Abstract

The human spirit to explore is the driving force behind this project. Remotely operated vehicles (ROVs) are often used to observe environments hostile to humans. ROVs are restricted by their requirement to be controlled by humans, which adds limitations to distance and time. The goal of this project is to create an autonomous underwater vehicle (AUV) to compete in the Association for Unmanned Vehicle Systems International (AUVSI) RoboSub competition in San Diego, CA, as well as the National Underwater Robotics Challenge (NURC) in Phoenix, AZ. Mechanically, the vehicle requirements include waterproofing, material selection, propulsion, actuators, CAD, and fabrication. Electronically, the AUV will need a passive sonar system to detect a 22-30kHz pinger source from up to 100 feet, an on-board power system, additional sensors such as an IMU, and the computer system. The system will require machine vision, artificial intelligence, and tactics for redundancy and verification.
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1 Introduction

1.1 Scope of Document

This critical design report details the design process and analysis of an autonomous underwater vehicle (AUV). The report has been broken into project scope, system requirements, high-level design, subsystem design, and analysis. Decisions for major design choices within each subsystem have been thoroughly documented, as well as the analysis to show the chosen system meets all functional, performance, and technological requirements.

Mechanical drawings for subassemblies can be found in Appendix B. Electrical designs have been drawn to the schematic level. However, the layout of printed circuit boards is a manufacturing problem to be accomplished in the production stage of the project. Flowcharts, state diagrams, and UML class diagrams are used to describe selected software components, along with relevant pseudo-code for particularly complex algorithms. Examples of various data structures and files can be found in Appendix D.

1.2 Problem Statement

With the advent of navigational and data intensive exploration projects, autonomous submersibles have evolved rapidly in recent times. Many commercial and military entities have found uses for AUVs in locating mines, surveying ocean floors, and subverting submarine drug trafficking. More recently, remotely operated vehicles were involved in finding a remedy for the Deepwater Horizon oil spill. Research institutions have turned to autonomy and modern sensors for recording chemical concentrations in lakes as well as the study of marine biology in underwater ecosystems.

1.3 Background Information

The Autonomous Underwater Vehicle – University of Arizona club was formed in September, 2012. The AUV-UA plans to enter an autonomous submersible in the annual Association for Unmanned Vehicle Systems International (AUVSI) RoboSub competition, co-sponsored by the US Office of Naval Research. The RoboSub competition, held in San Diego, California, in mid-July, tests the ability of high school and collegiate teams to develop systems capable of autonomous navigation. The 2012 RoboSub competition manual, detailing rules and field layout, can be found in Appendix E.

The club has also expressed interest in the National Underwater Robotics Challenge (NURC), held annually in Chandler, Arizona, in early June. The NURC enables roboticists of
all ages to compete at various levels, include collegiate, adult, and corporate teams. A mission is released on October 31st that generally involves heavy interaction with field elements. Each challenge is held at nighttime to simulate deep-sea diving without the risk or logistics challenge of holding an event in a deep-sea environment.

1.4 Project Scope

As the customer (AUV-UA) has desired, this project entails the creation of one autonomous underwater vehicle capable of, at a bare minimum, accomplishing the traversal of the RoboSub course. This requires two major tasks; the first, fabricating a machine that is waterproof and includes a method of propulsion, various sensors, and a main host computer for processing. The second task is the development of an intelligent framework that enables users to quickly create missions, tasks, and vision filters. The final product will be used by future AUV-UA members as a platform for research, development, and STEM outreach.

1.5 Product Expectations

The final design must be technologically competitive without exceeding the stringent $3000 budget provided by the engineering capstone course. It must, in addition, meet all requirements described in section 2.1, which have been imposed by various stakeholders listed in the following section. From a software perspective, modularity, portability, and robustness are of the utmost importance.

1.6 Stakeholders

1.6.1 AUV-UA

The primary stakeholder for this project is the Autonomous Underwater Vehicle – University of Arizona club, known as the AUV-UA. This newly formed club, formed by members of this team, aims to produce an AUV to enter in the annual RoboSub competition. The AUV-UA’s goal for the 2012-2013 academic year is simply to create a structural base to be used as a research platform for future competitions. The success of this platform will ensure a long future of research and STEM outreach for the club and Southern Arizona.

1.6.2 Carl Hayden High School Robotics Club

The robotics club at Carl Hayden High School, Phoenix, AZ, has entered in the RoboSub competition for two years. The team founded NURC in 2007 after several years in
the international MATE competition. The team purchased four Reson TC-4013 piezoelectric hydrophones. The AUV-UA club and the Carl Hayden robotics team formed a mutual agreement that the AUV-UA produce a pinger localization enclosure utilizing the four hydrophones that can be used by both parties in competition.

2 System Requirements

2.1 Summary of Requirements

The requirements for the system encompass three basic disciplines in functional, performance and technological requirements. The system’s requirements are based on the 2012 RoboSub competition rule set with many of the intermediate and advanced tasks not being taken into consideration. The scope of the project can be defined by the degree of difficulty relating to the tasks at hand and the overall difficulty of creating an underwater robotic sub. Taking into account the tenants of underwater robotics and the competition rules, the basic requirements are abundantly clear and essential to assuring success for the system.

2.2 Functional Requirements

Functional requirements define major system capabilities. This distinction allows us to differ between a ‘must’ and a ‘desire’ and can be crucial in characterizing our system’s basic needs versus its desired performance. The first functional requirement is based on the principle of underwater robotics, submersibility. The system must be capable of submerging itself underwater without error. A system that is incapable of being submersed for extended periods of time in water will have failed many of the criteria necessary for success in the competition field. After being submersed, the system will then need to perform a set of tasks defined by the user in order to navigate through the competition. Since the system will be autonomous and will not be controlled by a user, it must be able to perform pre-programmed tasks consistently without error.

Without a user defining inputs, the system must also gather information from its environment in order to determine its next course of action. With the help of sensors and pre-programmed algorithms, the system will have the ability to locate itself relative to the competition course and continue through the course as it senses the environment. Along with RoboSub, the system will also compete in the NURC, which requires human control of the vehicle as it performs tasks. This requires the system to have reconfigurable remote controls.
### 2.3 Technological Requirements

The degree of difficulty associated with the AUV system is partly responsible for many of its technical design attributes and the fundamental importance of autonomy. The complexity of autonomy in itself is tough to grasp immediately, and the concept of localization of the system and hydrophone signal analysis adds to that intricacy. Luckily, the technological requirements allow for a step back to observe the inner workings of the system and the required technology to run the system through the competition course. The main technological requirements include the system’s desired ability to utilize a general purpose CPU and motherboard for high-level software, cameras for object recognition, and motors and propellers for propulsion.

While the previous requirements are standard for this type of project and AUVs in general, the following requirements were necessary to compete in the RoboSub competition. Since beacon multilateration will be required in RoboSub, the system is required to use hydrophones to detect high frequency bursts within the pool. The importance of calibrating the location led to the system needing four hydrophones to find the location. Along with the hydrophones, an inertial measurement unit will be used for navigational purposes to help guide the system through the course.
Table 2: Technological Requirements

<table>
<thead>
<tr>
<th>Number</th>
<th>Type</th>
<th>Description</th>
<th>Source</th>
<th>Status</th>
<th>Priority</th>
<th>History</th>
</tr>
</thead>
<tbody>
<tr>
<td>101</td>
<td>Technology</td>
<td>The system shall use hydrophones for pinger tracking.</td>
<td>Customer</td>
<td>Approved</td>
<td>Must</td>
<td>9/12/2012</td>
</tr>
<tr>
<td>102</td>
<td>Technology</td>
<td>The system shall utilize cameras for object recognition.</td>
<td>Customer</td>
<td>Approved</td>
<td>Must</td>
<td>9/12/2012</td>
</tr>
<tr>
<td>103</td>
<td>Technology</td>
<td>The system shall use a general purpose CPU and motherboard.</td>
<td>Customer</td>
<td>Approved</td>
<td>Must</td>
<td>9/12/2012</td>
</tr>
<tr>
<td>104</td>
<td>Technology</td>
<td>Motors and propellers shall be used for propulsion.</td>
<td>Customer</td>
<td>Approved</td>
<td>Must</td>
<td>9/12/2012</td>
</tr>
<tr>
<td>105</td>
<td>Technology</td>
<td>The system shall use an Inertial Measurement Unit (IMU) for navigational information.</td>
<td>Customer</td>
<td>Approved</td>
<td>Desired</td>
<td>9/12/2012</td>
</tr>
</tbody>
</table>

2.4 Utilization Requirements

Using intelligent and cost-efficient spending in building the system is essential to properly utilizing the allotted funds. Due to the $3000 budget, many constraints had to be made in the overall design. However, several gracious in-kind donations to the AUV-UA have considerably enhanced the quality of the design.

Table 3: Utilization Requirements

<table>
<thead>
<tr>
<th>Number</th>
<th>Type</th>
<th>Description</th>
<th>Source</th>
<th>Status</th>
<th>Priority</th>
<th>History</th>
</tr>
</thead>
<tbody>
<tr>
<td>201</td>
<td>Utilization</td>
<td>The system shall conform to the constraints imposed by the RoboSub and NURC competitions.</td>
<td>RoboSub</td>
<td>Approved</td>
<td>Must</td>
<td>9/24/2012</td>
</tr>
<tr>
<td>202</td>
<td>Utilization</td>
<td>The system cost no more than $3000.</td>
<td>Customer</td>
<td>Approved</td>
<td>Desired</td>
<td>9/24/2012</td>
</tr>
</tbody>
</table>

2.5 Performance Requirements

After taking into account what the system is capable of doing in its functional requirements, it’s important to lay down stringent rules on how well it must perform these desired functions. These performance requirements will measure the system’s ability to perform various functions. The first functional requirement laid out was that the system be submersible. The related performance requirement states that the system withstand a depth up to forty feet without leakage. This means the system is required to be both submerged and waterproof up to forty feet for the duration of a competition run in order to satisfy the requirements of the competition.

Another measure of performance is the minimum runtime of the system. When placed in water, the system is expected to run for one hour on batteries. This ensures the AUV is
running at full capacity during the half-hour run at RoboSub. Finally, the performance of the system itself in the competition course is a huge factor on the system’s success. When performing tasks it is expected that the system behaves accurately and in a repeatable manner so as to guarantee consistent mission success throughout the course. This relates to the functional requirement that the system must have pre-programmed tasks. The performance requirement is the guarantee that the system operates as expected.

<table>
<thead>
<tr>
<th>Number</th>
<th>Type</th>
<th>Description</th>
<th>Source</th>
<th>Status</th>
<th>Priority</th>
<th>History</th>
</tr>
</thead>
<tbody>
<tr>
<td>301</td>
<td>Performance</td>
<td>The system shall be waterproof to a minimum of 40ft (depth of TRANSDEC pool).</td>
<td>Customer</td>
<td>Approved</td>
<td>Must</td>
<td>9/24/2012</td>
</tr>
<tr>
<td>302</td>
<td>Performance</td>
<td>The system shall have a minimum runtime of 1 hour on batteries.</td>
<td>Customer</td>
<td>Approved</td>
<td>Must</td>
<td>9/24/2012</td>
</tr>
<tr>
<td>303</td>
<td>Performance</td>
<td>The system shall perform tasks in an accurate and repeatable manner.</td>
<td>Customer</td>
<td>Approved</td>
<td>Must</td>
<td>9/24/2012</td>
</tr>
</tbody>
</table>

Table 4: Performance Requirements

3 Preliminary Design Review

3.1 Concepts Considered

During the high-level design phase, three concepts of varying complexity were considered. Each design features components common among autonomous submersibles: a frame, waterproof housing, modern processor, thrusters, batteries, cameras, and various sensors and digital outputs. However, the degree of quality, cost, and manufacturing time sets each design apart. Table 5 highlights the possible low-cost, well-balanced, and expensive solutions.

<table>
<thead>
<tr>
<th>Design 1: Current System</th>
<th>Design 2: Well-Balanced System</th>
<th>Design 3: Complex/Expensive System</th>
</tr>
</thead>
<tbody>
<tr>
<td>Already built</td>
<td>Ground-up design</td>
<td>Ground-up design</td>
</tr>
<tr>
<td>Steel strap frame</td>
<td>One or two compartments</td>
<td>CNC fabricated frame</td>
</tr>
<tr>
<td>Two compartments</td>
<td>Up to six thrusters</td>
<td>Vacuum formed dome</td>
</tr>
<tr>
<td>Four thrusters</td>
<td>Custom motor control</td>
<td>Several compartments</td>
</tr>
<tr>
<td>Custom motor control</td>
<td>General purpose CPU</td>
<td>Vectored COTS thrusters</td>
</tr>
<tr>
<td>fitPC2i embedded computer</td>
<td>Webcams, hydrophones, IMU</td>
<td>COTS motor controllers</td>
</tr>
<tr>
<td>Two webcams, one compass</td>
<td>Additional actuators</td>
<td>General purpose CPU + GPU</td>
</tr>
<tr>
<td>Custom Python framework</td>
<td>Arduino for interfacing</td>
<td>Additional sensors</td>
</tr>
</tbody>
</table>

Table 5: Three High-level AUV Concepts
Team 5374 – Competitive Autonomous Underwater Vehicle

Design one involves the upgrade of the current system, *Biff*, a relatively simple AUV produced by the family of a team member. *Biff* features an embedded processor, four vectored thrusters, two housings, a welded steel strap frame, and a custom Python framework. The scope of the project with regards to design one encompasses a rewrite on the software framework and the addition of sensors crucial to successful autonomous navigation. Designs two and three require a new build of the frame and enclosures, at varying degrees of complexity. A more powerful, versatile processor would be needed in both scenarios, but the third design incorporates a general purpose graphics processing unit (GPGPU), which increases the power requirements but greatly reduces image processing time.

### 3.2 Preferred Concept

Designs were subjectively ranked according to a series of metrics deemed necessary for success. Table 6 shows that designs were given scores between 0 and 10 for each criterion. Certain metrics were weighted more heavily than others to reflect a greater focus on achieving in those areas. Design two was chosen for its moderate cost and capability, increased flexibility over design one, and a fabrication level that matches the skill set of the team. The rubric chosen by the team may not reflect reality as accurately due to subjective decisions. The sensitivity of Table 6 to adjusted weights could change the outcome; for example, if minimal cost were to become a much higher priority, the shifting of weights could potentially place design one ahead of the curve. On the opposite end of the spectrum, increasing our reliance on high functionality and accuracy would clearly make design three the best option. However, design two offers the most flexibility both directions with regards to these sensitivities and is thus a more desirable platform.

Two different frame designs were created. One design focused on modularity. The other focused on general robustness. Figure 1 shows the general configuration of the strap metal design. This design was intended to enable the attachment of any component anywhere on

<table>
<thead>
<tr>
<th>Criterion</th>
<th>Weight</th>
<th>Design 1</th>
<th>Design 2</th>
<th>Design 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimal Cost</td>
<td>30%</td>
<td>8</td>
<td>5</td>
<td>2</td>
</tr>
<tr>
<td>Robustness</td>
<td>20%</td>
<td>5</td>
<td>6</td>
<td>8</td>
</tr>
<tr>
<td>Accuracy</td>
<td>15%</td>
<td>3</td>
<td>8</td>
<td>9</td>
</tr>
<tr>
<td>Functionality</td>
<td>15%</td>
<td>3</td>
<td>7</td>
<td>8</td>
</tr>
<tr>
<td>Minimal Labor</td>
<td>10%</td>
<td>7</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>Flexibility</td>
<td>10%</td>
<td>3</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td><strong>Totals:</strong></td>
<td><strong>100%</strong></td>
<td><strong>5.3</strong></td>
<td><strong>6.05</strong></td>
<td><strong>5.65</strong></td>
</tr>
</tbody>
</table>

Table 6: Concept Design Evaluation
the AUV. It allows for quick removal of one end cap of the electronics housing for servicing
the electronics inside. The thrusters are placed in the direction they would be propelling
the AUV. The second design, shown in Figure 2, was considered due to the availability of

![Figure 1: Strap Metal Frame Concept](image)

sheet metal. The sheet metal construction provides a solid frame for the AUV, but it lacks
modularity. The end cap on this design is also easily removable. The thrusters are vectored
so that the AUV may move and rotate in any direction it desires.

A compromise was needed to produce the final design, shown in Figure 3. This design
combines the modularity of the first setup with the robustness of the second design. Addi-
tional accessories may be attached anywhere on the rails if needed.

### 3.3 Changes Since PDR

Several changes have occurred since our preliminary design review. With a new partnership
forming between the AUV-UA and the Carl Hayden robotics team, the hydrophone array has
garnered increased attention. The team also acquired a generous donation of a motherboard
and mobile high-performance CPU for the competition. These partnerships have increased
the value, and risk, of completing the project on-time, and have given the team an added
incentive to achieve.
Figure 2: Sheet Metal Frame Concept

Figure 3: Final AUV Concept
4 Final Design Overview

4.1 System Overview

The finalized design combines the mechanical, electrical, and computer subsystems in a robust package capable of operating in a variety of demanding environments. Designed for simplicity and flexibility, the system will be rapidly configurable to accommodate a wide range of operating scenarios, including fully autonomous control.

![Block Level System Overview](image)

Figure 4: Block Level System Overview

4.2 Terminology

**AUV** – Autonomous Underwater Vehicle, a basic description of the entire system discussed in this document. A vehicle which can navigate an underwater environment and perform tasks without human control.

**Hull** – Main cylindrical housing for most electronic components, including CPU, motor controllers, and cameras. Made from polycarbonate tube with aluminum end caps.
Frame – Riveted aluminum sheet metal structure which hull, thrusters, battery compartments, and other manipulators are attached.

Thruster – Assembly consisting of waterproof motor (bilge pump), propeller, mounting hardware, and propeller guards.

Battery Compartment – Cylindrical tube containing batteries, isolating them from the rest of the electronic components.

Electronics Rack – Assembly inside hull which electronic components are mounted to. Includes system for heat dissipation, including dedicated CPU cooler and conduction plate for motor controllers.

Hydrophone Board – Circuit used for processing underwater acoustic signals sent from a pinger source. Resides inside waterproof hydrophone housing.

Pinger – Source of sound from a fixed location underwater. Used by AUV for navigation purposes.

4.3 Subsystems

The system incorporates three main subsystems: Mechanical, Electrical, and Computer. The mechanical subsystem consists of the vehicles main structural and dynamic elements, such as the frame and thrusters. The electrical subsystem combines several components used for environmental sensing and motor control. The computer subsystem is primarily comprised of software applications for autonomous and remote control.

4.3.1 Mechanical

The mechanical subsystem combines two main assemblies. The first assembly is a watertight hull containing the electronic components. The inner components are accessible through removable aluminum end caps which utilize pairs of rubber o-ring seals to prevent leaks during operation. The second assembly is the main frame of the system. This frame combines several aluminum sheet components using riveted joints. The main hull, thrusters, and other external components are mounted to the sheet metal frame.
4.3.2 Electrical

The electrical subsystem is the heart of the structure, supplying power to electro-mechanical thrusters and enabling sensors, actuators, and the CPU to engage with their surroundings. Two high-capacity, 22.2 volt lithium polymer batteries power the entire system for over an hour. Distribution of power is accomplished through the use of DC-DC converters, switching power MOSFETS, and the occasional linear regulator. Various sensors are employed to ensure any mechanical failures do not result in electrical issues; a leak sensor will be installed in each compartment to reduce the possibility of a normally catastrophic failure.

4.3.3 Computer/Software

The brains of the operation are in the software – more specifically, the intelligent planning agent that parses high-level commands into meaningful machine instructions and constructs bidirectional mission graphs to determine the next most plausible move. A complex problem has been reduced into four main subcomponents: a mission planner, a vision filter chain construct, an advanced logging and playback system, and the interface between the latter three systems and the physical world.

5 Mechanical Subsystem Design

5.1 Introduction

The mechanical subsystem is composed of the frame, watertight electronics housing, and the thrusters. The mechanical subsystem must be able to withstand any normal condition that it may experience while underwater.

5.2 Frame

The frame is the main support structure for the rest of the housings and external components of the vehicle. It consists of several sheets of 6061 Aluminum sheet (.080 inch thickness) riveted together to form a rigid and lightweight structure. The main plate has two downward bends which are used for mounting two lateral support plates. A pair of skid plates are added which run along the length of the vehicle, enhancing rigidity. Two hull supporting plates are used to fix the main electronics housing in place while allowing for easy access and removal should the need arise. Drawings for each part are available in Appendix B.
Several holes and auxiliary straps are added for design flexibility and ease of component mounting. These straps may be freely moved to different locations or modified to accept new external component geometries. Large sections are cut out to improve flow of water around the structure during movement, as well as to prevent air pockets from becoming stuck underneath. These cut-outs also increase camera visibility, allowing for clear views forward and downward.

![Frame consisting of main plate, two lateral plates, two skid plates, and two hull support plates.](image)

Figure 5: Frame consisting of main plate, two lateral plates, two skid plates, and two hull support plates.

### 5.3 Main Hull

The main hull is the largest watertight compartment on the vehicle. It houses most of the electronic components (excluding batteries) and is designed for rapid disassembly if required. An 8 inch outer diameter, 1/8 inch wall polycarbonate tube is used to allow visibility of electronic components as well as vision for internal cameras. Two aluminum end caps are pressed onto either end of the tube, using two bore seals on each end to prevent the caps from twisting or unseating themselves. The end caps are tied together with six steel threaded rods. Nuts are tightened on the outside of each cap to squeeze them together against the polycarbonate tube. This compression can be used to provide another watertight seal if desired.
The end caps are distinct from one another. One end cap is considered "fixed" to the rest of the vehicle’s frame. This end cap allows wires in and out of the main housing for transporting power to and from external components. The electronic components are also tied to this end cap via a removable electronics rack. The other end cap is easily removed, allowing access to internal components without major disassembly of the vehicle. Benefits include rapid replacement of parts or reconfiguration of electronic components if the need arises. The fixed end cap will also serve as a heat sink for the motor controllers. An aluminum plate will conduct heat from the controllers to the end cap, where heat is then dissipated in open water. The end cap will also have a coil which is connected to a dedicated CPU water-cooling system. This will ensure safe operating temperatures for all internal components.

5.4 Material Selection

The system makes use of several different materials. The main frame consists primarily of 6061 aluminum sheet due to its availability and popularity. Its light weight ensures flexibility in altering the mass characteristics of the vehicle by allowing for the placement of extra counter-masses. Aluminum is also more corrosion resistant than other materials such as steel, which is beneficial in an underwater environment. Structural strength is not a large concern, but sheet aluminum is sufficient for the low-impact nature of submersible vehicles. The end caps will also be made of aluminum for similar reasons, including its easy machinability compared to harder metals such as steel.

The main hull will be constructed using polycarbonate tube. This material is chosen for its light weight and transparency. It is also shatter resistant, making it a solid choice over other low strength plastic tubing. The team has experience making waterproof hulls using polycarbonate tubing. It can be machined easily cut to the appropriate size for this application.
Figure 7: Hull Access Process – six nuts are undone to allow the tube and free end cap to slide away from the AUV structure. The electronics rack will be mounted securely to the fixed end cap, allowing instant access to the motherboard, wiring, motor controllers, Arduino, and other sensors.

Other materials may include ABS tube for other external compartments and aluminum for mounting brackets and thruster mounts. Both are readily available and can be machined easily using university resources. Team members have had plenty of experience in metal-working and machining to create components with these materials once further design work has been performed.

5.5 Buoyancy and Stability

The system will be neutrally buoyant in order to prevent unwanted vertical movement when no thrusters are powered. The mass of the system must equal the mass of the water displaced in order for buoyancy and gravitational forces to cancel out. The system will be constrained to four degrees of freedom of motion: Translational movement in all three directions, as well as rotation about the vertical axis (yaw). In order to prevent pitch and roll rotation, the system must use a mass distribution which is gravitationally stable. This will be done by placing positively buoyant components (such as the hollow main housing) above negatively buoyant components (such as counterweights or batteries). Any deviation from the default vertical orientation will create a torque which will force the system to return to an upright orientation. For further stability, each pair of thrusters (where a pair consists of thrusters
which lie opposite one another) will have a plane of action which passes through the center of mass of the vehicle. When a thruster is powered, the vehicle will only be constrained to movement in the thrusters plane of action or about the axis of rotation perpendicular to this plane. This will allow for more predictable movement as well as increased stability for performing high precision tasks.

Preliminary mass analysis shows that the current design weighs 23.1 pounds, with a displacement of 32.8 pounds of water. This shows that 9.7 pounds of counterweights must be added to the vehicle to maintain neutral buoyancy. Without adding counterweights, the center of mass of the vehicle lies 3.9 inches above the main plate’s top surface. The plane of action of the horizontal thrusters lies 2.25 inches above this surface, so the center of mass must be lowered by 1.65 inches by use of 9.7 pounds of extra weight. Assuming the weights are of very small volume, they must be positioned 1.67 inches below the top plate surface in order for the center of mass of the vehicle to pass through both planes of action. This configuration maintains stability as well as overall neutral buoyancy.

5.6 Heat Dissipation

The electronic components in the main housing of the vehicle will produce significant amounts of heat during regular operation. Excess heat can negatively impact component performance and damage sensitive devices, so it is important that heat generated by high current devices is
transferred from the vehicle hull to the environment. Two components which require analysis are the CPU and each of the six motor controllers. The CPU/motherboard generates 45 watts under full power, while each motor controller will dissipate 1.25 watts at most. Two separate dissipation methods will be discussed for each of these components.

The CPU requires an environment where it can readily dissipate heat from regular operation. Excess heat will degrade performance and force premature shut-down if dangerous levels are reached. In the confined space of the main housing, air cannot sufficiently transfer heat from the CPU to the water outside. To solve this problem, a COTS water cooled system will be used to transfer heat from the CPU package to a coil which is exposed to the outside environment. This solution only requires installation of the cooling system in place of the default CPU heat sink, as well as routing the coolant through a copper coil to the outside.

The motor controllers use MOSFETs to regulate the amount of current passing through a corresponding thruster. Excess heat will increase the on-state resistance of the MOSFET, resulting in even higher heat generation and likely component failure. Since each controller dissipates significantly less heat than the CPU, dedicated cooling systems are not required. Each controller has two MOSFETs which are on at all times, with the heat generated by
the controller being spread equally between them. Exposing the dissipative surface of each transistor to open air does not allow for the required heat flow, so a metallic surface will be used to conduct the heat away from each MOSFET. The geometry of each FET is known, as well as the dimensions of the plate and the thermal boundary conditions present in the main hull of the vehicle. Initial thermal analysis shows that the temperature of a single MOSFET in the least optimal location will not reach unsafe levels. It can be seen that this method of heat dissipation should be effective for the system.

5.7 Analysis

A preliminary analysis was performed to determine the geometry required for adequate heat dissipation for all six motor controllers. A three-dimensional numerical simulation was performed using MATLAB. The geometry of the plate is adjustable, using different values for length, width, and plate thickness. Boundary conditions are assumed to be fixed temperature at the left and right surfaces of the plate, and insulated on all other surfaces (since heat will not be conducted to the open air in the main hull very easily). Even though this is a simplified analysis, it is helpful in determining the approximate thermal resistance of the plate when a source of heat is placed in a specific location. A worst-case analysis places all twelve MOSFETs in the center of the plate, so if the thermal resistance in this case is low enough to prevent overheating of the MOSFETs, then it is reasonable to assume that any configuration of MOSFETs will allow for adequate heat dissipation. Once the thermal resistance of the plate is found, it can be combined with thermal resistance values for end
cap-to-water convection to determine the overall thermal resistance. The dimensions of the plate used in this simulation are 11 inches long by 3 inches wide by 0.25 inches thick. The thermal conductivity of the plate (6061 Aluminum) is

$$k_{\text{plate}} = 237 \frac{W}{m^2K}$$  \hspace{1cm} (1)

The total heat generation (7.5 watts) is concentrated in a 0.4 by 0.263 inch area in the center of the top surface of the plate. A fixed temperature of 20 degrees Celsius (293 Kelvin) is assumed for the left and right ends, with all other surfaces considered insulated.

The maximum temperature reached in this simulation is 294.6 Kelvin, just a 1.6 degree difference from ambient conditions. This result yields a thermal resistance of 0.2133 K/W for the entire plate. Simplified thermal resistance calculations put the end-cap convective resistance at 0.7709 K/W, which shows that the convective effects are more limiting than the conductive resistance in the plate. The overall thermal resistance is the sum of these values, 0.9842 K/W. For a 7.5 watt source of heat, the temperature difference between ambient and the MOSFETs is just 7.382 K, which indicates that heat dissipation will likely not be an issue, even with twelve transistors dissipating heat at full power. The interface between the end caps and the dissipation plate is not accurately modeled in this example, so the true resistance of the system is likely to be higher. However, a thermal resistance of 17.33 K/W would be required for the MOSFETs to have a chance of overheating. The value obtained by this simulation is an order of magnitude lower than is required for excessive heating, and it is
likely that modeling simplifications were appropriate given the wide margin of acceptability.
6 Electrical Subsystem Design

6.1 Introduction

All electrical subsystems required for the vehicle will be discussed in the following sections. The electrical system will act as the middleman of the vehicle. It will connect the mechanical system with the software so all systems will function as a unit. The most challenging part through all these designs was to keep in mind that the system will be running off of batteries for a period of 30 minutes. Keeping power consumption to a minimum was paramount in the design. Preparing prototypes on breadboards gave confirmation that each system works perfectly, as there is little room for error.

6.2 Power Distribution

Starting with the power framework, there will be two 22.2 volt batteries capable of 4000 milliamp hours in parallel to ensure longevity necessary for the vehicle. From this point, there will be multiple breakpoints connecting each system. The CPU will have a COTS DC to DC converter called a picoPSU mini-ITX\textsuperscript{[2]}. All that is needed is to connect the battery directly and the CPU, motherboard, and USB peripherals’ power requirements will be satisfied. For all systems that do not require the full system voltage, they will most likely use a voltage regulator such as the LM22671, which automatically reduces the 22.2 volts to a more desirable and safe voltage for the system, or MOSFETS being fed with pulse width modulation so that only a percentage of the battery hits the load. Each connection from the batteries will have a necessary fuse as a safety net if things get wet.

<table>
<thead>
<tr>
<th>Minimum Capacity:</th>
<th>4000mAh</th>
</tr>
</thead>
<tbody>
<tr>
<td>Configuration:</td>
<td>6S1P / 22.2v / 6Cell</td>
</tr>
<tr>
<td>Constant Discharge:</td>
<td>20C</td>
</tr>
<tr>
<td>Peak Discharge (10sec):</td>
<td>30C</td>
</tr>
<tr>
<td>Pack Weight:</td>
<td>650g</td>
</tr>
<tr>
<td>Pack Size:</td>
<td>148 x 49 x 40mm</td>
</tr>
<tr>
<td>Charge Plug:</td>
<td>JST-XH</td>
</tr>
<tr>
<td>Discharge plug:</td>
<td>4mm Bullet-connector</td>
</tr>
</tbody>
</table>

Table 7: Battery specs for the Turnigy 4000mAh 6S 20C Lipo pack \textsuperscript{[1]}
6.3 Motor Control

The abundance of telemetry arriving at the AUV via USB connections, including the IMU, hydrophones, and cameras, is offset by the power necessary to enable movement. A motor control board will be fabricated that also connected to the host computer through a USB interface. The board will feature two high-voltage half H-bridge driver chips to adjust the magnitude and direction of motor rotation. Each H-bridge will be comprised of four high-current power n-channel MOSFETs. An on-board dedicated microcontroller will send a PWM signal to the drivers that allows a percentage of the batteries voltage to be applied the motor. The duty cycle for 12 volt motors in a 22.2 volt system will be 50%, providing an average of roughly 11.1 volts to each motor. The off-time of the PWM signal involves enabling both low-side MOSFETs to short the motor windings and prevent damage to sensitive components. In total there will be six 12 volt, 5 amp motors.

6.4 Sensors and Digital Outputs

A collection of sensors will be connected to ensure the vehicle is operating safe and at its full potential. A battery voltage sensor, in the form of the voltage divider shown in Figure 14, will indicate the battery voltage. An under-voltage detector will shut the system down and notify the user of the issue.

Next there is an Inertial Measurement Unit (IMU), which provides acceleration forces, gyroscopic forces, and a compass heading. This will be used for navigation and will give the submersible a sense of location underwater. There will also be a pressure sensor measuring the water pressure to provide a sense of depth. A pair of uninsulated wires will be employed at the base of each hull to alert the user of any leaks. Any detections of liquid will immediately halt execution and initiate an emergency surface maneuver.

For digital outputs, an Arduino UNO will be used, due mostly to its ease of use and wide support base. For high-current outputs, the Arduino will send out a high or low signal to turn a MOSFET on or off to perform external tasks that will be appointed prior to the competition.

6.5 Hydrophone Localization Board

The hydrophone localization board had to be built in such a way that it could be disconnected easily and shared with another team. As mentioned in section 1, the Carl Hayden robotics team purchased four TC-4013 Reson[3] hydrophones with the stipulation that our
Figure 13: Dual motor controller schematic, courtesy of ROVotron\cite{4}. The realization on this system will be a slightly modified version, and unlike the rovotron system, H-bridge half drivers will interface with a microcontroller instead of a CPLD.

The team fabricate an enclosure utilizing each hydrophone to determine the location of the pinger source.

Every 1.3ms a 22-30 kHz sinusoidal pressure wave is generated by an ORE model 4330B transponder. The TC-4013 Reson hydrophones are piezo-electric sensors that generate a differential voltage proportional to movements in water. Their frequency response is relatively flat up to high frequencies, making them ideal for this application.

As this task is quite isolated with respect to the real-world, there are no COTS solutions. The pinger task has also been, in past years, a key to success in competition, which has resulted in little documentation of teams’ efforts.
The first thoughts were to amplify the signal. An automatic gain control amplifier was considered, which would amplify the signal to a certain level and remain there. At first the idea was to amplify the actual signal for processing but the only information needed from the signal was phase information. With that in mind the circuit was drastically reduced to a single comparator. The comparator will take any differential signal and output a high or low rail voltage depending on the difference in inputs (positive or negative). No matter what the voltage difference is, it will hold a consistent output voltage. As stated earlier, the one piece of information needed was the phase difference from the comparator, which will be consistent with the hydrophone. The signal is then fed through a band-pass filter to remove high- and low-frequency noise. After the filter, the signal will pass through an analog-to-digital converter, which will digitize the signal at a several times the Nyquist frequency.
Finally, the digital value will be fed to a Texas Instruments TMS320 family digital signal processor for navigational telemetry calculations.

Figure 16: Hydrophone Localization Board Block Diagram

6.6 Analysis

The performance requirement 302, from Table 7, mandates a minimum runtime of 1 hour. Table 8 highlights most of the high power elements of the AUV. The chosen batteries have a 4000mAh capacity at 22.2 volts, which results in a power capacity of 88.8Wh. Two batteries combine for a total of 177.6Wh. The power consumption of the system, ignoring some low-power sections, is roughly 125Wh, well below the capacity of the batteries for a run time of one hour.

<table>
<thead>
<tr>
<th>Description</th>
<th>Power Draw (W)</th>
<th>Use per Hour</th>
<th>Wh</th>
<th>Quantity</th>
<th>Total Wh</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thruster</td>
<td>55.5</td>
<td>0.2</td>
<td>11.1</td>
<td>6</td>
<td>66.6</td>
</tr>
<tr>
<td>CPU</td>
<td>45</td>
<td>0.5</td>
<td>22.5</td>
<td>1</td>
<td>22.5</td>
</tr>
<tr>
<td>Motor Controller</td>
<td>0.625</td>
<td>0.75</td>
<td>0.469</td>
<td>12</td>
<td>5.625</td>
</tr>
<tr>
<td>Power Output</td>
<td>22.2</td>
<td>0.1</td>
<td>2.22</td>
<td>6</td>
<td>13.32</td>
</tr>
<tr>
<td><strong>Total:</strong></td>
<td><strong>124.695</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 8: Power Utilization Estimates

7 Computer/Software Subsystem Design

7.1 Introduction

The software system of the AUV is composed of several main sections. The AUV can be broken into two main components: the middleware system and the AUV System.
middleware system, or model, bridges the hardware and AUV System. The system will take raw sensor information, convert it to a digital signal, and filter its output. The system also responds to digital inputs, which takes analog signals and converts them to digital signals to be used by the AUV system.

The main software component in the entire software hierarchy is the AUV System. The system will be built using an open-source Linux stack. The software framework consists of several key components installed on top of the Linux system along with the AUV system (see Figure 17). The reason for each software package is discussed in section 7.2. The AUV System’s architecture is based on a Model-View-Controller, or MVC pattern. This abstracts the model of sensors, actuators, and data from the dashboard and control system. The system uses a technique in artificial intelligence known as an intelligent agent, which is the controller in the MVC pattern.

The agent can be broken into several key components. The kernel interconnects and communicates between all the other key sections. Additionally, the kernel sends and receives the state information from the AUV Bridge. The kernel has the responsibility of managing all of the connections between software components. The kernel also needs to be able to connect with and relay information to the dashboard. The kernel is responsible for hooking key features such as the mission planner, filter chain, logging, and state to interfaces within the dashboard. Finally, the kernel is responsible for keeping the system in a stable state. It must able to protect against malfunctioning subsystems.

The AUV Filter Chain runs captured image data through encapsulated OpenCV filter algorithms, which will allow the robot to detect objects via properties such as color and shape. The logging system takes all commands, status, or state information and logs that data. This can then be replayed back through the dashboard to rerun a mission. Refer to section 7.5 for a detailed description of image processing and the AUV Filter Chain.

The last main component is the AUV Planner. The planner is used to read in mission files and generate a plan of how to execute that mission. The commands and tasks to be performed are then passed back to the kernel, which relays the information to the bridge. Refer to section 7.3 for a detailed description of the planner.

The AUV bridge is composed of two key components: the model and a simulator. The model connects to hardware or a simulator. Commands sent to the model are then transferred to physical elements in the AUV hull. If the AUV bridge is connected to the simulator, the simulator will then emulate the intended commands within a graphical computer environment. Refer to section 7.6 for a detailed description of the model.
7.2 Software Frameworks

We have chosen several well tested frameworks to mitigate production time and increase reliability. The following is a selection of frameworks we felt fit the job description well and have been used by multiple RoboSub competitors for years:

Qt
Qt, developed by Nokia and recently acquired by Digia, is a platform-independent, open-source framework complete with a GUI creator and various libraries ranging from networking to XML file parsing. Qt has a large online community support base and has been used successfully by several collegiate RoboSub competitors. Qt will be used for the dashboard GUI and to parse XML files.

OpenCV
OpenCV is an open-source computer vision library written in C and C++. There is an OpenCV binding for python, which will greatly reduce the amount of time required for members to familiarize with the library. OpenCV is also compiled for easy integration into IDEs such as Qt Creator and any of the Visual Studio languages. The abundance
of high level pre-made filters such as Canny edge detectors, Hough transforms for line and circle detection, in conjunction with lower level image manipulation (at the pixel level) makes for a very powerful library.

**ZeroMQ**

Discussed later on, the AUV model and AUV kernel are separate processes, which complicates communication between the two modules. To mitigate this complexity, we intend to use ZeroMQ, an abstracted messaging library that handles many of the complications of socket level communication behind the curtains.

**Google Protocol Buffers**

A protocol buffer, an open-source product of Google, is a simple method of serializing an object for transmission to another process or computer. The beauty of protocol buffers is that they are language-independent – one `.proto` file is run through the protocol buffer compiler to generate C/C++ header files, python modules, or Java classes. When the data is serialized, any language can de-serialize the information into a native object in that language. Protocol buffers also require much less memory and overhead than XML files, and offer more flexibility. In conjunction with ZeroMQ, protocol buffers will standardize the commands between the AUV kernel and AUV model. The current version of the telemetry and command protocol buffer can be found in Appendix D.1.

### 7.3 Planning Agent

The majority of the artificial intelligence takes the form of a mission planning agent. This agent is responsible for loading and parsing mission XML files, generating a directed graph of tasks, and developing a plan to maximize mission points in the least amount of time. A new plan is generated after the completion (or failure) of every task. The PlanGraph class has been abstracted to allow for the development of several planning algorithms. The current plan is to implement an algorithm based on the uniform cost search or Dijkstra’s algorithm, but focusing instead on the path with maximum point value. A pseudo-code variation of Dijkstra’s algorithm exploring the largest point-value and taking time-cost into account is shown in Algorithm 1. This modified version uses heuristics, including task point-value and a scaled time-cost in points, to determine the highest-valued path to take. Distances in this modified version are assumed to be scaled to point-values – if a task worth few points is placed far from the current task, the agent may pass it up to increase the mission end time bonus.
Algorithm 1 Modified Dijkstra’s Algorithm

function MODIFIED-DIJKSTRA’S-ALGORITHM(Graph, Source, Destination)
    for all task \( v \) in Graph do
        \( \text{dist}[v] \leftarrow \infty \)
        \( \text{prev}[v] \leftarrow \emptyset \)
    end for
    \( \text{dist}[\text{Source}] \leftarrow 0 \)
    \( Q \leftarrow \) set of tasks in Graph
    while \( Q \neq \) Empty do
        \( u \leftarrow \) task in \( Q \) with smallest distance in \( \text{dist}[\ ] \)
        \( p_u \leftarrow \) point value of task \( u \)
        \( t_u \leftarrow \) time cost (in points) of task \( u \)
        \( h_u \leftarrow p_u - t_u \)
        if \( u = \) DESTINATION then
            break
        end if
        for all neighbors \( v \) of \( u \) do
            \( p_v \leftarrow \) point value of task \( v \)
            \( t_v \leftarrow \) time cost (in points) of task \( v \)
            \( h_v \leftarrow p_v - t_v \)
            \( \text{alt} \leftarrow h_u - \text{dist}[u] + h_v - \text{DISTANCE-BETWEEN}(u, v) \)
            if \( \text{alt} \geq h_v - \text{dist}[v] \) then
                \( \text{dist}[v] \leftarrow \text{alt} \)
                \( \text{prev}[v] \leftarrow u \)
                reorder \( v \) in \( Q \)
            end if
        end for
    end while
end function
Tasks are written with a custom language capable of control loops, variables, and basic built in functions. This enables high level description of tasks for quick creation and debugging. Tasks are broken down into actions, which are a command followed by several parameters following a unique syntax. Below are several examples of commands we intend to use:

**sleep** `millis`
continues current operation for the specified time in milliseconds

**move** `x, y, z, r`
sets the movement vector to the specified amount, from -1.0 to 1.0 for x, y, and z dimensions, plus rotation (yaw)

**save** `variable, type, value`
saves a value to a variable in a map for later use

Actions can also be basic control logic, such as *if* statements, *for* and *while* loops, and *switch* statements.

An interpreter is instantiated at the start of the mission that parses actions from the current task into meaningful commands. The interpreter is responsible for the control logic of the agent – it stores variables, requests filter chain outputs, and sends and receives digital inputs and outputs. The interpreter communicates to the AUV model via the kernel, which allows logging of particular messages.

### 7.4 Dashboard/GUI

The dashboard will be a graphical user interface which reports the state of the AUV. This will be a critical component in testing the AUV.

The main window will display the entire state of system. A design mock-up was created in Figure 18, which shows the main window. The main window is comprised of multiple layers. Telemetry information will be displayed and updated if the robot is currently running play-back information. The latest image data will display the robot’s current location and may contain additional information within the image that is produced by the filter chain. Finally, additional subsystems, such as torpedoes, will be presented to the viewer.

Additional features that are being considered include a filter chain editor and a mission planner. These additional features are optional requirements and may not be implemented. The filter chain editor will take a collection of encapsulated OpenCV filters to be chained
together and make a custom pipeline for filtering of image data. The mission planner will have a graphical interface where tasks could be placed upon a map. These positions would allow the robot to approximate its location when it goes to perform its tasks.

![Figure 18: Dashboard GUI Mock-Up](image)

### 7.5 Image Processing

The need for image processing is essential for several important tasks in the RoboSub competition. One major requirement for image processing is being able to align with a marker. To perform this task, the robot needs to be able to recognize both the shape and color. The main tasks these algorithms need to perform is object detection. This allows the agent to recognize objects and determine its next action to be performed.

Image processing will be done using the OpenCV Library. Images will be filtered using the AUV Filter Chain. The filter chain will contain filters which bind the OpenCV algorithms and filters to the AUV System. This gives consistency in the desired input and output formats.

The benefit of doing this is that we can construct a chain or pipeline of filters to perform operations in a dynamic manner. Also, the filter chain will be used to change the image within the AUV dashboard through a graphical interface. The updated chain can then be dynamically loaded while running a mission. A UML diagram of the filter chain is depicted in Appendix C.

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7.6 AUV Model

The AUV model is an abstraction for any form of AUV that interacts with the kernel. Because a standardized method of sending and receiving commands and telemetry has been put in place via a protocol buffer, any program written in C/C++, Java, or Python can be used to interact with the AUV agent. This includes physical manifestations, such as the system prescribed in this report, as well as simulated ones. By separating control of the AUV with the AUV itself, any realization can be used, allowing the agent codebase to be re-used and updated from year to year without affecting the AUV itself. This also allows for distribution of the agent to various other platforms, extending research possibilities to other academic or corporate entities.

For the purposes of this project, a model that interacts with the physical AUV will be developed. A UML diagram depicting various classes and their associations is located in Appendix C.

7.7 Peripheral Interface

The primary method for the host computer to interface with the physical world is through the Arduino peripheral controller. An Arduino UNO acts as a simple bridge, reporting digital and analog inputs and relaying commands to switch high power outputs. From a software perspective, the peripheral board must maintain a constant communication line with the host processor to ensure a high level of safety. Once a safety layer has been put in place, the only remaining work is to switch digital outputs to the desired setting and collect, package, and send basic telemetry information, including depth, battery voltage, mission switch status, and more. Figure 19 depicts program flow.

7.8 Pinger Localization

The hydrophone localization board will feature a Texas Instruments TMS320 digital signal processor (DSP). The DSP will be capable of performing Fast Fourier Transforms (FFT) on each of four hydrophone signals to determine the heading and altitude to the pinger source. The flowchart in Figure 20 depicts an overview of the sequence of events for locating the pinger.

The pinger generates a sinusoidal pressure wave at a constant frequency between 22kHz and 30kHz (in 1kHz increments, so 22kHz, 23kHz, 24kHz, etc. are all possibilities) for 1.3 milliseconds every two seconds. As such, the algorithm will require a peak detection scheme,
Figure 19: Arduino Peripheral Flowchart
Figure 20: Flowchart depicting hydrophone signal processing. Once initialized, a peak detection unit determines the start of a wave front. Four hydrophone channels are recorded for the duration of the ping (1.3ms). Then, phase shift between pairs of hydrophones is calculated. Finally, using the determined phase shifts and beacon frequency, the heading and elevation to the source are calculated and returned to the host.
such as an FFT on one hydrophone channel, to identify the front of the wave. Once the wave front is detected, each hydrophone channel will be recorded for the 1.3ms duration, then processed in the remaining two seconds until the next wave. Processing involves taking a high-point complex FFT of each channel, extracting the phase angle at the given frequency, and comparing phase shift between pairs of hydrophones.

Basic trigonometry and physics are used to determine the heading and altitude to the pinger. The hydrophones are arranged in a square pattern shown in Figure 21. Hydrophones are spaced apart by a maximum of the half-wavelength of the highest target frequency being measured – in this case, 30kHz. The equation relating wavelength to frequency and propagation speed is:

\[
\lambda = \frac{\nu}{f}
\]

The speed of sound in water, \(\nu_{\text{water}}\), is roughly 1500 m/s. Using equation 2, the half-wavelength at 30kHz is:

\[
\frac{1}{2} \lambda = (0.5) \frac{\nu_{\text{water}}}{f_{\text{max}}} = (0.5) \frac{1500 \text{ms}^{-1}}{30000 \text{s}^{-1}} = 0.025 \text{m}
\]

Therefore, \(d\) in Figure 21 must be less than or equal to 2.5cm. To maximize accuracy, \(d\) is set to 2.0cm – this is due to the sensitivity of \(\nu_{\text{water}}\), which may change due to weather conditions or the salinity of the pool water. To determine the pinger source, the first step is to calculate the maximum phase shift between two hydrophones, \(\Phi_f\):

\[
\Phi_f = 2\pi \frac{d}{\lambda_f}
\]

Here, \(\lambda_f\) is the wavelength of the target frequency, \(f\). The next step is to determine the phase shift between orthogonal pairs of hydrophones. This three-dimensional problem only requires three measurement points, as long as pairs are linearly independent. The fourth hydrophone is unnecessary, but adds additional resolution through overdetermination of a three-DoF system. The phase shift between hydrophone pairs is labeled as such:

\[
\phi_{i \rightarrow j} = \text{phase shift from } i \text{ to } j
\]

Phase shift is positive if \(i\) leads \(j\) and negative if \(i\) lags \(j\).

The heading is the most important measurement, as an AUV can navigate successfully to the beacon without an altitude reference. Heading will be measured in degrees clockwise from AUV north. If we create a right triangle with phase shifts \(\phi_{2 \rightarrow 1}\) and \(\phi_{2 \rightarrow 3}\), the hypotenuse would be defined as:

\[
\phi_h = \sqrt{\phi_{2 \rightarrow 1}^2 + \phi_{2 \rightarrow 3}^2}
\]
This is used to project the source angle onto the $xy$-plane. However, because $\phi_h$ is positive and $\sin$ is not one-to-one, a piecewise function must be used to determine the angle between $[-180^\circ, 180^\circ)$. This can be easily accomplished programmatically, much like the popular $atan2$ function. This new function, fondly dubbed $asin2$, is defined as follows:

$$
asin2\left(\frac{y}{x}\right) = \begin{cases} 
\sin^{-1}\left(\frac{y}{x}\right), & \text{if } \phi_{2\to3} > 0 \\
\text{sign}(y)180^\circ - \sin^{-1}\left(\frac{y}{x}\right), & \text{if } \phi_{2\to3} < 0 \\
180^\circ, & \text{if } \phi_{2\to3} < 0 \\
& \text{and } \phi_{2\to1} = 0 \\
& \text{and } \phi_{2\to1} \neq 0 
\end{cases}$$

(7)

Heading = $asin2\left(\frac{\phi_{2\to1}}{\phi_h}\right)$

(8)

Altitude is simply a trigonometric ratio between $\phi_h$ and $\Phi_f$, since the beacon will always be in the lower hemisphere underneath the AUV. Cosine is chosen to set the altitude as the angle with respect to the pool’s surface:

$$
\text{Altitude} = \cos^{-1}\left(\frac{\phi_h}{\Phi_f}\right)
$$

(9)
Figure 21: Hydrophones labeled 1 through 4 are arranged in a square pattern with sides of length $d$. The maximum side length is determined by the half-wavelength of the maximum target frequency, in this case 30kHz.

8 Development Plan

8.1 Milestones

The timeline in Figure 22 highlights key dates throughout the course of the capstone project. Familiarizing with software tools and frameworks will occur over Winter break, while the actual construction will begin in late January.

Figure 22: Project timeline including important course deliverables (diamonds) and team goals (circles).
8.2 Construction Techniques

The physical components of the vehicle (i.e. non-software related elements) will be developed and constructed in a number of ways. Metalworking skills will be most important, since the majority of the vehicle’s structure will be made from aluminum. A brief summary of the construction methods for the major physical features are described below.

The sheet metal frame contains a number of intricate features and cut-outs which require precision laser-cutting, hole punching, and bending. A computer numeric controlled (CNC) laser cutting and bending services will be contracted to create these parts. Simple sheet metal components, such as auxiliary attachment straps can be manufactured by team labor, since the majority of team members have metalworking experience. The frame parts may also be anodized or powder-coated for water resistance and cosmetics. The major frame components (main, lateral, skid, and tube support plates) will be riveted together to form a solid, permanent structure. Auxiliary straps will be attached using bolts, which will allow the frame to be reconfigured rapidly.

Aluminum end caps for the main housing will be fabricated in house. A lathe will be required to make the grooves and insets for the polycarbonate tube to fit into. Circumferential grooves will be cut out for the o-rings to rest in, with moderate tolerances required (.005 inches) to ensure a snug waterproof seal. Holes for wires will be drilled manually, as location is not entirely important. These holes will be countersunk with a step change in diameter. This will be accomplished by simply drilling a smaller, wire-sized hole and then a larger hold to fit the wire o-rings. Some holes may be drilled to a blind depth in the fixed end cap to accommodate the electronics rack mounting. These holes will be tapped to fit common screw sizes. Holes for the tensioning rods will be drilled in the end cap, using pilot holes for initial drilling and gradually stepping up the drill size until the required size is reached. If any large holes are required (for waterproof connectors, for example), then a milling machine may be used to create these features.

Non-metal parts, such as the polycarbonate tube for the main hull, will only need to be cut to the appropriate size. Some sanding may be required to smooth the ends of the tube if face seals are implemented. The electronics rack may be made of non-metallic materials, but will likely be made of aluminum bars to facilitate ease of construction. The locations for the electronic components will first be determined, with the support structure then designed around the component locations. This will allow the electronics sub-team to create specifications for the mechanical sub-team to design and build the electronics rack.

Electrical printed circuit boards (PCBs) will be layed out in-house using University of Arizona licensed software. Although PCB design is a current skill one or more members have,
it will take time to familiarize with the particular software available through the UA. As such, much of Winter break will be utilized in learning the intricacies of such software. PCB gerber files will be sent to a PCB fabrication house to be made professionally. A prototype board will be purchased for each unique board prior to final production to ensure perfect operation with minimal cost and to reduce the amount of errors in the end product. The majority of parts will be surface mount to reduce layout size and, in effect, cost.

Software will be developed simultaneously on multiple machines, so a revision control hub will be needed to simplify merging of code. Github, a popular online repository system, will be used for this purpose. To ensure code is easily modifiable by future members, the computer subteam will put extra emphasis on proper documentation techniques.

9 Budget

A primary goal for the team was to reduce the overall cost of the system to within the confines of the design course budget of $3000. Through careful planning and outreach, the cost has been lowered further to under two-thirds of the allocated funds. This was accomplished by partnering with several entities to shave high-budget electronics from the list. All donated items have been listed in Table 9. The overall cost, along with the overall value (which includes donated items) is also listed. This table shows only a preliminary cost estimate, as many items are subsystem specific and will be determined as a more detailed system design is formed. As a club sponsor, the AUV-UA reserves the right to increase the allowable budget as funding becomes available.
<table>
<thead>
<tr>
<th>Item Description</th>
<th>Vendor</th>
<th>Vendor P/N</th>
<th>Quantity</th>
<th>Unit Price</th>
<th>Extended Price</th>
<th>Donated Value</th>
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<td>NTE89410</td>
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<td>NTE2975</td>
<td>20</td>
<td>2.94</td>
<td>58.8</td>
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</tr>
</tbody>
</table>

| Total Cost: | 1879.13 | Total Value: | 6687.13 |

Table 9: Budget
10 Requirements Review

When reviewing the requirements for the AUV, it’s important to take into account many of the cost constraints that were necessary to make the system as cost-efficient as possible. While satisfying every functional requirement, there were some constraints on how well each one would be satisfied. For example, the system will be able to sense its environment with the help of an IMU, cameras, and other sensors that will determine location. The affect of money on the project led to the use of an IMU and the absence of Doppler Velocity Logger, which can pinpoint absolute position. Other than this, all other requirements were properly satisfied without issue.

11 Acceptance Test Plan

The performance requirements for this system will need to be evaluated in an actual operational environment, and therefore satisfaction cannot be determined as easily as functional, technological, or utilization requirements. The following test plan is put in place to evaluate these requirements.

Requirement 301:
The system shall be waterproof to a minimum of 40 feet depth.

Test Plan: Disassemble waterproof housings (main and battery) and remove all components to prevent damage. Compartments will likely be buoyant and may need to be weighed down. Compartments are then sealed in a typical manner. The compartments are then submerged in water to a depth of 40 feet, or placed in a pressurized water tank to a pressure equivalent to that of 40 feet of water (18 psi above atmospheric). The compartments are submerged for one hour (standard mission duration). After time has passed, compartments are removed and dried externally. The housings are then opened and inspected for leaks by using a paper towel and wiping down the inside of the housing. If no moisture is detected, then the housings meet this requirement.

Requirement 302:
The system shall have a minimum run time of one hour on batteries.

Test Plan: Assemble system in a typical configuration, with batteries fully charged. The system is then run at full power under operator control (not autonomous) in order to readily determine if performance deteriorates or if system response quality worsens (these are symptoms of batteries nearing full discharge). The system is run
for one full hour performing high power tasks such as movement, object manipulation, and image processing. If after one hour, the operator determines that the system maintained performance quality throughout the test, and the voltage of the batteries has not significantly decreased, then the system meets this requirement.

**Requirement 303:**
The system shall perform tasks in an accurate and repeatable manner.

*Test Plan:* Since the system will be designed to perform a multitude of different tasks, it is difficult to verify overall system repeatability over the wide spectrum of possible program configurations. This requirement will be tested using simple tasks such as movement between locations, simple image recognition, and vehicle response to external stimuli. A simple program will be loaded (for instance, ”swimming a lap” in a large pool) into the system and performed numerous times under slight to moderate variation of operating conditions (initial vehicle placement, lighting conditions, etc.). This ensures that the system will not rely on human accuracy in order to successfully perform a desired operation. If the system can successfully perform the given task with greater than 90% reliability, the system is verified to have repeatable performance.

## 12 Risk Analysis and Mitigation Plan

The size of the proposed project increases the number of possible risks that can prevent a successful build or competition run. Table 10 lists a collection of risks and their associated frequencies and severities, which are graphed accordingly in Figure 23. Most issues are self-explanatory. X2 is the case where the system becomes unaware of its location relative to pool elements and fails to correct its trajectory. X7, mechanical failure, means one or more thrusters or task-related actuators has failed. None of the risks lie in the high-frequency, high-

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<th>Reference</th>
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<th>Severity</th>
<th>Frequency</th>
<th>Total Risk</th>
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<td>X1</td>
<td>Leakage</td>
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<td>18</td>
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<td>X2</td>
<td>Lost</td>
<td>3</td>
<td>4</td>
<td>12</td>
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<tr>
<td>X3</td>
<td>Dead batteries</td>
<td>1</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>X4</td>
<td>Bad telemetry</td>
<td>7</td>
<td>3</td>
<td>21</td>
</tr>
<tr>
<td>X5</td>
<td>Entanglement</td>
<td>4</td>
<td>2</td>
<td>8</td>
</tr>
<tr>
<td>X6</td>
<td>Overheating</td>
<td>2</td>
<td>1</td>
<td>2</td>
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<tr>
<td>X7</td>
<td>Mechanical failure</td>
<td>1</td>
<td>6</td>
<td>6</td>
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</tbody>
</table>

Table 10: Risks
severity quadrant, simply because most risks can be mitigated through constant vigilance during competition.

To prevent failures in competition, a log will be present during each pool test leading up to the competition. Any issues falling under the listed risks will be recorded. Prior to RoboSub, a risk mitigation plan will be drafted detailing procedures to eliminate any possibility of the seven shown risks from occurring.

13 Project Management Update

13.1 Project Status

The current state of the project is on track. Designs are being finalized, and we are inspecting part distributors and preparing to make purchase orders. Construction will being near the end of January as intended.

13.2 Gantt Chart

The following Gantt chart provides a detailed time-segmented list of all processes, deliverables, and milestones within the context of this design course. Beyond design day, additional testing and verification will be performed.
Figure 24: Gantt Chart Schedule
Figure 25: Gantt Chart
14 Closure

14.1 Project Review

This report encompassed the major design elements of an autonomous underwater vehicle to be constructed over the next five months. The design meets all necessary requirements and sufficient design work has been performed to complete all systems on schedule. The vehicle will utilize an aluminum frame with a transparent waterproof housing for electronics components. Thrusters will be used for vehicle movement in three translational and one rotational degree of freedom. The electronics package consists of an Intel Quad Core CPU and a Mini ITX motherboard for raw processing power and image processing capability. A custom motor control board will be used to regulate the power for each thruster, allowing for greater control and flexibility. An Arduino will be used for peripheral communication between sensors/transducers and the Intel processor. Sensors will include cameras for vision, hydrophones for locating a sonar pinger, and an inertial measurement unit for accurate position tracking. The hydrophones will interface with a custom control board which processes the sound signal in order to triangulate the position of the vehicle relative to the pinger source. Other sensors and actuators may readily be added should the need arise. A unique software framework utilizing well known libraries will be written which allows fast, seamless population of missions, tasks, and vision filter chains. Various microcontrollers throughout the system, including a TI digital signal processor, will require low-level, high performance software development.

The AUV will compete in two events (RoboSub and NURC) to test both its autonomous and remote operation capabilities. After these events, the system will be utilized as a test-bed for research in underwater exploration and autonomy. The system will hopefully prove to be a useful tool for many years to come.

14.2 Next Steps

With much of the preliminary design work done, the remainder of the project will consist of making specific design decisions regarding the placement of electronic components and integration of mechanical and electronic subsystems. Some components will be purchased in order to aid mechanical design and construction. The electrical subsystem will be assembled to test sensors and allow for application of the software developed thus far. Further analysis will be required for the hydrophone assembly, along with prototyping of mechanical components and waterproof enclosures. Software development will be an ongoing task until the day
of competition. Other immediate and long term goals can be seen in the attached project management schedule.

References


A Team Member Contributions

Alexander Abel

• Electrical Subsystem Introduction
• Power distribution
• Motor Control
• Sensors and Digital Outputs
• Hydrophone Localization Board

Evan Briones

• Computer Software Subsystem Introduction
• Dashboard/GUI
• Image Processing

Kevin Forbes

• Introduction
• Preferred Concept
• Changes Since PDR
• Electrical Subsystem Analysis
• Software Frameworks
• Planning Agent
• AUV Model
• Peripheral Interface
• Pinger Localization
• Milestones
• Budget
• Risk Analysis and Mitigation Plan
• Project Management Update

Kevin Geisler

• Summary of Requirements
Team 5374 – Competitive Autonomous Underwater Vehicle

- Functional Requirements
- Technological Requirements
- Utilization Requirements
- Performance Requirements
- Requirements Review

Cliff Mai

- Concepts Considered
- Mechanical Subsystem Introduction
- Main Hull
- Material Selection

Sean Topping

- Final Design Overview
- Frame
- Buoyancy and Stability
- Heat Dissipation
- Mechanical Subsystem Analysis
- Construction Techniques
- Acceptance Test Plan
- Closure
B Drawings

B.1 Lower Lateral Plate

Figure 26: Lower Lateral Plate
B.2 Plate

Figure 27: Plate
B.3 Skid Plate

Figure 28: Skid Plate
B.4 Tube Support

Figure 29: Tube Support
B.5 Fixed End Cap

Figure 30: Fixed End Cap
C  UML Diagrams

C.1 Planning Subsystem

Figure 31: Planning Subsystem Class Diagram
### C.2 Model and Simulation System

![Diagram of Model and Simulation Class Diagram](image)

**Figure 32: Model and Simulation Class Diagram**
C.3 Logging System

![Logging Subsystem Class Diagram]

Figure 33: Logging Subsystem Class Diagram
C.4 Filter Chain System

Figure 34: Filter Chain Subsystem Class Diagram
D Data Structures

D.1 Protocol Buffer

```protobuf
# AUV protocol buffer

# AUV model --> agent
message AUV_State {
  required bool mission = 1;
  required float batt = 2;
  required bool aligning = 3;

  message Telemetry {
    optional float heading = 1;
    optional float depth = 2;
    optional float acc_x = 3;
    optional float acc_y = 4;
    optional float acc_z = 5;
    optional float yaw = 6;
    optional float pitch = 7;
    optional float roll = 8;
  }

  enum CameraLocation {
    FORWARD = 0;
    DOWN = 1;
    PORT = 2;
    STARBOARD = 3;
  }

  message Camera {
    required CameraLocation auv_loc = 1;
    required string file_loc = 2;
  }

  repeated Camera camera = 9 [packed=true];

  message Pinger {
    required float heading = 1;
    required float elevation = 2;
  }

  optional Pinger pinger_loc = 10;
}

optional Telemetry telemetry = 4;
optional string msg = 5;
}

# agent --> AUV model
message Command {
  message Movement {
    required float x = 1;
  }
}
```
required float y = 2;
required float z = 3;
optional float yaw = 4;
optional float pitch = 5;
optional float roll = 6;
}

optional Movement speed = 1;

optional float heading = 2;
optional float depth = 3;
optional uint16 freq = 4;

message Output {
  required string id = 1;
  required float value = 2;
}

repeated Output outputs = 5 [packed=true];
}
Official Rules and Mission

AUVSI & ONR's 15th Annual RoboSub Competition

“Ides of TRANSDEC”

17 July – 22 July 2012
Space and Naval Warfare Systems Center
SSC SD TRANSDEC Facility
San Diego, CA

Goals

The goals of the AUVSI student competitions are to provide opportunities for students to experience the challenges of system engineering, to develop skill in accomplishing realistic missions with autonomous vehicles and to foster relationships between young engineers and the organizations developing and producing autonomous vehicle technologies.

The primary emphases of the AUVSI student competitions are learning and outreach. These events are not grand challenges designed explicitly to progress the state-of-the-art. The objective is to produce the people who will push the envelope in the future. Major innovations may be spawned in these events, but this is a by-product, not an objective. Most important are gaining an appreciation for the trade offs inherent in any system design and the lessons learned in transitioning from a working bench prototype to operating reliably in the real world.

When competitiveness and collegiality are in balance, learning is maximized. The AUVSI competitions strive to maintain this balance. The nominal winners are those teams that have scored the most points. The real winners are all those participants who have learned something lasting about working together to create an autonomous system that accomplishes a challenging mission in a complex environment.

The legacy of the student competitions can be found today throughout government and industry. Employers and venture capitalists seek out prospects with the kind of resourcefulness and team management experience that former competitors offer.

Points of Contact:
Dr. David Novick
Karissa Bingham
Daryl Davidson
Melanie Hinton

Sandia National Labs, Technical Director – rules, procedures, specifications
AUVSI, Competition Logistics – logistics, housing, team registration, general information
AUVSI Foundation, Competition – coordination, sponsorship
AUVSI, Media Requests
# Checklist & Due Dates for RoboSub

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<td>Hotel reservations deadline</td>
<td>June 26</td>
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<tr>
<td>Website, team intro videos, journal paper and resumes</td>
<td>July 2</td>
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<tr>
<td>Team check-in and orientation</td>
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<tr>
<td>Static Judging (presentation in team uniforms)</td>
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<td>Semi-final runs</td>
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Visit RoboSub team central for the most up-to-date deadlines
[http://www.auysifoundation.org/robosubTeamCentral](http://www.auysifoundation.org/robosubTeamCentral)
Schedule*:

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<td>Semi-final Runs</td>
<td>Friday</td>
<td>July 20, 2012</td>
</tr>
<tr>
<td>Semi-final Runs</td>
<td>Saturday</td>
<td>July 21, 2012</td>
</tr>
<tr>
<td>Finals</td>
<td>Sunday</td>
<td>July 22, 2012</td>
</tr>
<tr>
<td>Awards Party (evening)</td>
<td>Sunday</td>
<td>July 22, 2012</td>
</tr>
</tbody>
</table>

*subject to change

SCHEDULE

Teams will register at the mandatory Team Check-in & Orientation meeting. Practice time will be all day on practice days (and both sides of the pool will be set-up for practice runs). Safety inspections will be conducted when a vehicle is brought up to the staging area to be lowered into the water. Depending on the number of competitors, a vehicle may need to autonomously pass through the gate once during the practice days in order to advance to the semi-final rounds. (see Drawing 6). Based on performance, teams will be selected to compete for the Finals round. As usual, the Awards Party will take place Sunday evening after the finals.

1. MISSION & ARENA

The fundamental goal of the mission is for an AUV to demonstrate its autonomy by completing an underwater IDE of TRANSDEC mission. The vehicle will be able to commence in training (dock/release buoys), pass over an obstacle course (PVC pipe to pass over), enter the gladiator ring (drop markers), Et tu Brute? (shoot torpedoes through a cutout), feed grapes to the emperor (manipulate a cylinder), and finally collect the Laurel wreath and crown the emperor (find a pinger, grab an object and move/release the object).

1.1 Splitting the Arena

The venue is large enough to operate vehicles in both halves of the arena at once. The layout in the two halves will be quite similar, as shown in Drawing 4 (however, there will be only one wreath on the practice side). To increase the number of teams at any given time, we will operate vehicles in both halves of the arena at once.

During the practice days, both sides will be arranged in the practice configuration. For the semi-final rounds and final round, the competition side of the arena will be changed, first for the semi-final rounds and again for the final round. If our staffing permits, teams that are not making their semi-final run will be allowed to practice during the semi-final runs.

1.2 Starting Point

Each vehicle will be launched from the launch platform, whose approximate location is indicated on the arena plan.
2. DESCRIPTION OF TASKS

The tasks will be placed in such a way as to not have any three elements along a single line.

2.1 Path

This task consists of line segments constructed from flat PVC sheet snaking its way from the Gate to the training area, the obstacle course, the gladiator ring and Et tu Brute, feeding the emperor grapes and finally to the Wreath/Emperors palace.

The “path” will be constructed of 6 inch (15 cm) wide by 4 feet (1.2 m) long sections of flat PVC sheet. It will be covered with Blaze Orange Duck tape. The “path” is raised off the floor of the pool 1-2 feet (0.3-0.6 m) and each segment will not have a relative angle between two pieces of more than 90° (except for the segments which point between the path split). The segments are situated in such a way that if you follow a heading along the line segment you will (eventually) meet with the next task. The next path segment will be located on the “far side” of the obstacle 1-3 ft (0.3-0.9 m). Distances between segments will vary depending on the positioning of the tasks. The order of the tasks will always be: Training, Obstacle Course, Gladiator Ring/ Et Tu Brute, Obstacle Course and the Laurel Wreath, with the Feed Emperor Grapes task located near the center of the facility. You may complete the tasks in any order (with the Gate required to be first before starting anything else).

2.2 Training (Buoy)

This task consists of three moored 9” (23 cm) diameter buoys (RED, GREEN, YELLOW). The buoys may* stay moored to the floor of TRANSDEC. The goal is to strike two of the three buoys in the given order. If you are told to strike GREEN, then RED, you must strike them in that order to get the full amount of points. The last two buoys that are touched are counted as your attempt at the task. The three buoys will be separated by 4ft (1.2m) from each other, and will be contained within a box that is a minimum of 6ft (1.8m) off the bottom to 9ft (2.7m) off the bottom (the heights of the buoys can vary by 3ft (0.91m) ), and within a 3ft (0.91m) width along the bottom.

The buoys will be constructed so that they can take a decent blow. The mooring “line” will be nylon webbing to minimize chances of the vehicle becoming entangled. You may hit the buoy from any direction.

*(I’ll hopefully design a release mechanism that is easy and reliable.)

2.3 Obstacle Course (PVC to pass over)

The task consists of two 2” (5.1 cm) diameter, 6ft (1.8 m) long PVC with two 2 ft (0.6 m) PVC floating risers on each end. The vertical risers will be tied 2ft (0.6m) above the horizontal section, and be free to move. The PVC is colored using Neon Green Duck Tape, and suspended 4-6 ft (1.2 – 1.8 m) above the floor. The vehicle must cross within the “box” (the bottom and sides, plus the imaginary top) to get points. If the vehicle’s mid-line (or more) passes inside the rectangular box, you will receive more points.

2.4 Gladiator Ring (Bins)

This task consists of a BLACK bin surrounded by a white border. The bins will be 1-2 feet (0.3-0.6 m) off the bottom. The four bins will be positioned side-by-side (along their longest side). In each bin, there will be one RED silhouette (Gladius [sword], Scutum [large oblong shield], Trident, Iaculum [net]). One in each bin. They will be centered within the bin.

A vehicle may carry up to two markers to drop within the bins. One silhouette will be designated as the primary target, and one will be designated as the secondary target. The most points will be awarded for dropping one marker in the primary target, and one in the secondary target. Partial points will be awarded for dropping markers in any bin.

2.5 Et Tu Brute? (Window Cutouts)

This tasks consists of a two sided board with circular cut-outs 4 feet (1.2 m) off the bottom. One side will be
**RED** Duck Tape, the other side will be **BLUE** Duck Tape. There will be 2 different sized circle cut-outs on each side, a larger one (body shot) and a smaller one (head shot). More points will be awarded for firing the torpedo through the smaller cut-out.

A vehicle may carry up to two torpedoes to fire. One must be marked as **RED**, and one as **BLUE**. The most points will be awarded for firing the red torpedo through the smaller red circle, and the blue torpedo through the smaller blue circle.

### 2.6 Feed Emperor Grapes (Manipulation Task)

This task consists of two 1” (2.5cm) diameter by 4” (10.2cm) long cylinders positioned vertically and horizontally within cutouts on a 4ft x 4ft (1.2m x 1.2m) board. The board will be suspended 6-8 ft (1.8-2.4 m) from the surface, secured at the cantilevered bridge at TRANSDEC. The board will be colored using **Yellow** Duck Tape, and the cylinders using **Red** Duck Tape. Each cylinder is positioned on a tab on the cutout to hold it in place. Each cylinder must be moved off the tab (vertically or horizontally) before it can be extracted from the cutout. Each cylinder will be tethered to the board.

To obtain full points, a vehicle must remove and release both cylinders.

### 2.7 Laurel Wreath & Emperor’s Palace (PVC recovery and octagon)

This task consists of an acoustic pinger located 2 ft (0.6 m) off the floor. Floating above the pinger, on the surface will be a single octagon representing the Emperor’s palace. The octagon will be constructed from ½” PVC pipe and have a “diameter” of 9 ft (2.74 m). On the competition side, there will be two octagons placed in different locations. At the start of each run, one of the two pingers will be turned on.

Positioned directly above each pinger will be a fixture which holds a PVC Laurel “Wreath”. This fixture will constrain the “Wreath” from movement and rotation in such a way that you have to lift it up from the fixture to remove it. The “Wreath” will be colored using **Blaze Orange** Duck Tape. The weight of the wreath will be adjusted so that it is just slightly negatively buoyant.

In order to obtain full points for surfacing, your vehicle must surface fully inside the octagon (no portion of the sub touching the structure). In order to obtain full points for recovery, the “Wreath” must be captured (maintains control) by the vehicle when it surfaces. A capture consists of constraining the object in at least 3 degrees of freedom (grabbing the object with a dangling line does not count). In order to obtain full points for the drop off, once the vehicle has surfaced, the “Wreath” must be released from the vehicle and sink back down (the object must first be properly recovered in order to drop it). No part of the object can be hung up on the vehicle. **(NEW)** Additional points will be awarded, if after the vehicle surfaces, it replaces the “Wreath” on the fixture. Full points will be awarded for a wreath that is in some way, hanging on the fixture.

The team captain can choose to switch the active pinger, after the vehicle has recovered the Wreath, but before the vehicle has surfaced. The vehicle can then transport the Wreath to the second octagon, surface, and release/replace the Wreath.

The competition and practice side will ping at a rate of 0.5 Hz (2 seconds), and will be separated by 0.9 seconds. The pingers will be synchronized. The schedule will be:

- Unit 1 (Competition)  ping t = 0s
- Unit 2 (Practice)     ping t = 0.9s
- Unit 1 (Competition)  ping t = 2.0s
- Unit 2 (Practice)     ping t = 2.9s
- Etc.

This give the reverbs from each pinger (near) maximum time to die out. Note that for the final runs, the competitors will have the choice to keep the practice pinger on, or turn it off.

The ping duration is 1.3ms with a sound level of ~187 dB.
2.8 **Interference**

Vehicles that interfere with competition elements may be disqualified at the judges' discretion. “Interference” does not include cases where, in the opinion of the judges, a vehicle is attempting to complete one of the tasks. If a vehicle becomes entangled in an objective, the run will be declared completed. Teams may keep the points earned on that run, or may have the AUV returned to the launching platform and start another new run. If a new run is begun, all points for the previous run are lost. See “Official Rules, Submissions and Fees” for more information on interference.

2.9 **Acoustics**

The pingers that we will lease will be ORE model 4330B transponder/responder units ([http://www.ore.com](http://www.ore.com)). They will be operated in responder mode, and each unit will be preset to one of the following frequencies: 22, 23, 24, 25, 26, 27, 28, 29 or 30 kHz. Since we cannot specify the frequency settings of the units we will receive, we will not be able to report the frequencies used to the teams until the start of the practice runs.
3. Weight and Size Constraints

3.1 Vehicle
For the International AUV Competition, each entry must fit within a six-foot long, by three-foot wide, by three-foot high "box" (1.83m x 0.91m x 0.91m). Table 1 shows the bonuses and penalties associated with a vehicle's weight in air.

<table>
<thead>
<tr>
<th>AUV Weight &gt; 125 lbs</th>
<th>Bonus</th>
<th>Penalty</th>
</tr>
</thead>
<tbody>
<tr>
<td>(AUV Weight &gt; 56.7 kg)</td>
<td>N/A</td>
<td>Disqualified!!</td>
</tr>
<tr>
<td>125 lbs ≥ AUV Weight &gt; 84</td>
<td>N/A</td>
<td>Loss of 250 + 5(lb – 125)</td>
</tr>
<tr>
<td>(56.7 kg ≥ AUV Weight &gt; 38 kg)</td>
<td></td>
<td>250 + 11(kg – 56.7)</td>
</tr>
<tr>
<td>84 lbs ≥ AUV Weight &gt; 48.5</td>
<td>Bonus of 2(84 – lb)</td>
<td>N/A</td>
</tr>
<tr>
<td>(38 kg ≥ AUV Weight &gt; 22 kg)</td>
<td>4.4(38-kg)</td>
<td></td>
</tr>
<tr>
<td>AUV Weight ≤ 48.5 lbs</td>
<td>Bonus of 80 + (48.5 – lb)</td>
<td>N/A</td>
</tr>
<tr>
<td>(AUV Weight ≤ 22 kg)</td>
<td>80 + 2.2(22-kg)</td>
<td></td>
</tr>
</tbody>
</table>

3.2 Markers
Each marker must fit within a box 2.0” square and 6” long (5.08 x 5.08 x 15.24 cm). Each must weigh no more than 2.0 lbs (0.91 kg) in air. Any marker that exceeds these limits by less then 10% will result in a 500 point penalty. Any marker that exceeds these limits by more than 10% will be disqualified. Each marker must bear the team name or an emblem. Markers will be cleared from the arena after each run. A reasonable amount of time will be spent looking for lost markers, however consider them expendable and have back ups.

3.3 Torpedoes
The torpedoes size, weight, markings and potential "loss" are identical to the Markers. The torpedoes must travel at a "safe" speed. A "safe" speed is one that would not cause a bruise when it strikes a person.

4. OFFICIAL RULES, SUBMISSIONS AND FEES


2. An Intent to Compete form, available on the website, and the entry fee must be completed. The submission must be in English and is not considered official until the entry fee has been received by AUVSI Foundation. As the competition format cannot handle an unlimited number of entries, the organizers reserve the right to limit the total number of entries that are allowed to compete by declaring the competition closed to new entries before the due date above. As with all official information, this announcement (should it be necessary) will appear on the official website.

3. During the competition, the vehicle must operate autonomously, with no control, guidance, or communication from a person or any off-board computer. The vehicle and any parts connected to the vehicle must submerge and remain submerged. No item may break the surface or be left floating while
the vehicle is underway.

4. Teams may comprise a combination of students, faculty, industrial partners, or government partners. Students may be high school, undergraduate and/or graduate students. Interdisciplinary teams are encouraged. Members from industry, government agencies, or universities (in the case of faculty) may participate, however, full-time students must compose at least 75% of each team. Participants must be enrolled at their schools as a full-time student per quarter/semester during winter and spring to be considered “students.” The student members of a joint team must make significant contributions to the development of their vehicle.

5. One student member of the team must be designated as the “team captain”. The team captain, and only the team captain, will speak for the team during the competition run.

6. Only the student component of each team is eligible for the cash awards.

7. No team member is allowed to enter the arena at any time (this includes wading, swimming, and diving as well as floats, boats, etc.). Competition officials will be responsible for recovering lost vehicles. Officials will make all reasonable efforts to recover a lost vehicle but cannot guarantee that they will be able to do so. All teams recognize that by entering the competition, they risk damage to or the loss of their vehicle. The judges, officials, hosts, and sponsors can take no responsibility for such damage or loss.

8. The officials will suspend the competition at any time they deem it is required by safety or security considerations.

9. There will be a semi-final round that most/all teams will compete in. After the semi-final round, the judges will convene and tally their scores. The judges have the discretion to select the number of teams entering the finals that they deem appropriate. Teams will be accepted into the final round in rank order from the semi-final round. We anticipate that three to five teams will be accepted into the finals.

10. Depending on the number of contestants, in order to be considered for selection in the semi-final round, a vehicle must show that it can submerge and pass through the gate during the practice days. A vehicle that autonomously passes through the gate is guaranteed a position in the semi-final round. If this requirement is necessary, it will be announced on the official website.

11. After the competition, the judges will issue overall standings. Any team that is accepted into the final round will be ranked ahead of all teams that are not accepted into the final round.

12. Each team will have 20 minutes of competition time. The first 5 minutes constitute the preparation period. During this time, the vehicle may not be deployed in the water. The 15-minute-long performance period immediately follows. These times are subject to change depending on the number of contestants.

Preparation period: The vehicle may remain on the crane, or be placed on the dock, but not in or touching the water. A team may waive any portion of the 5-minute-long preparation period and start the 15-minute-long performance period. Once the performance period starts, the team loses any unused time in the preparation period.

Performance period: When the officials signal the start of the performance period, the team may ask to have the vehicle deployed into the water and released to perform the mission. Only tournament officials may deploy and recover the vehicle. The time required to deploy and/or recover does not count against the 15-minute limit (see: Ending a run and retrieving a vehicle). This is to prevent unsafe actions in an attempt to speed the recovery and deployment process.

13. Multiple runs: A team may attempt multiple runs during the performance period. Once a team has the officials re-deploy their vehicle, all points earned in previous runs are lost.

14. Ending a run and retrieving a vehicle: At any time while the vehicle is running, the team captain can signal the end of the run and request the retrieval of the vehicle. Only officials may retrieve a vehicle and return it to the dock. The countdown clock for the performance period stops when the official touches the vehicle to recover it. The clock continues its countdown once the team establishes communication with the vehicle, or the vehicle is safely back at the dock, whichever is first (i.e. if a team
has wireless communication with the sub, the countdown clock continues while the diver is returning the sub to the start).

15. Depending on the time, a team may use any of their 15-minute-long performance period time to survey the arena. The survey, however, must be completed autonomously. Unlike performing a competition run, the clock will continue to run while retrieving a vehicle. **This is subject to change depending on the number of contestants.**

16. If a vehicle experiences a significant interference from a piece of equipment, line, cable or diver deployed in support of the competition, the team captain may ask, at that time, to have the clock stopped, the vehicle returned to the dock, and for the judges to add back to the clock their best estimate of the time used in that run up to the point of interference. If the team captain does not make this request in a timely manner (as determined by the technical director or his designee) then the option is lost. Interference with a gate, light, or target object does not qualify for this option, and a vehicle interfering with those items may be disqualified at the judges’ discretion.

17. The mission ends when any of the following occur:
   - The performance period time limit ends.
   - The judges order the end of the mission.
   - The team captain requests the end of the mission.
   - The vehicle breaches the surface (as determined by the judges, see: Breaching for more details).

### 4.1 Onsite Expectations

1. The organizers have made every attempt to provide the competitors with maximum resources at the Competition site, including electrical power, test pools, Internet access, and practice time in the main pool. This event is not only open to the public, but there is a very high possibility that a potential future employer or sponsor may also be observing the event.

2. It is expected that **ALL** teams will be present during **ALL** days of the competition. If your team does not make it into the finals, it is expected that your team will display your vehicle and be present in the tent during this time (ALL teams, **ALL** days!)

### 4.2 Vehicles

1. Each team may enter only one vehicle into the competition. Each vehicle will be physically-inspected by the competition judges. The judges may disqualify any vehicle that they deem to pose an unreasonable safety hazard.

2. The judges will confer with representatives of the host facility, and any vehicle that, in the opinions of the judges or the representatives of the host facility, pose an unreasonable risk to the integrity of the host facility will be disqualified. The AUVSI and the host organization, their employees and agents, as well as the organizing committee, are in no way liable for any injury or damage caused by any vehicle, nor for any damage or injury caused directly or indirectly by the disqualification of a vehicle.

3. Each vehicle must operate autonomously during its dive. While carrying out the mission, no communication is permitted between the vehicle and any person or off-board computer. Vehicles must operate solely on their ability to sense and maneuver in the arena using on-board resources.

4. The weight of each vehicle must be less then the maximum allowed. Note that bonus points are awarded to vehicles that are below a certain value, and penalties assessed for those that exceed it (Table 1). The entire vehicle must fit within a box that is 6 feet long, 3 feet wide, and 3 feet deep (1.83m x 0.91m , 0.9m).

5. All vehicles must be battery powered. All batteries must be sealed to reduce the hazard from acid or caustic electrolytes. Batteries may not be charged inside of sealed vessels at any time while on the site.
of the competition and/or while engaged in the competition. The open circuit voltage of any battery (or battery system) in a vehicle may not exceed 60 VDC. If a team has any questions or concerns, they are encouraged to contact the organizing committee.

6. No materials (except for the markers/torpedoes and compressed air used to blow ballast) may be released by the vehicle into the waters of the arena.

7. For the safety of your vehicle, we require it to be slung on a harness or sling of some type. Even if the vehicle is light enough to hand carry, we wouldn't want anyone to slip and destroy their vehicle. Also, we need to weigh the vehicle, and require that the vehicle be slung somehow for the measurement. Please see the document Harnessing the Submarine for hints and ideas on how to accomplish this.

8. All vehicles must bear a clearly marked kill switch that a diver can readily activate. The switch must disconnect the batteries from all propulsion components and devices in the AUV. Note, this does not have to kill the computer. Upon reactivation, the vehicle must return to a safe state (props do not start spinning).

9. All props must have shrouds. The shrouds must surround the prop and have at least a 2" (5.08 cm) distance between the spinning disk of the prop and the edges of the shroud (front and back). If you have a guard across the opening, this distance can be minimal. Commercial thrusters qualify as is, as long as they are shrouded.

10. A vehicle will not be allowed in the water without a properly working kill switch and prop shrouds.

11. All vehicles must be buoyant by at least one half of one percent (0.5%) of their mass when they have been shut off through the kill switch.

12. The officials will suspend the operation of a vehicle at any time they deem that it is required by safety or security considerations. Teams may be required to submit technical descriptions of their vehicle to the officials in advance of the competition, with the goal of identifying potential safety concerns well in advance. When required, such technical information submitted to the judges will be held in confidence until the end of the competition.

### 4.3 Journal Paper

1. Each team is required to submit a journal paper in English that describes the design of their vehicle and the rationale behind their design choices. This paper may be no more than 10 pages long (including all figures, reference, and appendices). Additionally, each journal paper must include an abstract of no more than 250 words. The journal paper and abstract must be "printed" on standard 8.5 x 11-inch paper, with margins of at least 1 inch on all sides, and all text must be 12-point or larger font. Each page must bear a footer with the page numbering and the team name. The journal paper will be evaluated as described below in the section on scoring.

2. The journal paper must be received in pdf format via email. Teams that do not meet the deadline may be disqualified from the competition.

3. Along with the paper, each team will also submit a 3-5 minute video. The video will introduce the team and their approach to the event. This video will be scored and will be used online and on-site during the webcast. It will not be used for the oral presentation. This video should introduce the team, their craft, as well as special features and/or strategies for the competition. The video should have good quality audio with as little background noise as possible (ideally making use of an external mic plugged into the camera rather than using an internal camera mic) and steady shots using a tripod or stabilizing equipment whenever possible. Visit RoboSub team central (http://www.auvsifoundation.org/robosubTeamCentral) for instructions on how the final video should be compressed, and where it should be uploaded.

### 4.4 Resumes

1. One goal of the competition is to foster links between young engineers and the companies, universities, and government agencies involved in AUV development. To advance that goal, we request that each
team provide resumes of each team member, along with class year and expected graduation date. These resumes (when submitted) will be circulated to our sponsors and employers who will be considering opportunities for full-time employment, internships and co-op programs. Your participation in this program is strongly encouraged.

2. Electronic versions of team member resumes should be zipped together with the journal paper.

4.5 Static Judging
1. Each vehicle will be subject to static judging during the competition.
2. During the static display time, each team will be visited by the judges, and by the public, the press, and representatives of other organizations.
3. The judges will evaluate each vehicle for technical merit, safety, and craftsmanship as described below in the section on scoring. Teams are strongly encouraged to make a poster describing the vehicle. The posters can be set up next to the vehicle during the static display period.
4. Each team is required to have at least one member attending their vehicle throughout the static display period (not just during the judges’ scheduled visit).
5. Representatives of the press and of other organizations will be encouraged to visit each team during this period.

5. SEQUENCE OF EVENTS DURING THE COMPETITION

5.1 Static display period
Each team will receive a visit from the judges during this period for the static judging. Additionally, members of the public, the press, and representatives of other organizations will be encouraged to view the vehicles and talk with team members. The judges may all work together or break apart into small groups resulting in multiple judge visits per team.

5.2 Practice runs
Practice time slots will be scheduled on an ad-hoc basis by the technical director or the designee during the practice days. It is our intent to provide as much practice time in the arena as is practical and to ensure minimal idle time for the arena. Each vehicle must be approved by the technical director or the designee before it will be allowed into the arena.

If required, this is the time for the vehicle to pass through the gate autonomously to be eligible for time slots for the semi-final rounds.

5.3 Time slots announced for competition runs
Competition time slots will be awarded based on standings after the static judging. The team that is in first place will have first choice, etc. Ties will be broken by a coin toss or random draw.

5.4 Semi-final round of the competition
Each qualifying team will be assigned a time slot to perform the mission. Twenty minutes before the beginning of their time slot, the team may enter the staging area near the launch site. At the beginning of their time slot, the team may move to the launching site on the dock.

The first 5 minutes are for preparation. During this period, the vehicle may not be deployed in the water. When
the 5-minute limit has expired (or the team has waived the balance of the preparation time), the judges will begin
the **performance time** clock. These competition minutes are for the vehicle to perform the mission. Once this
period has begun, the team may ask to have their vehicle placed in the water to begin it's mission.

Vehicles will be put into and taken out of the water by tournament officials. The time required to do so will not
count against the **performance time** limit. If a vehicle is in the water, the team may request that it be lifted onto
the dock. Tournament officials will move the vehicle onto the dock and (when requested) re-deploy the AUV into
the water. Again, the time required to move the vehicle into and out of the water will not count against the
**performance time** limit. However, time spent by the team on the dock does count against the **performance
*time** limit. The exception is when the vehicle is performing an autonomous survey, the clock will continue to run
while the vehicle is retrieved.

The mission will continue until the **performance time** limit has expired, or the team captain requests the end of
the mission, or the judges order the termination of the mission, or the vehicle breaches the surface. The judges
may order termination of the mission at their discretion. Once the judges order the end of the mission, no further
points may be scored. The judges' decisions on the termination of the run are final.

### 5.5 Final round of the competition

After the semi-final round, the judges will tally their scores. Teams will be accepted into the finals in rank order
from the semi-final rounds. The judges have the discretion to select the number of teams entering the finals that
they deem appropriate. We anticipate three to five teams competing in the finals. The finals round will be
conducted in the same manner as the qualifying rounds.

### 6. SCORING

#### 6.1 Breaching

When completing the sequence of tasks, a team may choose to complete the surfacing task first (surface within
the octagon). In this case (and only this case) a vehicle may breach the surface and then submerge again to
complete the remaining tasks without risking disqualification. For a vehicle to continue after breaching, it must
surface inside of, or touching the octagon. A breach outside of the octagon would end the run.

#### 6.2 Final Round

After the semi-final round, the judges will rank-order the teams based on their scores from the semi-final round,
and select the top teams (as deemed by the judges) to compete in the final round. The point totals and ranking
for the teams not selected are frozen. For the final round, all point totals are set to zero. The ranking of teams
selected for the finals will be determined by the points their vehicle score in the final round based on the
Performance Measures alone. Any team that is selected to be in the finals will finish ahead of the remaining
teams which where not selected.
### 6.3 Point Breakdown

<table>
<thead>
<tr>
<th>Subjective Measures</th>
<th>Maximum points</th>
</tr>
</thead>
<tbody>
<tr>
<td>Utility of team website</td>
<td>50</td>
</tr>
<tr>
<td>Technical merit (from journal paper)</td>
<td>50</td>
</tr>
<tr>
<td>Written style (from journal paper)</td>
<td>50</td>
</tr>
<tr>
<td>Technical accomplishments (from static judging)</td>
<td>75</td>
</tr>
<tr>
<td>Craftsmanship (from static judging)</td>
<td>75</td>
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<tr>
<td>Team uniform (from static judging)</td>
<td>10</td>
</tr>
<tr>
<td>Team Video</td>
<td>50</td>
</tr>
<tr>
<td>Discretionary static points (awarded after static judging)</td>
<td>40</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>400</strong></td>
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</table>

<table>
<thead>
<tr>
<th>Performance Measures</th>
<th>Maximum points</th>
</tr>
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<tbody>
<tr>
<td>Weight</td>
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</tr>
<tr>
<td>Marker/Torpedo exceeding weight or dimensional specifications by &lt; 10%</td>
<td>-500 per marker</td>
</tr>
<tr>
<td>Pass through the validation gate</td>
<td>100</td>
</tr>
<tr>
<td>Maintain a fixed heading through gate</td>
<td>150</td>
</tr>
<tr>
<td>Follow the “Path”</td>
<td>50/segment</td>
</tr>
<tr>
<td>Training (any one, correct two)</td>
<td>500, 1500</td>
</tr>
<tr>
<td>Pass over Obstacle Course (&gt;½ above, &lt;½ below)</td>
<td>600, 800</td>
</tr>
<tr>
<td>Marker: Correct marker in correct bin</td>
<td>1400</td>
</tr>
<tr>
<td>Marker: incorrect marker</td>
<td>700</td>
</tr>
<tr>
<td>Et Tu Brute (incorrect large, incorrect small, correct large, correct small)</td>
<td>400, 600, 1400, 1800 / torpedo</td>
</tr>
<tr>
<td>Feed Emperor Grapes</td>
<td>2000 / grape</td>
</tr>
<tr>
<td>Surface within an Octagon</td>
<td>500</td>
</tr>
<tr>
<td>Surface within the correct Octagon</td>
<td>2000</td>
</tr>
<tr>
<td>Surface with the Wreath</td>
<td>1200</td>
</tr>
<tr>
<td>Transport Wreath to second Octagon</td>
<td>800</td>
</tr>
<tr>
<td>Drop the Wreath</td>
<td>500</td>
</tr>
<tr>
<td>Replace Wreath</td>
<td>800</td>
</tr>
<tr>
<td>Finish the mission with T minutes (whole + fractional)</td>
<td>T x 100</td>
</tr>
</tbody>
</table>

### 6.3.1 “Subjective Measures” description

**Technical accomplishment and Craftsmanship:** These considerations will exclude any components of the design that are or could be (in the opinion of the judges) commercially available or do not include a significant contribution by team members. In other words, if you use a well-built, well-designed, off-the-shelf computer, your
team does not get points for the computer’s good technical design. You will get points for selecting a computer that is, in the opinion of the judges, well suited to the engineering needs of the vehicle.

6.3.2 “Performance Measures” description

Passing through the validation gate: The judges discretion will determine whether nor not the vehicle satisfactorily passes through the validation gate.

Maintain a fixed heading through the gate: Did the sub travel in a straight line through the validation gate?

Follow the “Path”: How well did the vehicle find/follow the segments?

Training: Full points for touching the buoys. Partial points are awarded if you track the buoy but you brush by instead of a head on bump.

Pass over Obstacle Course: Did the vehicle pass over the PVC without touching it? What percentage of the vehicle passed over the top of the object?

Gladiator Ring: There is only one correct X and one correct O, two markers in either one only counts once. There are two secondary choices Two markers in a secondary choice will count twice.

Et Tu Brute: Full points for each torpedo that passes through the circle. Partial points are awarded if the torpedo touches a side. Partial points may be awarded if the torpedo passes close to the circle.

Feed Emperor Grapes: Both cylinders must be free from their cutouts in order to obtain full points. Partial points may be awarded if an attempt is made which does not free a cylinder.

Surface within the Octagon: The sub must fully surface within the octagon to obtain full point value. Partial points may be awarded with judges’ discretion. If a sub surfaces within both octagons, only points for “Surfacing within an Octagon” will be awarded.

Grabbing the Wreath: The structure must be captured and constrained by the vehicle to obtain full points. Partial points may be awarded for a partial capture.

Transporting the Wreath: The structure can be carried from one octagon to the other. It must remain constrained by the vehicle during the transport.

Releasing the Wreath: The structure must be free to fall from the vehicle to obtain full points. The structure hanging on the vehicle may be awarded partial points with judges’ discretion.

Replacing the Wreath: The structure must be handing from the static fixture to obtain full points. Partial points may be awarded for the structure touching the fixture, but not being secured to it.

Time Bonus: At a minimum, a sub must touch the buoy, pass over Lovers Lane, drop at least one marker “in” the bin (or fire one torpedo through the window), and fully surface within one of the octagons to obtain the time bonus. These tasks can be completed in any order.

The time bonus is a calculation of whole minutes remaining plus fractional seconds. For example, with a remain time of 7:13, a team will receive \((7 + \frac{13}{60}) \times 100 = 721.667\) points (approximately).

7. AWARDS

Cash prizes (and serious bragging rights) will be awarded at the discretion of the judges.
8. Diagrams

Laurel Wreath (2) – Et Tu Brute
Gladiator Ring
Feed Emperor Grapes
Obstacle Course
Training
Path

*Drawing 1: Path to the Emperor*
Drawing 2: Aerial photo of facility. The bridge structure has no piers or supports in the pond.

Drawing 3: Cross section of arena showing the depth profile in feet. Note that the acoustic trap (the 16ft deep section around the perimeter) varies in width around the pond.
Drawing 4: General layout of the arena. The arena is split into a competition side (right half of this view) and a practice side (left half).
Drawing 5: Validation gate. The gate is constructed of 3 inch diameter black PVC pipe. It will be buoyant, and will be moored to the bottom. The vertical legs will be masked with orange Duck tape.

Drawing 6: Valid ways to pass through the validation gate during the practice days.
**Drawing 7: Training (buoy), mooring line and base.**

**Drawing 8: Obstacle course (PVC pipe) and mooring lines**
Drawing 9: "Path" and Gladiator ring (target bins). Distance between the path segments will vary.

Drawing 10: Expected distance and angles for the path segments
Drawing 11: Et Tu Brute? (PVC window) and mounting.
Drawing 12: Feed Emperor grapes (manipulation) and mounting.
Drawing 13: Wreath & Emperors Palace. The Palace is marked on the surface with a floating 1/2" PVC pipe. The acoustic pinger is mounted on a pole in the center of this area. The wreath to be recovered is positioned directly above the pinger and held in place in such a way that you have to lift it to remove it from its base.
Drawing 14: Laurel Wreath (thanks to Kevin Fuhr)