing for a discrete array of omni-directional elements is generally taken as d=λ/2.

3.7.4.5 Shading

From the plot of the pattern function, G(u) in Figure 3-24, it can be noted that there is a main lobe and side lobes. The noise signal received at the side lobes will reduce the performance of the array. It is beneficial to reduce the side-lobe levels obtained for the uniform aperture function to further increase the directivity index of the array. This can be accomplished by "shading" or windowing the aperture function [5].

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Comment [19]: Julia, I think this is referencing stuff that was included in an earlier version of this section, which no longer exist

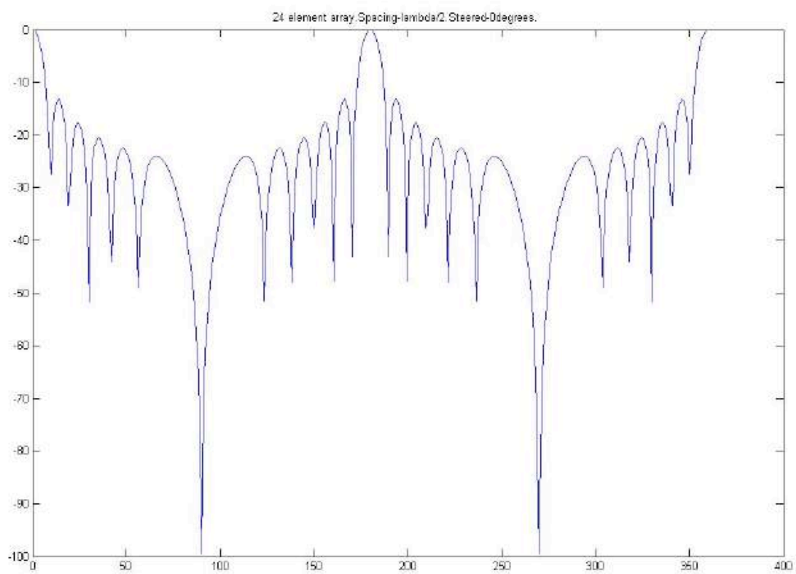

Figure 3-24 Plot of the Pattern Function

This shading is achieved using a tapering window function. The tapering window adjusts the response of the array elements to provide the most desirable pattern for a given purpose.

Typically, the array is shaded with the maximum response in the center of the array and the least response on the ends of the array. This type of tapering, in effect, reduces the side-lobes of the corresponding pattern function, G(u), at the expense of an increased width of the main lobe.

3.7.4.6 Beam Steering

Up to this point in the discussion, the beam forming has resulted in a pattern function whose Main Response Axis (MRA), or main lobe, is along the perpendicular to the main axis of the array. However, it is sometimes useful to be able to "steer" the MRA in a particular direction to fully receive plane waves approaching from different angles. This operation can either be accomplished mechanically, by physically changing the orientation of the array and thus the acoustic aperture, or electronically. When beam steering electronically with a discrete array, several receiving beams can be simultaneously created in different directions.

Electronic beam steering is accomplished by introducing a phase shift to the signal received by each hydrophone of the array. The phase shift is a linear function of frequency and distance along the array. For a single frequency the effect of a phase shift is equivalent to a time delay. When the appropriate time delay is applied to each hydrophone, the correct phase shift occurs regardless of frequency [5]. The time delay is selected to cancel the geometric time delay at each element of the array of a plane wave arriving at a particular angle. The result is that all of the elements receiving a plane wave from a direction will add in-phase. The pattern function, for the discrete line array with or without shading, steered to the angle ψ_0 is:

$$G(u-u_0)=\frac{1}{N}\frac{\sin\left[\pi Nd\left(\sin\psi-\sin\psi_0\right)/\lambda\right]}{\sin\left[\pi d\left(\sin\psi-\sin\psi_0\right)/\lambda\right]} \qquad (3.6\text{-}14)$$

Where N is the number of elements, d is the element spacing, ψ_0 is the steering angle and λ is the wavelength.
The effective length of the array is equal to the projected length along the array, or Lsin ψ_0 , where L is the length of the array. Thus, the effective length decreases as ψ_0 increases. Consequently, as the steering angle ψ_0 approaches 90 degrees the effective aperture is reduced. The result is that the beamwidth of the main lobe increases.

3.7.4.7 Practical Application

In addition to the hydrophone there are several components of a sonar system that will be necessary for operation. **Error! Reference source not found.Error! Reference source not found.** Figure 3-25 presents an example block diagram of the possible components of a sonar system. The system may consist of the Pre-Amplifier, the Analog to Digital Converter, a Data Acquisition device, and a device that will process the data. Occasionally the receiver will have a built-in pre-amplifier. Additionally, the data acquisition converter may have an A/D converter.

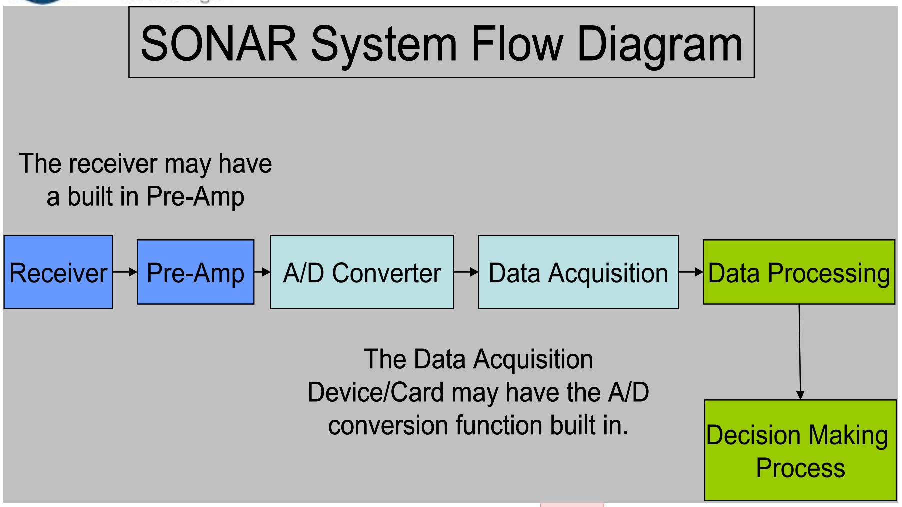

Figure 3-25. Typical Sonar System

Rafael.R.Rodriguez 1/22/07 6:16 PM
Comment [20]: Is this figure referenced anywhere?

When choosing a hydrophone it is important to match up the performance capability to the environment that you expect to work in. Typically the specifications for the hydrophone will provide a plot of the pattern function or beam pattern. Examples are given in Figure 3-26 and Figure 3-27. This will indicate the directivity of the hydrophone. It can be seen that this is essentially an omni-directional hydrophone. A sensitivity plot is also provided (Figure 3-28). This is the response of the hydrophone in V/μPA for the band of frequencies of the hydrophone. A simple example is worked out below.

Consider a line array of three elements. The central frequency, F, is 30kHz. The wavelength, $\lambda = c/F$, is 0.05m.

To determine what range of voltage we can expect at the A/D converter, consider the SONAR equation:

SNR = SL-TL+DI+G
SL = 190dB
TL = 20log(r) with r = 50m
DI = 10log (n) with n=1
G = 10 dB Gain of the Pre-Amp

We have SNR = 190 -34 + 0 +10 = 166 dB

If we add to the SNR the sensitivity of the hydrophone at the frequency, (F) from Figure 3-28, it is about -173dB reV/μPA.

Electrical signal in dB = 160-173 = -7 dB reV/μPA
Electrical Signal in Volts (rms) = $10^{(-7/20)}$ = 0.446 V

Here the sampling frequency according to the Nyquist theorem would have to be 60kHz or greater. The data should be filtered with a low-pass filter before the A/D converter. These simple calculations can be done to determine the dynamic range of the A/D converter necessary to avoid clipping or saturation of the device.

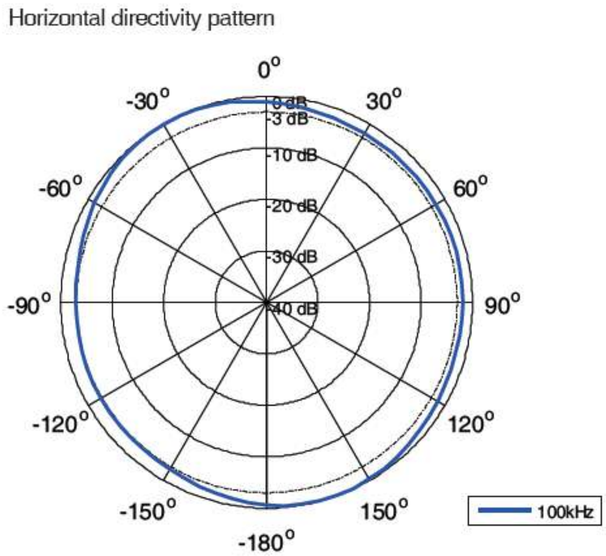

Figure 3-26. Horizontal Directivity Pattern

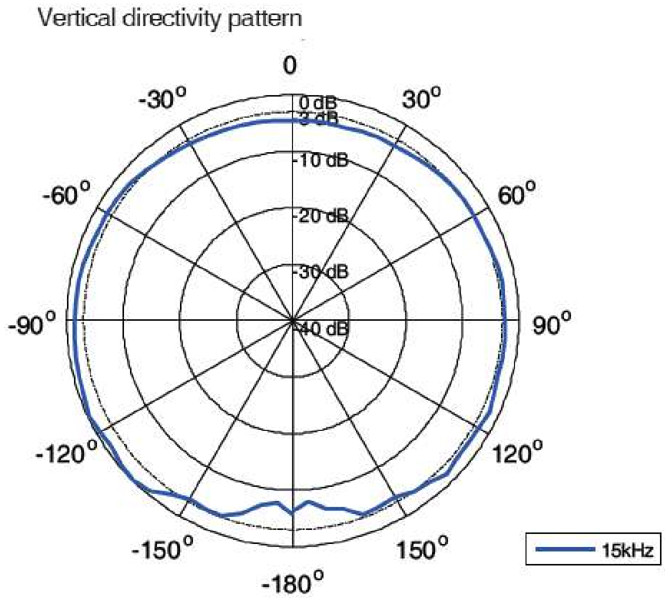

Figure 3-27. Vertical Directivity Pattern

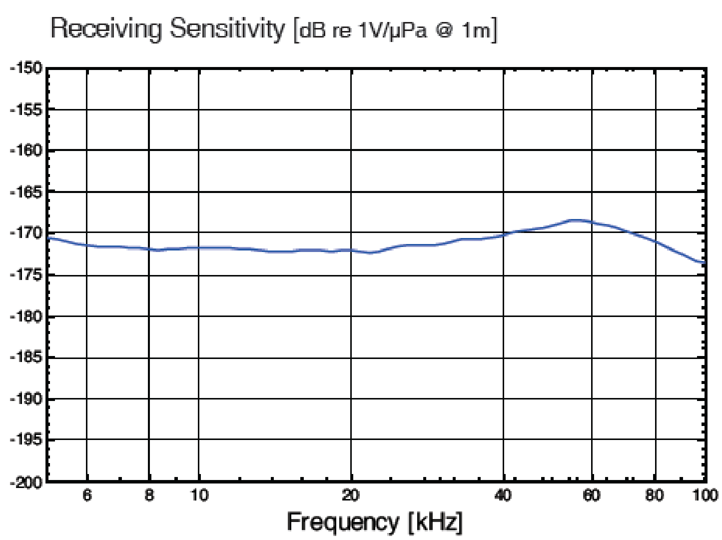

Figure 3-28. Receiving Sensitivity

3.7.5 References

[1] L. E. Kinsler, A. R. Frey, A. B. Coppens and J. S. Sanders, *Fundamentals of Acoustics,* John Wiley and Sons, Inc., third edition, 1982.

[2] Robert J. Urick, *Principles of Underwater Sound.* McGraw-Hill, Inc., third edition, 1983.

[3] Robert J. Bobber, *Underwater Electroacoustic Measurement*, Peninsula Publishing, Los Altos, Ca. 1988.

[4] Sanjit K. Mitra, *Digital Signal Processing- A Computer-Based Approach.* McGraw-Hill, Inc., second edition, 2001.

[5] William S. Burdic, *Underwater Acoustic System Analysis.* Prentice Hall, Inc., second edition, 1991.

[6] Alan P. Oppenheim and Ronald W. Schafer, *Discrete-Time Digital Processing*, Prentice Hall, Inc., 1999.

3.8 Underwater sensing and operating: Depth and Altitude Sensors

Most AUVs depend upon a pressure sensor of some type to determine the vehicle's depth relative to the sea surface (pool water surface). Some additionally use an acoustic fathometer to measure altitude above the sea floor (pool bottom). While the sea surface can vary somewhat with wave action and swell, the bottom can vary greatly, even over relatively small distances. Useful measurements of both depth and altitude must be sufficiently accurate and free from drift over time and/or with changing temperature.

Depth is usually calculated based upon the output of a pressure sensor. As a rule of thumb, one can approximate the depth in fresh water by using the simple equations:

$$D = 2.3 \, x \, P \qquad (3.7\text{-}1)$$

Or

$$P = \frac{D}{0.43} \qquad (3.7\text{-}2)$$

where D = depth below the water surface and P = pressure measured at that depth. However, there are a number of additive pressure effects that contribute to the overall pressure measured, and the characteristics of the sensor itself (such as overall sensor range, sensing accuracy, resolution (for digital units), non-linearity, zero offset, hysteresis, temperature stability, drift, and aging effects) can further affect the measurement result.

Underwater pressure measurement can essentially be thought of as measuring the pressure produced by the total weight of the column of water above the sensor. The pressure measurement will vary with the density of the water, atmospheric pressure over the water, and even gravitational variations (which affect the weight of the water column). Pressure measurements can also be influenced by the placement and orientation of the sensor on the vehicle; vehicle dynamics can affect the pressure sensed (imagine a forward facing pressure sensor's reaction to the forward motion of the vehicle), so the vehicle's control system and software will need to account for such effects. Of course, some of these factors have relatively minor impacts compared to others, particularly for shallow depths, but they should all be considered when high depth accuracy is important for the AUV's mission performance.

Depth sensors measure absolute, differential, or gage pressure. Absolute pressure measurements are referenced to a perfect vacuum (a barometer measures absolute pressure of the atmosphere, for example). Differential pressure measurements reflect the difference between two pressures (such as across a venturi or orifice). Gauge pressure measurements are actually differential pressure measurements where atmospheric pressure is one of the two pressures; the effect of atmospheric pressure is essentially removed from the measurement (tire pressure measurement is an example).

Pressure is often expressed in units of pounds per square inch (PSI) or Pascals (often KiloPascals – KPa). The following are useful unit conversion factors for pressure measurements.

$$1 \text{ PSI} = 6.8947 \text{ KPa}$$

$$1 \text{ KPa} = 0.14504 \text{ PSI}$$

Accuracy and resolution are important considerations in the design of an AUV pressure (depth) sensing system. Measurement errors will result if the sensor does not produce a linear change in output proportional to the changing pressure applied, if there is hysteresis between increasing and decreasing measurements, if any offset at zero pressure is not accounted for, and if the sensor's performance changes with temperature (such as when the vehicle's depth is calibrated in air on a hot summer day, before launch for a mission in relatively cold water). The overall range of the pressure transducer used as the depth sensor should be selected based upon the maximum depth at which the vehicle will operate. For example, using a 1,000 PSI pressure transducer for a situation where the water is only 40 feet deep will yield a very small measurement change from surface to bottom. Further, if an analog-to-digital converter is used to measure the sensor's output, it should digitize with enough bits such that the measurement is adequately resolved for use by the vehicle's control system. For example, an 8-bit A/D converter covering the output range (full span) of a 100 PSI pressure transducer would yield a measurement resolution (depth increments indicated by a change of the least significant bit) of almost one foot. That may not be adequate for precise vehicle control relative to other objects.

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Comment [21]: Should we define hysteresis?

Calibration is an important consideration. Typically calibration will result in a simple linear equation for conversion of pressure to depth, accounting for any offset at zero depth and expressing a proportional relationship between pressure and the sensor's voltage or digital output. If the result is not linear, a polynomial curve fit can be used to more accurately characterize the output for changing depth. As noted above, changes between the calibration environment and the operating environment (differences in water density, temperature, and even large changes in atmospheric pressure) may affect sensor calibration.

Modern pressure sensors are usually temperature compensated, and often have digital outputs, sometimes in addition to analog outputs. They typically have relatively good linearity, and do not require extensive calibration procedures.

Altitude sensors for AUVs measure the vehicle's distance above the sea floor. They are usually acoustic devices that transmit short, high-frequency signals and then detect bottom-reflected return signals using an acoustic receiver. The measurement of acoustic travel time, divided by two, is used to calculate the distance, based upon the sound speed in water. The key factor for accurate altitude measurement is accurate timing of the signal transmission and reception, as accurate knowledge of the speed of signal propagation is not critical for operation close to the bottom, with relatively small signal travel times.

The fathometer may use separate acoustic transducers for transmitting and receiving (a projector and a hydrophone), or a single transducer may serve both functions. The beam pattern, or directionality of the transmitting transducer is typically relatively narrow, enabling the acoustic energy to be directed at the bottom. As with any acoustic projection system, care should be taken to ensure that the fathometer does not interfere with other acoustic systems that may be in use on the AUV. Vehicle software can usually be designed to time the use of multiple acoustic systems to minimize interference. However, for vehicles that rely on acoustic modems for communication or other continuously-operating acoustic systems, extra care may be needed to prevent interference, even when the systems operate at greatly different frequencies, due to electrical cross-talk, signal side-band energy, or signal harmonics.

Examples of fathometers and depth sensors are provided in Section 4.5.2.

3.9 Underwater Sensing and Operating: Underwater Optics and Light

3.9.1 Suspended Materials In The Water

Optical properties of water depend greatly on the quantities and identities of the materials suspended in the water. Generally speaking, suspended materials can consist of biological and/or mineralogical particles. Water in the TRANSDEC pools is described as "chemically treated fresh water, continuously circulated to maintain isothermal conditions", and "although not filtered, the water clarity in the pool is excellent for photographic work and optical experiments." (see http://www.spawar.navy.mil/depts/d70/d74/AppliedTechnology.html#project1). Because the pool is chemically treated, the amount of biological materials can be expected to be quite minimal. However, because the pool water is not filtered, the amount of suspended mineralogical materials in the water may be significant.

Left undisturbed, the suspended mineralogical material will tend to settle at the bottom of the pool. However, a burst by a downward-directed thruster (or a kick by a support-diver's fin) can be expected to be quite efficient at re-suspending these sediments. Accordingly, during the competition you should not expect "swimming-pool quality" water. Be prepared to deal with turbid water. Additionally, the turbidity of the water may increase as the competition progresses.

3.9.2 Spectral Dependence

The optical properties of water also have a large spectral dependence. In pure water, blues and greens are transmitted quite well. However, even in pure water reds are attenuated quite strongly (Figure 3-29). Specifically, the absorption coefficient of pure water at 620 nm is 0.309/m, while it is only 0.0257/m at 500 nm. This has several implications. First, the perceived color of an object will depend strongly on the range of the camera from the target. Secondly, reds are very difficult to detect at significant range.

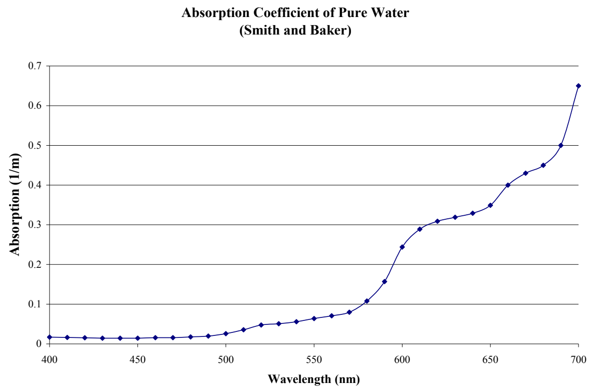

Figure 3-29. Absorption Coefficient of Pure Water (Smith, R.C. and K. Baker, 1981, Applied. Optics 20(2), 177-184)

3.9.3 Ambient Light

Ambient light is an important consideration for any optical system in water. The presence of ambient light can be helpful, e.g., when trying to image an object underwater without using artificial lighting. However, the presence of ambient light can also be very detrimental, e.g., when trying to detect the location and other characteristics of an underwater light source.

Underwater ambient light levels depend upon many factors, including latitude and longitude, time of day, day of the year, weather conditions, surface conditions, shadowing, depth, and substances in the water.

The ambient light levels can also change rapidly in space and time. This is particularly the case if the sun is overhead on a clear day, and there are surface waves. In this case, the surface waves can cause strong focusing (“caustics”) and defocusing of the ambient light on the bottom. These caustic patterns change rapidly as the surface wave structure changes.

3.9.4 Artificial Lights

Artificial lighting can be employed to attempt to give more consistent lighting than that which ambient light may provide. If artificial lighting is employed, several factors should be considered. First, in addition to absorbing light, water and suspended particles scatter light. This scattering is highly directional (Figure 3-30), being strongly peaked in both the forward and the backward directions. Because of the strong backscatter component, every effort should be employed to maximally separate the artifical light source(s) from the camera(s). Doing so will significantly reduce the amount of backscatter noise in the images.

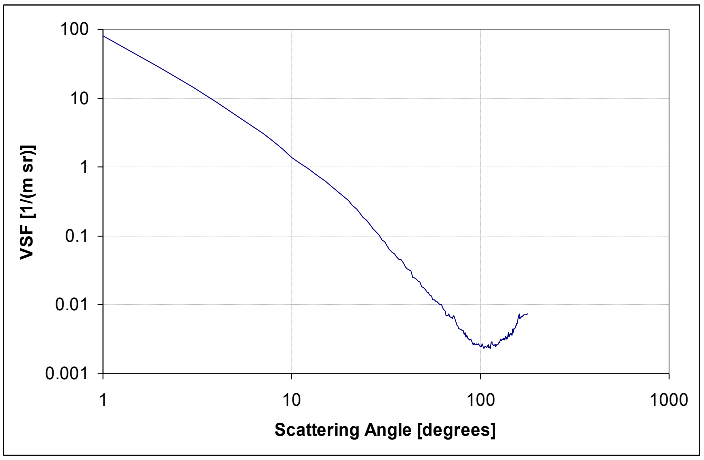

Figure 3-30. Volume Scattering Strength vs. Scattering Angle

3.9.5 Docking Station (Station A)

Because red is strongly attenuated, detecting the red signal from a significant distance is quite difficult. It is particularly difficult if sediments are suspended in the water. You may wish to employ a filter whose spectral characteristics (center wavelength and bandwidth) are matched to those of the known source. This will be quite beneficial in terms of reducing the detrimental impact of the ambient light, which will frequently be much stronger than the red signal which you are striving to detect. An amplified detector with variable gain may also be beneficial. Finally, electronically filtering for the 3kHz signal may also be beneficial in attempting to differentiate it from the competitive ambient light.

3.9.6 Pipeline Inspection (Station B)

Artificial lighting may be useful for reducing dependence upon ambient light levels. If artificial lights are used, consider separating them maximally from the cameras to reduce the impact of backscatter noise.

If processing power permits, consider using the Hough Transform to look for straight lines. Be prepared to deal with changes in apparent color with range.

3.9.7 Random Order Light Display

Consider similar comments to those from Station A.

Camera systems must be selected and designed based on the mission requirements set up by AUVSI Foundation. Sample camera systems are shown in Figure 3-31.

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Comment [22]: Should these sections be removed? They seem to be comments/suggestions for the competition organizers

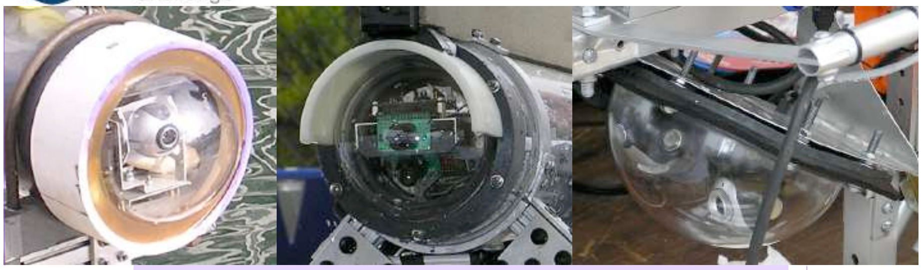

Figure 3-31. Camera system examples from the 2006 AUVSI Competition

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3.10 Underwater Components

3.10.1 Electrical Connectors for the Marine Environment

Several types of electrical connectors are available for use in the marine environment, including basic water/splash-resistant designs, fully waterproof connectors intended for above-water (or very shallow water) applications, underwater connectors, and underwater-mateable (pluggable) connectors. All are intended to provide reliable electrical connections while preventing water from entering the area of the electrical contacts.

3.10.1.1 Connector Types and Design Considerations

As with all types of electrical connectors, the size of the contacts and the types of insulating materials used will determine the current-carrying capacity and the maximum voltage that may be applied. Shielding may be an important consideration for applications involving small signal levels or a mix of small and large signal levels. Care should always be taken to fully understand the ratings and limitations of candidate connectors before selecting them for use in an AUV.

Some connectors can be mated and unmated while energized, while others can be damaged due to arcing across contacts. For situations where the system is energized when connections are made or broken, such as may occur when an undersea vehicle is launched, the order in which individual pins make and break their connections should be considered, as that can have a significant impact on system performance.

Most connectors provide a means to correctly align the contacts before making the connection. This may be accomplished by using a larger pin as a guide, by a key and keyway molded into the connector bodies, or by the physical shapes of the mating pairs. A locking sleeve or other restraining mechanism is often included. Care should be taken not to over-tighten locking sleeves, which can tend to strip the threads or distort the connector seal, potentially causing water to leak into the contact area.

3.10.1.2 Water/Splash-Resistant Connectors

Water/splash-resistant connectors are simply intended to prevent rain or splashed water from intruding into the electrical contacts. They usually have a gasket seal of some kind as well as a cover to protect the contact area. They are usually not intended to be fully submerged. These connectors may be suitable for AUV test systems operated near the water's edge, or outside in inclement weather.

3.10.1.3 Waterproof Connectors

Connectors that are rated as "waterproof" have a more substantial seal than water-resistant connectors, often using a rubber o-ring or other sealing mechanism. They can usually be submerged in shallow water, or left in contact with water for extended time periods. Because they are not designed for the higher-pressure environments of deeper water, they are not the best choice for use on external AUV subsystems or mission applications. Such connectors may be useful for connecting test equipment or AUV support systems in the competition environment, or for related outdoor and waterfront area applications.

3.10.1.4 Underwater Connectors

True underwater connectors are rated for long-term, submerged use. They are best for most AUV applications, such as interconnecting AUV subsystems in flooded sections, or for connecting external sensors. They are designed with rubber seals to prevent water intrusion under pressure (to the rated depth), and corrosion-resistant contacts to survive well in a marine environment. They can be found as inline connector pairs or as cable connectors that mate with bulkhead connectors. The cable connectors often have a "pigtail" molded onto the connector at the factory. The pigtail is intended to be joined with a longer length of underwater cable using a molded splice or terminated in an electro-mechanical "cable seal" assembly integrated into a sensor or a pressure vessel.

The bulkhead portion of the underwater connector pair is often screwed into a threaded opening in an end cap of a pressure housing and sealed with an o-ring, typically using a face seal. The electrical contacts are typically of the pin and socket type. In designing the AUV connections, the contacts associated with power sources are usually on the socket side of the connection, to minimize the chance of accidentally coming in contact with or shorting pins that may be energized.

Underwater connectors of this type should never be mated or unmated while submerged, and the electrical contacts should not be exposed to water. Blanking or "dummy" plugs are usually available to protect the bulkhead connectors when the mating cable assembly is not in place. Some blanking plugs can also be submerged, just like mating connectors. This capability is useful when external AUV connections are needed for testing or monitoring purposes; blanking plugs can then be installed before AUV launch. Alternatively, an underwater connector can be used as a simple on/off switch by shorting connections within a mating connector.

3.10.1.5 Underwater-Mateable Connectors

Connectors that are designed to be mated and unmated while submerged are known as underwater-mateable connectors. The male half of the connector pair often consists of a resilient pin with multiple cylindrical, electrical contacts located along its length. It is inserted into a female, socket-type connector that has recessed contacts inside. The male pin is typically slightly flared at the tip, with a slightly larger diameter than the female socket, to provide a wiping action and an interference-fit for a positive seal when inserted. The male pin forces water in the socket out through a vent as the connection is made.

Figure 3-32. Sample Underwater Connector Parts

As with underwater connectors, the energized side of the circuit is best placed on the female connector, rather than on the male connector, with its exposed contacts. These connector pairs may be of the cable-to-cable or the cable-to-bulkhead style.

In all types, lubrication is an important consideration. Silicone grease is typically used, and re-lubrication is recommended every few mating cycles.

3.10.1.6 Connector Care and Maintenance

Underwater connectors can be expensive and difficult to replace when damaged. Care should be taken to prevent pins from becoming bent during mating cycles, and protective caps should be placed on all connectors when not mated.

All underwater connectors used in the marine environment require periodic maintenance. The contacts can be degraded due to oxidation or corrosion, particularly in a salt-water environment. Light cleaning of male contacts or pins using emery cloth or paper (such as #800 wet/dry type) can help to ensure good electrical connections. Female sockets may be cleaned using a cotton swab and rubbing alcohol, or a small bore brush. Underwater-mateable connectors should be rinsed with fresh water and dried after use in a salt-water environment.

3.10.2 Cable Seals

3.10.2.1 Types of Cable Seals

Cable seals provide a means for mechanically terminating a cable, for strength, while making electrical connections to the conductors within the cable, such as for connecting an underwater cable into a pressure vessel (e.g., a sealed AUV housing). Instead of using an underwater connector pair, the cable is connected directly to the pressure vessel using a mechanical assembly on the end of the cable that can simply be inserted into a hole machined in the pressure housing. Such assemblies typically use a double o-ring seal, and can be much more reliable than commercially available connectors, particularly for long-term applications.

When using a cable seal, it is important to individually seal to all elements within the cable in order to prevent water from entering the pressure vessel, should the cable leak or be cut. It is also important to uniformly terminate all strength members in the cable, so that failure of the weaker members will not cause a ripple effect, causing others to break as well, as they each take on more of the failed members’ share of the load.

Due to the rather specialized nature of cable seals, and the expertise needed to build them, connectors are typically used for student AUV competitions.

Figure 3-33: Sample connectors from the 2006 AUVSI Competition vehicles

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Comment [24]: caption?

3.10.3 Underwater Cables

3.10.3.1 Underwater Cable Types

Many of the key features of underwater cables are the same as for terrestrial (above-water) cables; they need to have a sufficient number of conductors, of appropriate capacity, to carry the power and/or signals required; they must have sufficient shielding to prevent cross-talk between signals or interference from outside sources; and they must be mechanically robust enough for the environment in which they are used. The added key feature for underwater cables is that they must keep all water out of the cable. Although student AUV developers may be tempted to try to fabricate their own cable assemblies using off-the-shelf cable components and various tubing or other jacketing materials, such cables rarely perform well. Leaks can be disastrous during an AUV competition, and the project is difficult enough without adding unnecessary risks.

3.10.3.2 Cable Materials

The outer cable jacket and the internal construction of underwater cables are usually significantly different from those of terrestrial cables. Even a small pin-hole in a cable jacket can present a significant leakage problem when the cable is exposed to the relatively high pressure of an underwater environment. Underwater cables that are designed to be laid on the sea floor have different mechanical requirements than working cables, such as those used in AUV applications. A good underwater cable will contain interstitial fillers for water-blocking, to limit the wicking or movement of water within a cable (should a jacket leak occur), and sufficient strength members to provide the required tensile strength under load, without allowing any damage to the conductors.

Typical underwater cables have jackets made from well-proven, waterproof materials, such as polychloroprene (neoprene), polyethylene, or polyurethane. The jacket material is an important consideration; some jacket materials better support molding of splices or pigtailed connector assemblies, while others are better for use with mechanical cable seals. Some are more flexible, while others are much more resistant to damage from abrasion.

Minimizing the number of underwater connections will help to optimize the reliability of an underwater system. When many individual connections are needed, a system with a single, multi-conductor cable with appropriate terminations/connectors will generally be more reliable than multiple, small cables, each with individual terminations/ connectors. Multiple underwater cables can be wrapped or tied together to form a single, larger cable for ease of handling if necessary; however, their connections will remain separate, so overall system reliability will be reduced.

3.11 General Safety

Safety is always a concern when designing and testing engineering systems. It is necessary to consider how the vehicle components will be handled, stored, and safely integrated into a user friendly final product. In this section, general safety topics as well as specific concerns will be presented. Specific safety examples and mishaps will be described in Section 4.

Batteries: Battery safety factors include the type, size, charging, circuit design considerations, out-gassing characteristics.

Ballast: A ballasting system often incorporates compressed air to control fluid levels in the ballast tanks. Using compressed air on board the vehicle requires extra care when dealing with recharging compressed gas bottles or compressed gas cartridges. When recharging bottles, it is imperative that the valve stem of the source and receiver bottles are 'pointing' away from any personnel. These bottles are highly 'charged' and if the valve stem breaks the valve will be propelled with significant force away from the bottle. Therefore, always be aware of 'flying valves.'

Vehicle cradle: When working on the vehicle, it is often most convenient to have a form fitting stand, or cradle, in which the vehicle can sit. A cradle is often constructed from wood and has two to three support points distributed along the fuselage. A cradle will provide a secure frame in which the vehicle can rest when it is being worked on or in storage. The cradle may have locking wheels which will allow it to roll but can be locked in position when needed. When leaving the vehicle on the cradle for long periods of time, ratcheting straps can be used to tighten the AUV into position on the cradle.

Vehicle packaging: When transporting the vehicle, a crate can be built in which the cradle can be secured. This will provide external protection as well as an internal molded seat for the vehicle. Protective materials can be packed around the vehicle or the cradle can be secured where the vehicle is clear from other padded supports and packaging.

Vehicle harnessing: The vehicle must be designed not only to 'swim' but also to be handled. The vehicle must be designed with lifting points or lifting methods in mind as well as launching and retrieval methods. Hard point lifting rings can be built into the fuselage or bulkheads and a sturdy framework may provide sufficient structure to lift against. Lifting straps must be selected which are long enough so as not to put a compressive force on the hull of the vehicle.

Propellers: The propeller introduces operational safety considerations as well as general handling concerns. The propellers should be handled with care since the blades can be sharp and potentially cut personnel moving around them. Shrouded propellers are required per competition rules.

Testing around water: It is always important to keep safety in mind when testing and operating around water. This is relevant to system operations (flooding, shorting systems, dropping hardware to the bottom of the pool) and especially to personnel safety. Keep flotation devices handy and always test with multiple people present. Team members should be watching out for each other and members who do 'get wet' should be able to swim.

Test Readiness: A final hardware systems safety check out should be performed prior to the competition. This should include checking connecters to make sure they are sealed, checking o-rings for damage, checking wires to make sure they aren't crossed, etc. Developing a safety checklist is a good way to make sure the check process is standardized and it helps ensure that nothing is overlooked.

Kill Switch: A kill switch is required for all vehicles at the competition. The switch must "disconnect the batteries from all propulsion components and devices in the AUV," according to competition rules. However, it is a good idea to keep software running so that data taken during a run is not lost.

3.12 Battery Safety

The U.S. Consumer Product Safety Commission (CPSC) estimates that approximately 3,700 people a year are treated in hospital emergency rooms for battery-related chemical burns. Approximately 20 percent of people treated in these cases are children under the age of 16.

Safe procedures when working with batteries need to be followed to avoid injury or possibly death. Batteries should be considered extremely dangerous and thus need to be treated with appropriate respect and prudence. Various hazards exist for each type of battery. Some general safety guidelines are provided below. Manufacturer safety instructions should be followed and supersede this guidance when conflicting information is given.

3.12.1 Battery Inspection

Battery inspection should confirm that:

1. Assembled batteries contain all of and only the parts listed in the Bill of Materials.
2. Battery assembly has each part in its proper location.
3. All inter-cell connections have been properly made and torqued.
4. All wiring is properly and neatly routed.
5. Battery weights and dimensions are within specifications and requirements.
6. Electrolyte fill level and concentration are within specification requirements (if possible).
7. Batteries are visually clean.

3.12.2 General Battery Safety

1. Do not smoke or allow flames or sparks near any battery.
2. When working near batteries do not simultaneously touch both terminals or cause a short circuit in any other way.
3. Household type batteries can rupture or overheat due to: attempted recharge of primary batteries; using the wrong charger for rechargeable batteries; mixing battery types (i.e. alkaline & carbon-zinc); or improper battery installation in devices. Care should be taken to avoid these possibilities.
4. When lifting a heavy battery, avoid back injuries by lifting with the legs or using lifting devices.
5. Many batteries are capable of a high discharge rate, therefore batteries should be in a discharged state when connections, disconnections, or replacements are made.
6. Batteries should always be treated as if they are in a charged state.
7. The following safety equipment should be available for personnel servicing batteries: splash proof goggles, face shields, rubber gloves, and rubber aprons.
8. The following facilities should be available when servicing batteries: eyewash, shower facilities, and adequate water sources to neutralize and wash down inadvertent spills.
9. When servicing batteries, all metal articles, such as watchbands, bracelets, and rings should be removed. Inadvertent contact of metallic objects with connectors of opposite polarity could result in fusing of the metal and severe burns to the wearer.
10. Avoid directly breathing gasses vented from batteries.
11. Batteries should be in an upright position during transportation, maintenance, charging and storing.

12. Avoid contact with electrolytes, which are caustic in nature. Study all Material Safety Data Sheet (MSDS) documents for appropriate actions should contact occur.
13. Electrical wiring and connectors associated with battery systems should always be handled as if they are energized by fully-charged batteries.
14. Individuals working around or with the batteries should be accompanied by at least one other person at all times.
15. Charging batteries in closed containers may cause excessive build up of flammable or explosive gasses. Proper ventilation practices should be used during charging operations (see Battery Gasses section below).
16. Hazards can occur when assembling batteries using cells of different charge states, or substituting cells with different charge states into battery packs (such as during hasty field repairs at the competition). As less-charged cells are inserted in series, they can reverse polarity when depleted while the more fully charged cells in the battery pack continue to discharge. Thus, only similarly charged batteries should be inserted.
17. Batteries typically contain heavy metals and caustic liquids. Thus, defective, exhausted, or unserviceable batteries should be disposed of in a manner as described by the manufacturer, MSDS sheets, or state ordinances.

3.12.3 Battery Shipping

When shipping or carrying batteries, they should be insulated from each other and from possible shorts. Make sure each battery is secure within the container as they may dislodge during handling causing possible damage or shorts. Special attention must be exerted when shipping batteries by air. Always treat batteries as if they are in a charged state. Shipment of lithium batteries is not allowed on passenger aircraft. For further information, visit the web sites of the National Electrical Manufacturers Association, the U.S. Department of Transportation, and the International Air Transport Association (referenced below), or contact the appropriate government agency.

3.12.4 Battery Gasses

Battery storage, maintenance, and charging areas should be kept well ventilated. Many batteries will release gasses when charged, over-charged, discharged, and over-discharged. Typical gasses vented from batteries are hydrogen and oxygen. If allowed to build up, gasses can explode causing severe damage, bodily injury, and death. Hydrogen gas concentration must stay below 3.5 percent at all times to prevent the possibility of explosion. A mixture of 4 to 8 percent concentration of hydrogen gas will burn if ignited by spark or flame. Concentration above 8 percent of hydrogen in air will explode with increasing force as hydrogen concentrations increase.

Additionally, it is recommended that battery housings be purged with inert gasses (i.e. nitrogen or argon) to avoid potentially explosive air/hydrogen mixes during operations. If charging is to occur in enclosed areas (i.e. room, workshop, small garage) mechanical ventilation, as recommended by the NEC 1999 National Electrical Code, Article 625 - Electric Vehicle Charging System, Section 626-29, Indoor Sites as referenced below, should be followed.

3.12.5 Some Quick Battery References

www.BatteryUniversity.com This is an educational website that offers practical information for battery users. The material is condensed into essays of about 1000 words and covers most aspects of battery use.

www.buchmann.ca This is an informational website that carries the book entitled: "*Batteries in a Portable World — A handbook on rechargeable batteries for non-engineers*". The website also includes articles suggesting the best battery choice for a given application, how to restore weak batteries and maintenance methods to prolong battery life.

ibet.asttbc.org/batterys.htm The first part of this two-part article by Isidor Buchmann, focuses on the needs of the different battery chemistries, what applications are suitable and how one can get the most out of them. The second part touches on cell behavior.

www.madkatz.com/ev/nec1999Article625.html NEC 1999 National Electrical Code, Article 625 - Electric Vehicle Charging System, Section 626-29, Indoor Sites. This National Electrical Code article provides insight into ventilation requirements/recommendations when charging batteries.

www.nema.org National Electrical Manufacturers Association web site.

www.dot.gov U.S. Department of Transportation web site.

www.iataonline.com International Air Transport Association web site.

www.fedex.com/us/services/options/express/dangerousgoods/resources.html FedEx offers helpful aids and procedures for shipping dangerous goods such as batteries.

www.seabird.com/pdf_documents/LithiumBatteryShippingGuidelines_003.pdf
This site provides interpretations of shipping requirements and laws for lithium batteries as interpreted by Sea-Bird Electronics, Inc.

www.rayovac.com/technical/ev_faq08.htm Rayovac cites regulations and requirements regarding shipment by air of Lithium primary and rechargeable batteries as provided by IATA in its Dangerous Goods Regulations.

www.cpsc.gov/CPSCPUB/PUBS/5088.pdf The Consumer Product Safety Commission produced this simple product safety alert for discussing household batteries and how they may rupture or cause chemical burns.

http://www.ehso.com/ehshome/batteries.php This site provides information regarding household batteries. Included are some examples of environmental hazards and disposal methods as well as general information regarding battery types.

4 APPLYING THE TECHNOLOGY

4.1 Hull Forms

The hull will help determine your vehicle's hydrodynamic properties. Hull shape and thruster configuration is highly dependent on the mission at hand. Keep in mind that for the AUVSI competition, the vehicle must be able to maneuver well in a relatively small pool. Torpedo shaped AUVs such as the Hydroid REMUS AUV, are very efficient in open water, but would fail at the AUV competition because the torpedo hull shape combined with a single aft prop limits vehicle maneuverability, especially with respect to hovering.

GazagnaireJ 9/14/06 3:34 PM
Comment [25]: should we reference the hydrodynamics section?

GazagnaireJ 9/14/06 3:31 PM
Comment [26]: Should we be mentioning REMUS? Shouldn't it be more general

4.1.1 Open Frame Hull

Many teams choose to use an open frame (or semi-open frame) hull. In this design, the pressure vessel (housing the majority of electronics) is usually visible and mounted on a frame. External sensors and thrusters can be added and moved around the frame easily, allowing for greater flexibility and modularity in the design. Waterproof cables and connectors running along the frame supply power and allow the components of the AUV to communicate with one another. In order to lower drag or help predict hydrodynamic properties, floodable shells can be used to enclose the open frame.

Using several thrusters, open frame hulls can achieve a great deal of maneuverability, which is especially useful for the competition.

4.1.2 Closed Hull

Some AUVs integrate all the electronics, sensors and thrusters into a single closed hull. In such a design, the pressure vessel is designed to allow water penetration to give the appropriate sensors access to the environment. While this design can lead to a compact AUV, a closed hull is constricting and more difficult to alter later on. The Hydroid REMUS vehicle uses a closed hull design. The REMUS vehicle has a single "torpedo" shaped pressure hull containing the electronics, batteries, and sensors. Penetrations in the hull give the propeller and several sensors access to the water.

4.1.3 Common Mistakes In Hull Design

4.1.3.1 Flooding

Flooding is every team's worst fear, yet it happens consistently at competitions. As a general rule of thumb: all pressure vessels should have double o-ring seals that are clean and greased with silicon. Components should be tested (under pressure!) for extensive amounts of time before electronics are installed. Oftentimes wires or dirt can become lodged between seals at the competition or in practice, causing a vehicle to flood. A checklist and thorough inspection of the o-ring and groove can help avoid this, and a good way to check your seal is to vacuum seal your pressure housings. If your vehicle can hold a vacuum in air, then it will be waterproof once it is submerged, which takes the worry out of submerging the vehicle. A small hole with an o-ring screw will allow you to pull a vacuum using an electric or hand pump. The screw is inserted immediately after the pump is turned off and secured. An internal pressure sensor will allow you to monitor pressure changes inside the housing and detect leaks.

4.1.3.2 Flotation/Righting Moment

In order for the vehicle to be stable in water, you must pay attention to the vehicles weight and volume properties. As a general rule, flotation and lighter equipment should be located towards the top of your vehicle, and heavier equipment and weight (e.g. batteries) should be housed at the bottom of your vehicle. This will give your vehicle a strong "righting moment" and helps avoid pitch and roll instabilities once the vehicle is in the water and moving. However, do not let this rule stifle your innovation. A growing area of research in underwater vehicle design is controlling vehicle instabilities, allowing for more degrees of freedom and maneuverability underwater.

GazagnaireJ 9/14/06 3:35 PM
Comment [27]: reference hydrostatics section?

4.1.3.3 Heat

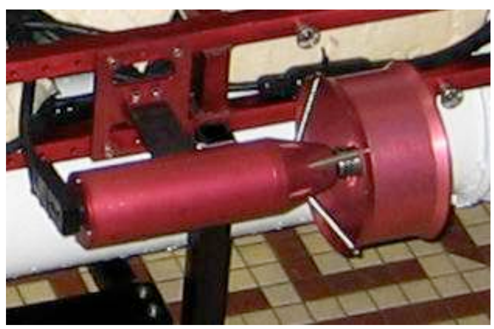
Pay attention to the materials you use. Unlike a home CPU with constant access to cool air, your electronics will heat up in a closed container. Design for environmental conditions. Utilize the cool water that comes in to contact with the hull. While it may seem attractive to plumb water through the hull for cooling, this is generally a bad idea - simply moving the air around with a small fan often does wonders. Oftentimes vehicles do not have heat problems until the competition; sun and warm water have been known to overheat vehicles!

4.2 Propulsion

For small AUVs, thrusters that produce 6-12lbs of force should be sufficient. Teams have used a variety of propulsion systems in past competitions. Thrusters are most commonly used, although participants have also shown success with less common methods of movement such as Nektors™, which use oscillating flexible fins to propel the vehicle. Innovation is awarded greatly in the AUVSI competition, so finding and utilizing alternative propulsion techniques is a good way to set your team apart.

4.2.1 Thrusters – Custom Built

Teams have used both commercial and custom-built thrusters in past competitions. Manufacturing your own thrusters can be more cost effective, depending on the type of machining available to your team. It is possible to design custom thrusters that are of higher quality than commercially available products.



Designing your own thrusters consists of selecting a motor/motor controller pair that is suitable for your needs, and manufacturing a waterproof housing for the motor. Thrusters can have either a direct drive to the propeller (requiring a waterproof bushing or o-ring seal), or can be magnetically coupled to the propeller (avoiding housing/water penetration). Expect to spend $600 and up for reliable and accurate motor/motor controller systems. Cheaper systems have been used in the past with minimal success. In prior competitions, teams have opted to modify trolling motors or bilge pumps designed for near surface use. These have been known to leak and cause problems.

4.2.2 Thrusters – Off-The-Shelf

Several companies design off-the-shelf thrusters for ROV and AUV applications. Commercial grade thrusters can run $2,000 and up per thruster. Teams have successfully used thrusters from SeaBotix and Civek in the past. Tecnadyne thrusters have been notorious for failures in both the AUVSI competition and industry. Commercial thrusters utilize a variety of control protocols, and care should be given to ensure compatibility with your system. For example, Tecnadyne thrusters have a built-in motor controller card, requiring an input voltage of +/- 5V as a control signal (-5V full reverse, +5V full forward). SeaBotix thrusters require an I2C input for thruster control.

Common Mistakes When Building/Purchasing Thrusters

- Budget wisely; thrusters (especially professional grade) can be extremely expensive
- Note that the thrusters you design or buy must work with the voltage and current limitations of your vehicle. Many off-the-shelf thrusters are designed for ROV's, which usually use 220V shore power. Expect manufacturing delays of up to 6 months for motors at lower voltages.
- Thrusters fail every year at the competition. Even the best manufactured thrusters can fail at any time. When ordering or building your thrusters, budget for at least two spares for every one you use.
- Thruster performance can vary greatly in the forward/reverse directions. Often a variety of propellers are available to counter this effect.

Signe A Redfield 9/14/06 3:20 PM
Comment [28]: Might seem? Seems?

4.3 Underwater Connectors

Unless your vehicle design is entirely closed hull, waterproof cables and connectors are necessary to link modules, sensors, and propulsion to one another. Cables and connectors are a common source for failure and leaking, and care should be taken when selecting them.

4.3.1 Off-The-Shelf Connectors and Cables

Connectors and cables are available commercially from companies such as SeaCon, Subconn and Impulse. These companies are reputable and specialize in making underwater cables and bulkhead penetrators. With enough notice, custom cables can be ordered in a variety of configurations. Though they are expensive, commercially available cables and connectors can avoid a number of problems that may be encountered with a cheaper solution.

4.3.2 Do-It-Yourself Cables

While it is often tempting to use standard shielded wire with a rubber or plastic coating, this is not recommended. Cables not specifically made for the water environment will leak. Water-proof and true submersible cables are very different. A very small cut or crack in a wire will allow water to enter, and at depth this water will push through the wires and into your pressure vessel at surprisingly high rates. Custom bulkhead penetrations can be machined out of plastic or metal, but most designs allow the same wire to contact both the sea environment and the inside of the pressure vessel. With this type of design, your vehicle is at great risk of flooding, since water can push through the wire.

4.3.3 Potting

Cables can be spliced together and available to use underwater within 24 hours. The individual wires of an underwater cable are spliced together and soldered. The open wires are then waterproofed and secured using a potting material. Custom molds can be used to contain the wires and create a “bulb” for the potting material to flow into. Heat shrink tubing can also be used as a mold. Both ends of the underwater cables should be scuffed using sandpaper and cleaned using alcohol to allow the potting material to grip. To use heat shrink tubing, hang the cables lengthwise and heat shrink the bottom portion below the soldered wires. Next, inject the potting material using a large syringe into the top of the heat shrink. Fill the tubing entirely with potting material stopping slightly below the top of the heat shrink. Then use a heat gun to slim the top portion of the heat shrink until the potting material reaches the top of the tube. The material will harden overnight and be available for use the next day. 3M ScotchCast 51/50 or Polyu 6366K47 have been used successfully by multiple teams.

4.4 Cameras

The AUVSI competition usually requires vision-based decision making as a large component of the mission. Teams in the past have used a large variety of cameras, from $50 USB web cams to expensive professional underwater cameras (from companies such as DeepSea Power & Light, Tritech, Insite Tritech, Kongsberg, etc.). Keep in mind that real-time image processing will have to occur; having extremely high resolution images may not be useful. More importantly, the camera you choose should operate well in a wide variety of lighting conditions. The competition could be indoor, outdoor, or change on the fly from sunny to cloudy. A camera that reacts well to light changes and has contrast and iris adjustments is useful.

In addition to selecting a camera, you will often need to convert the analog signal of the camera to a digital file (either video or still frame). Teams in the past have conquered this task by selecting USB or FireWire compatible cameras, or by using a frame-grabber.

4.4.1 Common Mistakes in Selecting Camera Systems

- In past competitions, electromagnetic interference has caused significant distortion and or failure on camera feeds. Consider shielding options when integrating your camera.
- High resolution images are expensive to process. Weigh the relative importance of spatial resolution and processing requirements.

4.5 Sensors

4.5.1 Passive Acoustics

The AUVSI competition requires the use of hydrophones to locate an acoustic pinger. Because of the short range, challenging acoustic properties of small concrete pools, and required accuracy, there are very few (if any) commercial products available for solving this task. Historically, this task has provided a great amount of difficulty to the teams. Often, acoustic systems that work well on the bench fail at the competition due to changing environmental factors, acoustic properties of the pool, and integration problems with the AUV. Teams have consistently shown success with this task by combining a Pyramidal cluster of hydrophones with a digital signal processor (DSP) microcomputer. The DSP measures the time delay of the signal between hydrophones and calculates a direction and angle to the pinger. Echoes from the concrete environment must be considered when designing a passive acoustic system. There are several sources of off-the-shelf hydrophones, such as from Reson (but they are expensive).

4.5.2 Depth Sensors

A variety of depth sensors are available with a wide degree of accuracy, reliability, and pricing. If your budget permits, stay clear of low grade pressure sensors from retailers such as McMaster-Carr. These pressure sensors are typically not adapted for underwater use, sporadically stop working, or output analog signals that vary too heavily for good vehicle control. Some pressure sensors are potted into a cable and have a wet-mateable connector. Other pressure sensors are designed to sit in the endcap of a vehicle’s electronics housing. In this configuration, the drum of the pressure sensor penetrates the bulkhead and is exposed to open water. Find a pressure sensor that is tuned for shallow water environments, as this will provide a higher degree of accuracy when working in the competition pool.

4.5.3 Navigation Sensors

Knowing your position underwater is essential to performing well at the AUVSI competition. Since GPS communication does not penetrate water (and surface antennas are prohibited), students must find creative alternatives for determining position. This can be as simple as counting prop rotations and recording compass direction, or as sophisticated as combining the logic of multiple sensors using Kalman Filtering techniques. There are several sensors available to aid in vehicle navigation, including Inertial Measurement Units (IMU), Doppler Velocity Loggers (DVL), and Compasses. Students are also encouraged to explore creative ways of determining position using less conventional techniques.

4.5.3.1 Inertial Measurement Unit (IMU)

IMU’s contain 3 accelerometers and gyros set on orthogonal axes. These devices can serve several purposes. In a basic sense, cheap IMU’s (i.e. $1000-$2000) can output 3-axis accelerations and rates to the control system. In very expensive ($50,000+ and usually physically large) systems, the accelerations are integrated twice to produce an estimate of position, making the unit an Inertial Navigation System (INS). In short periods of time, INS's are accurate in tracking changes in position. Due to the double integration of acceleration values, INS's position information tends to drift over time. If calibrated correctly, using just an INS may be reasonable considering the competition time lasts less than 15 minutes. However, combining an INS in a navigation suite with other sensors will provide the most accurate and rewarding results.

4.5.3.2 Doppler Velocity Logger (DVL)

DVLs contain 4 beams of sonar transducers angled 45 degrees apart. The transducers ping the sea floor or water layers and detect the doppler shift of the sonar signal. The unit then outputs velocity in relation to the vehicle's orientation. This velocity can be combined with a compass and integrated to record position. DVLs are generally more accurate than INSs over longer periods of time, because the instrument signal only needs to be integrated once, while the INS, requires double integration. Error accrues less frequently for this reason. Teams have demonstrated drift rates of less than a meter using a DVL at the competition. RD Instruments (www.dvlnav.com) produces the most common DVLs in the industry. The units are expensive (approx $25,000), however RDI has been known to loan devices, offer discounted rates, and offer payment plans to universities. Teams are encouraged to make these arrangements early in the year.

4.5.3.3 Compass

Compasses are an integral part in any navigation system because they give an absolute heading that does not accrue error over time. However, compasses cannot be trusted entirely at the competition because of the magnetic properties of most concrete pools (this same problem occurs in harbor environments and around ship hulls). Several off-the-shelf compasses are available, such as models from Honeywell.

4.6 Power

One of the most limiting factors in the operation of small AUVs is power. Power often dictates mission parameters – endurance, speed, operational depth, distance, and payload are all determined by the limitations of the power source. Because of the size and safety requirements in the AUVSI competition, batteries are the most practical way to power a vehicle. There are several types of batteries – Lithium Ion, Lithium Polymer, Lead Acid, Nickel Cadmium (NiCd) and Nickel Metal Hydride (NiMH). Non-rechargeable batteries are not practical for the competition because their cost and bulk would severely hinder vehicle testing.

The main considerations for selecting a battery type are energy density (power vs. weight and volume), voltage, recharge/discharge rates, cost, and safety.

4.6.1 Lithium Ion

Lithium Ion (li-ion) batteries are well known for being extremely high energy density. Li-ion units also have the ability to charge/discharge at any point in the battery cycle without creating battery memory problems. The downside to using this technology comes with cost and safety.

Custom Li-ion packs have a relatively high danger of exploding or catching fire if they are charged or discharged improperly. For this reason, designing a custom Li-ion system for an AUV can be costly and more time consuming than other options. While there are many off-the-shelf Li-ion options at low voltages and current loads, higher amperage and voltage systems are harder to come by. If an off-the-shelf system is purchased, it is important to select systems with integrated monitoring circuitry. These will at a minimum prevent overcharging or discharging that could cause the battery to explode or stop functioning. Some batteries have circuitry that can communicate voltages and other battery information to the AUV computer. This information can be used to monitor the health and charge status of the cells.

Autonomous and remote control air vehicles have surged a large hobbyist demand for lightweight battery packs. Some of these packs are reliable, reasonably priced, and safe enough to be used in AUVs. In general, use the highest quality batteries and charging technology you can afford.

4.6.2 Lithium Polymer

Lithium Polymer batteries behave much like Li-ion batteries, except with about 20% higher energy density. Li-Po uses a solid polymer composite such as polyacrylonitrile instead of the organic compound found in Li-Ion. These cells are less likely to catch fire, and can be shaped for specific applications because the polymer is gel-like. On the downside, individual Li-Po packs have a voltage range of 2-4 volts, so several packs need to be combined to provide a high voltage system. Each of these packs needs to be regulated in a way such that one pack does not charge/discharge more than the others. A high quality charger designed for Li-Po cells is essential. Higher voltage Li-Po packs have been designed for hobbyist and UAV applications. These packs may already have monitoring and safety circuitry integrated. ThunderPower Li-Po packs have been used by at least two teams at the AUVSI competition.

> **NOTE: Li-Po and Li-Ion batteries should always be shipped at 25% capacity, and depending on the authorization from the manufacturer may need to be shipped in a hazardous material (HAZMAT) container. When shipping your batteries to the competition, allot enough time for these batteries to be shipped under HAZMAT regulations. These batteries cannot be carried on airplanes.**

4.6.3 Nickel-Metal Hydride

NiMH batteries have the next highest energy to weight ratio compared to lithium-based cells. NiMH batteries are cheaper and safer to use than lithium-based batteries, but their energy density is about 30% lower than Li-Ion cells. NiMH batteries also have some memory effect, and discharge at a rate of 5% in the first 24 hours following a charge, followed by 0.5-1% each consecutive day.

4.6.4 Nickel-Cadmium

Nickel-Cadmium batteries have attributes similar to NiMH except the batteries should be completely discharged before recharging. NiCd batteries can have a significant memory effect. The main advantages of using NiCd are availability and price. NiCd batteries can have a high discharge rate, making them useable for electric motors.

4.6.5 Lead Acid

Lead acid batteries are extremely cheap, robust, and abundant at the voltage and power requirement levels of AUVs. Lead acid batteries are also one of the safest options for powering an AUV. Unfortunately, the energy per weight ratio is very low compared to Lithium, NiMH and NiCd options.

4.6.6 Important Considerations When Choosing A Power System

- Design your system so the batteries can be easily charged outside the pressure housing. Accidentally overcharging a battery can cause the battery to catch fire or explode. If the battery is housed in a pressure vessel, there must be a way (such as a pressure dependant vent) for the battery to vent in the event of a catastrophe. Don't inadvertently turn your battery housing into a bomb.
- Have several battery sets, and design your AUV so these sets are easy to swap and charge. During testing, batteries often limit the amount of work you can accomplish in a setting. Many teams plan to operate their AUV for a few hours during the competition, not realizing that a solid day of testing could last over 12 hours. If your batteries have to charge overnight, and you don't have spares, you are wasting valuable time.
- Purchase a quality battery charger that is designed to charge the type of battery in your AUV. Quality chargers can charge your cells quickly, fix glitches in the batteries, and shut down once the cells are charged. Make sure you buy several chargers, so you can charge multiple battery sets at a time. The Orbit Microlader charger has been used by teams in the past, and is considered one of the best hobbyist chargers.
- Use fuses and MOVs, and isolate power. Your propulsion system should be electrically isolated from computers and sensitive sensors. Sometimes teams have completely separate batteries for thrusters, and communications to those thrusters are fed through opto-isolators. Fuses combined with Metal Oxide Varistors (MOVs) are essential in preventing short circuits and damaging spikes. Fuses trigger after long term spikes, while MOVs smooth out short-term current spikes. Both of these should be placed as close to the thruster as possible. Each thruster should contain its own fuses and MOVs and should be isolated from every other thruster. For computer and sensor protection, Connect Tech makes a 12 port isolated serial controller for PC/104 form fit. This is a good option for isolating power on all of your serial lines.
- Design your AUV for higher voltages when possible. A thruster at 12V will draw 4 times the current of a thruster designed for 48 volts. Higher currents will require thicker wire and cause more heating problems. DC/DC converters can step power down for low voltage applications.

4.7 Controls

Control systems vary greatly depending on the vehicle. See the theory section for more details on the basics of controls. When designing a control system, keep in mind several factors:

- Theory (complex) vs. Practicality (simple)

- Time required to “tune” parameters

Developing a control system can prove very difficult and time consuming. Sticking to the KISS principle may save time and frustration. For example, if implementing a PID controller you may not need to calculate/tune every parameter. Using only proportional control may be enough for some parts of the vehicle. This can save time and energy for other parts of the vehicle.

4.7.1 Depth Controller Case Study

Ryan Stenson 9/14/06 3:20 PM
Comment [29]: Are we missing something here?

Error = desired – actual
Thrust = P * error
Tune P such that you get a plot like below

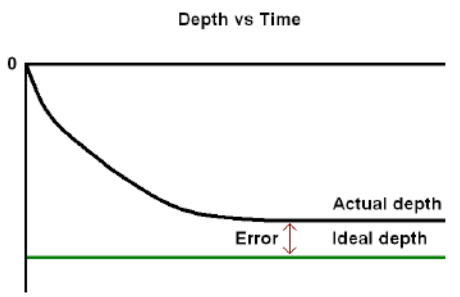


Figure 4-1. Depth Plot with Proportional controller

The buoyancy from the vehicle is constantly pushing the vehicle to the surface. Adding additional variables to the controller can alleviate the problem, or you can just trick the controller by saying that you want to go deeper than you really need to go.

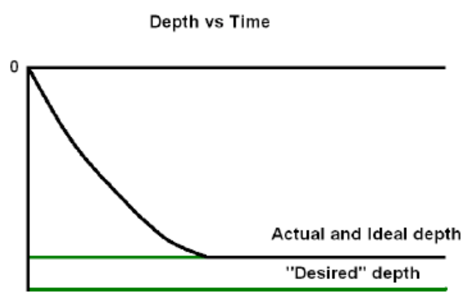


Figure 4-2. Depth Plot with Same Controller

This is not ideal, but it can save valuable time before the competition. Taking these shortcuts to an extreme can be dangerous. For instance, if you are trying to look for something below the vehicle with a camera, but the vehicle rolls from side to side or is constantly bobbing up and down in the water, the camera may never get a stable image to process.

A well designed and tuned plant and control system are ideal for any vehicle. However, time, knowledge, or experience may limit what you can do, so try to simplify whenever you can: KISS. Most importantly, test the vehicle in the water as soon as possible.

4.7.2 General Controls Troubleshooting

Murphy's law of computing reminds us that "A computer program will always do what you tell it to do, but rarely what you want it to do." –

> *Log all sensor, vehicle state, and control values. This makes troubleshooting far easier.*

Sensors, thrusters, and actuators act unpredictably when supplied with insufficient power. Always check the batteries. If possible, log all sensor data, vehicle state data, and control outputs on the vehicle all of the time. Compare the sensor data, where the vehicle thought it was, and where the vehicle actually was:

- Is the vehicle where it thinks it is?
- Is the sensor data accurate?

If this is ok, look at the controller/thruster outputs against the vehicle state data:

- Is the vehicle going where it's told?
- Is the vehicle being told the right way to go?

> *Controls don't have to be perfect; they have to work.*

4.7.3 Specific Problems

- The 0° – 360° problem: "My vehicle is literally spinning in circles" First, as with any problem, check the batteries. Also check the thrusters and control surfaces (fins, etc.). The problem may lie in your control system. Say you're trying to go north (0°). You have implemented a basic controller: error = desired heading – actual heading. No controller or sensor is perfect, so you will never be heading exactly north. If you are heading at 1° your error is small (-1 = 0 – 1). If you are heading at 359° your error will be huge (-359 = 0 – 359) so the vehicle will turn all the way around to make the error 0. A simple check on your controller should solve this problem. Every year at the competition (and even on some Navy vehicles) this problem is accidentally demonstrated.

- "My vehicle sinks and doesn't come up after it reaches a certain depth. What is wrong with my controller?" Don't be so hasty to blame your controller. Most likely, your buoyancy is changing over depth. See the buoyancy section, otherwise perform general controls troubleshooting.

4.7.4 Other Problems

- "Our vehicle works great for 523 seconds but then it freezes." This problem is often accompanied by "Our vehicle freezes unless we have a cpu/monitor plugged in." This is an interesting problem that has been demonstrated several times at the competition. Interestingly, it has also been demonstrated in industry. "We used to have a 238 second problem, now it's 617 seconds. We're showing improvement." – actual quote from a meeting on why a vehicle didn't work, (the numbers aren't exact, but the message is clear). The problem here (as it was with the industry robot) may be in buffering. When the vehicle is underwater, it has no monitor to display all the print statements that your software is generating. So it buffers the output. Once the buffer is full, the vehicle may freeze. Rather than deleting all the print statements (they may be useful in troubleshooting), just pipe the output to a file. In Linux this is done as follows:

```
$ some-command > /path/to/some/file
```

4.8 Autonomy

"Autonomous: independent and having the power to make your own decisions"
– Cambridge Advanced Learner's Dictionary

An *autonomous* robot moves without outside control, exists independently and responds and reacts to its environment without an external mediator. Autonomous robots generally use behaviors to perform actions. A *behavior* is any part of a program that tells the robot to do a particular distinct action. Keep in mind that the vehicle will have to get to an objective, perform an operation, and get to another objective.

4.8.1 Major Approaches To Developing Autonomous Systems

"It is said that the Limbic system of the brain controls the four F's: Feeding, Fighting, Fleeing, and Reproduction."
–Karl Pribram

All autonomous systems share the need to react appropriately to complex environments. There are three main approaches to handling this complexity.

- ***Deliberative*** systems assume a model of the vehicle's environment and abstract the complexity to how the model is created from the sensor data. [0, pp.21-24]
- ***Reactive*** systems assume robust behaviors and abstract the complexity to interactions between them. Reactive systems are prone to *emergent* behavior [0, pp. 24-27 and 104-115]; new actions that occur as the result of planned or unplanned interactions between existing behaviors. Be aware of potential undesirable side effects when designing behaviors. Any situation that seems unlikely will be faced by your robot over and over.
- ***Hybrid*** systems assume both the model and the behaviors. They are generally preferred since it is sometimes possible to reduce the complexity of specific problems by handling some parts at the behavioral or model level, leaving a slightly less complex problem for the interface. [0, pp. 205-235]

You will eventually have to figure out how the vehicle can get the information it needs and what it should do with it. This will almost always require *ad hoc* parameter settings.

4.8.2 Behaviors

"The great end of life is not knowledge, but action."

– Thomas Henry Huxley

The control system (Section 3.6) handles the basics: how to turn, how to go straight, how to aim for a waypoint, how to follow a path. But an autonomous system also needs to combine these techniques into more complex behaviors: avoid obstacles; go to the red ball, follow the pipe. Behavior design is how basic commands are converted into autonomous functionality.

Sensorimotor Control. There are several mechanisms used to control vehicles as a function of sensed objects. *Reactive* methods generally use some function of the sensor readings as input to the actuators. For example, if the object is closer, the vehicle turns more/faster. If the object is far away, the vehicle turns less or more slowly. This is good for self-preservation, but less helpful when the vehicle needs to react to objects it knows are there but cannot sense because of either distance or occlusion. *Potential fields* are used to mediate between several sensors and to incorporate information the sensors cannot supply. If the vehicle is getting signals from one sensor to turn left, and from its goals to turn right, the relative strengths of the potential fields will determine what heading the vehicle actually attempts.

The biggest sensing problem for autonomous vehicles is *perception*, or how to separate objects from their environment using sensory data. The best sensor and the most elaborate perceptual algorithms won't do you any good if you can't process the data quickly enough (if your vehicle can't monitor it, your vehicle can't react to it). If your robot needs to sense something in its environment, and you have a choice of sensors (Sections 3.7, 3.8 and 3.9 in theory, and 4.4 and 4.5 in applied), try to make distinguishing between your target and the rest of the world easy.

Avoidance. Like many artificial intelligence problems, this initially seems trivial and quickly takes on a monstrous form. There are many algorithms available, depending on your vehicle's configuration (round and point-like vs. long and narrow), your mobility (turn radius vs. turn speed), and your sensors (quickly updated sonar readings vs. intermittent images vs. depth sensor). Use your vehicle to help you choose between them or come up with your own. Making avoidance work almost always involves lots of parameter tweaking in the target environment. Try to make it easy to adjust parameters on the fly. You will almost certainly have to either manually adjust parameters or perform a calibration run once you reach the competition environment.

In almost all cases, behavior development can be reduced to three phases:

- Identify the **behavior** needed (follow path, avoid, goto waypoint, get into position to pick up/drop object, pick up object, drop object)
- Identify the **trigger** to start that behavior, generally a combination of a sensor reading and the vehicle's state (no obstacle detected and in survey state, obstacle detected in path, homing state, vehicle/location or vehicle/object relationship identified, object found)

- Identify the **termination criteria** (reached end of path, no more obstacles in path, reached waypoint, object picked up, object dropped) which can also be a trigger for the next behavior

These three phases translate nicely into if-then statements in programs: *if* {trigger state} *and* {sensor} *and* {termination criteria not met} *then* behavior. If you want to use a mechanism like potential fields that combines weighted desired behaviors into actuator commands, then your program may look more like: *if* object's field important *then* include in field computation. In that case the field computation generates the behavior during run-time and the trigger and termination criteria are used either to define the field or to define the limits of the field.

Actuation. Consider maneuverability constraints. Do you need a tight turn radius? Or perhaps the ability to hover or stop? Do you need to pick something up? Once you've chosen actuators that are capable of performing the actions you need, make sure you have a behavior that performs those actions. You will need to test your behaviors extensively in the target environment to set their parameters.

Navigation and Mapping. Work out how much you need to know about where you are. Sometimes it's critically important to be able to identify your location in a larger context (take the thing to location X). Sometimes you only need local information (pick up the red ball and put it in the nearest yellow box). Sometimes you don't need either (go west, avoiding). Your vehicle may need to go from one specific location (waypoint) to another, avoiding obstacles but staying as close to the path as possible. Figure out how much you need to know, and how accurately you need to know it. Use your sensors for trigger and termination criteria. Then let navigation (Section 3.5) figure out how to do it.

SLAM (simultaneous localization and mapping) enables robots to obtain a good relative position in their environment and build a map at the same time. However, mapping is processor/sensor intensive. It is also generally difficult in an environment that doesn't have many salient features. Figure out where you want to spend your processing resources.

Communication. While you're developing its behaviors, your vehicle should be able to communicate with you, and you should be able to communicate with it. There are many options; pick the one that matches your problem and your vehicle. Vehicles can send signals through acoustic modems or wireless ethernet connections to transmit information, or they can change the environment in some way that can be sensed by whoever needs to get the message (*stigmergic* communication), or they can just store everything on board for you to download after the fact. Autonomy isn't necessarily linked to lower communications: often you want more information while you're developing the system than you will need to operate it.

4.8.3 Summary

Make sure you have behaviors that address each aspect of the problem you need to solve. Generally either the individual behaviors are simple (avoid, detect, go to waypoint) and the interconnecting mechanisms are complex (avoid but don't get too far off the path to the waypoint; stop if you detect a target but avoid if you're going to hit something before you stop), or the individual behaviors are complex (search, collect and carry object, deploy) and the interconnecting mechanism is simple (if search finished, collect and carry object).

4.8.4 Practical Considerations

DO NOT ASSUME THAT IF THE BEHAVIOR WORKED IN SIMULATION IT WILL WORK ON YOUR VEHICLE! Apparently unlikely situations arise constantly in the real world.

Simplify your behaviors and their interconnections as much as possible. Then make sure you can still do all the tasks. Be alert for undesired interactions between behaviors.

Make sure the vehicle is unable to hurt itself or you while you're debugging.

Do one thing at a time. Attempting to optimize more than one thing generally leads to poor performance in all of them.

CALIBRATE your sensors and actuators in the target environment! Make sure your code lets you easily adjust sensor and actuator thresholds. As soon as you put your vehicle in a new environment, everything changes. Put in lots of debugging code, if you can.

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4.8.5 References

1. Arkin, Ronald C. (1999). Behavior-Based Robotics. Cambridge, MA: The MIT Press
2. Braitenberg, Valentino (1984). Vehicles: Experiments in Synthetic Psychology. Cambride, MA: The MIT Press

4.9 Underwater / Ocean Engineering Advice For AUV Teams

Teams new to the Student AUV Competition have at times needed to learn the basics of underwater engineering practices the hard way, by repairing a flooded or damaged vehicle during the heat of a competition. As an aid in avoiding such common problems as leaks, ground loops, short circuits, vehicle component degradation, and inconvenient access to internal vehicle subsystems, the following general advice is offered for consideration by vehicle designers.

4.9.1 Job #1: Keeping the Water on the Outside of the Vehicle. The task of packaging AUV electronics and sensors has one overarching requirement – keeping these items dry when operating underwater, while still enabling ready access for testing, modifications, and repairs when out of the water. A number of innovative packaging approaches have been used in the AUV competitions. Most involve metal or plastic pressure vessels for the electronics and sensor housings and either lids with compression seals or end caps with o-ring seals.

Seals and O-Rings. Because ambient pressure increases as an AUV submerges, both compression and o-ring seals become tighter with increasing depth. The key to success is to size the sealing materials properly and machine the sealing surfaces carefully to ensure an effective initial seal when out of the water. Then, as the vehicles proceed to depth, the seals will continue to function. However, the designer must also account for the maximum pressure (depth) that the pressure vessel can tolerate. As pressure builds, water will eventually push past a seal, and if the pressure housing deforms or cracks due to over-pressure, even the best seals will be of no help.

O-rings are the common sealing method for cylindrical pressure vessels, as shown in Figure 4-3. These housings are often made of metal (usually aluminum), polyvinylchloride (PVC), or a see-through material, such as polycarbonate. The advantage of the latter is the ability to observe the vehicle's internal components during testing or demonstration. This also allows indicator lights or display devices inside the vehicle to be viewed to aid in understanding vehicle status and/or troubleshooting. Single or double o-ring seals are used on the end caps, which may also be metal or plastic. Metal is frequently used in order to facilitate connector installation and reliability, as well as end cap durability.

Figure 4-3. Double o-ring seal used on the end cap of cylindrical pressure housing.

End caps must be secured to the pressure vessel. This is typically accomplished by small bolts installed around the edge of the end cap. Sometimes, for student competition vehicles where frequent openings and closings are needed, clips, clamps, or other devices are used to restrain the end caps. The important thing is to adequately restrain the end caps so that they do not pop out at an undesired time. Depending upon the size of the pressure vessel, getting the end caps installed can sometimes be difficult, due to the need to compress air within the housing as the end caps are inserted. Installation of a small pressure relief port (a threaded hole through the end cap) will solve this problem. In addition, such an opening (which is re-closed with a sealed machine screw before submersion) can be used to pull a partial vacuum during end cap insertion, which can help to pull an end cap into its fully-seated position.

O-rings are designed to be lubricated for a proper seal. Special o-ring greases are available for this purpose (note that some greases are not compatible some types of housing materials; in particular, some greases are not recommended for use with polycarbonate). Besides enabling the end caps to slide in and out of the pressure housing more easily and without damage to the o-rings, the grease actually swells the o-ring slightly, facilitating a better seal. However, care must always be taken to keep the o-ring surfaces clean and free of foreign material. A simple hair across an o-ring seal can provide a water intrusion path sufficient to flood a vehicle. AUV competition sites are not necessarily clean. They are usually outdoors, and often teams set up in areas that are not even paved (bringing along a large tarp for the "floor" of the team's work area can be a big help). Dirt or bits of debris allowed to get stuck to the o-ring grease can also cause a leak. Well-prepared teams bring plenty of spare o-rings and replacement seals of all sizes used on their vehicle. They are relatively inexpensive and take up little space in the team's spares box, but are usually difficult to obtain at the competition site. In addition, routine maintenance is important; don't expect one end cap o-ring to last the life of the vehicle. Inspect the o-rings frequently.

The need to open a vehicle many times during development and competition events has led a number of teams to design their pressure housings with simple lids, sometimes transparent. Vehicle pressure housings with lids require some kind of face o-ring or compression seal and carefully designed fasteners, such as shown in Figures 4-4 and 4-5. For a cylindrical housing such lid seals usually won't tolerate as much pressure as a well-designed o-ring seal, but they can provide faster and easier access to the vehicle electronics. Care should be taken to design the fasteners for uniform performance and relatively quick release (to avoid defeating the advantage of using a lid assembly). Lid fasteners can break, either in use or during vehicle transport. On at least one occasion, a vehicle required inspection before international transport, and the inspectors, who could not figure out how to open the latches, managed to break one off in their attempt to solve the puzzle. Designing latches for easy replacement (and having spares) can save the day at a competition.

Figure 4-4. AUV pressure housing with a clamped lid and an o-ring face seal.

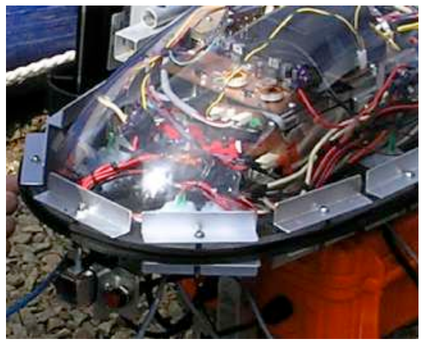

Figure 4-5. AUV pressure housing with a clamped lid and a compression seal.

Another regrettable example was experienced by a team in a hurry to close their vehicle to meet the deadline for their competition run. The vehicle was designed with commercially manufactured pressure-proof boxes, with a simple waterproof seal for their hinged lids. Although the team may have taken care to ensure that the sealing surface had no dirt or debris before closing a box lid, they apparently did not notice that a wire tie had not been properly tucked into the box before the lid was secured. Figure 4-6 shows the problem, as identified after the vehicle was placed into the water and observed to sink rapidly, ending the competition for the team.

Figure 4-6. A plastic wire tie protruding through the seal on a waterproof box, resulting in the AUV sinking and in serious damage to electronics throughout the vehicle.

An important reminder: when hurrying to reassemble an AUV be sure to install ALL of the end caps and lids. At least one team has arrived for vehicle launch having forgotten to install an end cap on their AUV's lower pressure housing; the error was fortunately noticed by the launch crane operator before any damage was done.

Essential recommendation: whether using lids or end caps, always inspect compression seals and o-rings as well as their mating surfaces before installation. This can require quite a bit of team discipline, particularly during sometimes frantic repair and modification efforts at competitions. However, the vehicle and all of a team's work can be lost if care is not taken to keep the water on the outside of the vehicle.

Dealing with the Effects of Humidity. Another potential way for water to get into an electronics housing is through condensation in humid environments. Unfortunately, humidity and in-water test sites tend to go together. If warm, humid air is trapped in pressure vessels, particularly those with a large amount of air space (as often used by student AUV teams), and the vehicle is placed in relatively cold water, significant condensation can occur. This effect can be seen in the clear-lidded vehicle of Figure 4-7. Condensation can also occur when a vehicle containing humid air becomes very warm inside when operated out of water, which can create relatively high temperatures inside the pressure vessel compared to ambient air outside the housing. (The source of this heat can be from the electronic components or sunlight.)

Figure 4-7. Potentially damaging condensation inside an AUV pressure housing.

A droplet of condensed water mixed with small amounts of salts or other contaminants in the pressure vessel can affect sensitive circuitry or even cause a short circuit and serious damage to the electronics. Techniques to help avoid such problems include minimizing air space within the pressure housing, pulling a partial vacuum after closing the housing (ideally, the housing would be back-filled with dry nitrogen; however, that may not be practical for student AUV competitions), and checking housings and lids to remove any previously trapped condensation present before final closure.

Issues Related to Cables and Connectors. A well-designed AUV can fail due to simple problems with cables and connectors. Rough treatment of these items can cause intermittent connections or broken wires. Even proper restraint of external cables can be important. AUV designers should seek a good balance between modularity (with many interconnected subassemblies) and reliability (often improved by a minimized number of interconnections). Although the ability to quickly remove and replace a sensor or external assembly can be beneficial, when many such elements exist in a design, the overall system reliability can suffer. In addition, considering the relatively high cost of good-quality underwater connectors, the use of a large number of interconnected assemblies can drive up the cost of the AUV. No matter how many external cable assemblies are used, don't let the AUV cables become "handles." Long and unrestrained cables hanging from an AUV may be snagged by a diver during handling, potentially opening a connection or damaging the cable. Figure 4-8 shows an example of some AUV cabling that might benefit from at least a few additional cable ties.

Figure 4-8. Example of unrestrained external cabling that could become snagged or damaged during AUV launch and retrieval.

Use of the highest quality connectors affordable for the AUV is a wise design approach, but this is still not a guarantee against leakage. Often bulkhead connectors have o-ring seals, and they should be cleaned, greased, and inspected when installed. With repeated mating of underwater connectors, the pins are at high risk of becoming bent. Taking sufficient time to mate the connectors and carefully aligning keyways will help to avoid bent pins. Care should also be taken to avoid mating connector pairs when power is applied, as arcing that can damage the pins may occur. Strain relieving, protective, and/or locking sleeves or caps should always be installed when provided for connectors.

Exposing Open Connections to Water. On numerous occasions, vehicles at student AUV competitions have been observed to be placed in the water with either open (uncapped) connectors or open CAT 5 or USB cables connected to the vehicle. This is not a good practice. Not only can the connectors deteriorate over time, but ground loops, electrical noise, undesired current paths, or damage to the vehicle (and control computer) can occur. All open connections should be properly capped whenever a vehicle gets wet. "Dummy plugs" or protective caps are available for this purpose.

4.9.2 Environmental Considerations.

AUV performance can be affected by the environment, particularly by temperature and pressure. Changes in temperature can affect the physical dimensions of components as well as the performance of sensors and electronic circuits. Pressure can affect sensors and physical dimensions also, and at deep depths the performance of hydrophones and other sensors can be degraded. Student AUV designers should be particularly attentive to potential heat build-up within a vehicle when operated in air for long periods, and even during in-water operation. Heat sinks that transfer heat to a metal pressure vessel can help to dissipate heat from internal components.

When a vehicle is operated in salt water, a post-run rinse in fresh water is important in order to reduce the potential for corrosion and for salt to migrate into vehicle's connectors or even its internal electronic assemblies as the AUV is handled and disassembled.

4.10 Testing

There is absolutely no substitute for testing. The vehicles that do the best at the competition are most often the ones in the water the most. Time at the competition should be dedicated to in water practice.

Some basic tips for testing and troubleshooting:

- A checklist: List all the things to check before putting the vehicle in the water. A poorly sealed end cap is easy to detect in water as the vehicle sinks but is better checked on the surface.

- Simple tests on subsystems: For every sensor, thruster, and manipulator, a simple test program/procedure that can test the part is very helpful. If a thruster or sensor doesn't seem to work when testing the whole vehicle, a 5 second program can answer whether it works on its own or if it is broken.

- Check the batteries: If something seems to be acting funny, it could be getting inadequate power. A 30 second check can save hours of troubleshooting.

- Test in pieces and slowly add pieces to get to a fully working vehicle. It is much easier to troubleshoot when you can limit what has changed. There will be enough finger crossing as it is, the more you can limit the possible problems the better. However, don't try to perfect subsystems before putting everything together; you may lose valuable integration time.

- When starting the vehicle, try to reset the settings (data rates, etc.) on every part you can. Yes, the manual says "do this once and the setting will be saved." But things happen. An errant current may have changed something or a team member may have tried an experiment, changed some setting and forgotten to change it back. 5 seconds or less of startup time can save a lot of headaches.

- Loose wires: Eliminate as many loose wires as possible. Nothing is worse than when your vehicle works perfectly on the bench but fails right as it starts its competition run because of a loose wire. Or how about the vehicle appearing to work right but failing to complete the mission because the camera cable came loose halfway through the run (it's happened).

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4.11 Fund Raising

There are a variety of ways to obtain funds for your organization both through your school and in industry. The first few years after your organization is formed tend to be the hardest for raising money. The first step to successful fundraising is to generate a solid business plan for your team. Elect a fundraising lead as soon as possible. In order to be taken seriously, you first must demonstrate a solid student backing, and create a persuasive presentation, informational handouts, and a website. Your school (and industry) will be much more likely to donate resources if you can show that their donation is helping a large amount of students rather than just one or two individuals.

The first place to start fundraising is within your school. Student body governments, engineering student governments, and alumni councils usually have money available for student organizations. This money is often allocated early in the year, so it's important to pay attention to deadlines. Communicate strongly with your school's alumni association and have a strong presence during alumni reunions. If possible, have your AUV (or components) on display. Engineering alumni are much more inclined to become involved if they can see a product in progress. Video footage is crucial for generating interest. Coordinate with your Engineering Alumni Council and seek out alumni who may have ties to relevant industries. Frequently alumni are eager to donate parts such as motors or sensors rather than money.

Partnering with industry is crucial to fundraising. The RoboSub Competition generates media hype. Oftentimes AUVs are shown on news stations, the Discovery Channel, and science magazines. In essence, your AUV is a swimming billboard. Exchange advertising space for discounted products and cash donations. Create fundraising packages that allow the donor to know they will be getting a return. For example, if the donor knows that $1,000 buys them a 2 inch logo on the AUV, recognition in all publications, and a logo on the team website, they will be more inclined to donate. Keep in mind that a majority of your team's fundraising may come from donated or loaned products, rather than cash.

Another good avenue for fundraising is attending trade shows. You will get a chance to check out the latest and greatest hardware for your vehicle in addition to forging partnerships with vendors who might be able to donate or discount hardware. In addition, this is a good opportunity to network for internships or future employment. Examples of trade shows are Sun JAVA, AUVSI, Oceans, Sensors, and AUV Fest.

The number one mistake made by students is procrastination. Fundraising must start early to be successful. Even if an organization has promised you a cash or product donation, it may take months to receive the payment or product. Follow-up phone calls are crucial to keeping your team on the donor's priority list.

4.12 The Competition

If anything can go wrong, it will

- Murphy's Law

Prepare for everything to go wrong at the competition; odds are that most things will. We have collected a laundry list of recommendations and lessons learned. We've broken down this guide into three groups:

- Shipping (Getting you and your vehicle to the competition and back)
- Surviving (Staying alive during the competition)

- Winning (Etiquette and procedures at the competition)

4.13 Shipping

- Shipping batteries/Hazmat: There are lots of restrictions for shipping HAZMAT); plan ahead to deal with them so you don't have to leave anything behind.
- Pelican cases: Shipping/moving your vehicle in a proper container can save the vehicle from damage. Pelican cases are widely used in industry.
- Shipping to the hotel: The hotel you are staying at should receive and hold any packages you ship. Call ahead to make sure this is ok. Send everything early so it will be there before you arrive at the competition and you don't waste time at the competition waiting on a shipment.

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Comment [33]: Trademark symbol? Endorsement issues?

4.14 Surviving

- Enjoy the competition and its host city! Try not to just stay in the hotel and work on the vehicle day and night.
- Select a designated driver. The driver should get a good night's sleep every night. This is not just for safety. Someone from the team should be awake and coherent early in the morning so your team doesn't miss anything important at the competition (usually this can be the team leader). Teams have slept through their competition runs. Don't let that happen to you!

4.15 Winning

- Show up to the competition on time every day. Empty team booths do not look good in the eyes of the judges.
- Bring spares of everything. Anything that can break at the competition (and even things that can't break) will break. Test the spares beforehand.
- Use a checklist to prepare for in-water time. Check all seals, batteries, and connections so you don't waste valuable in-water time.
- Don't be afraid to ask for help from other teams. Every team wants to win, but everyone is very open and helpful. Also, be respectful to other teams asking for help.
- Listen and be nice to the competition organizers and the divers. Everyone is volunteering their time to make sure you have a fun, safe time, so if they are trying to tell you something, it's probably to your benefit to listen.
- Utilize every minute of in-water time you can.
- Don't make unnecessary changes to the vehicle at the competition. The time for trying risky ideas is over, don't risk a perfectly good vehicle to try out a new idea.

- Be open to people visiting your team. Have resumes handy. Employers go to the competition to hire so be prepared.

4.16 Summary

THE NUMBER ONE FAULT GENERALLY OBSERVED/EXPERIENCED:
– NOT ALLOCATING ENOUGH TIME.
The underwater engineering industry is SLOW. Even if you've paid for an "in stock product" it could take 6 months or longer to receive it. Waiting for parts to arrive will be the biggest factor in missing deadlines.

Test your vehicle in water as early and often as possible. This will test your design, components, and hardware. It will also give your team invaluable experience.

5 SUMMARY

The RoboSub Competition is a chance for students to use their creativity and engineering education in order to come up with unique solutions to a given set of challenges. This document was written to help those students with the basics of underwater vehicle design as well as give them some "lesson's learned" from past competitions. This document will be updated as updated information is available. Further guidance can be found on the AUVSI Foundation website at www.AUVSIFoundation.org or www.RoboSub.org