



Autonomous Vehicle for Gathering Oceanographic Data in Littoral Regions

Engineering Design I

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Executive Summary

Researchers are interested observing how the properties of shallow bodies of water such as rivers and bays change with respect to time and space. Current methods for making oceanographic observations involve fixed stations such as buoys from which measurements are taken and transmitted, and mobile platforms such as boats and ships which can be used to suspend or tow instruments at a specified point in the water column. However, current methods have difficulty providing measurement data at the resolution desired by researchers without considerable investments in time and money. The goal of this project is to design and build an autonomous vehicle for use in gathering this data in littoral regions.

To this end, the Chesapeake Baywatch Team interviewed two customers, CDR Andy Gish and Prof. Joe Smith, both from the U.S. Naval Academy, and worked with them to develop a list of customer requirements that includes the cost of the system, the ability to take samples and make them available to the user, the ability to cover a specified search area in a reasonable time, and the ability to be man-portable and launchable.

Each member of the team developed a design concept using both creative thinking and systematic design methods. These include “Trapped Under the Sea: Part I” an autonomous underwater glider and “Swept Away” a large towed array. Ultimately, the towed array was selected because of its ability to cover a large area quickly. The manufacturing plans for the initial prototype will be developed during Detail Design.

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1 Problem Definition and Need Identification

1.1 Customer's Problem Statement

The problem statement initially communicated from the customer was:

Design and build an autonomous underwater vehicle for use in gathering oceanographic data in littoral regions.

1.2 What is the problem? What about the current situation is unsatisfactory?

Researchers are interested observing how the properties of shallow bodies of water such as rivers and bays change with respect to time and space. For example, they might be interested in studying how roadway runoff affects the health of the marine life in an estuary. To that end, they would like to measure parameters such as the temperature, pressure, and salinity at different points and times within the estuary and use computational models to complete the picture and draw conclusions from their observations. The problem is, current methods include buoys that can take data over a long time period but only in one location and boats which can take data over a wide area but can't achieve the sampling resolution desired by researchers without a significant time commitment.

1.3 Customer Identification

CDR Andy Gish (Figure 1) of the Naval Architecture and Ocean Engineering (NAOE) Department at the U.S. Naval Academy originally proposed the project and was identified as the initial customer. It should be noted that he is interested in finding a solution on behalf of other researchers but not necessarily interested in the data himself.



Figure 1: CDR Andy Gish, USN, PhD of the NAOE Department initiated this project and has agreed to act as the primary customer¹.

Prof. Joe Smith (Figure 2) of the Oceanography Department at the U.S. Naval Academy was also recommended by CDR Gish as an additional customer and potential source of information.



Figure 2: Prof. Joe Smith of the Oceanography Department conducting field observations².

Prof. Smith is a geochemist who according to his faculty webpage studies the “cycling of inorganic and organic constituents in water, soil, and sediments.”

Additional potential customers include but are not limited to research scientists (Figure 3), engineers, and students from both government and non-governmental organizations and people associated with the do-it-yourself (DIY) community.

¹ Profile page, LinkedIn, https://media.licdn.com/mpr/mpr/shrinknp_400_400/p/2/000/190/3c4/3adadab.jpg, accessed June 19, 2015

²USNA faculty page, <https://www.usna.edu/Users/oceano/jpsmith/>, accessed June 26, 2015



Figure 3: Research scientists and students conducting field observations from a small surface vessel³.

1.4 Gathering Information from Customers

With the problem statement in hand and customers identified, the next step in the design process was to gather information from customers. Sources of customer information included customer interviews, complaints, and general research conducted online. The results were compiled and are presented here.

1.4.1 Customer Interviews

Initial interview with CDR Gish

CDR Gish was initially interviewed on June 18, 2015. He mentioned a number of needs and wants during the interview. He was focused primarily on AUVs as the solution to the problem though he mentioned that he would be open to all solutions that met his criteria. Among his primary requirements are the need to measure and record oceanographic data. He stated that specific measured parameters are not as important as the ability to measure *something*. He suggested temperature, pressure, and salinity at several points during the interview. He also mentioned the need to record the position and time at which the measurements were taken and the fact that they needed to be taken simultaneously.

³ GEO-CAPE Chesapeake Bay Oceanographic campaign with DISCOVER AQ, Ocean Ecology Science Research Portal, http://neptune.gsfc.nasa.gov/uploads/images_db/geo-cape2.jpg, accessed June 26, 2015

The measurement resolution, that is how close the measurements are taken in space and time, was an open question and is assumed to depend on the gradient of the measured parameters.

CDR Gish stated that the design needed to be autonomous, carrying out its measurements without human assistance. In the case of an AUV, it should return to its initial position if possible. His thought was that the design should store the data onboard for later retrieval, but also mentioned the possibility of using telemetry to transmit data intermittently. He stressed that it should be easy to recover the data, regardless of exactly how.

With regard to the physical size and weight of the system, CDR Gish stated that the design should be able to be handled by two people without the use of special equipment such as a crane or davit. Also, the design should be able to be transported in a small boat such as a RHIB, thus limiting the overall dimensions. When asked if Commercial Off The Shelf (COTS) parts were important, CDR Gish responded by stating that their use was important only insofar as keeping costs down. He stated that the overall production cost for the design should be on the order of \$1,000 or less.

With regard to operating requirements, CDR Gish said he would like the system to operate for at least 24 hours on a single charge. He also mentioned that upon full discharge, the design should be positively buoyant so as to return to the surface. The design should also be easy to find once on the surface.

One lesson he learned from previous experience which he offered was that the system, assumed to be dry inside, should feature an overpressure valve as the electronics inside previous prototypes have caused an increase in pressure which discharged unexpectedly upon opening creating a safety hazard.

CDR Gish mentioned biomimicry, or the ability of a design to act like an organism in the natural world, as something he'd be interested in seeing with regard to design propulsion.

He provided several benchmarks, with the assumption being that a glider is the best solution. Gliders are a special class of AUV. They're typically torpedo-shaped and are propelled through the water by changing buoyancy. Gliders traverse a sinusoidal path through the water column by drawing in water,

which causes them to become negatively buoyant. They glide forward as they sink toward the seafloor. Approaching the seafloor, they expel the water, causing them to become positively buoyant, and thus rise back to the surface. The profile of a glider is shown in Figure 4.

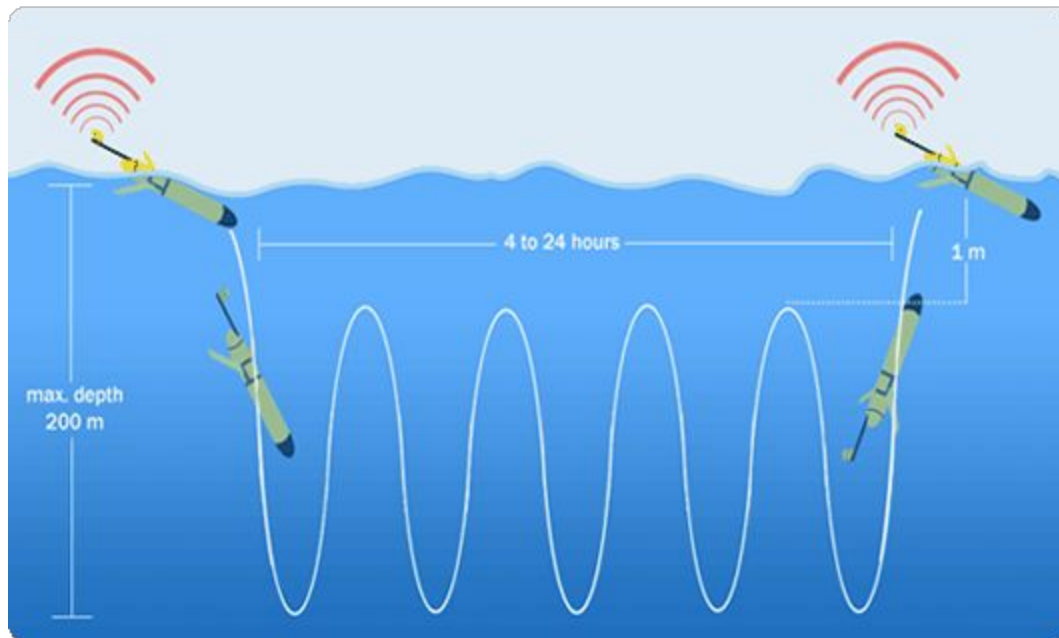


Figure 4: the sinusoidal profile of a glider-type AUV⁴.

The benchmark solutions include the Slocum Glider manufactured by Teledyne Webb Research, the Spray Glider manufactured by Bluefin Robotics, and the Sea Glider developed by the University of Washington Applied Research Laboratory. Benchmarks will be discussed in more detail in the Quality Function Deployment Section.

Initial Interview with Prof. Joe Smith

Professor Smith was interviewed on Wednesday, June 24. He also mentioned a number of wants and needs during the interview with the overarching goal of the design being to “build the physical tapestry” of the environment being surveyed.

⁴ Underwater Drones: US Navy to wage new war with sea-powered machines, Before It's News, <http://www.marine-knowledge.com/wp-content/uploads/2013/10/gliderdiagram.gif>, accessed June 19, 2015

To do this a number of measurements can and are generally made including current velocity, temperature, salinity, pressure, Ph, reduction potential (also known as Eh), and water chemistry parameters. However, he mentioned that a good first goal would be to “map the bathtub” meaning the measurement of the temperature, pressure, salinity and bathymetry (seabed depth contours) in a littoral region.

This information is then used to build an operational hydrographic model of the hydrosphere, which then can be used to help researchers understand the environment in question.

Data sets are generally collected from a small boat in the littoral environment since, in the local area for example, the draft on many research vessels is too deep to get the measurement equipment where the measurements need to be taken. He mentioned buoy data is also used when available and aggregated with measurements made from ships to provide a more complete picture. He gave an example from a recent survey he conducted of the Potomac River in which he took measurements at two depths and at seven locations over six hours from a small boat.

Professor Smith mentioned several other potential customers, discussing them in order of general proximity to a particular body of water. First, people who live and work on the river or bay would be customers, however peripheral, of an environmental monitoring system would help to ensure they have clean water for recreation, fishing, etc. Next, he mentioned researchers who are interested in the basic science to include the processes that occur in the environment. At the highest levels, government organizations including local, state, and federal agencies would benefit from such a design in their efforts to manage waterways as an environmental and economic resource. Uses for the data sets include academic journals, environmental reports, and government studies, depending largely on what the question is and who is asking it.

When asked about sampling rate and spatial resolution he stated that generally, “...you don’t have enough time or money to do the sampling resolution that you need.” However, he mentioned that the 10 m resolution provided by commercial GPS would represent a considerable improvement over current capabilities. He also mentioned several times during the interview that the question one is trying to answer is what drives the requirements. High heterogeneity requires small measurement resolution which drives up the expense and complexity of

measurement apparatus. He suggested the ability to survey an area such as the area between the Severn River Bridge (U.S. 50/301) and Trident Light (Figure 5) as being a worthy goal of such a system.



Figure 5: The survey area (shaded in red) suggested by Professor Smith between the Severn River Bridge and Trident Light at the U.S. Naval Academy (Google Earth).

With regard to cost, Professor Smith mentioned that equipment he regularly uses costs approximately \$15,000. He also mentioned that the risk of loss is considerable, therefore a cheaper, more easily procured system is a better system.

When asked to describe how an operator might use the system, he mentioned that it should be capable of being launched from a small boat, beach, or pier without the use of a davit or other support equipment. He also mentioned that two people should be able to carry and handle it.

Stating again that the question one wants to answer will drive the operating environment, Professor Smith suggested that a good goal for the project might be to operate in the environment local to the Severn River, year-round. He also mentioned that an autonomous design should have the ability to avoid obstacles such as boats, piers, nets, etc., and that it should provide a means of finding it in the event it cannot return to base.

Speaking specifically to the glider solution suggested by CDR Gish, Professor Smith mentioned that in his opinion gliders are not well suited for littoral operations because the bottom is too shallow and the currents are too swift.

1.4.2 Customer complaints

An autonomous environmental monitoring system is not a commercial product in the sense that one cannot simply drive to a store and purchase one or order one online. Thus, customer complaints specific to this design were unobtainable. However, there are myriad other autonomous systems designed to cover a prescribed area and perform a task. One such system whose reviews were found to be useful was the iRobot *Roomba 880 Vacuum Cleaning Robot* which features many of the desirable qualities of the autonomous environmental monitoring system. First, and perhaps most obviously, it operates autonomously. Also, it is started, performs its function, and returns to a pre-determined location. At \$649 on Amazon.com⁵, it's also of the same order of magnitude in terms of cost.

A survey of relevant customer complaints include:

- Operation not intuitive
- User inputs to navigation system, specifically, are unclear
- System fault information is difficult to obtain
- Inefficient path
- Obstacle avoidance success depends on obstacle shape
- The system would get “stuck” and stop
- High relative cost for minimum benefit
- System not rugged enough for operating terrain
- Control system support not sufficient (directions and troubleshooting)
- Speed is either too fast or too slow
- Number of battery recharge cycles is too low
- Battery replacement is difficult and expensive (requires a special battery)
- Limited parts support

⁵ iRobot Roomba 880 Vacuum Cleaning Robot for Pets and Allergies, Amazon.com, http://www.amazon.com/iRobot-Roomba-Vacuum-Cleaning-Allergies/dp/B00IO9PBPS/ref=sr_1_1?s=vacuums&ie=UTF8&qid=1435850387&sr=1-1&keywords=roomba&pebp=1435850413363&perid=1Z354MBESP3Q0G1FKERT, accessed July 2, 2015.

1.5 Revised Customer’s Problem Statement.

In light of feedback received from the project customers, the original problem statement was broadened to include all environmental regimes, not just underwater vehicles. The revised statement is as follows:

Design and build an autonomous vehicle for use in gathering oceanographic data in littoral regions.

1.6 Initial Draft of Customer Requirements

Once a basic understanding of the problem was in hand and the voice of the customer was heard, customer inputs were synthesized into a list of customer requirements. Garvin’s Eight Dimensions of Quality⁶ were used as an outline for ensuring completeness. The initial customer requirements are included in Table 1.

Table 1: Initial draft of Customer Requirements

Dimension	Description	Kano Class.
Performance	Must be autonomous	Expecter
	Must measure something at multiple points in time and space*	Spoken
	Measurements must be geolocated and time-stamped*	Spoken
	Must navigate some specified area*	Spoken
	Must make measured data available to researchers*	Spoken
	Must be light enough to be carried by at most two people	Spoken
	Must be launched from a small boat, pier, or beach	Spoken
	Should cost less than \$1000 to fabricate and operate*	Expecter
	Should operate for at least 24 hours without interaction	Spoken
	Must be recoverable following loss of power or malfunction	Spoken

⁶ G. Dieter and L. Schmidt, *Engineering Design, 5th Ed., McGraw-Hill, New York, 2013, pg. 82*

Table 1 (cont.): Initial draft of Customer Requirements

Dimension	Description	Kano Class.
Performance	Should measure temperature, pressure, salinity, bathymetry	Spoken
	Could be reconfigurable to measure additional parameters	Exciter
	Should cover an area the size of the lower Severn River	Exciter
	Should return to a specified position	Spoken
	Data should be easy to retrieve	Spoken
	Should avoid obstacles	Exciter
	Operation should be intuitive	Unspoken
	Should communicate fault information	Exciter
	Could feature biomimicry	Exciter
Reliability	Must be able to complete one survey*	Expecter
	Should be able to extricate itself from a confined space	Unspoken
Durability	Should last the school year	Expecter
Serviceability	Should maximize the use of COTS parts	Spoken
	should be plug-and-play	Unspoken
	Should be easy to disassemble and reassemble	Spoken
Conformance	Conform with all government regulations	Unspoken
Conformance	Comply with safety and environmental standards	Unspoken
Aesthetics	Should not look like a weapon	Unspoken
	Should be easy to see and avoid	Unspoken
	Should reflect positively on the Naval Academy*	Unspoken

* Critical to Quality Customer Requirements

Clearly, time and resources do not allow for each of these wants and/or needs to be addressed. However, even as a prioritized list is developed, attention will be paid to trying to meet as many of these as reasonably possible as they help to provide context of the customers' vision.

1.7 Gathering Information on Existing Products

1.7.1 Overview

Current methods for making oceanographic observations involve fixed stations such as buoys from which measurements are taken and transmitted, and mobile platforms such as boats and ships which can be used to suspend or tow instruments at a specified point in the water column (Figures 6 and 7). Within the last several decades autonomous vehicles have been employed with increasing frequency and success for the same purposes. So far, vehicles have primarily included autonomous surface vehicles (ASVs) and Autonomous Underwater Vehicles (AUVs).

Observations can be made from discrete samples, meaning water is collected from a specific location to be tested at a later time, or *in situ* sampling, meaning the measurement equipment is used in the field for direct observation.

There are many, many examples of the aforementioned systems, far too many to review and summarize here. Therefore, the survey of existing products will focus on the smallest most inexpensive devices used for oceanographic survey, including examples that do not meet these criteria but are still useful for purposes of comparison.



Figure 6: ATLAS mooring buoy and NOAA research vessel, two current means of gathering oceanographic data⁷.

⁷ Online log of the research vessel Ron Brown, <http://amma-international.org/implementation/sites/ocean/journal/ronbrown.htm>, accessed June 19, 2015

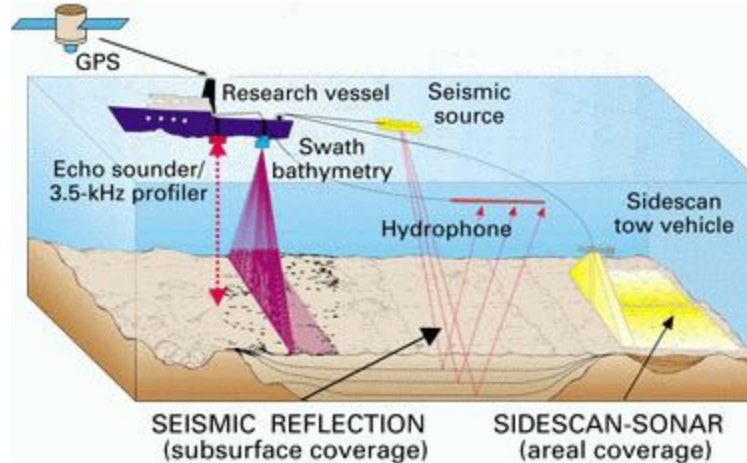


Figure 7: An example of the methods used to conduct oceanographic survey from surface vessels⁸.

1.7.2 Product Dissection

During academic year 2015, a previous capstone design team worked on this project. *Team Dreamrider* cleverly called their design the *SeaQPR 2.0* (Figure 8). The primary customer, CDR Gish, vectored the team toward a glider design. Their final product measured nearly 4 ft. long and weighed just over 50 lbs.

The team successfully connected the data acquisition equipment, including a thermometer and pressure transducer. The device was to be propelled through the water using variable ballast provided by eight large syringes.

The team was able to test portions of their design including a check of the battery system's ability to sample and cycle the ballast motors. They also successfully cycled water in and out of the ballast tanks and conducted water-tight tests of the hull to their satisfaction.

Unfortunately, the team did not have enough time to evaluate the design's ability to glide or turn and included these in the Future Work section of their final report.

⁸ Tuah Unggul Resources, Hydrographic Survey Services, <http://www.ukurtanah.com/wp-content/uploads/2014/02/Hydrographic-Survey.gif>, accessed June 25, 2015



Figure 8: The SeaQPR 2.0, a glider design created by the Waver Rider team of academic year 2015.

Also unfortunate is the fact that the team's final report was not saved to the shared drive and was thus unavailable for further reference. However, Professor Flack, the team's mentor is available should additional information be needed.

1.7.3 Technical Literature

A survey of technical literature was conducted. The information pertaining to the present problem is summarized here.

In their 1993 paper entitled *Autonomous Oceanographic Sampling Networks*⁹, Curtain et al. present a system of AUVs and buoys as a possible solution to the four dimensional (three spatial and one temporal) sampling problem. They also included methods for determining the effective survey velocity, estimated power consumed by a single AUV and the total energy required per unit distance of track covered (assuming constant propulsion power). Predicting cooperative autonomous vehicles of the future, they recommended multiple vehicles for covering a single region as a means of reducing the energy required per vehicle.

⁹ Curtain et al., *Autonomous Oceanographic Sampling Networks*, Oceanography Vol 6., No. 3, 1993, pp. 86-94.

In his 2008 paper entitled *Unmanned Surface Vehicles, 15 Years of Development*¹⁰ Justin Manley of Battelle Applied Coastal Environmental Services reviewed the development of Unmanned Surface Vehicles (USVs) from MIT's ARTEMIS in 1993 to the technology of the present, including many of the systems reviewed in the next section. In addition to his review of the technology, Mr. Manley stated that the most significant challenge to the development and commercial availability of USVs is the ability to detect and avoid other surface traffic.

In *The Stingray AUV: A Small and Cost-Effective Solution for Ecological Monitoring*¹¹, Barngrover et al. discuss their design for a small AUV that features a low-drag stingray hull form (Figure 9). Primarily fielded as a student project and the result of collaboration amongst a number of teams, the design is primarily an educational testbed. However, the hydrodynamic design provides excellent food for thought with regard to an energy saving hull design, and much of the control architecture is listed, including components, which could be useful during detail design.



Figure 9: The Stingray AUV: solid model (left) and carbon-fiber hull design (right)

The paper *Design of an Autonomous Surface Vehicle Used for Marine Environmental Monitoring*¹², was written by Wang, Gu, and Zhu in 2008 and outlines their design of an ASV (Figure 10) used for marine environmental monitoring and hydrologic survey. The design is a catamaran design measuring 2.7 m (9 ft) and is propelled by two propellers. The power supply is a set of lithium ion batteries with a 60 Ah capacity. The paper details the team's

¹⁰ Manley, Justin E. "Unmanned surface vehicles, 15 years of development." In *OCEANS 2008*, pp. 1-4. IEEE, 2008.

¹¹ Barngrover et al., *The Stingray AUV: a small and cost-effective solution for ecological monitoring*, *OCEANS 2011*, vol., no., pp.1,8, 19-22 Sept. 2011

¹² Wang, Jianhua, Wei Gu, and Jianxin Zhu. "Design of an autonomous surface vehicle used for marine environment monitoring." In *Advanced Computer Control, 2009. ICACC'09. International Conference on*, pp. 405-409. IEEE, 2009.

hydrodynamic considerations and testing as well as the control architecture. Tests demonstrate the ability to patrol at a speed of 1.5-2 m/s (3-4 kts) for 135 minutes.



Figure 10: The two-hull design prototype including ducted propellers (left), and the ASV during testing (right)

In 2009, Dunbabin, Drinham, and Udy wrote a paper entitled *An Autonomous Surface Vehicle for Water Quality Monitoring* describing their design of a 16 ft. long solar catamaran (Figure 11) capable of navigating complex inland waterways while monitoring water quality parameters¹³. In their paper they outline many of the same design and operational considerations desired by the customers of this design including the ability to operate for 24 hours continuously, profile the water column, and return to base autonomously.



Figure 11: the Lake Wivenhoe ASV, a solar powered catamaran design measuring 16 ft.

¹³ Dunbabin, Matthew, Alistair Grinham, and James Udy. "An autonomous surface vehicle for water quality monitoring." In *Australasian Conference on Robotics and Automation (ACRA)*, pp. 2-4. 2009.

Intended primarily as a navigation test platform, the Lake Wivenhoe ASV has demonstrated the ability to navigate autonomously and avoid obstacles such as other water craft and non-navigable shoals.

1.7.4 Consumer and Product Literature

Iver3 Nano AUV. Although the Iver3 Nano (Figure 12) is well out outside the specified price range at around \$50,000 USD, it meets nearly every other requirement specified by the customer, and is thus included here.



Figure 12: The Iver3 Nano autonomous underwater vehicle made by Ocean Server¹⁴.

The Iver3 is an autonomous vehicle designed specifically for oceanographic survey and environmental monitoring. It measures 1.7 m (165 in.) long and has a mass of 18 kg (weighs 65 lbs.). The sensor package includes GPS, a pressure sensor, and an internal navigation system (INS). It also features a side scan sonar system capable of seafloor mapping at distances of up to 100 m. On a single charge (267 WHrs, 24 V), it can operate for 5 hours at a survey speed of 2.5 kts depending on the sea current and the equipment operating.

¹⁴Iver3-450-Nano AUV, Ocean Server Products, <http://www.iver-auv.com/iver3Nano.html>, accessed July 6, 2015.

The propulsion system features a 36 V brushless DC motor and it can maneuver in pitch, roll, and yaw. It has an integrated wireless data transmission system, 4 GB of memory for control and collection, and a 64 GB solid state drive for data storage.

REMUS 100. Similar to the Iver3 Nano, the REMUS 100 (Figure 13) was specifically designed for environmental monitoring (REMUS stands for Remote Environmental Monitoring UnitS). It is also of similar size with a length of 1.6 m (63 in.) and a weight of 37 kg (80 lbs.). Standard sensors include bathymetry, temperature, water velocity (current), salinity (conductivity), optical backscatter, diver visibility, sidescan sonar, and fluorescence. Endurance is stated at 22 hours at 1.5 m/s (3 kts.) depending on current speed and sensor configuration on a single 1 kWh charge. Propulsion is provided by a brushless DC motor connected to a three-bladed propeller.



Figure 13: The REMUS 100 autonomous underwater vehicle made by Hydroid, LLC¹⁵.

Unlike the Iver3, however, the REMUS was designed to conduct hull inspection, and can therefore hover in position as well as follow along the hull at a set standoff distance. It can also operate in conjunction with up to four other REMUS 100 vehicles. The REMUS 100 features GPS and INS, but navigation input can also be provided via at least two transponders.

¹⁵REMUS 100 Brochure, [http://www.km.kongsberg.com/ks/web/nokbg0397.nsf/AllWeb/61E9A8C492C51D50C12574AB00441781/\\$file/Remus-100-Brochure.pdf?OpenElement](http://www.km.kongsberg.com/ks/web/nokbg0397.nsf/AllWeb/61E9A8C492C51D50C12574AB00441781/$file/Remus-100-Brochure.pdf?OpenElement), accessed July 6, 2015

Slocum G2 Glider. As previously discussed, the Slocum Glider (Figure 14) is a high-endurance AUV that traverses the hydrosphere very efficiently using a buoyancy engine. The glider is 1.5 m long (60 in.) and has a mass of 54 kg (120 lbs.) depending on the configuration. Standard measurements include currents, conductivity, temperature, depth, turbidity, chlorophyll, backscatter, and dissolved oxygen. It also features a hydrophone for collecting acoustic information. Average horizontal speed is 0.35 m/s (0.68 kts.) using the buoyancy engine or 1 m/s (2 kts.) in propeller mode. There is an optional littoral buoyancy engine available in addition to the deep water system, though it is not clear from the available literature how “littoral” is defined in terms of depth. The deep sea variant can be deployed for periods of up to 12 months, depending on the battery pack configuration and operating environment. The Slocum Glider navigates using a combination of GPS, depth (pressure) sensing, and dead reckoning.



Figure 14: the Slocum G2 glider made by Teledyne Webb Research¹⁶.

¹⁶Teledyne Webb Research Slocum G2 Glider Datasheet, http://www.webbresearch.com/pdf/Slocum_Glider_Data_Sheet.pdf, accessed July 6, 2015

Wave Glider SV3. The Wave Glider is a combination float and submarine joined by a tether. The float measures just over 3 m long and the submarine just over 2 m long. They have a combined weight of 330 lb. Because the system is solar powered (rated at 150 W collection rate), it has an advertised endurance of 1 year. Average data collection speed is 0.9 m/s (1.8 kts) with a maximum system speed of 1.5 m/s (3 kts.). The system can carry up to 100 lb of additional payload. It uses a solid state magnetometer in conjunction with GPS to navigate. With regard to communications, the system features Iridium (RUDICS), and 802.11 WiFi, with cellular connection optional. The system shown in Figure 15 costs on the order of \$300,000 USD¹⁷.

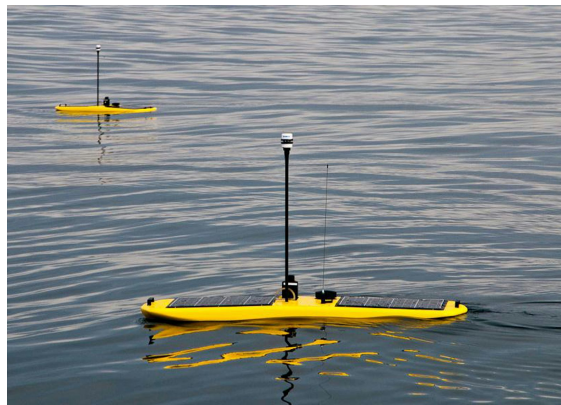


Figure 15: Liquid Robotics Wave Glider SV3, with only the floating portion shown¹⁸.

MIT SCOUT. SCOUT stands for Surface Craft for Oceanographic and Undersea Testing. The SCOUT is an autonomous Kayak built primarily from COTS parts (Figure 16). The keel length is 3 m (10 ft.). It can operate for approximately 8 hours at a maximum speed of 1.5 m/s (3 kts) drawing from five Absorbed Glass Mat (AGM) lead acid batteries. The system weighs approximately 180 lb. and can be manipulated by two people. The scout has three modes of control: direct, indirect, and fully autonomous. The SCOUTS can also be programmed to operate in a swarm.

¹⁷ Wave Glider SV3 Specification Sheet, Liquid Robotics, <http://info.liquidr.com/specification-sheets?submissionGuid=11c382ee-c4c5-4449-bb07-5bc630ef6a43>, accessed June 25, 2015

¹⁸ Liquid Robotics' Wave Glider ASV Collects Typhoon Rammasen Data, Unmanned Systems Technology, <http://www.unmannedsystemstechnology.com/2014/07/liquid-robotics-wave-glider-asv-collects-typhoon-rammasen-data/>, accessed June 25, 2015.

The vehicle is propelled by an electric trolling motor and steering is achieved using a hobby servo motor. The vehicle is meant to act as a “pickup truck” allowing the user/operator to install whatever equipment is necessary for the mission. Collision avoidance measures were under development in 2005.

The entire system can be purchased for approximately \$500 USD. Unfortunately, the SCOUT is not available for purchase, nor are the plans available to the public.



Figure 16: MIT Scout during operation (left) and in preparation for deployment (right)¹⁹.

1.7.5 Patent Literature

A preliminary patent search was conducted on the U.S. Patent Office website (<http://patft.uspto.gov/>) using the keywords *autonomous* and *water* or *underwater* and *vehicle* and *oceanographic* and *survey*. The search produced 24 hits including the following:

US patent 8,995,229 awarded to Melvin II et al. in 2015 for a method of determining the position of a submersible vehicle within a body of water which uses a transmitter aboard the vehicle and listening stations distributed through the operating area to locate it. The patent paperwork includes diagrams and flowcharts that might prove useful in the concept generation stage.

US patent 8,397,657 awarded to Guerrero et al. in 2013 for a single robot or system of robots that can be used to venture to a precise location on the seafloor

¹⁹ Joseph Curicio, John Leonard, and Andrew Patrikalakis, *SCOUT - A Low Cost Autonomous Surface Platform for Research in Cooperative Autonomy*, Marine Technology Society (OCEANS) Conference, 2005

(Figure 17). The robots are dropped and move downward trading potential energy for kinetic energy. However, it is unclear how they are intended to return to the surface. Again, though it does not represent a complete solution, the concept of dropping small modules to the floor and having them collect information or take samples directly on the way down may be useful to consider during concept generation.

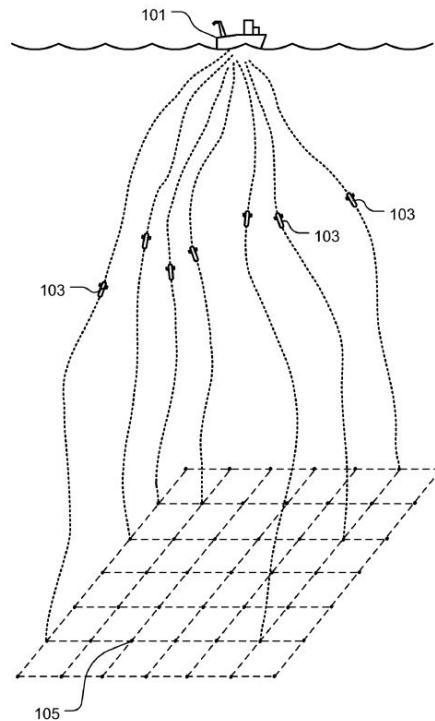


Figure 17: the patent description of *Vertical Glider Robot*, patent number 8,397,657.

US patent 5,687,137 awarded to Schmidt et al. in 1997 for methods and apparatus for adaptive oceanographic sampling. The system includes several stationary tomography (i.e. imaging by sections using a penetrative electromagnetic wave) stations along with at least one underwater autonomous vehicle (Figure 18). The patent is for the specific adaptive algorithm, but the entire system provides some insights for future work.

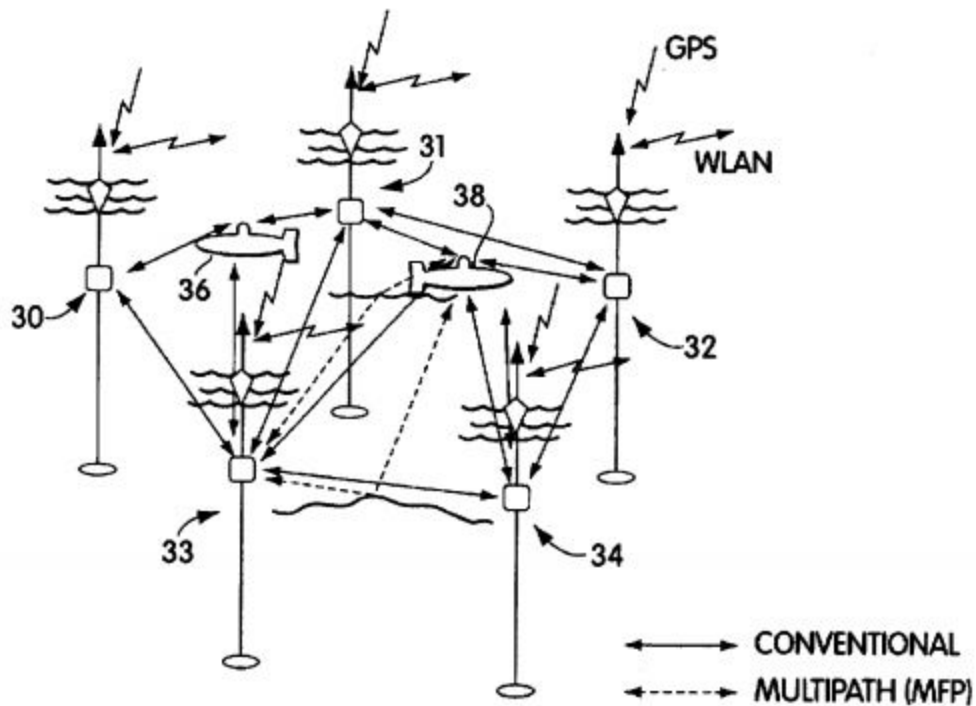


Figure 18: the patent description of *Methods and Apparatus for Adaptive Oceanographic Sampling*, patent number 5,687,137.

1.7.6 Applicable Codes and Standards

There are no prohibitions in the U.S. Code of Federal Regulations specifically regarding autonomous vehicles. It was, however, determined that ASTM Standard volume 15.11 governs unmanned maritime vehicle systems (UMVSs). Unfortunately, the standards must be purchased and as a result were unavailable as of the time of this writing.

Peripherally, Occupational Safety and Health Administration (OSHA) Standard 1926.106 describes the personal protective and lifesaving equipment required when employing such a system.

From a considerable review of local, state, and federal codes and regulations, it's clear that which codes and standards might apply is based largely on the ultimate form of the design. For example, if a buoy system is used, the state of Maryland

has specific requirements for mooring buoys²⁰ including where they are placed and how they must appear, but it is unclear if there are specific requirements for non-mooring buoys. It stands to reason that if one were to deploy a buoy or a system of buoys, permission would be needed from some local government organization. As another example, if the system uses WiFi to transmit and receive information, it will be subject to the IEEE 802.11 communication standard.

Also, if the design solution includes the use of a surface vessel, autonomous or not, it stands to reason that all regulations applicable to such craft should be observed.

1.7.7 Global, Economic, Environmental, and Societal context

Global. Autonomous vehicles are at the forefront of current technology. They are being used in applications ranging from covering freeway traffic jams and delivering consumer goods to conducting reconnaissance and launching weapons. Water-borne vehicles used for environmental monitoring could potentially be used in every corner of the globe. An effort should be made to ensure the vehicle's form reflects its benign function to preclude it being mistaken for a weapon.

Economic. The cost of high-tech components has dropped precipitously in the past decade. Computer processors, cameras, navigation equipment, and so much more can now be purchased cheaply online and delivered within days or even hours. How-to tutorials are readily available online. This is the environment in which this vehicle is designed. The primary purpose of this project is to provide a bill of materials and some instruction so that anyone with interest and a nominal budget can have the capability of oceanographic survey.

More broadly, a breakthrough technology in this area has the potential to be widely adopted, thus creating a lucrative business opportunity in support of environmental scientists and conservation groups. Also, considering the significance of waterways like the Chesapeake Bay as a national economic resource, cost-effective wide-scale monitoring could have a tremendous positive impact on the myriad economic interests that rely on them.

²⁰Single Recreational Mooring Buoys, Department of Natural Resources, <http://dnr2.maryland.gov/Boating/Pages/srmbuoys.aspx>, accessed July 24, 2015

Environmental. As his Uncle Ben tells Peter Parker in the *Spiderman* comics, “With great power comes great responsibility.” The components used to create an environmental monitoring system must be robust enough to withstand the harsh operating environment of the sea. As such, the same properties that allow them to withstand the marine environment make them unlikely to degrade when discarded or lost. Moreover, batteries and other such materials can be harmful to the local environment. Every effort must be made to recover the system, not only for purposes of data recovery and future use, but in the spirit of responsible environmental stewardship.

The impact of a successful system, on the other hand, would be a tremendous boon to environmental conservation efforts and natural science.

Societal. The underlying purpose of this project is to better understand the marine environment in an effort to improve and preserve the health of local waterways. To put it simply, clean water is good for everyone from wildlife to residents who live along the water to the people who earn their living from it. The stated purpose of many an engineering professional group is to better society. An autonomous environmental monitoring system would support that goal directly.

1.7.8 Engineering Models

At this point in the design process no design concepts have been proposed. However, there are some solution-neutral questions that can be answered or at least estimated based on some back-of-the-envelope calculations. These include:

- How far does a vehicle need to travel?
- How much time would it take?
- How much energy would this require?

Considering the previous survey of benchmarks, some designs are propelled constantly (e.g. REMUS 100, Wave Glider, etc.) while others are intermittent (Slocum Glider). In an effort to get an idea of the high end of the power requirement, constant propulsion was assumed with the understanding that a design such as a glider could potentially require less energy.

As a first approximation, the search area was assumed to be the Severn River, south of the Severn River Bridge and north of Trident Light, the white shaded area shown in Figure 19. According to the Google Earth polygon tool, the area encompasses 1.8 km² (0.7 mi²). It was assumed that it would be a single vehicle

conducting the survey. It was also assumed that at the time of survey there would be no current through the search area. It is understood that this is not an entirely realistic assumption, but a higher degree of fidelity can be included in later models. A horizontal velocity of 1 m/s was assumed as a reasonable starting point based on the quoted velocities of the benchmark products.

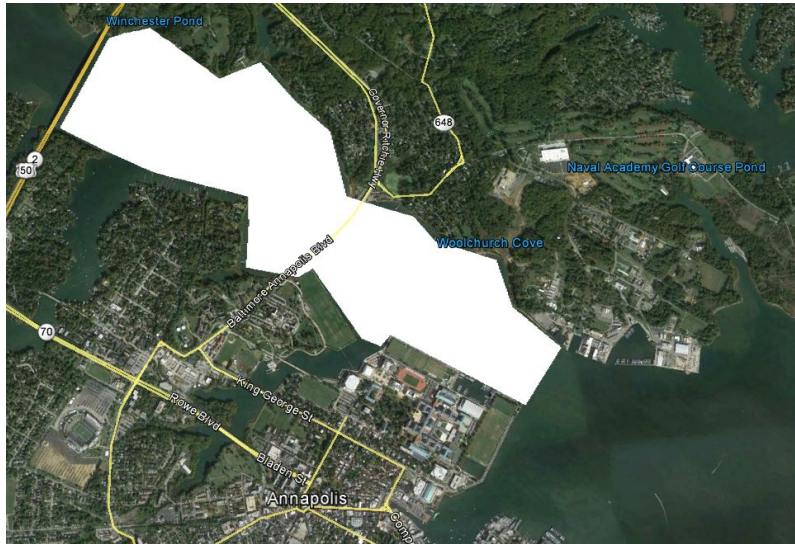


Figure 19: the search area with the Google Earth polygon used to calculate the area, shaded in white.

For the purpose of rough estimation, the search area was reduced to simple rectangles overlaid on Nautical Chart 12280 *Chesapeake Bay: Severn and Magothy Rivers* as shown in Figure 20. The perimeter of the search box was placed at approximately the 10 ft. (3 m) depth line. Assuming a creeping line search pattern (shown using the black, dashed line in Figure 20), the total search distance would be approximately 156 km. At 1 m/s, it would take a little over 43 hours to complete a single survey. Prof. Smith mentioned that the tidal cycle in the Severn River is on the order of 6 hrs. In order to search the entire area in 6 hours, the vehicle would need to travel 7.2 m/s (14 kts.). Or, considered another way, a vehicle traveling at 1 m/s could search along 3600 m per hour. At 10 m spacing between lateral tracks (the highest fidelity of commercially-available GPS), with lateral tracks 500 m long, the vehicle could search 60 m in the direction of advance or 0.03 km² per hour. If a swarm of vehicles were used, the search area could be covered in 6 hrs. by 10 vehicles.

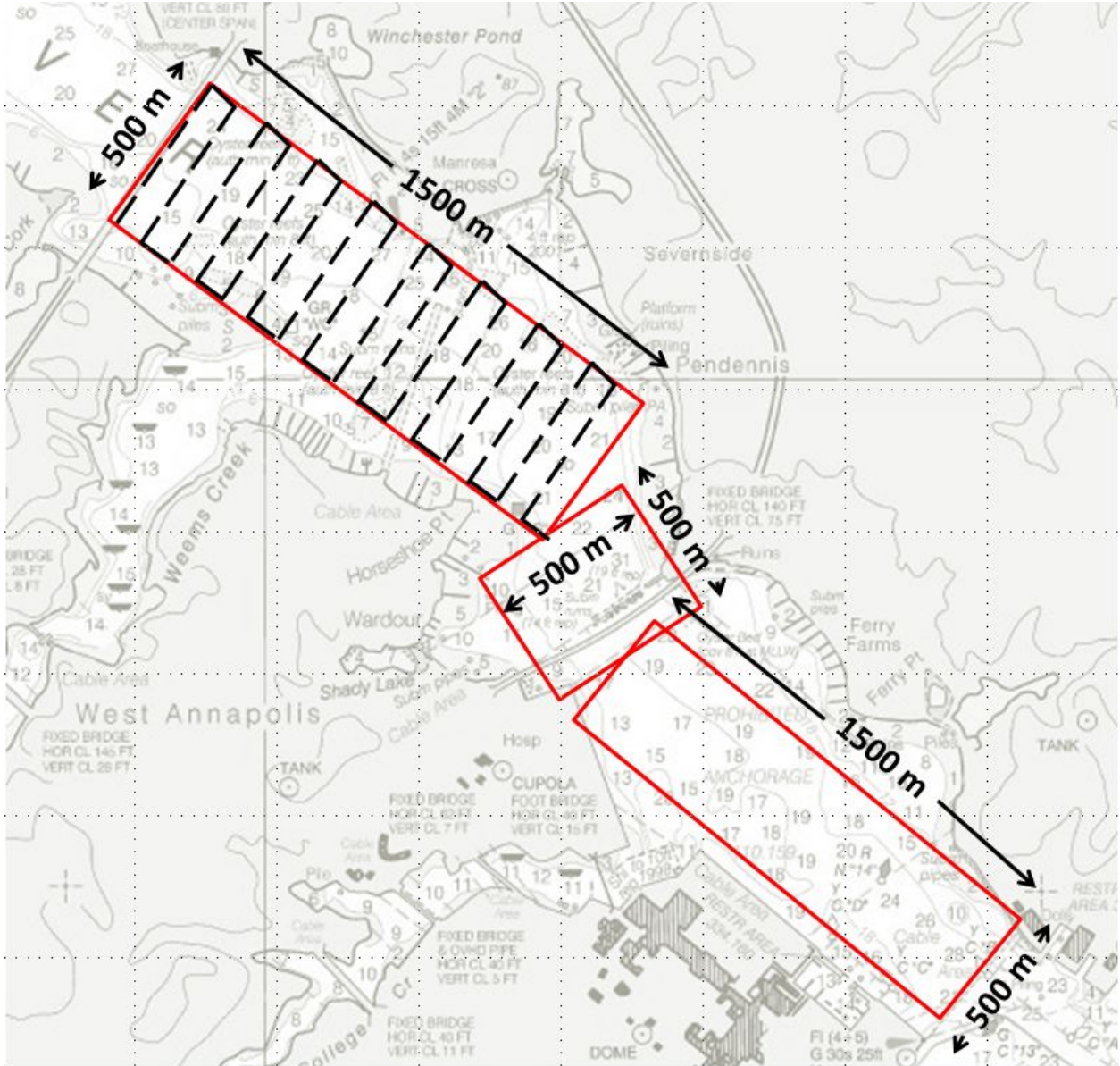


Figure 20: Nautical Chart 12282 Chesapeake Bay: the Severn and Magothy Rivers overlaid with approximate search area boxes, shown in red, and dimensioned, shown in black text. The black dashed line in the upper left search box depicts the creeping line search pattern, though is not shown to scale.

As previously mentioned, Curtin et al. also provided an equation to estimate the required search velocity:

$$V_e = A/(2Lt) \tag{1}$$

Where V_e is the effective survey velocity, L is the resolution, defined as the maximum horizontal distance from any point in the area from the survey track, in

this case, $L = 10 \text{ m} / 2$ or 5 m . In Equation (1), t is the survey time. For a search area of 1.8 km^2 ($1,800,000 \text{ m}^2$), a resolution of 5 m , and a time of 6 hrs. ($21,600 \text{ sec.}$), the effective search velocity is 8.33 m/s which is larger but on the same order of magnitude as the first estimation.

The amount of energy required to search the area does depend on the solution, specifically the shape and size of the hull, the speed of the vehicle through the water, the efficiency of the propulsion system, etc. However, a back-of-the-envelope estimation can be made using parameters from the REMUS 100 spec sheet. From Curtin et al., the power required can be calculated using:

$$P = (rDSV^3)/(2h) + H \quad (2)$$

where P is the power required, r is the density of salt water (1025 kg/m^3), D is the drag coefficient (assumed 0.1 for a long streamlined body), S is the surface area (0.9550 m^2 , assumed a cylinder using the length and diameter of the REMUS 100), V is the search velocity (8.3 m/s , calculated above), h is the propulsion efficiency (estimated to be 0.7 from Curtin et al.), and H is the hotel load (i.e. power used for functions other than propulsion, in this case assumed 5 W based on proportion of total power quoted on the REMUS 100 spec. sheet). Given these parameters, the required power was 40 kW , a prohibitively high value. It was decided that search speed should be reduced to the value quoted in the REMUS 100 spec. sheet, 1.5 m/s , which yielded a much more reasonable 240 W . The operational power quoted on the REMUS 100 spec. sheet is 45 W , a much lower figure, but perhaps the power conversion efficiency is higher or the drag coefficient is lower for the REMUS.

Also from Curtin et al., the energy required per unit track covered is given by the equation:

$$E = [(rDS)/(2h)](V/N)^2 + NH/V \quad (3)$$

where E is in J/m and N is the number of vehicles used to cover the search area. Using the previous problem parameters, the required energy is 160 J/m . A single vehicle covering the entire search area of 156 km would require $2.5\text{e}7 \text{ J}$ of energy. Assuming a battery has a capacity of 100 Ah and is operating in a 12 V system, the battery would have $4.32\text{e}6 \text{ J}$ of energy. Thus six batteries would be required to traverse the search area. The code used to calculate these estimates is enclosed in Appendix A.

These are rough estimates, however, they demonstrate that a solution might reasonably be found using current technology.

1.8 Quality Function Deployment

1.8.1 Customer Requirements

A second interview was conducted with CDR Gish and Prof. Smith. They were shown the initial table of customer requirements (Table 1) to ensure the team properly understood their needs and wants, and asked if they would identify a handful of the highest priority requirements. They were also asked to rank those requirements in order of priority on a scale of 1 to 5 where 1 is least important and 5 is most important. Each of them provided different inputs, but together the team agreed upon the appropriate priority to ascribe to each customers' comments. The revised list of customer requirements are included in Table 2.

Table 2: Revised Customer Requirements

A successful design should:	Priority
Take measurements and make them available to the user	5
Be cheap	5
Cover a specified search area in a reasonable time, autonomously	4
Be man-portable and launchable	3

1.8.2 Customer Assessment of Competing Products

CDR Gish and Prof. Smith were also asked to rank their evaluation of several benchmark designs based on the established customer requirements. Their inputs are included in Table 3.

Table 3: Customer assessment of competing products.

Customer Requirements	Prof. Smith			CDR Gish		
	REMUS 100	MIT SCOUT	Slocum Glider	REMUS 100	MIT SCOUT	Slocum Glider
Take measurements and make them available to the user	5	5	3	5	5	5
Be cheap	1	5	1	1	5	3
Cover a specified search area in a reasonable time, autonomously	5	5	1	5	3	5
Be man-portable and launchable	5	5	5	5	5	5

Benchmarks were rated on a five-point scale with regard to customer requirements. Designs that performed well with respect to a particular customer requirement were given a score of 5. Likewise, designs that performed poorly were given a score of 1. Both customers scored the MIT SCOUT highly indicating that the design team could use many of its features in a new design. Cost was a considerable detractor for both customers for both the REMUS 100 and the Slocum Glider. On the other hand, the SCOUT scored well because of its low cost. It's also clear from the scoring that CDR Gish is interested in technology similar to the Slocum Glider, whereas Prof. Smith is less enthusiastic about it. Each of the benchmark designs scored well with respect to size, giving the design team a clear target size for a new design.

1.8.3 Engineering Characteristics

From these customer requirements, a list of engineering characteristics was developed in order to quantify system performance with regard to customer requirements. These are included in Table 4.

Table 4: Customer requirements and their corresponding engineering characteristics along with the rank of relative importance.

Customer Requirements	Engineering Characteristics	Units	Direction of Improvement	Rank Order
Take measurements and make them available to the user	samples stored/transmitted	#	↑	2
Be cheap	cost	\$USD	↓	1
Cover a specified search area in a reasonable time, autonomously	area coverage	%	↑	5
Cover a specified search area in a reasonable time, autonomously	search area	m ²	↑	3
Cover a specified search area in a reasonable time, autonomously	search rate	m ² /s	↑	3
Be man-portable and launchable	mass	kg	↓	6

In Table 4, *area coverage* likely requires further explanation. Coverage area is defined as the area searched divided by the total area defined. The search area would be the path integral of the search route given the system position resolution (10 m). Another way to think about this would be the *completeness* of the search.

Rank order was calculated using the methodology outlined in Dieter and Schmidt, Section 3.6.2²¹. System cost was determined to be the highest priority of this design, which makes sense in light of the fact that systems are readily available that meet most if not all customer requirements except for the prohibitive cost of most and the inaccessibility of the only affordable option (i.e. the MIT Scout, which is not currently available for purchase, nor are plans available online).

To these engineering characteristics is added a list of constraints, in this case a list of “yes/no” requirements including:

- Operate autonomously
- Conform to all applicable codes
- Comply with safety regulations
- Comply with environmental standards
- Does not look like a weapon
- Reflect positively on the U.S. Naval Academy

²¹ G. Dieter and L. Schmidt, *Engineering Design, 5th Ed.*, McGraw-Hill, New York, 2013, pg. 99-110

The last two constraints are included with consideration of the event a prototype is lost and recovered by someone in the surrounding community.

1.8.4 Technical Assessment

The performance of each of the benchmark systems with regard to the established engineering characteristics was determined, when possible, and included in Table 5. Surprisingly, most of the specifications listed on the information sheets do not describe the *goodness* or completeness of search. This is perhaps due to the variability associated with setting different system parameters such as the sampling frequency, search path, etc. As such, the performance of each benchmark design with regard to the engineering characteristics outlined in the previous section was difficult to obtain for all categories. When necessary, a qualitative assessment was made.

Table 5: Technical assessment and target values for each engineering characteristic.

Engineering Characteristic	samples stored/transmitted	cost	area coverage	search area	search rate	mass
Units	#	\$USD	%	m ²	m ² /s	kg
REMUS 100	many	50,000	high	medium	low	37
MIT SCOUT	many	500	high	low	low	82
Slocum Glider	many	100,000	low	very high	low	54
Targets	20,000	1000	50	18,000,000	12	25

1.8.5 Target Values for Engineering Characteristics

The target value for the number of samples was arrived at by taking the estimated track length, 156 km, and dividing it by the expected GPS position resolution, 10 m which yields 15,600 samples. The final value is rounded up from this figure with some margin deemed nominal considering the low cost and space associated with data storage. The cost target figure was taken directly from customer inputs. The coverage area target is an estimate of what might reasonably be considered success with the thought that follow-on projects might improve navigation and maneuvering. The search area target is also taken directly from the customer, as previously discussed. The search rate is the total search area, 1.8 km², divided by the estimated time to search as previously

calculated for a vehicle cruising at 1 m/s, 43.3 hrs. The mass target was derived from human subject testing during which team members carried weights, kneeled, and held the weights at arms' length to simulate system deployment. Masses above 25 kg were deemed too heavy for the old and infirm (i.e. the faculty). It is recognized that the mass target is considerably lower than the other benchmarks and may be too low to be achievable, despite physical testing.

1.9 Project Management

Table 6 includes all of the project-specific tasks and milestones anticipated at this time. It also includes the person assigned to complete the task and the anticipated date of completion. Near-term tasks are known with higher certainty than those later in the semester or next semester.

Table 6: Project-specific tasks, resources, and completion dates.

Milestone/Task	Person Assigned	Date of Completion
Initial interview with CDR Gish	Lust	6/18/15
Initial interview with Prof. Smith	Lust	6/24/15
Field trip to Northrop Grumman undersea systems	Lust, Stevens	9/3/15
System Requirements Report initial draft	Lust	9/4/15
System Requirements Presentation dry-run	Lust	9/9/15
Individual design concepts complete	Lust, Stevens	10/7/15
Design selection	Stevens	10/8/15
Preliminary Design Report initial draft	Lust	10/12/15
Preliminary Design Presentation dry-run	Lust	10/15/15
TSD Interview	Lust, Stevens	10/22/15
Purchase orders submitted	Stevens	10/19/15
Work orders submitted	Lust	10/19/15
Detail Design Report initial draft	Lust	11/30/15
Detail Design presentation dry-run	Lust	12/3/15

Table 6 (cont.): Project-specific tasks, resources, and completion dates.

Milestone/Task	Person Assigned	Date of Completion
Prototype demonstration in LeJeune Pool	Stevens	2/18/15
Prototype demonstration in College Creek	Stevens	3/3/15
Final Testing	Stevens	3/17/15
Prototype demonstration for customers	Stevens	3/31/15
Final Design Report initial draft	Lust	4/7/16
Final Design Presentation dry-run	Lust	4/14/16
Capstone Day/Final Design Presentation	Lust, Stevens	4/27/15
Final Design Report	Lust	4/28/15

1.10 Budget

The budget for the previous team was initially \$3,000 of which \$1210 was spent. This is likely an appropriate estimate for this project. The previous team did not build more than one prototype, but the remaining funds would likely have been sufficient to cover them should they had the time. Furthermore, the MIT SCOUT reportedly costs \$500 total. This figure surely doesn't account for research and development costs, but demonstrates the approximate total cost of all the components in a working prototype.

Aside from a fact-finding field trip to Northrop Grumman, located in Annapolis, there is no anticipated travel associated with this project. A vehicle from the motor pool will be requested and the excursion will take place between meals, thus no travel funds will be required.

The total budget requested for this project is \$3000.

2 Concept Generation

2.1 Physical Decomposition

Prior to concept generation, the current features of the benchmark designs were reviewed and compiled in Table 7.

Table 7: Compilation of benchmark subsystems and specific features.

Subsystem	Features
Navigation	Magnetometer Global Positioning System (GPS) Inertial Navigation System (INS) Digital Ultra Short Baseline (DUSBL) Control planes and propulsion
Power	Batteries (Li ion, Alkaline also available) Solar panels
Propulsion	Brushless DC motor Propeller (3-bladed) Buoyancy engine
Payload and Instrumentation	Water speed sensor Automatic Identification System (AIS) receiver Weather receiver Acoustic Doppler Current Profiling (ADCP) Sidescan sonar Conductivity Temperature Depth (pressure) Bathymetry (produces KMZ files compatible with Google Earth) Oxygen Optode pH Oxidation Reduction Potential (ORP) Video Hydrophone Turbidity Plug and play architecture Modular design to accept multiple systems
Communications and Operation	Satellite: Iridium Cellular WiFi Gateway buoy Transponder Chart-based GUI Waypoint navigation Status monitoring via text and e-mail

The purpose of this exercise was to review, in detail, the means by which the benchmark designs serve their required functions. From the contents of Table 7, a

general schematic approximately representing an amalgamation of the benchmark systems was created (Figure 21).

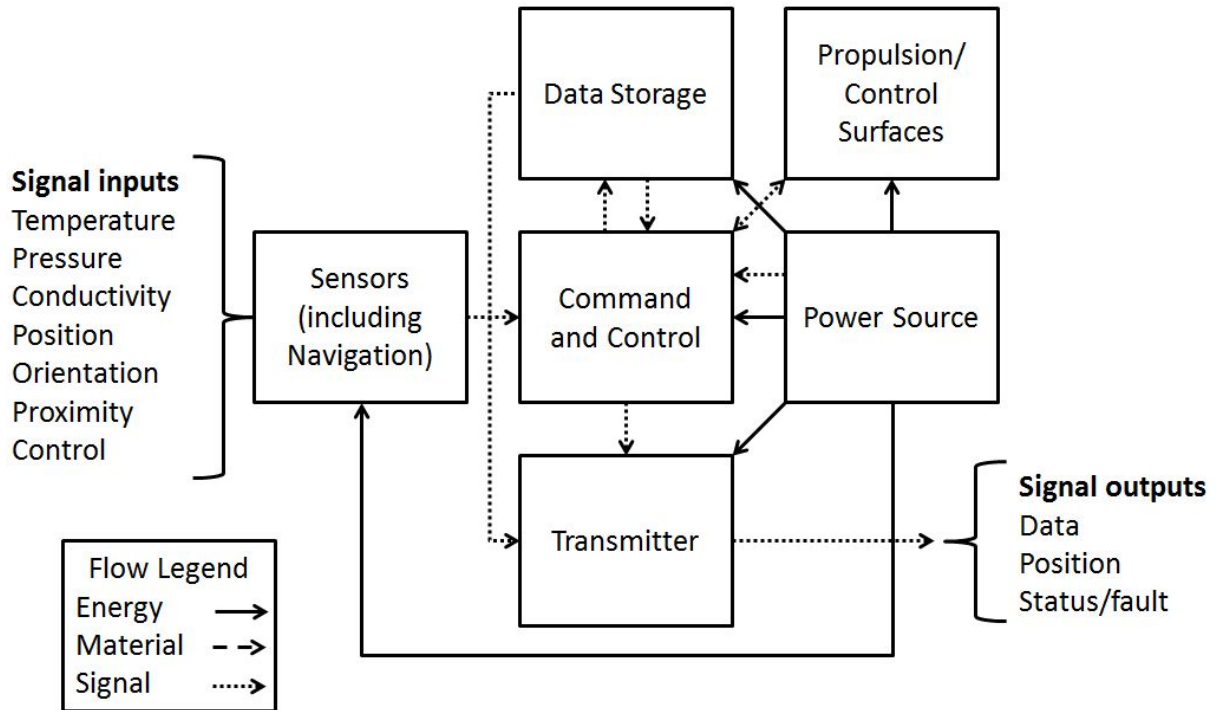


Figure 21: General product dissection schematic including energy, material, and signal flows.

From this general, non-solution specific product dissection the major required components was clear as was how they might exchange energy and information. This was useful in the development of a functional decomposition (Figure 22), which represents each of the tasks the device must perform as functions rather than specific components which allowed for more creative solutions.

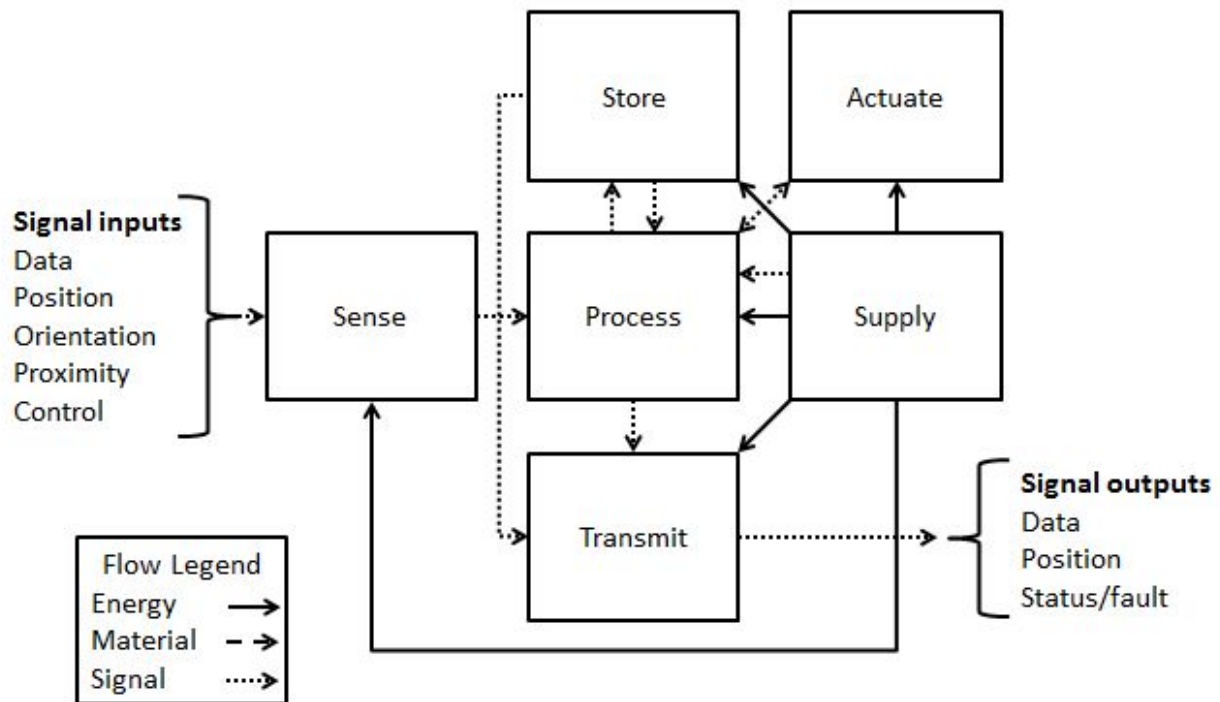


Figure 22: Functional decomposition schematic including energy, material, and signal flows.

The functions listed were taken from the Standardized Function Names²². These functions were then incorporated into a Morphological Chart (Table 8). Further research was conducted as to the available means by which each function could be accomplished. For example, in exploring the *sense (measurements)* function, many small, cheap transducers for temperature, pressure, and water quality were found, many of which came with instructions on how to connect them to an Arduino processor. This will certainly prove useful during detail design.

Each “Chinese Restaurant Menu” combination of means for each function represents a distinct design. However, the functions that will result in the most obvious differentiation is undoubtedly the *Transport* function, since many of the other functions are satisfied with a similar selection of components. Table 8 was used for guidance during the brainstorming sessions.

²² G. Dieter and L. Schmidt, *Engineering Design, 5th Ed., McGraw-Hill, New York, 2013, pg. 220*

Table 8: Morphology Chart including the required functions and possible means to achieve them.

Function	Means					
Sense (measurements)	Digital	Sample collection				
Sense (position)	GPS	INS (partial)	Triangulation	Physical reference to known position		
Sense (proximity)	Light (laser, IR)	Sound (Ultrasonic)	Bumper	Accelerometer	Pressure sensor	
Sense (control)	WiFi receiver	Cellular receiver	Radio receiver			
Process	Arduino	Raspberry Pi	Picaxe	Launchpad		
Store	Micro SD					
Transport	Propeller	Buoyancy engine	Flapping fins	Water jet	Sail	Currents/ drift
Supply	Battery	Solar panel	Directed energy			
Transmit	WiFi	Cellular	Radio			

2.2 Creative Thinking Methods

In addition to the *systematic methods for designing* used as described in Section 2.1, creative thinking methods were also used. As the team is composed of only two people, three additional volunteers were invited to assist in the conceptual design process. Initially, the members of the team sketched silently. Once individual momentum flagged, each of the members of the team briefed their sketches and ideas to the others. Then, members of the team annotated comments on each other's sketches. Several designs were identified as being liked by all members of the team. The *Five Whys* method was used to flesh out some of the detail. This concluded the initial brainstorm.

Two days later, a second brainstorm was held. Team members were asked to consider the design ideas they'd seen during the initial brainstorm as well as those illuminated by the systematic design methods. Another round of silent sketching was followed by another round of sharing and annotation. At this point, each member of the team had a rough outline of his or her own design concept. Of the five concepts, two were selected for further development - one representing the expected solution and one representing an unexpected, innovative solution.

2.3 Design Concepts

2.3.1 “Trapped Beneath the Sea: Part I” - the autonomous underwater glider

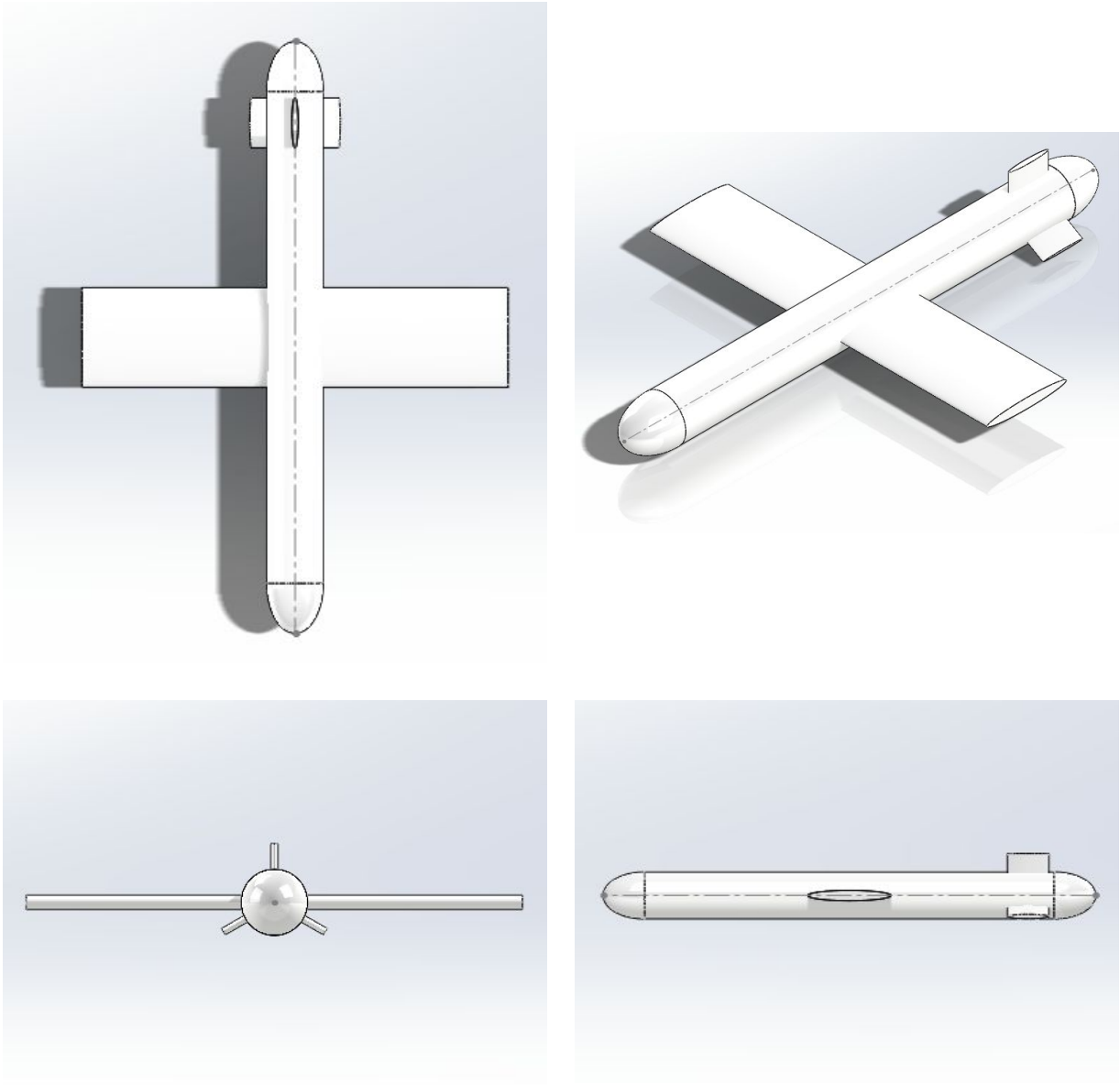


Figure 23: *Trapped Beneath the Sea: Part I*, the autonomous underwater glider design concept.

CDR Gish, one of the team’s primary customers, is very interested in a Slocum Glider-like design as it appears from the consumer product and technical literature to be one of the most energy efficient designs yet imagined. While *energy efficiency* is not an

Engineering Characteristic, *search area* is and an energy efficient design is more likely to have a larger search area.

Slocum gliders certainly exist, but do not currently meet the customers' needs because they are prohibitively expensive. The purpose of this design would be to try and develop a very inexpensive version out of COTS parts. It is also anticipated that control system architecture will be complex, so an additional deliverable, should this design be selected, would be to provide the open source control code along with a bill of materials.

Design Performance Modeling

To review, the top six most important ECs and their associated targets are included in Table 9.

Table 9: Top six Engineering Characteristics.

Rank Order	Engineering Characteristics	Units	Direction of Improvement
1	cost	\$USD	↓
2	samples stored/ transmitted	#	↑
3	search area	m ²	↑
3	search rate	m ² /s	↑
5	area coverage	%	↑
6	mass	kg	↓

The following constraints, established previously, also need to be addressed by any feasible design:

- Operate autonomously
- Conform to all applicable codes
- Comply with safety regulations
- Comply with environmental standards
- Does not look like a weapon
- Reflect positively on the U.S. Naval Academy

As cost and mass are two of the top six ECs, the rough dimensions and materials required to create the prototype design were determined. This is not meant to suggest detail design, only to provide a good approximation of what the detail design might include. Cost and weight accounting are included in Table 10.

Table 10: Engineering model of cost and mass for autonomous glider design concept.

Component	Description	Unit cost (\$)	Units	Subtotal (\$)	Component weight (lb.)
Hull ¹	4.5 in. OD Sch. 40 PVC pipe	30 per 5 ft. length	1	30	5.4 ⁴
Nose and tail cones ¹	6 in. PVC rod	100 per ft.	1	100	2.6 ⁴
	O-rings, 4.5 in. OD multipurpose	3 per 10	1	3	0.1 ⁵
Wings ¹	1" x 4" PVC bar	20 per ft.	4	80	8.9 ⁴
Ballast tanks ¹	syringes 140 ml	13	8	104	1.0 ⁵
Motors ²	60 RPM DC servo motors	40	4	160	2.0
Motor controller ²	Arduino Mega	45	1	45	0.1
Batteries ³	NiMH Battery 12 V 20 Ah	240	1	240	7.3
CPU ²	Arduino Uno	25	1	25	0.1
Information storage ²	MicroSD card with shield and adapter	30	1	30	0.1
Temperature sensor ²	Waterproof temp sensors	10	1	10	0.1
Pressure sensor ²	Waterproof pressure sensor	60	1	60	0.1
Conductivity sensor ²	EZO Conductivity circuit	200	1	200	0.1
GPS antenna ²	GPS Antenna	60	1	60	0.1
INS ²	Triple axis accelerometer	50	1	50	0.2
Total				1197	28.2 lb (12.8 kg)

¹www.mcmaster.com, ²www.sparkfun.com, ³www.batteryspace.com, ⁴Calculated using SolidWorks model, ⁵No data available; estimated.

Note: If the weight for the component was specified to be less than 0.1 lb., 0.1 lb. was listed to account for the component weight any ancillary equipment while still observing significant digits.

An initial sketch was made, laying out the general form and dimensions. An effort was made to keep the design as simple as possible in order to reduce cost and avoid advanced manufacturing requirements. The overall size was selected toward the upper limit of the target range while remaining man-portable to ensure that all necessary components would fit within the hull and to maximize the glider speed. Drag is reduced for long, slender objects as compared to stout ones and a larger size means a larger displacement of the center of gravity compared with the center of buoyancy allowing for greater acceleration and speed.

In order to predict the cost, an estimated bill of materials was created including all likely components and their approximate costs (Table 10). Again, specific components were not selected at this stage, thus prices were rounded to represent an anecdotal average value of available components. The bill of materials from SeaQPR 2.0 was used as a starting point, which itself was taken from Teledyne Webb Research's Slocum Glider.

When all the component costs were added up, the grand total came out to approximately \$1,200. The most expensive components were the batteries (\$240) and the conductivity sensor (\$200) followed by the motors (\$160). This figure is above the target value of \$1000, but not prohibitively so. Detail design could involve system optimization which may reduce the size and number of components. Compared with Prof. Smith's current unit cost of \$15,000, the proposed glider is still a comparative bargain.

When all the component weights were added up, the corresponding total mass was 12.8 kg (28.2 lb.), well under the target value of 25 kg. The wings (8.9 lb.), batteries (7.3 lb.), and hull (5.4 lb.) were the heaviest components. Again, optimization in the detail design process may provide the opportunity to further reduce the overall mass, however, this prototype would be well within the target range, as is. For reference, SeaQPR 2.0 weighted approximately 40 lb. (18.2 kg). In fact, in order to be neutrally buoyant, 12 lb. of ballast would need to be added (SeaQPR 2.0 added approximately 10 lb.), which would bring the total weight to approximately 40 lb. (18.2 kg), still within the target value. The additional ballast could be supplied using additional batteries, providing additional endurance. A 10 Ah battery was found, which weighs 3.5 lb. and costs approximately \$100. Thus, an additional 30 Ah capacity could be added (one additional 20 Ah battery plus one 10 Ah battery for a total of 50 Ah), costing an

additional \$340 and increasing the system weight by 10.8 lb. This would reduce the required ballast to approximately 1.5 lb. Additional components or hull modifications could be made during detail design in order to minimize deadweight (ballast) and maximize functionality.

In order to predict the remaining four ECs: samples stored/transmitted, search area, search rate, and area coverage, a mathematical model of the system was built and is included in Appendix D.

At the detail design stage, a fully dynamic model would be appropriate. This would require determination of a number of specific parameters such as motor RPM, syringe plunger velocity, longitudinal wing position, etc. However, at the conceptual design stage, a reasonable estimate of performance is sufficient. Thus, for the sake of estimation, a popular symmetrical airfoil shape was selected, the NACA 0012 airfoil (Figure 24).

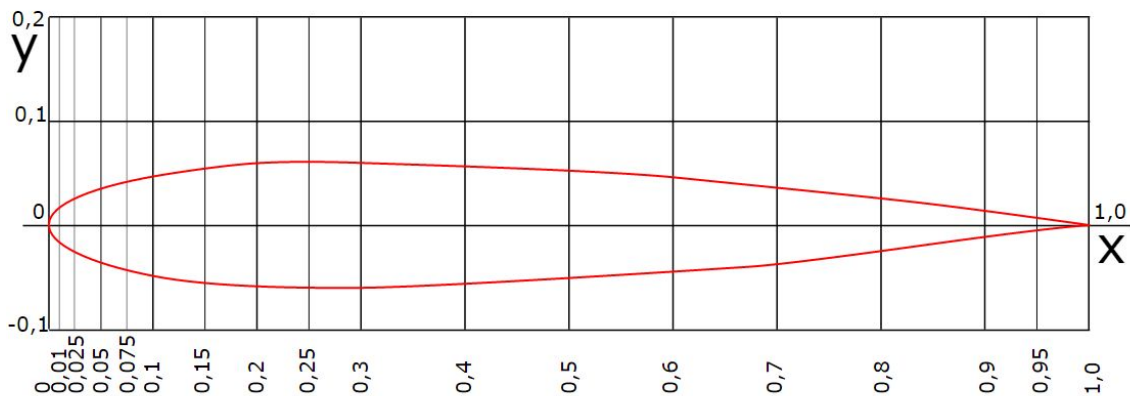


Figure 24: the NACA 0012 symmetrical airfoil²³.

Gliders operate by drawing in water in the nose, which causes them to become heavier and also shifts the center of gravity forward resulting in forward motion. As the glider traverses a sinusoidal path (Figure 4), it speeds up as it dives, reaching a maximum velocity at the deepest depth, and slows as it climbs, reaching a minimum velocity at the shallowest depth. The dive angle of the Slocum Glider is small, on the order of 5° - 7° ²⁴. This likely provides two benefits. First, smaller oscillations are more readily controlled.

²³ NACA 0012 airfoil, Wikipedia, https://upload.wikimedia.org/wikipedia/commons/c/c4/NACA_0012_Demo.svg, accessed September 11, 2015

²⁴ Paul Simonetti, SLOCUM GLIDER: Design and 1991 Field Trials, Webb Research Corp. contract report, Woods Hole Oceanographic Institution, Contract No. N000014-90C-0098, <http://www.webbresearch.com/pdf/SlocumGlider.pdf>, accessed September 11, 2015

Second, small pitch angles require smaller changes in ballast, which use less energy (lower operating time and lower shaft speed which equate to lower overall energy use). Looking at the lift vs. angle of attack plot for the NACA 0012 airfoil (Figure 25), the maximum lift coefficient is achieved at 16° angle of attack. This was used as a basis for selecting the maximum dive and climb angle of the glider with the understanding that they Reynolds number depicted in the figure was much higher than the one anticipated for the glider, and that the likely angle of attack corresponding to the maximum lift coefficient is likely lower.

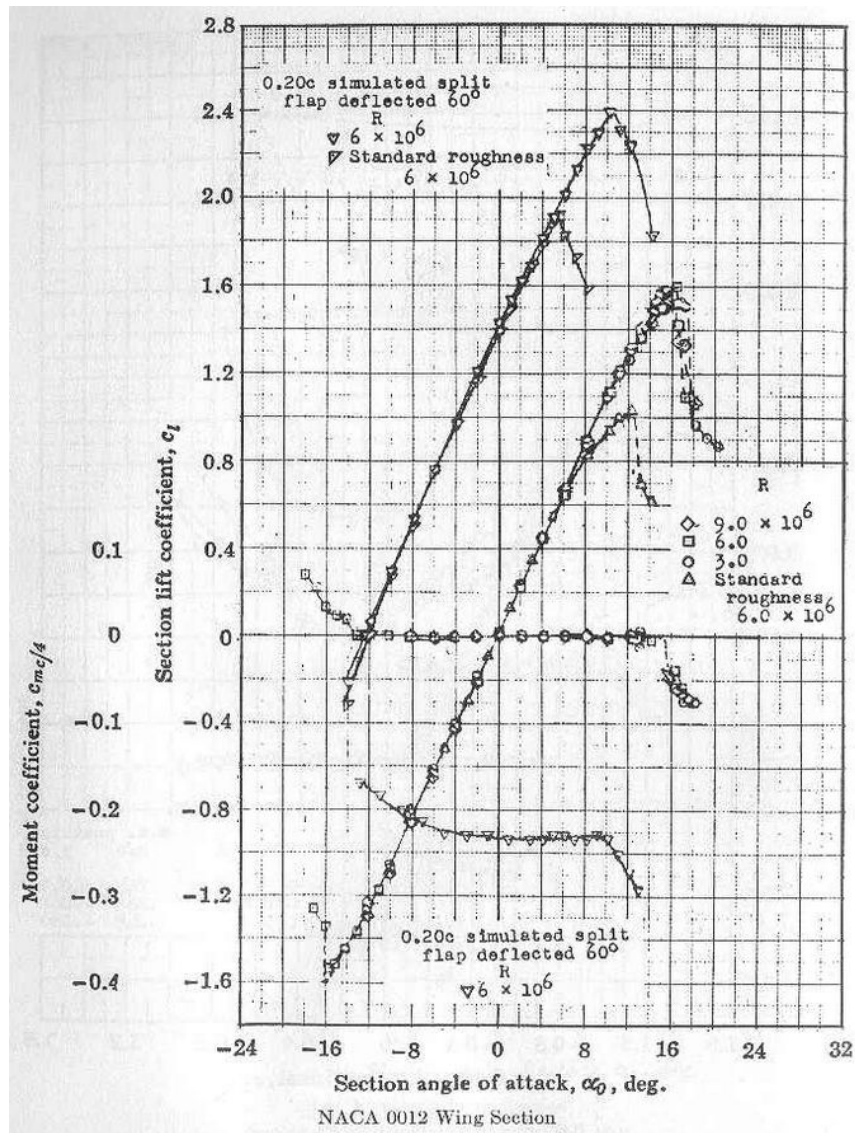


Figure 25: Section lift coefficient as a function of angle of attack for a NACA 0012 airfoil²⁵.

²⁵ Ira H. Abbott, A.E. Von Doenhoff, Theory of Wing Sections: Including a Summary of Airfoil Data, Courier Corp. Dover, Mineola, 1959, pg. 462.

The linear wave equation (Equation 4) was used to plot the glider's traverse path through the water (Figure 26a).

$$y = a \cos(kx) \quad (4)$$

where y is the vertical position (depth) in m, a is the traverse path amplitude in m, k is the wave number in m^{-1} and x is the horizontal position in m. Again referencing Nautical Chart 12282 *Chesapeake Bay: the Severn and Magothy Rivers* an anecdotal average of approximately 3 m (10 ft.) was selected for the height of the water column. The amplitude of the glider oscillation was estimated to be 1.25 m (2.5 m from the shallowest point to the deepest point) to preclude surfacing or contacting the seafloor. The wave number was determined by limiting the maximum value of the derivative of the function to 16° thus ensuring the pitch angle of the glider never exceeds this value. The corresponding wave number is 0.3975. The corresponding wave length (i.e. the horizontal distance over which the wave repeats) is $2\pi/k$ or 15.8 m.

According to the initial prototype research conducted on the slocum glider²⁶, for a pitch angle of 16° , the corresponding velocity for their glider was approximately 0.1 m/s. Even for their advanced, second generation gliders, the average horizontal velocity was around 0.2 m/s. According to the Slocum G2 Glider datasheet, the average horizontal speed with the buoyancy engine is 0.35 m/s²⁷. This provides a ballpark estimate of what should be expected. It seems most reasonable to assume comparable performance of initial prototypes, thus it was assumed that the average horizontal velocity of the glider would be approximately 0.1 m/s. Again, it is understood that this value could be calculated with a detailed dynamic model, however, at the conceptual design stage, actual performance of similar, tested benchmarks assumed to be more accurate.

²⁶ Paul Simonetti, SLOCUM GLIDER: Design and 1991 Field Trials, Webb Research Corp. contract report, Woods Hole Oceanographic Institution, Contract No. N000014-90C-0098, <http://www.webbresearch.com/pdf/SlocumGlider.pdf>, accessed September 11, 2015

²⁷ Webb Teledyne Research, Slocum G2 Glider datasheet, http://www.webbresearch.com/pdf/Slocum_Glider_Data_Sheet.pdf, accessed September 11, 2015

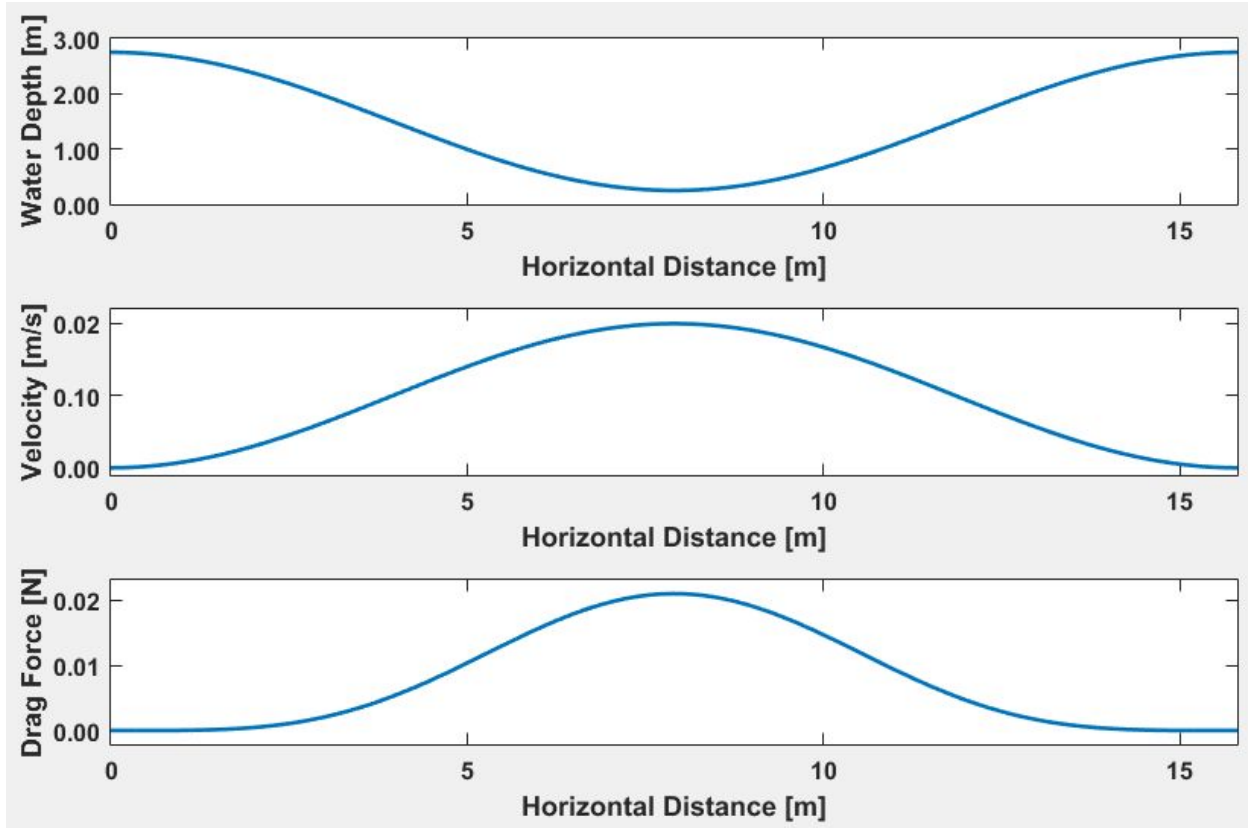


Figure 26: a) (top) the traverse path profile of the glider, b) (middle) the velocity along the glider path, and c) (bottom) the drag force.

The number of samples stored and/or transmitted, the search area, and the area coverage all depend on the vehicle endurance, or how long the vehicle can operate on a single battery charge. In order to determine this, an electrical load analysis was conducted. It was assumed that all the sensors and processors converted battery energy at a constant rate. It was also assumed that the electric motors ran for 10% of the traverse period at each peak and trough (20% total), approximately 16 sec., which is on the same order of magnitude as was demonstrated by the previous team. Assuming a 50 Ah battery pack, as previously described, and the appropriate component voltages with the rated current draw indicated on each component's respective data sheet, the glider was predicted to operate for 85 hrs. Given the assumed velocity of 0.1 m/s, this would yield a horizontal track length of 30.5 km. Assuming a search swath of 2.5 m on either side of the traverse path and a creeping line search pattern with 5 m track spacing, the search area would be 152,350 m² (0.15 km²) and the search rate would be 0.5 m²/s.

With a forward velocity of 0.1 m/s it was assumed reasonable that a turn radius is less than the GPS resolution of 5 m, thus the area coverage would be 100%. This is

corroborated by field testing described in Simonetti 1991²⁸, in which a glider operating at 0.2 m/s had a turn radius of 7-13 m. It was assumed that a slower glider should be able to turn with a tighter radius. For reference, however, a turn radius of 7 m results in 84% area coverage and a 13 m turn radius results in 58% area coverage, both above the 50% target value.

The number of samples stored and/or transmitted is a function of the resolution of the GPS as the sampling rates for all of the sensors are at least on the order of 1 Hz or more. In general, the GPS modules surveyed had a resolution of 5 m, which means that a georeferenced temperature, pressure, and conductivity datum point can be taken at that resolution or larger, yielding approximately 6,100 samples per battery charge. The resulting predicted performance values are summarized in Table 11.

Table 11: Top six Engineering Characteristics with predicted performance values for the *Trapped Beneath the Sea: Part I* autonomous glider design and targets included for comparison.

Rank Order	Engineering Characteristics	Units	Direction of Improvement	Predicted Performance	Target
1	cost	\$USD	↓	1,550	1,000
2	samples stored/transmitted	#	↑	6,100	20,000
3	search area	m ²	↑	152,350	33,000
3	search rate	m ² /s	↑	0.5	12
5	area coverage	%	↑	100	50
6	mass	kg	↓	21	25

As shown, the glider design is predicted to be more expensive than the target range, but detail design could bring this down to within range. Also, compared with current methods, this cost is quite reasonable. The number of samples stored/transmitted is smaller than the target range, but the limiting factor is the range of the vehicle and the resolution of the sensor. With solid state memory capacity currently available, the number of samples that can be stored shouldn't be an issue. The predicted search area is much higher than the target, approaching what would be required to search the search area as initially defined. This is due, in large part, to the additional battery capacity which could be used to displace necessary ballast. The search rate for the

²⁸ Paul Simonetti, SLOCUM GLIDER: Design and 1991 Field Trials, Webb Research Corp. contract report, Woods Hole Oceanographic Institution, Contract No. N000014-90C-0098, <http://www.webbresearch.com/pdf/SlocumGlider.pdf>, accessed September 15, 2015

glider is very slow which is largely a function of its low horizontal speed. This appears to be true for glider designs in general and may be the critical weakness of the design. Area coverage is predicted to be high, near 100%, but highly dependent on turn radius and the ability of the glider to stay on the defined search path, which may be difficult or impossible in anything greater than moderate currents. The mass is below the target range but close, largely the result of adding additional batteries. Again, as a preliminary design, the glider is likely overbuilt. Design optimization conducted during detail design could reduce this.

Address of Constraints

This system is potentially autonomous, but the control systems architecture will have to be fairly detailed to control the pitch movement, follow the search track, and avoid obstacles. Thus, it potentially meets the first constraint although the complexity of the system should be taken into consideration during design selection.

No additional codes, regulations, or standards were identified after an additional search, thus there are no obvious restrictions on testing and use. There is a strong precedent that AUVs should be considered vessels in the eyes of the law, but due to the size of this vehicle, no additional regulations apply. However, prudence would suggest having spotter boats operating in the vicinity to warn river traffic of ongoing testing.

The design is torpedo-shaped, which may suggest a malevolent function to some. However, prior to field testing, perhaps the design could be painted a definitively benign color such as fluorescent orange. It should also be marked with a message stating what its function is and to whom it belongs.

An effort should be made, prior to field testing, to ensure the design form suggests quality. Craftsmanship should be evident and markings should be professional such that if someone should find the prototype they would be impressed by the work of the student design team. As currently realized, the design form certainly does not suggest *unprofessionalism* and is therefore likely to satisfy this constraint.

2.3.2 “Swept Away” - trolling for oceanographic data

The second design concept is more unorthodox. It was developed independently during team brainstorm as a means of creating a very large sampling “rake” that could be towed behind a research vessel. The idea is to dramatically reduce the number of passes made by a research vessel by allowing scientists and researchers to take samples over a much larger area in a much shorter amount of time. Additionally, all samples could be georeferenced using a single position fix from the research vessel, reducing the amount of equipment necessary to conduct the survey.

After further research it was learned that such a setup is already in use by fishermen for open water trolling (Figure 27). The primary mechanism for this system is the planer board (Figure 28). The design concept would work similarly, except the fishing rig would be replaced by conductivity, depth, and temperature (CDT) sensors. A side-scan sonar system could also be used to provide bathymetry information.

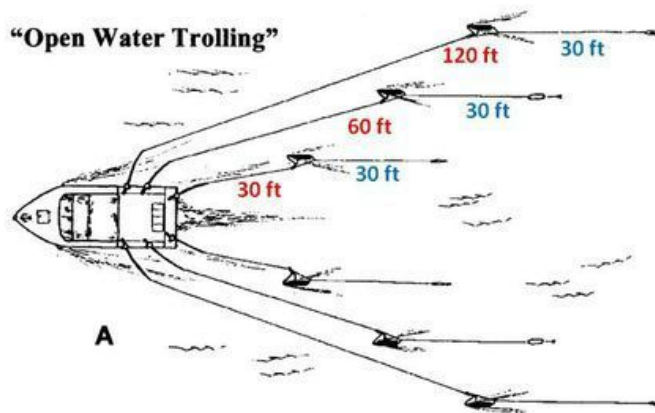


Figure 27: Open water trolling technique used by fishermen to place multiple fishing lines in the water from a single vessel²⁹.

²⁹ Planer Boards, Chitown-Angler, http://www.chitown-angler.com/2fish/albums/userpics/10391/Planer_Board_Presentation.jpg, accessed September 12, 2015



Figure 28: a) an example planar board used for trolling³⁰ and b) three planar boards in use during trolling operations³¹.

The *Swept Away* design concept (Figure 29) adapts the planar board fishing troller design, replacing the fishing tackle with sensors. The design features a small boat such as a RHIB, the type currently used for non-autonomous oceanographic studies and possessed by the USNA Waterfront Readiness Department.

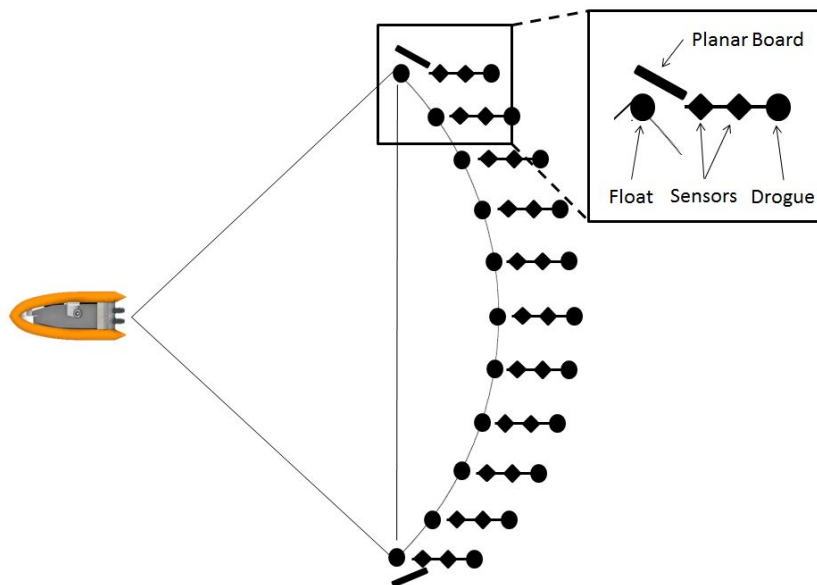


Figure 29: *Swept Away* design concept using a planar board trolling system as a model, replacing fishing tackle with Conductivity, Temperature, and Depth (CTD) sensors. The RHIB is shown traveling from right to left.

³⁰TX-22 Special, Erie Outfitters, <http://erieoutfitters.com/index.php?cPath=72>, accessed September 12, 2015

³¹ Trolling with Planar Boards for Walleye, Fishidy Blog, <http://blog.fishidy.com/wp-content/uploads/2015/04/planer-boards-in-water.jpg>, accessed September 12, 2015

The system would be deployed from a rig structure attached to the boat similar to what might be used for waterskiing, meant to hold the towing gear above the outboard motor(s).

As the boat is started and accelerated, the rig is payed out. The water flow over the planar boards creates lift, causing them to move perpendicular to the path of the vessel. If a spread of something on the order of 100 m could be achieved, the time required to make observations over a wide area would be dramatically reduced.

To turn, the rig could be partially reeled in or, if space allows, the vessel could maneuver in a manner similar to a Zamboni machine which is used to refresh the surface of the ice in an ice rink (Figure 30). The operator would have to be cognizant of surface obstructions that could potentially be tangled in the rigging, but the cables could be made to ride above the surface of the water at a height sufficient to clear many of the typical-sized local buoys.

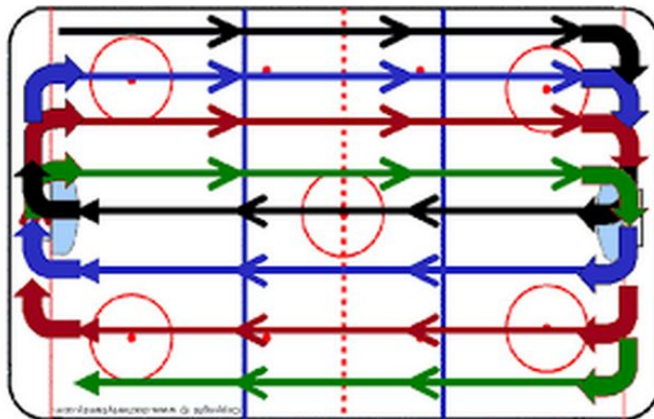


Figure 30: The wide path described by a Zamboni machine is it refreshes the surface of the ice in a skating rink³².

The measurements would be georeferenced using a single GPS module by knowing the position of each of the sensors relative to the surface vessel. This, in turn, could be achieved using a camera fixed to the vessel along with flags on each of the floats. A function could be developed that would take the images and tow rope speed as inputs, identify the relative position of all of the flags, and translate that into position data for each of the sensor tethers. Beneath the floats,

³² Farming Simulator, Reddit (web page blocked access to primary source), https://www.reddit.com/r/farmingsimulator/comments/38atrv/found_a_faster_way_to_spray_my_fields/, accessed September 17, 2015.

the tether could be rigid and equipped with an inclinometer (three-axis accelerometer), shown in Figure 31, to provide more exact position if greater position resolution is required.

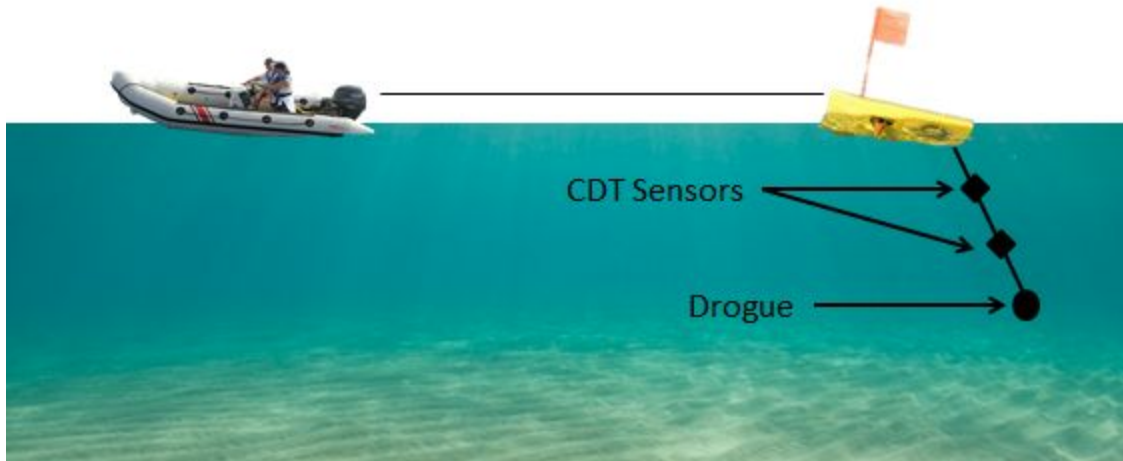


Figure 31: A simplified schematic (right view) depicting the surface vessel towing the sensor array with the sensors extending down into the water column^{33, 34}.

Design Performance Modeling

With regard to system cost, it was assumed that the organization wishing to make oceanographic observations would have access to a small surface vessel such as a RHIB or dinghy. For example, both CDR Gish and Prof. Smith would have access to the vessels managed by USNA Waterfront Readiness and perhaps even the Oceanography Department. Although the cost of the boat and motor are not included in the total design cost, the fuel cost should be. The cost of fuel is a function of the price of fuel as well as the amount required, both of which are difficult to estimate with great accuracy. According to www.waterwayguide.com, the current price for fuel at the Annapolis City Marina is \$3.15 per gallon. The amount of fuel consumed varies greatly with a variety of factors including hull size and shape, speed, and the drag of the rig in the water. Based on anecdotal information viewed online, an estimation of 1 L of fuel per nm was assumed. The refined search area (College Creek) would require very little fuel. Thus, the original search area (the Severn River between the Severn River Bridge and Trident Light) was used for purposes of estimation. Using the same scheme of

³³ Image Gallery, Flower Garden Banks National Marine Sanctuary, http://flowergarden.noaa.gov/image_library/expedition/coralspawn08/emmatracyrhilb.jpg, accessed September 18, 2015

³⁴ Underwater Natural History Photography, Seaframes.com, <https://seaframes.files.wordpress.com/2012/12/life-recycles-3.jpg>, accessed September 18, 2015

estimating the size of the search area used in Section 1.7.8 (Figure 20), it was estimated that with an array width of 100 m, five passes along the length of the river would have to be made, a distance of approximately 9.5 nm. At 1 L of fuel consumed per nm, the total required fuel would be approximately 9.5 L (2.5 gal) costing approximately \$30. Even doubling the consumption rate, the fuel price would be small in comparison to the total cost of the system.

The amount of line required for this design was estimated assuming an array width of 100 m and a 45° spread angle θ , shown in Figure 32. Although no empirical evidence was found, 100 m seems to be the anecdotal limit based on the online testimony of experienced fishermen³⁵.

The catenary (i.e. the arc described by the line connecting the planar boards and holding the sensors) was calculated using the following expression:

$$y = a \cosh(x/a) \quad (5)$$

where y is the vertical coordinate in m, x is the horizontal component in m, and a is the catenary shape factor also in m for dimensional consistency, a function of the drag on the system. The greater the drag, the smaller the shape factor. The drag on the connecting line, including the floats, sensor tethers, and weights or drogues was assumed small in comparison to the lift generated by the planar boards, thus the shape factor was assumed to be on the order of 1 (i.e. the catenary was assumed to be fairly shallow, as approximated in Figure 32). All calculations, including those required to determine the array towline length, are included in Appendix E. The total length of line predicted is 246 m.

In order to get a rough estimate of the size of the planar boards required, an estimate of the drag of the array was required. In order to estimate the drag on the cable itself, Morison's Equation for drag on slender cylinders was used. However, if it is assumed that the system is at steady state and the curvature of the cable is small, the equation reduces to the standard drag equation shown in Equation 6:

$$D = 1/2 \rho C_d A U^2 \quad (6)$$

³⁵ Using Planar Boards to Spread Your Baits, Scheels Community, <http://www.scheelscommunity.com/2013/07/16/using-planer-boards-to-spread-your-baits/>, accessed September 18, 2015.

where D is the drag force in N, ρ is the density of seawater in kg/m^3 , C_d is the drag coefficient is assumed to be 0.3 (circular rod in turbulent flow)³⁶, A is the frontal area of the line, and U is the flow speed.

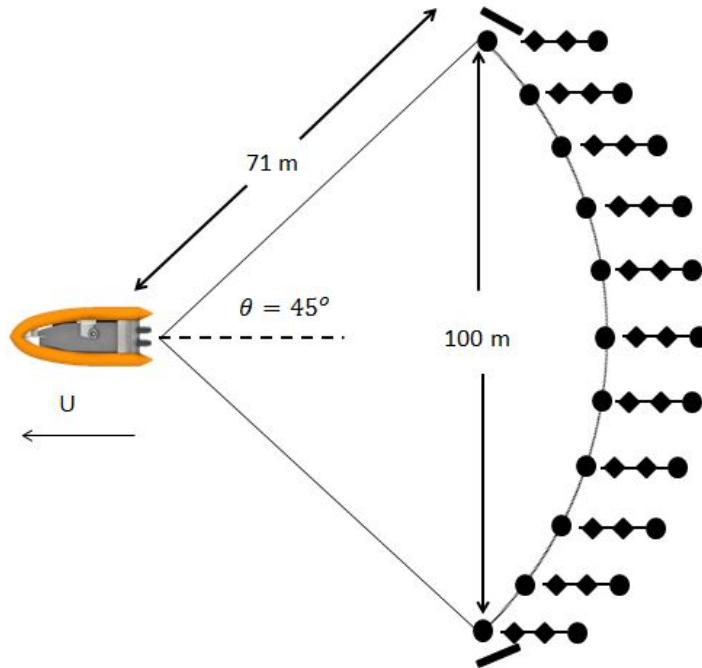


Figure 32: A simplified schematic (top view) depicting the surface vessel towing the sensor array with the sensors extending down into the water column.

The flow speed is also the cruising speed of the boat. Since planar boards are used for fishing the cruising speed should be fairly low, on the order of 1 to 2 kts (0.5-1 m/s). However, in order to maximize the search rate, the fastest possible boat speed should be used. The boat speed is limited, if not by the system drag, then by the sensor resolution. All sensors including the CTD sensors and GPS module have sampling frequencies on the order of 1kHz or above, thus this is not a limiting factor. A speed of 5 m/s was selected as a compromise between search rate and the array drag.

Additionally, it was assumed that the sensor tethers, aligned with the direction of flow, would be small, on the order of 1-2 lbf. (4.5 - 9 N) per tether. The estimated cable drag force is 4,550 N (approximately 1,000 lbf.) including the drag from the tethers.

³⁶ Yunus Cengel and John Cimbala, *Fluid Mechanics: Fundamentals and Applications*, McGraw Hill, New York, 2006, pg. 584.

The planar boards are essentially flat plates or kites. The lift coefficient for a flat plate is approximated by Equation 7:

$$C_L = 2\pi\alpha \quad (7)$$

where α is the angle of attack (the angle between the plane of the board and the direction of the boat during steady state operations) in radians. Similarly, the drag coefficient for a flat plate is approximated by Equation 8³⁷:

$$C_D = 1.28 \sin(\alpha) \quad (8)$$

The desired angle of attack is the one that maximizes lift while minimizing drag. Thus, the maximum value for C_L / C_D is 45° because the lift force is much larger than the drag force and the lift force is maximized at 45° . Thus, a freebody diagram showing the forces is included in Figure 33.

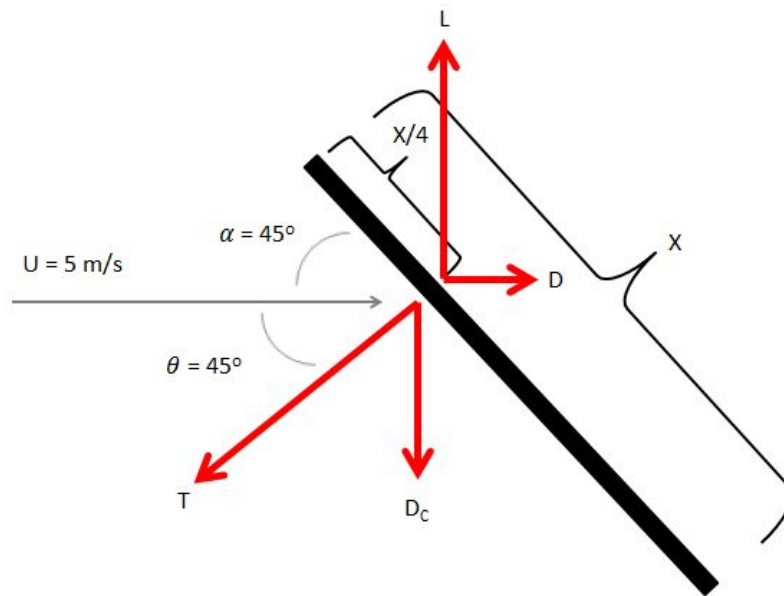


Figure 33: Freebody diagram of the planar board.

Again, assuming the catenary to be fairly flat (calculated on the order of 1°) and using the lift and drag approximations expressed in Equations 7 and 8, the required area of the planar board works out to be 0.0448 m^2 . Assuming a

³⁷ Kit Inclination Effects, National Aerospace and Space Administration, <https://www.grc.nasa.gov/www/K-12/airplane/kiteincl.html>, accessed September 18, 2015

streamwise to vertical aspect ratio of 2:1, following the look of existing planar boards, the submerged dimensions of the planar boards would need to be approximately 0.15 m by 0.30 m (approximately 6 in. by 12 in.). This seems small, especially when compared to the actual size of commercially available planar boards, the longest dimension of which being approximately 30 in (0.76 m), however, even if the boat speed was reduced by half and the required area quadrupled to compensate, the planar board dimensions would still only be 0.45 m by 0.9 m (18 in. by 36 in.) - not prohibitively large.

The pressure measured during oceanographic research observations is typically used to determine the depth at which the measurement was taken. In this case, if the tethers were rigid and fixed with inclinometers, the depth could be determined geometrically, thus alleviating the need for pressure sensors.

Unlike the other design concept, the *Swept Away* design allows for a little more space for equipment. A laptop computer could be used in lieu of one of the small CPUs as the data acquisition unit. It was assumed that the person or persons conducting the study could muster a laptop and thus it was not included in the overall accounting. This could also be useful for navigation of the search track pattern.

Also, Prof. Smith mentioned that bathymetry data would be appreciated. The *Swept Away* design could include a hull-mounted bathymetry sensor, but one was not included in this accounting.

It was imagined that all of the gear necessary to conduct observations, not including the laptop and side-scan sonar sensor, could be packaged in a Pelican Case that could be deployed easily just forward of the RHIB's transom, include a collapsible cable support structure, and facilitate easy deployment and recovery. This idea will be further explored in the detail design phase.

The system component costs and masses are estimated and summarized in Table 12. Compared to the other two designs, *Swept Away* is well beyond the target values of \$1,000 and 25 kg. However, the design could potentially provide much better measurement resolution at $\frac{1}{3}$ the cost mentioned by Prof. Smith during his initial interview as a benchmark for his current methods (\$15,000). Also, 200 lb. is a fairly large weight to maneuver into a small RHIB, however, the original target was based on lowering the design into the water from a kneeling position, which would not apply in this case. Moreover, many cases come with

wheels which would make it easy to move the equipment, and much of it could be divided and carried separately, reducing the weight of the equipment that would have to be carried at any given time.

The reason this design is so much more expensive than the other is the size (i.e. physical dimensions) of the design, the number of components, and the cost of each of those components. However, during detail design, further consideration could be given to optimizing the solution to minimize these. For example, Finding a conductivity sensor that was 50% of the price of the one found on sparkfun.com would reduce the total cost by approximately \$1,000.

The number of samples stored/transmitted, assuming a sample was taken every 5 m of travel of the boat, would be the track distance in m (in this case 17,500 m), divided by the GPS resolution, multiplied by the number of sensors (in this case 22, two per each of the 11 tethers), or approximately 77,000 samples. At the estimated 77000 samples, even with 64 bits per sample, would be on the order of 5 MB of storage capacity. Clearly, this is not a limiting factor. Factoring in multiple runs, data storage can be as large as a 16 GB Solid State Drive for less than \$50.

The energy requirements for the *Swept Away* system are for the single board computing required for the data collection and storage. It requires approximately 50-100 W to operate a standard laptop computer. For 6 hrs. of operation, that equates to 600 Whr (max), or 2.16 MJ of energy (1 Watt is equal to 1 Joule per second). As such, a set of rechargeable batteries that provides 2.16 MJ of energy is all that is necessary. Three 12 V lead acid batteries in parallel at 18 Ah (0.8 MJ each) is sufficient and will cost around \$120.

The data collection system is simplified by keeping all processing equipment on board the RHIB and running a zero-tension communication cable to the planar boards and the outermost sensor arrays and across the catenary. Two communication cables - one going down the length of each tow cable - could be used for redundancy. Each sensor will send data to the processing unit on the RHIB where the data is stored.

The search area is largely a function of the fuel tank size and was assumed as large as the original search area, 1,800,000 m². The search rate would then be approximately 500 m²/s, requiring a little over an hour to search the entire area. The area coverage would be approximately 100%, largely dictated by the ability of the driver to maintain track as the sensors are spaced at 5 m increments across the array.

The predicted performance of the *Swept Away* design are summarized in Table 13. As previously discussed, although the design concept performance with regard to the cost and mass Engineering Characteristics are well above target values, the high performance of the design with regard to the other ECs makes the *Swept Away* design very competitive.

Table 12: Engineering model of cost and mass for the towed array concept.

Component	Description	Unit cost (\$)	Units	Subtotal (\$)	Component weight (lb.)
Tow line ¹	3/16 OD polyester yacht braid	\$0.70 per ft.	300 m (985 ft.)	700	20 ²
Planar boards ³	Fiberglass covered foam board (30"x80")	\$50 per sheet	1	40	40
Tether floats ¹	Mast buoy	\$50	11	550	1 ²
Tethers (rods) ⁴	Fiberglass rod ¼" dia. 10 ft. length	10	5	50	1 ²
Weights ¹	Trolling weight 6 lbs.	\$30	11	330	66
Temperature sensor ⁵	Waterproof temp sensors	10	1	10	0.1
Sensor cable ⁶	3 conductor shielded	\$30 per 20 ft.	5	150	12
Inclinometer ⁵	3 axis accelerometer	\$14	11	155	1 ²
Conductivity sensor ⁵	EZO Conductivity circuit	200	11	2200	10 ¹
GPS antenna ⁵	GPS Antenna	60	1	60	0.1
Camera module ⁵	Camera module	35	1	35	0.1
Pelican Case	Case with wheels and protective foam	500	1	500	45
Total				\$4780	200 lb. (90.7 kg)

¹ www.westmarine.com, ² estimated, ³ www.precisionboard.com, ⁴ www.mcmaster.com, ⁵ www.sparkfun.com, ⁶ www.amazon.com, ⁷ www.pelican_case.com

Table 13: Top six Engineering Characteristics with predicted performance values for the *Swept Away* towed array design concept and targets included for comparison.

Rank Order	Engineering Characteristics	Units	Direction of Improvement	Predicted Performance	Target
1	cost	\$USD	↓	4,780	1,000
2	samples stored/ transmitted	#	↑	77,000	20,000
3	search area	m ²	↑	1,800,000	33,000
3	search rate	m ² /s	↑	500	12
5	area coverage	%	↑	100	50
6	mass	kg	↓	90	25

Address of Constraints

This system is clearly not autonomous. However, both CDR Gish and Prof. Smith were asked if the *Swept Away* would still be an acceptable design. The argument was made that the problem is not that the vehicles *must be autonomous* but that autonomous vehicles search while the researcher is doing something else, dramatically reducing the amount of time he or she is directly involved in data collection. If the entire search area could be observed in just over an hour using a system such as *Swept Away*, this would also dramatically reduce the required time. They both agreed that by this logic, it would be an acceptable solution.

There are codes governing the use of towing rigs by surface vessels, however, since the vessel is small (less than 8 m long) and engaged in non-commercial operations, these regulations do not apply, according to Title 46, Part 15 of the U.S. Code of Federal Regulations. However, prudence would suggest operators should follow rules similar to those used when towing people behind a boat (i.e. water skiing, tubing, etc.), including having a safety observer on the boat during survey operations and surveying only during daylight hours. Also, prudence would suggest that spotter vessels be used for testing.

This particular design does not bear much resemblance to a weapon, but in addition to painting components bright colors for safety and visibility, doing so will reduce the potential for onlookers to view operations with suspicion.

Similar to the previous design concepts, an effort should be made, prior to field testing, to ensure the design form suggests quality. Craftsmanship should be evident and markings should be professional such that if someone should see the prototype during operations they would be impressed by the work of the student design team.

2.4 Summary of Predicted Performance

The performance of each of the design concepts was predicted with respect to the Engineering Characteristics established in the previous stage of design. Those performance parameters are summarized in Table 14.

Table 14: Top six Engineering Characteristics with predicted performance values for each design concept and targets included for comparison

Rank Order	Engineering Characteristic	Units	Trapped Beneath the Sea: Part I (AUV - glider)	Swept Away (towed array)	Target Values
1	cost	\$USD	1,550	4,780	1,000
2	samples stored/transmitted	#	6,100	77,000	20,000
3	search area	m ²	152,350	1,800,000	33,000
3	search rate	m ² /s	0.5	500	12
5	area coverage	%	100	100	50
6	mass	kg	21	90	25

In addition to performing well with regard to the established Engineering Characteristics, each design must potentially satisfy the design constraints to be considered a viable solution. Table 15 summarizes the performance of each design with regard to the established constraints. Discussion with regard to the satisfaction of each constraint by each design concept was included at the end of each design concept section.

Table 15: The satisfaction of each of the design constraints for each of the design concepts.

Constraint	Trapped Beneath the Sea: Part I (AUV - glider)	Swept Away (towed array)
Operate autonomously	Yes	No, but approved by customer
Conform to all applicable codes, standards, and regulations	Yes	Yes
Does not look like a weapon	Yes	Yes
Reflect positively on the U.S. Naval Academy	Yes	Yes

As shown, both designs potentially meet all constraints with the exception of the *Swept Away* design not being autonomous. However, as previously stated, this was discussed with and approved by the customers.

2.5 Design Concept Selection

Once the performance was predicted for each design concepts, the concepts could be compared objectively using a weighted decision matrix. The weighting factors were taken from the *Importance Ranking* in room 5 of the House of Quality. A 5-point scale (0-4) was used to evaluate the performance of each design concept with respect to each EC. The weight factors were then applied to the ratings and summed for each of the designs as shown in Table 16.

The towed array design had the most points and was therefore deemed the selected design by a small but significant margin. The ratings were manipulated for each design to ensure the subjectivity of rating did not significantly impact design selection (i.e. rating a design a 1 versus a 2 in a heavily weighted category).

Consideration was also given to combining the best parts of each design (e.g. using an autonomous surface vessel to tow the array), but the towed array design was deemed sufficiently complex in scope for a single project.

Table 16: The weighted decision matrix showing the towed array design as the selected design.

			<i>Trapped Beneath the Sea: Part I</i> Autonomous Glider			<i>Swept Away</i> Towed Array		
ECs	Units	Weight Factor	Magnitude	Rating	Subtotal	Magnitude	Rating	Subtotal
cost	\$USD	0.1952	1,550	3	0.59	4,780	1	0.20
samples stored/ transmitted	#	0.1712	6,100	2	0.34	77,000	4	0.68
search area	m ²	0.1678	152,350	2	0.34	1,800,000	4	0.67
search rate	m ² /s	0.1678	0.5	1	0.17	500	4	0.67
area coverage	%	0.1575	100	4	0.63	100	4	0.63
mass	kg	0.1404	21	4	0.56	90	1	0.14
Total					2.62			2.99

2.6 Selected Design

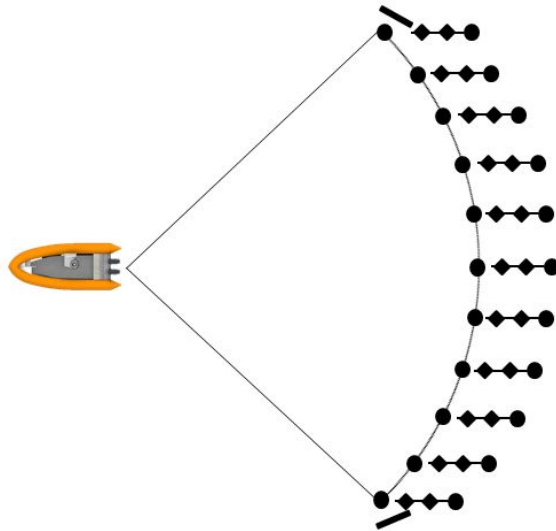


Figure 34: The Swept Away towed array design was selected for detail design.

The *Swept Away* towed array design, despite its considerable cost and mass, was selected by the team for detail design. To be prudent, the team reviewed their design concepts, analysis, and design selection process with the customers. Although the design was not what either expected, both agreed that they would be interested in seeing a detailed design and the preliminary testing of a prototype.

Appendix A - Preliminary Engineering Model of the System

%% Engineering Model Calculations

clear; close all; clc

% Calculations for estimating search speed, power required, and energy per
% unit distance track covered

% parameters

A = 1.8 * (1000^2); %search area, m^2

L = 10/2; %search resolution, m

t = 6 * 3600; %search time, s

% calculate the search velocity, in m/s

$V_e = A / (2 * L * t);$

%% Power consumed by AUV

% specifications taken from REMUS 100 spec sheet

% parameters

h = 0.7; %propulsion efficiency (guess)

r = 1025; %density of salt water, kg/m^3

D = 0.1; %drag coefficient (assumed long streamlined body)

d = 0.19; %AUV diameter

l = 1.6; %AUV length

S = pi*d*l; %surface area

H = 5; %hotel load (power used for vehicle functions other than propulsion)

V = 1.5; %AUV velocity, m/s

% calculate the total power consumed, in W

$P = (r * D * S * V^3) / (2 * h) + H;$

C = 1000*3600; %battery capacity for the REMUS 100, J

T = 22*3600; %system endurance, s

P_remus = C/T; %the power consumption, W

% P_remus is 45 W, which is corroborated by their spec sheet. It's much
% higher than the power requirement calculated above. Perhaps the drag
% coefficient is lower or the propulsion efficiency is higher.

%% Energy required per unit distance of track covered, E

% parameters

N = 1; %the number of vehicles used to cover the search area

% calculate the energy required per unit distance of track covered, in J/m

$E = ((r * D * S) / (2 * h)) * (V / N)^2 + (N * H) / V;$

% to cover the entire track of 156 km, the required energy would be:

```
E_total = E * 156000;
```

```
% that's a lot!
```

```
% calculate the number of batteries required
```

```
C_battery = 100; %assume 100 Ah battery capacity, converted to J
```

```
V_system = 12; %assume 12 V system
```

```
E_battery = C_battery * V_system * 3600; %battery capacity in J
```

```
N_batteries = E_total/E_battery;
```

```
% to search the entire area, we'd need 6 100 Ah batteries.
```

Appendix B - Agreement of Project Deliverables (Version 1)

Design Project Deliverables
Agreement between
USNA Student Design Team (“Chesapeake Baywatch”)
and Customers
Version 1

The purpose of this document is to clearly communicate expectations with regard to project deliverables between the student design team, faculty advisors, and the project customers. It is not intended to be a contract or any other legally-binding document.

In general:

We, the students, will give our best effort with the time and resources available with the intent of providing the customers with a design that will satisfy their requirements to the best of our understanding and abilities.

We, the faculty, will do our best to assist the students through the design process including helping them maintain a workable timeline, providing technical assistance when needed, and giving them access to resources as they are necessary and available.

We, the customers, understand that this is a student design project and an educational experience above all. The students must be allowed to make engineering design choices based on their own judgement. Failure, though the students, faculty, and staff will strive to ensure it is avoided, must always be an acceptable outcome.

In detail:

On Capstone Day, Wednesday, April 27, 2015, the team will provide the following:

A working prototype that is capable of autonomously traversing the area of College Creek between the footbridge and the corner of the sea wall as shown in Figure B1. It should be pointed out that this is a much smaller area than stated in the original requirements draft. However, it was agreed by all parties, that the reduced scope would provide a much more realistic chance for success while still providing a challenge and learning experience for the students.

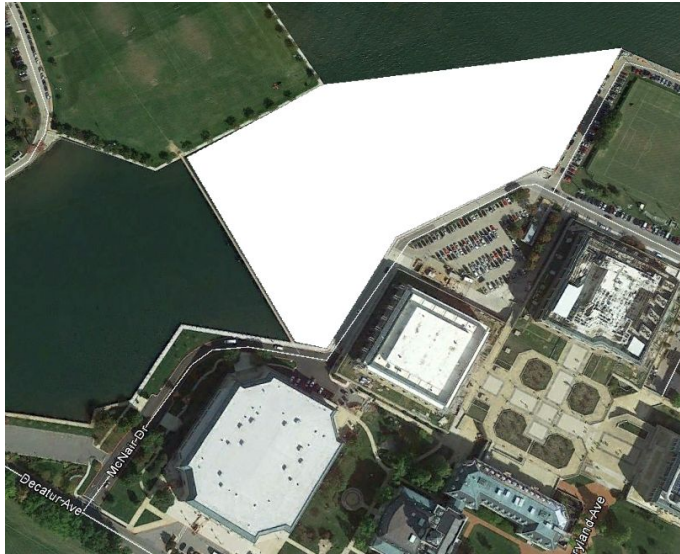


Figure B1: An overhead view of the revised search area including the area downstream of the pedestrian bridge to the line between the adjacent corners of the Hospital Point and Dewey Point seawalls.

The revised customer requirements and their associated engineering characteristics, including targets, are included in Table B1. Target values were calculated using the same analysis used previously, updated for the reduced search area.

Table B1: Revised Customer Requirements and Engineering Characteristics.

Customer Requirements	Engineering Characteristics	Units	Direction of Improvement	Rank Order	Target
Take measurements and make them available to the user	samples stored/ transmitted	#	↑	2	300
Be cheap	cost	\$USD	↓	1	1,000
Cover a specified search area in a reasonable time, autonomously	area coverage	%	↑	5	50
Cover a specified search area in a reasonable time, autonomously	search area	m ²	↑	3	33,000
Cover a specified search area in a reasonable time, autonomously	search rate	m ² /s	↑	3	9
Be man-portable and launchable	mass	kg	↓	6	25

Deliverables also include any intermediate prototypes requested as well as a copy of the Final Design Report.

Student Design Team:

LCDR Ethan E. Lust: *Ethan E. Lust, 4 SEP 15*

CDR John D. Stevens: *John D. Stevens, 4 SEP 15*

Faculty Mentor and Technical Advisor:

CAPT John P. Jones: *John P. Jones, 4 SEP 15*

Jacques-Yves Cousteau: *Jacques-Yves Cousteau, 4 SEP 15*

Customer(s):

CDR Andy Gish: *Andrew Gish, 4 SEP 15*

Prof. Joe Smith: *Joseph Smith, 4 SEP 15*

Appendix C - Team Charter

Team: Chesapeake Baywatch



Project Description: Autonomous Vehicle for Gathering Oceanographic Data in Littoral Regions

Name	Team Role	Cell Phone Number
Ethan Lust	Team Leader, Design Comm. Editor	757-636-8727
John Stevens	Safety Officer, Purchaser, TSD Liaison	123-456-7891
J.P. Jones	Team Mentor	USNA Chapel Crypt x1776
J. Cousteau	Technical Advisor	Aboard the Calypso ????

Weekly Meeting Schedule: W6, Rickover Hall, room 229

Conflict Resolution Statement: If there is a disagreement, we'll try to talk it out by identifying the source of conflict and discussing it. If we still can't come to an agreement, we'll bring the issue to CAPT Jones for arbitration. We will work to treat each other with respect, both professional and personal, at all times. Also, LCDR Lust will do whatever CDR Stevens says.

Personal Statements:

"Besides fulfilling the graduation requirement, I look forward to working on a real-world problem in an effort to help someone who needs it. I'm also interested in putting the education earned over the past several years to use. I think the experience of working in a team and also with customers and other professionals will provide valuable insight into the design process and how engineering design in the commercial world works." - Ethan Lust

"I'm just in it for the money." - John Stevens

Appendix D - Engineering Model of “Trapped Beneath the Sea: Part I” - the autonomous underwater glider

```
%% glider calculations

clear; close all; clc
% parameters
g = 9.81;           %gravitational constant, m/s^2

% calculate the traverse path
a = 1.25;           %amplitude of the traverse path, m
k = 0.3975;         %wave number, 1/m
lambda = 2*pi/k;    %wavelength, m
x = linspace(0,lambda,1000); %horizontal position of the traverse path, m
t = 0;              %time, s (set to 0 to look at the wave as a function of space only)
w = 1;              %wave angular frequency, 1/s (set to 1 because if t = 0 it doesn't matter)
h = 3;              %the height of the water column, m

y = h/2 + a.*cos(k*x + w*t); %vertical position of the traverse path, m

% plot the traverse path
% subplot(3,1,1)
% plot(x,y,'linewidth',2)
% xlabel('Horizontal Distance [m]')
% ylabel('Water Depth [m]')
% axis([0 x(end) 0 h])
% set(gca,'fontsize',12,'fontweight','bold')

% ensure that the maximum pitch angle, A_p, is less than 16 deg
i = find(x >= pi/2,1);
A_p = atand((y(i-1) - y(i))/(x(i-1) - x(i)));

% assume a mean velocity (from Simonetti 1991)
U = 0.1; %mean speed, in m/s, based on experimental data found in Simonetti, 1991

% if the mean speed is 0.1, then a sinusoidal velocity distribution must go
% between 0 and 2*U
v = U + U.*cos(k*x + w*t); %vertical position of the traverse path, m

% plot the velocity profile as a function of horizontal distance
% subplot(3,1,2)
```

```

% plot(x,v,'linewidth',2)
% xlabel('Horizontal Distance [m]')
% ylabel('Velocity [m/s]')
% axis([0 x(end) -0.01 max(v)*1.1])
% set(gca,'fontsize',12,'fontweight','bold')

% calculate the drag on the glider
C_d = 0.1; %estimated for a long, streamlined body from www.engineeringtoolbox.com
rho_w = 1025; %density of seawater, kg/m^3
Do_hull = 4.5 * convlength(1,'in','m'); %outside diameter of the hull, m
A_fontal = pi/4*Do_hull^2;
D = (1/2)*C_d * rho_w*v.^2*A_fontal;

% plot the drag
% subplot(3,1,3)
% plot(x,D,'linewidth',2)
% xlabel('Horizontal Distance [m]')
% ylabel('Drag Force [N]')
% axis([0 x(end) 0-0.1*max(D) max(D)*1.1])
% set(gca,'fontsize',12,'fontweight','bold')

% calculated the energy dissipated via drag
% pre-allocate memory for the line length and energy
c = zeros(size(x));
e = zeros(size(x));

% calculate the length of each line segment and the energy dissipated
for i = 1:length(x)-1 %the last line segment is negligible
    c(i) = real(sqrt((x(i)-x(i+1))^2+(y(i)-y(i+1))^2));
    e(i) = c(i)*D(i);
end

% calculate the overall line length
% since the sinusoid is very shallow, should be close to the horizontal
% wave length
l = sum(c);

% calculate the total energy required per meter of horizontal distance
% travelled, J/m
E = sum(e)/lambda;

% calculate the time period, s
T = lambda/U;

```

```

% calculate the energy required per meter travelled
% motors
% assume the motors run 10% of the time at each peak and trough
i_motor_no_load = 0.12;    %no load current, A
i_motor_stall = 1;        %peak load current, A
V_motor = 12;            %motor voltage, V
E_motor = 2*0.1*T*i_motor_stall*V_motor + (1-2*0.1*T)*i_motor_no_load*V_motor; %motor
energy per period, J

% motor controller
i_controller = 0.2;        %controller current, A
V_controller = 12;        %controller voltage, V
E_controller = i_controller*V_controller*T; %controller energy per period, J

% CPU
i_cpu = 0.2;              %cpu current, A
V_cpu = 12;              %cpu voltage, V
E_cpu = i_cpu*V_cpu*T; %CPU energy per period, J

% temperature sensor
i_temp = 0.0015; %temp sensor current, A
V_temp = 3.6; %temp sensor voltage; V
E_temp = i_temp*V_temp*T; %temp sensor energy per period, J

% pressure sensor
i_press = 0.0014; %press sensor current, A
V_press = 3.6; %press sensor current, V
E_press = i_press*V_press*T; %press sensor energy per period, J

% conductivity sensor
i_conductivity = 0.004; %conductivity sensor, A
V_conductivity = 3.3; %_conductivity voltage, V
E_conductivity = i_conductivity*V_conductivity*T; %conductivity sensor energy per period, J

% GPS antenna
i_gps = 0.042; %gps current, A
V_gps = 3.3; %gps voltage, V
E_gps = i_gps*V_gps*T; %GPS energy per period, J

% accelerometer
i_acc = 0.0036; %accelerometer current, A
V_acc = 3; %accelerometer voltage, V

```

$E_{acc} = i_{acc} * V_{acc} * T$; %accelerometer energy per period, J

% total energy estimate per sinusoidal cycle

$E_{per_wave} = E_{motor} + E_{controller} + E_{cpu} + E_{press} + E_{conductivity} + E_{gps} + E_{acc}$;

% battery capacity, J

$C = 50$; %total battery capacity, Ah

$E_{battery} = C * 12 * 3600$; %battery energy, J

$endurance = E_{battery} / E_{per_wave}$; %number of waves per charge

% total range

$range = endurance * lambda$; %the total horizontal distance traveled, m

% total time

$T_{total} = endurance * T / 3600$; %the total operating time, h

% glider mass

$m_{glider} = 12.8$; %mass of glider components from SolidWorks, kg

$V_{glider} = 425.66 * convlength(1, 'in', 'm')^3$; %volume of glider components from SolidWorks, in³

$\rho_{glider} = m_{glider} / V_{glider}$; %glider density, kg/m³

$F_b = \rho_w * g * V_{glider}$; %buoyant force, N

$B = (F_b - m_{glider} * g) * convforce(1, 'N', 'lbf')$; %ballast weight, lbf

% search area

$resolution = 5$; %gps resolution on either side of the search path, m

$search_area = range * resolution * 2 / (1000^2)$; %search area, m²

% search rate

$search_rate = resolution * U$; %search rate, m²/s

% coverage

% assume 100 m track width with 13 m resolution

$track_length = 100$;

$turn_radius = 13$;

% estimate using rectangles with dimensions of track length by resolution

$coverage = (track_length * (turn_radius + resolution) - (turn_radius - resolution) * (track_length - resolution)) / (track_length * (turn_radius + resolution))$

% number of samples per charge

$n_samples = range / resolution$;

Appendix E - Engineering Model of “Swept Away” - the towed array

```
%% Swept Away - trolling for data
% panel board design calculations

clear; close all; clc

% parameters
rho_w = 1025; %seawater density, kg/m^3

%# calculate the line length
theta = 45; % tow line spread angle, deg.
array_width = 100; %array width, m
towline_length = sqrt(2)*array_width/2^2; %two tow lines, m

a = 1; %catenary shape factor
x = linspace(-0.5,0.5,1000); %normalized distance between planar boards
y = a*cosh(x/a)-a; %corresponding horizontal positions
x = x.*array_width; %dimensional distance between planar boards, m
y = y.*array_width; %dimensional horizontal positions, m
gamma = tand(abs(y(2) - y(1))/abs(x(2) - x(1)))

% verify catenary
% plot(x,y)
% axis equal

catenary_length = sum(sqrt(diff(x).^2 + diff(y).^2)); %catenary length, m
line_length = towline_length + catenary_length; %total length of line needed, m

% fuel estimation
fuel_price = 3.15; %price per gallon of fuel, $
fuel_rate = 1; %fuel consumption rate per nautical mile, L/nm
L = 1500 + 500 + 1500; %the length of the search area as outlined in section 1.7.8 of the report
W = 500; %the width of the search area
search_length = L*W/array_width/1852; %the search path length, nm - 1 nm = 1852 m
fuel_volume = search_length * fuel_rate;
fuel_volume_gal = fuel_volume/3.79;
fuel_cost = fuel_price * fuel_volume;

% calculate cable drag
```

```

C_d = 0.3; %drag on a cylinder in turbulent flow
U = 5; %boat speed, m/s
D = 7/16 * convlength(1,'in','m'); %line diameter, m
A = D * catenary_length; %frontal area, m^2
cable_drag = 0.5 * rho_w * C_d * A * U^2;

n_tethers = 11; %number of sensor tethers
sensor_drag = 9; %sensor drag, N
array_drag = n_tethers * sensor_drag + cable_drag; %total array drag, N

%% calculate lift vs drag on planar boards
clear C_d
alpha = linspace(0,pi/4,1000);
C_l = 2*pi*alpha;
C_d = 1.28 * sin(alpha);
LoverD = C_l./C_d;
[LoverD_max iMax] = max(LoverD);
alpha_max = alpha(iMax)*180/pi;
subplot(3,1,1)
plot(alpha,C_l)
% xlabel('Angle of Attack [rad]')
ylabel('Coefficient of Lift')
subplot(3,1,2)
plot(alpha,C_d)
% xlabel('Angle of Attack [rad]')
ylabel('Coefficient of Drag')
subplot(3,1,3)
plot(alpha,LoverD)
xlabel('Angle of Attack [rad]')
ylabel('C_l/C_d')

%% calculate the forces on the planar board
alpha = 45; %
theta = 45;
gamma = 1;

A_guess = 0.0448;

% sum the forces in the x (streamwise) direction
Cd = 1.28*sin(alpha);
D = 0.5 * rho_w * Cd * A_guess * U^2;
Dcx = array_drag/2*sind(gamma);
Tx = D + Dcx;

```

```
% sum the forces in the y (vertical) direction
Cl = 2*pi*alpha*pi/180;
L = 0.5 * rho_w * Cl * A_guess * U^2;
Dcy = array_drag/2*cosd(gamma);
Ty = L - Dcy;
err = abs(Tx-Ty);
T = sqrt(Tx^2 + Ty^2);

X = sqrt(A_guess/2);
Y = 2*X;

%% calculate the number of samples
n_samples = search_length * 1852 / 5 * 22;

search_area = 1800000;
search_time = search_length * 1852 / U;
search_rate = search_area / search_time;
```