Autonomous Underwater Vehicle

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Team Number: MEM-28

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ABSTRACT

Autonomous Underwater Vehicles (AUVs) have many applications ranging from submerged pipeline inspection and maintenance to mapping and clearing mine fields. The purpose of this project is to design and construct an AUV capable of navigating in 3 dimensions, and perform elementary autonomous tasks such as obstacle detection and avoidance. The AUV would operate in shallow water (depths of 20 ft or less). It would be suited to applications such as ship hull inspection, bridge inspection, mapping, and photography in shallow waters. This project will provide a platform for future development of AUVs at Drexel, namely the gradual addition of better sensing and navigating capabilities.

The complete design for this robot requires construction and integration of several mechanical and electrical sub-systems. A propeller driven mode of locomotion coupled with a ballast system will allow the robot to navigate in 3 dimensions and fix its position (i.e., "hover" in one spot). A communication scheme will be implemented to operate the vessel to depths of 20 ft with an operational radius of 15 ft. A sensor suite comprised of accelerometers, a compass, and transducers will estimate the robot's orientation and detect obstacles in its path. The robot will require regulated and properly protected power supply and electronics systems. All individual components and subsystems will be tested on land. Following integration, the completed system will be tested in water, with the objective of demonstrating navigational and obstacle detection capabilities. This process will be directed at discovering design tradeoffs and areas where future research and development are needed.

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1.0 PROBLEM STATEMENT

Like submarines, Autonomous Underwater Vehicles (AUV) operate underwater. Unlike submarines they are small, unmanned, and often tele-operated. While development of AUVs was fueled primarily by military applications such as mine detection and ocean mapping, AUVs are "increasingly becoming viable for commercial ventures such as seabed surveys, oceanographic data collection, offshore oil and gas operations." [1] AUVs have been employed to inspect pipelines, map and clear mine fields, and place communication cables.

Many universities are involved with AUV research, producing multifaceted robots capable of a wide variety of applications. To date, Drexel University has produced only one underwater robot with limited functions [2]. One of the objectives of the project is to increase this arsenal and foster future research in this field at the University. To this end, an AUV of approximate dimensions 24" x 12" x 6" will be designed and constructed. It will be capable of navigating in three dimensions and performing simple autonomous tasks such as obstacle detection both above and below the water. Along with object detection, the robot will have the ability to estimate its position and orientation accurately, and stay in a fixed position through neutral buoyancy. The design will be directed at shallow water applications, at depths of 20 ft or less with an operational radius of 15 ft at maximum depth (see Figure 1). Applications for a robot such as the one proposed include hull inspection, bridge inspection, mapping of shallow waters, and photography in shallow waters.

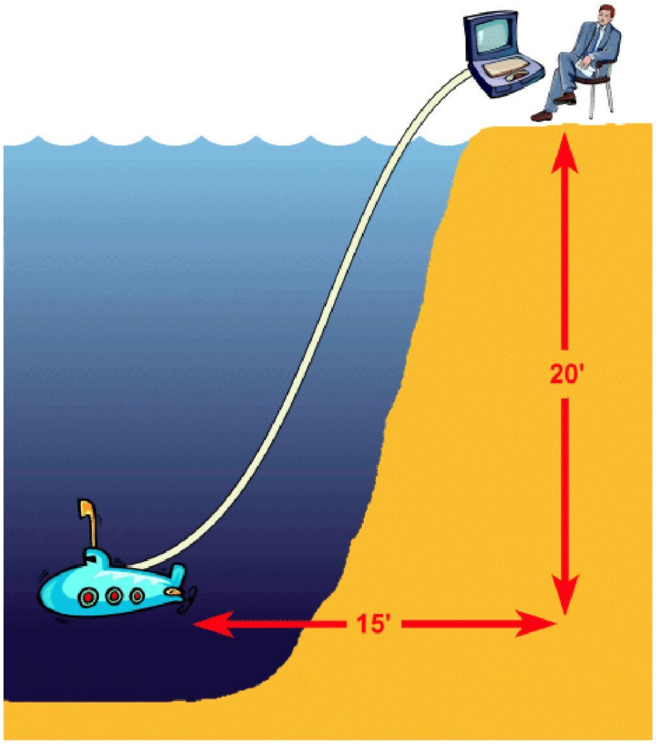

Figure 1
Operational radius of 15 ft and depth of 20 ft

2.0 METHOD OF SOLUTION

The design and construction of the robot can be split into several sub-systems. These areas would be Mechanical, Communications, Sensor Suite, and Controls as discussed in greater detail below.

2.1 MECHANICAL

2.1.1 Hull

The design of the robot's hull is primarily governed by the need to protect the electronics and other components from exposure to water. Factors of material cost, workability, and availability were also identified to facilitate construction and iteration of the design process. While resistance to increased pressure was also a concern, it was not weighed heavily since the increase in pressure experienced at a depth of 20 ft is relatively small.

Several materials and fabrication techniques were taken into consideration in designing the hull. The materials considered were steel, aluminum and polycarbonates. Each of these materials could be used to construct a hull by purchasing the material in a premade hull form, machining the material, or by using rapid prototyping and casting. It was determined that machining and casting would be costly and time consuming endeavors. Steel and aluminum are materials that are expensive, heavy, and relatively difficult to work with. It was therefore decided that Polyvinylchloride (PVC) pipe would be the best solution. PVC pipe is also made to withstand specified pressures (see Appendix B), comes with fixtures and products for sealing, and comes in a wide range of sizes.

The size of pipe will be determined by the size of the electronics and motors to be contained within. An internal frame will be needed in order to support the electronics. The main focus of hull construction will be ensuring that all holes made in the pipe (such as those for the motor and tether) are well sealed. A removable hatch will also be needed to allow access to the "guts" of the robot. In the case of problems with leaking, a valve could be added to the hull to allow the hull to be pressurized.

2.1.2 Propulsion

The primary means of directing the vessel is the propulsion system. As such, the propulsion system must be able to translate the robot in the x, y and z directions. Beyond the basic need to move the robot, the propulsion system should consume as little power as possible, be easy to implement and cost effective.

Most watercrafts utilize propellers for locomotion, but some AUVs mimic biology in their means of propulsion, swimming through water like fish or eels [3]. These forms of propulsion were ruled out, as they appeared very mechanically intensive and unfeasible to implement in the allotted time frame. A promising solution was found in a small, inexpensive AUV nicknamed DRIP [4]. DRIP used several hobby pumps to propel itself through water. However, after contacting the researchers it was found that this method consumed a lot of power, resulted in relatively slow movements, and leakage occurred in the pumps at depths of approximately 15 ft. It was therefore decided that propellers would be the most feasible solution.

In designing a propeller system, the most crucial part of the construction will be ensuring that shafts are properly lubricated and sealed to prevent any leakage. Propeller drive packages that are designed for the size of this vessel are generally used for model boats, which operate at surface pressure. Extensive pressure testing will need to be done to ensure that the propellers chosen to not leak at 20 ft.

2.1.3 Ballast

The ballast system will be used to control the depth of the AUV. In order for the robot to perform tasks underwater, it must be able to balance its buoyancy. The ballast system introduces a level of risk into the design because the ballast draws water into the robot contrary to the focus of preventing water from entering the robot. The ballast system must therefore reliably draw water in and force water out of the robot without leaking.

Submarines implement a ballast system that allows air to be forced out of the ballast by the surrounding water. This necessitates stored pressurized air to force the water back out in order to surface. Such a system would be costly to implement on the AUV, requiring pressure tanks and solenoid valves. A less expensive and easier to implement solution was discovered in the model submarine field. Some submarine hobbyists use a plunger type ballast that operates like a piston, powered by either a servo or worm gear [5].

In designing the ballast, careful attention will need to be paid to how the ballast is positioned on the craft and how the ballast will fill with water. Failure to do so could result in the craft pitching or rolling unnecessarily.

2.2 COMMUNICATION

Water is a particularly difficult environment to work under due to its complex and dynamic nature. Water contains certain conductive properties depending upon the impurities it contains. Signal attenuation[1] increases significantly corresponding to the conductivity of the water it passes through [6]. This causes underwater wireless communication at appropriate depths to be extremely challenging. Underwater wireless communication exists but it is a technology that is still under development. Therefore, the most reliable and effective communication system between the user and robot would be a direct link between the two. For this reason, the robot will be constructed to receive control and command signals through an umbilical tether that is connected to a surface unit computer. This tether will be approximately 25-35 ft in order to ensure a working depth and radius of 20 and 15 ft respectively. Also, since this robot is to be a platform for future endeavors in the AUV field, the communications design will include options for a wireless remote control system to be implemented.

Commercially off the shelf (COTS) technologies that currently exist are acoustic telemetry modems [7] and underwater diver sets for voice transmission [8]. These, however, are very expensive and beyond the project's budget of limitations. Another form of underwater communication is Infrared (IR) transmission. This method must share information over a line-of-sight: nothing can block the light from a transmitter to a receiver. Since the robot will be built to perform obstacle detection, these obstacles could come between the transmitter and receiver. Therefore, IR would not be an optimal solution.

2.3 SENSOR SUITE

The sensor suite chosen will consist of 4 types of sensors. These sensors were chosen to meet the constraints outlined in the Appendix C. Accelerometers will be used to determine the pitch and roll of the vessel. A two axis digital compass will work conjointly with the accelerometers to transmit the specific direction and heading (yaw) for the robot. A pressure sensor will be used to control the ballast system and thereby fix the robot's depth. The motions measured by these orientation sensors are depicted in Figure 2. The "eyes" of the robot are sonar transducers taken from a COTS fish finder and implemented to achieve object detection. These transducers will be used in pairs, one to transmit the

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[1] $\alpha = 0.0173\sqrt{(f\sigma)}$

α = attenuation in dB/meter

f = frequency in hertz

σ = conductivity in mhos/meter

sonar beams and the second to receive. All of these sensors will send signals to the microcontroller for interpretation and processing.

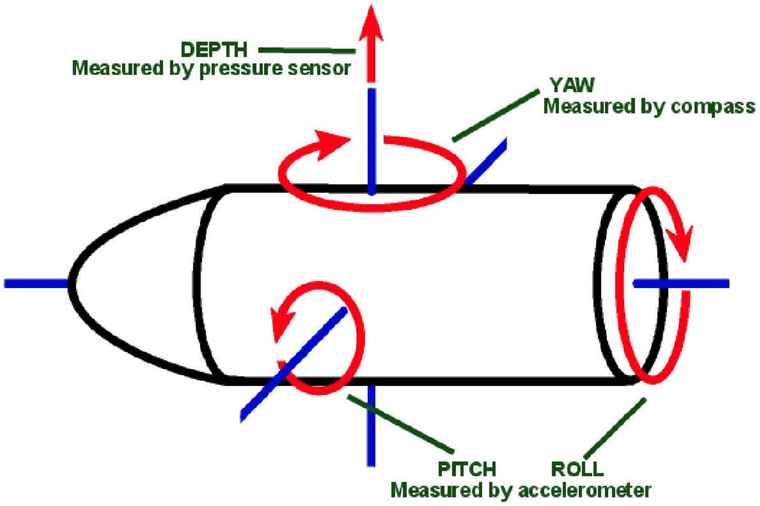


Figure 2

Motions of robot and sensors used to measure those motions

There were several other approaches taken into consideration when forming the sensor suite. The pressure transducers, accelerometers, and compasses that were taken into account had specifications that met the constraints of this design. The significant difference that governed the final decision was cost and size of the sensor. Though precision was sacrificed for affordability, the sensors chosen met the design specifications.

There were several systems that were researched before making a decision on an obstacle detection system. A vision system employing an underwater camera could be used coupled with software to identify objects. This solution was not applicable for murky water conditions therefore it was ruled out. Similarly, infrared sensors are difficult to implement in water that is not clear. This would prevent the robot from being used in natural environments. Infrared also requires highly reflective objects in order to achieve precise detection [9]. Such objects are not common to the applications outlined. In order to achieve accurate object detection without significant error in non-ideal waters, another approach was taken. Sonar systems were researched, but most were very expensive and too large. A type of sonar utilizing transducers found in COTS fish finders had been implemented in other AUV designs for obstacle detection [10]. This alternative proved to be the most practical and cost effective solution.

The implementation of these four types of sensors will greatly affect the precision of the sensor suite. One concern is placement of the accelerometers. If the accelerometers are placed at the center of gravity of the robot, they will directly measure the pitch and roll of the robot. If the sensors are not placed at the center of mass, then corrections will have to be made to compensate for rotational accelerations that will be produced when changing courses. The compass placement is also a key consideration. If the compass is not parallel to the yaw plane then a steady state error in the measurement will be present. The positioning and encasing of the sonar transducers must also be considered. The transducers will be placed in the front part of the robot. Echoing might occur if the transducers are placed inside the hull of the robot. If the transducers are placed on the outside of the vehicle then they will have to be waterproofed appropriately.

2.4 CONTROLS

2.4.1 Software

The main function of the microcontroller is to produce the control signals necessary to maneuver the AUV. These control signals will originate from both the incoming signals generated at the receiver and the information gathered by the sensor suite (see Appendix D). The sensor suite components will inform the microcontroller of object detection (fishfinding sonar), depth of AUV (pressure sensor), pitch and roll of AUV (accelerometer), and yaw (compass). Upon detection of an object in the path of the AUV, the microcontroller will be programmed to indicate the presence of the object. Also, a signal could be sent back to the operator on the controlling device to indicate object detection.

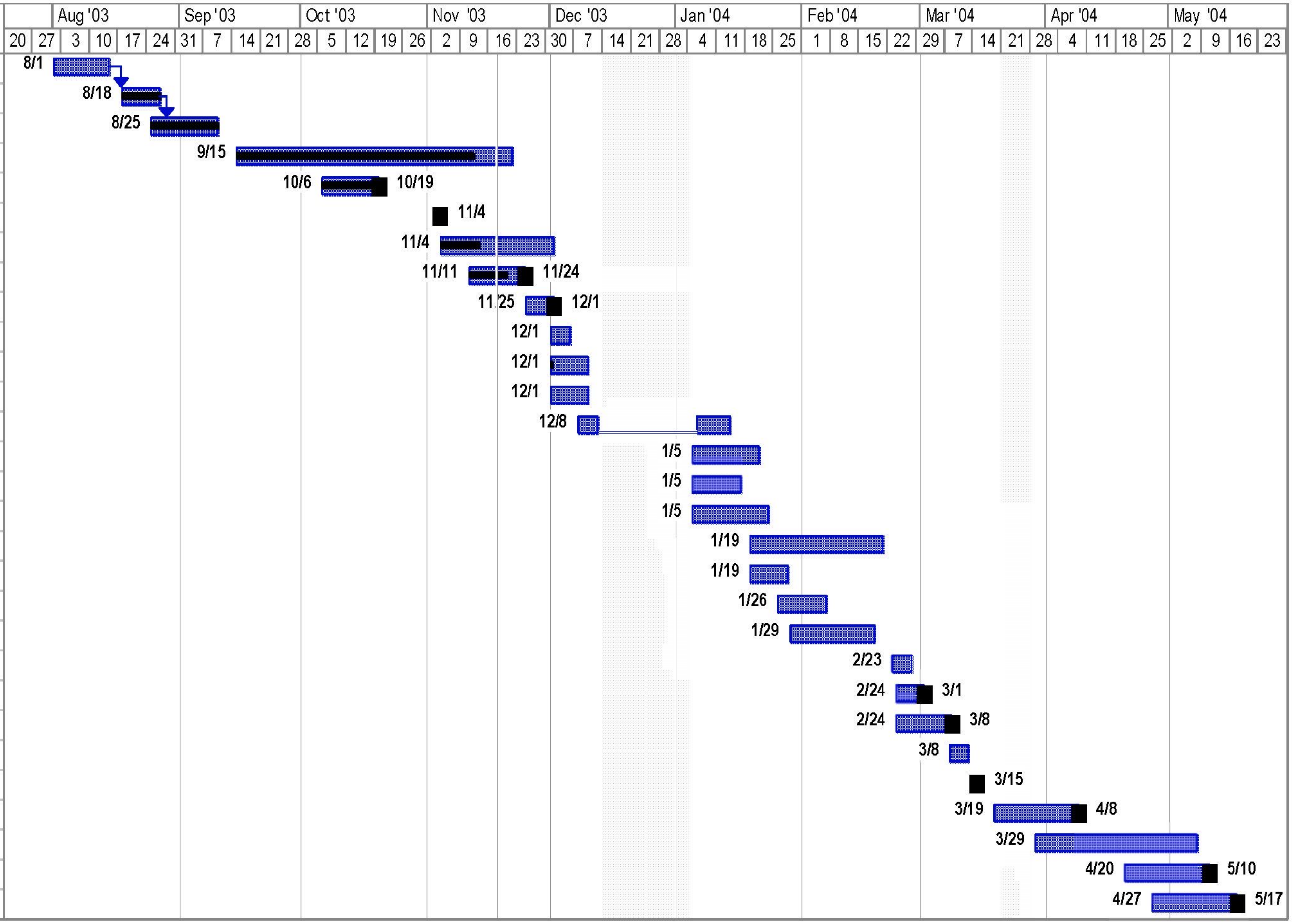
The PIC18F458 microcontroller was chosen for our AUV based on the specifications described below. In order for the sensor suite to operate correctly, an analog to digital (A/D) converter is needed. An Inter-integrated Circuit Bus (I^2C) is necessary to communicate with the sensors and could be used as the protocol for communication with the control system. Another requirement of the microcontroller is the ability to read and write Pulse Width Modulation (PWM) signals which are required for the sensors, motors, and servo system. The microcontroller will process the PWM signals sent by the sensors and relay the processed information back to the operator. The microcontroller will also send PWM signals to the motor to control speed and direction. The microcontroller is required to command the servos to a specified position. A Dual Inline Package (DIP) was chosen to facilitate ease of programming, replacement, and circuit construction. A minimum of 32 Input/Output (I/O) pins was decided upon to interface with several sensors and motors and the communication system. Additionally, the I/O pins will allow for expansion in the future. The PIC18F448 also matched the requirements of the chosen microcontroller. However, the F458 is superior to the F448 in program memory.

2.4.2 Controller

The robot will be controlled by a computer operator interface. This interface will consist of two bi-directional joysticks that will be able to direct the speed, direction, and depth of the vehicle. The yaw of the robot will be controlled by applying pressure to the left or right of one of these joysticks. Pressure in the forward or backward directions will control forward and backward movement of the robot. The controlling device should have an analog output to communicate to the speed controller how fast the motors should operate, thereby allowing variable speed adjustment. The second joystick will control the pitch of the robot as well as the ballast system. Pitch direction will be accomplished by communicating to the servos via an analog output the proper tilt for the propellers.

3.0 WORK SCHEDULE*

ID	Task Name	Duration
1	Form Group	2 wks
2	Find Advisor	1.5 wks
3	Decide on Project	2.5 wks
4	Research Alternatives	10 wks
5	Pre-Proposal	2 wks
6	Project Approved	0 wks
7	Initial Design	4 wks
8	Proposal	2 wks
9	Proposal Presentation	1 wk
10	Model of Design	1 wk
11	Order Electronics	1.5 wks
12	Order Materials/Mechanical Parts	1.5 wks
13	Mechanical Design/Modeling	2.5 wks
15	Develop/Test Sensor Circuits	2.5 wks
16	Learn Microcontroller	2 wks
17	Develop/Test Communication Circuit	3 wks
18	Construct Vessel	5 wks
19	Develop Motor/Servo Control	1.5 wks
20	Integrate Electronics	2 wks
21	Develop/Test Computer Interface	3 wks
22	Water Test Vessel/Fix Leaks	1 wk
14	Advisor Progress Presentation	1 wk
23	Progress Report	2 wks
24	Install Electronics	1 wk
25	First Test	0 wks
26	Abstract	2 wks
27	Retest/Revision	6 wks
28	Final Report	3 wks
29	Final Presentation	3 wks



*Important milestones such as project deadlines have been marked with black diamonds. The schedule addresses all the important phases of the project. Deadlines are fixed; start dates and finish dates are undetermined and vary according to estimated duration and relationship to other tasks. The Fall term concentrates on research, design, and proposal development. It is intended that parts will be ordered by term break. The winter term focuses on integration of all subsystems and construction aimed at accomplishing an initial test by the end of the term. Spring term should primarily consist of revision and retesting, allotting time to prepare the final report and presentation by the end of the term.

4.0 BUDGET

4.1 PROTOTYPE BUDGET*

MECHANICAL			
PART	**QTY**	**PRICE**	**TOTAL**
Graupner Schottel Drive Unit I	2	$49.95	$99.90
Performance servo C 4041	2	$52.15	$104.30
SPEED 600 Eco 7.2 V electric motor	2	$20.90	$41.80
SPEED Profi 50 Speed Controller	2	$95.90	$191.80
Ballast Parts	---	$40.00	$40.00
Ballast Motor	2	$25.00	$50.00
Ballast Relay	2	$35.00	$70.00
PVC Pipe	1	$15.00	$15.00
Internal frame materials	---	$30.00	$30.00
Misc. Hardware/Materials	---	$50.00	$50.00

ELECTRONICS			
PART	**QTY**	**PRICE**	**TOTAL**
Waterproof Tether Cable	1	$50.00	$50.00
Rocker Switch	1	$0.76	$0.76
Rocker Switch Seal	1	$1.99	$1.99
12-Volt 2.9 AH Battery	2	$28.50	$57.00
Waterproof ports	2	$20.00	$40.00
3x5 Printed Circuit Board	2	$50.50	$101.00
PIC18F458 Microcontroller	1	$6.26	$6.26
10 MHz Crystal	1	$2.78	$2.78
20 MHZ Crystal	1	$2.78	$2.78
Misc. Parts (Resistors, Capacitors, etc.)	---	$50.00	$50.00
Logitech® Freedom 2.4™ Cordless Joystick	1	$45.99	$45.99
Fuse block	1	$10.00	$10.00
Fuses	20	$1.00	$20.00

SENSORS			
PART	**QTY**	**PRICE**	**TOTAL**
Dual Axis Accelerometer	1	$11.64	$11.64
Compass	1	$41.00	$41.00
Transducers	2	$19.99	$39.98
Pressure Sensor	1	$69.00	$69.00

TOTAL BUDGET FOR PROTOTYPE PARTS	$1,242.98

+

REQUIRED RESOURCES			
RESOURCE	**HRS**	**RATE**	**TOTAL**
Testing (Facilities, fees, etc.)	10	$50.00	$500.00

PROTOTYPE TOTAL	**$1,742.98**

*The prototype expense anticipated is approximately $1,740.00. Funding will be sought out through soliciting corporate sponsors and university and faculty assistance.

4.2 INDUSTRY BUDGET*

RESOURCE	RATE	PERIOD	QUANTITY	TOTAL
Engineering Design/Labor @ 40 Hrs/week	$5000.00/mo	8 months	4	$160,000.00
Technical Labor @ 40 Hrs/week	$4000.00/mo	2 months	---	$8,000.00
Handtools	$1,600.00		---	$1,600.00
Table Tools	$15,000.00		---	$15,000.00
Office Software	$1,500.00		---	$1,500.00
Computers	$4,800.00		---	$4,800.00
Design Software	$10,000.00		---	$10,000.00
Board Fabrication	$300.00		---	$300.00
Surface Mount Soldering Station	$1,000.00		---	$1,000.00
TOTAL BUDGET FOR RESOURCES				$202,200.00
				+
Overhead (office rental, bills, benefits, insurance)				15.00%
INDUSTRY TOTAL				**$232,530.00**

*The industry budget reflects the costs of developing a manufactured prototype in an industry setting. The estimated labor for the project is based on 4 engineers working full-time over an 8 month period specified in the work schedule (section 3.0).

4.3 COMPLETE BUDGET

GRAND TOTAL	**$234,272.98**

5.0 SOCIETAL AND ENVIRONMENTAL IMPACT

Societal and Environmental implications of this vehicle are numerous due to the wide range of immediate applications for the proposed design and imminent applications for future models. The impact discussed in this paper will be predominantly concentrated on effects of the prototype vehicle proposed.

One of the largest sponsors of AUV research is the Navy. Using an AUV, such as the one proposed for this project, as a defense weapon is ambiguous as a positive or negative impact. The Navy has already employed AUVs in the most recent wars in Iraq and Afghanistan to detect and help clear mine fields. While this does remove the dangerous explosives from the water, it also allows US warships to invade foreign nations and facilitates war. Explosives could be attached to the robot, creating smart bombs that could maneuver to targets with greater precision than current maritime weapon systems. The impact of this technology reaches beyond naval interests. Jobs related to underwater exploration - such as pipeline or bridge inspection – are greatly downsized by the use of AUVs. Where inspecting an oil pipe used to take round the clock supervision by a team of technical personnel, the same job can be done by a single AUV [1].

The most immediate consequence of the AUV is its effect on the environment in which it operates. Unpredictable malfunction of the robot could leave it stranded in an inaccessible region. Waste products, such as oxidation and battery leaks, or any parts of the robot that manage to become detached are potential pollutants to the environment. The AUV introduces an unnatural element to the underwater ecology, disrupting sea life and interfering with natural balances. For example, the propellers, the electromagnetic fields, or the sonar system of the AUV could physically harm sea life [11]. Presence of the AUV could drive out wild life and force migrations to other habitats.

While the negative impacts of the vessel are significant, its benefit to society outweighs these detriments. AUVs used for ship hull inspection would automate the task, cutting down on inspection times while raising the reliability of the process. This would ensure safer ships and less time spent at dock. Similarly, bridge inspection would become an exceedingly easier task, allotting for more frequent inspections and early detection of problems.

An AUV equipped with the ability to map shallow waters could help scientists study ecosystems and keep track of changes in the environment. In areas such as Yellowstone National Park where a resident super volcano is quickly bulging the land and building pressure [12], surveying of the land (including those areas submerged in water) helps geologists note the progress of the volcano. The AUV could also be modified to monitor aquatic environments through applications such as pH sampling and detection of toxins or impurities in the water. An AUV trolling the Great Lakes could provide real time information regarding Polychlorinated biphenyls (PCBs), pesticide or heavy metal concentrations, giving scientists insight into cause and effect relationships regarding contamination. With an added sensor suite and automated sampling bay, the robot could also be used to measure environmental stress occurring in natural bodies of water.

6.0 SUMMARY AND CONCLUSIONS

The AUV field is rapidly growing following advancements in navigation, sensing, control techniques, and materials. The proposed project would create an experimental AUV platform that would give Drexel University a solid foundation in AUV development and design. The final product would be of approximate dimensions of 24" x 12" x 6" and would be able to navigate in three dimensions, estimate self position and self orientation, and stay in "fixed" position. The project is currently in the initial design phase. Once parts have been selected (around December 1st, 2003) the construction of the robot will commence. During construction, balance of the robot's weight and proper sealing will be of utmost concern. Perhaps the greatest challenge will be using the microcontroller to process simultaneously sensor data, data from the operator, and output control signals to the motors, and than send these data back for real time processing to the operating system. Another forthcoming challenge would be obtaining adequate testing facilities. The resulting prototype would navigate in up to 20 ft of water and detect obstacles in its path, paving the way for future AUV developments at Drexel.

REFERENCES

[1] Doolittle, Daniel. “The Payoff is in the Payload: Using AUVs in Scientific Research.” *Underwater Magazine* March/April 2003.

[2] Liolios, Tom, Michael Nicolaides, Justin Refice, Brian McCurdy, and Jo-Ann Viray. "Underwater Coin Retrieval Robot." *Drexel University Senior Design* ECE-007 (2002): 4-12.

[3] Ayers, J., J. Witting, C. Wilbur, P. Zavracky, N. McGruer, and D. Massa. “Biomimetic Robots for Shallow Water Mine Countermeasures.” *In: Proc. of the Autonomous Vehicles in Mine Countermeasures Symposium.* Naval Postgraduate School (2000) CD Rom..

[4] Miller, David. "Design of Small Cheap UAV for Under-Ship Inspection and Salvage." *The Proceedings of the 1996 IEEE Symposium on Autonomous Underwater Technology* (1996): 18-20.

[5] Freudenrich, Craig, Ph.D., and Marshall Brain. *How Submarines Work.* How Stuff Works. 2003 <http://people.howstuffworks.com/submarine1.htm>.

[6] Butler, Lloyd VK5BR. “Underwater Radio Communication.” *Amateur Radio* April 1987.

[7] *Underwater Acoustic Modems.* Link Quest Inc.. 2003 <http://www.link-quest.com/index.htm>.

[8] *Divelink Product Overview*. Divelink. 2003 <http://www.divelink.net/index.htm>.

[9] Wirz, Ben. *IR Sensor Info Page*. Element Products, Inc. <http://www.wirz.com/info/ir.html>

[10] Josserand, Tim. *Exploring affordable underwater robotics with the MAUS*. First Internet Robotics Contest. 2003 <http://dec1.wi-inf.uni-essen.de/~astephan/FIRC2000/s_2.html>.

[11] Jepson, P. D. et al. “Was sonar responsible for a spate of whale deaths after an Atlantic military exercise?” *Nature*, 425 (2003). pgs. 575 – 576.

[12] Hesselberg, Robert J. and John E. Gannon. *Contaminant Trends in Great Lakes Fish.*USGS. <http://biology.usgs.gov/s+t/noframe/m2131.htm>

[13] Johns, W. E.. *Notes on Pipe*. 2003 <http://www.gizmology.net/pipe.htm>

APPENDICES

Appendix B- PVC Specified Pressures [13]

Nominal Pipe Size	Outside Diameter	Inside Diameter			Wall thickness			Weight lbs/ft			Max PSI		
		40	80	120	40	80	120	40	80	120	40	80	120
1/8"	0.405	0.261	0.203		0.068	0.095		0.045	0.058		810	1230	
1/4"	0.540	0.354	0.288		0.088	0.119		0.081	0.100		780	1130	
3/8"	0.675	0.483	0.407		0.091	0.126		0.109	0.138		620	920	
1/2"	0.840	0.608	0.528	0.480	0.109	0.147	0.170	0.161	0.202	0.223	600	850	1010
3/4"	1.050	0.810	0.724	0.690	0.113	0.154	0.170	0.214	0.273	0.295	480	690	770
1"	1.315	1.033	0.935	0.891	0.133	0.179	0.200	0.315	0.402	0.440	450	630	720
1-1/4"	1.660	1.364	1.256	1.204	0.140	0.191	0.215	0.426	0.554	0.614	370	520	600
1-1/2"	1.900	1.592	1.476	1.423	0.145	0.200	0.225	0.509	0.673	0.744	330	470	540
2"	2.375	2.049	1.913	1.845	0.154	0.218	0.250	0.682	0.932	1.052	280	400	470
2-1/2"	2.875	2.445	2.289	2.239	0.203	0.276	0.300	1.076	1.419	1.529	300	420	470
3"	3.500	3.042	2.864	2.758	0.216	0.300	0.350	1.409	1.903	2.184	260	370	440
3-1/2"	4.000	3.520	3.326		0.226	0.318		1.697	2.322		240	350	
4"	4.500	3.998	3.786	3.572	0.237	0.337	0.437	2.006	2.782	3.516	220	320	430
5"	5.563	5.017	4.767		0.258	0.375		2.726	3.867		190	290	
6"	6.625	6.031	5.709	5.434	0.280	0.432	0.562	3.535	5.313	6.759	180	280	370
8"	8.625	7.943	7.565		0.322	0.500		5.305	8.058		160	250	
10"	10.750	9.976	9.492		0.365	0.593		7.532	11.956		140	230	
12"	12.750	11.890	11.294		0.406	0.687		9.949	16.437		130	230	
14"	14.000	13.072	12.410		0.437	0.750		11.810	19.790		130	220	
16"	16.000	14.940	14.214		0.500	0.843		15.416	25.430		130	220	
18"	18.000	16.809	16.014		0.562	0.937		20.112	31.830		130	220	
20"	20.000	18.743	17.814		0.593	1.031		23.624	40.091		120	220	
24"	24.000	22.544	21.418		0.687	1.218		32.873	56.882		120	210	

Appendix C- Design Constraints/Decisions

HULL MATERIAL/FABRICATION		
MATERIAL/METHOD	**PROS**	**CONS**
Metal/Machined	-Solid/robust construction -Handles pressure well -Flexible design	-Heavy -Expensive -Time consuming (design and manufacturing)
Metal/Molded	-Solid (not as much as machined) -Handles pressure well -More flexible design	-Heavy -Expensive -Time consuming -Have to be sent out
Plastic/Machined	-Handles pressure reasonably well -Flexible design -Resistant to harsh environments	-Expensive -Time consuming
Plastic/Molded	-Handles pressure reasonably well -More flexible design -Resistant to harsh environments	-Expensive -Time consuming -Have to be sent out
Fiberglass	-Handles pressure well -More flexible design -Resistant to harsh environments -Relatively cheap	-Difficult to manufacture -Time consuming -If broken, difficult to replace
PVC pipe	-Handles pressure reasonably well -Cheap -Easily acquired -Quick/easy to manufacture -Resistant to harsh environments	-Constrained design -Restriction on pressure

PROPULSION		
METHOD	**PROS**	**CONS**
Propeller	-Well developed/understood -Existing parts -Efficient use of power	-Difficult to manufacture -Time consuming (design/construction)
Pump	-Easily integrated -Flexible/easily reconfigured	-Less efficient -Not designed for this application -Less thrust than propeller

OBJECT DETECTION SENSORS		
MATERIAL/METHOD	**PROS**	**CONS**
Sonar	-Well developed/understood -Many alternatives -High resolution	-Large -Expensive -Unnecessary resolution
IR	-Well developed/understood -Small systems -Cheap -Easily integrated	-Refraction issues -Wouldn't work in murky water
Vision System	-Well developed/understood -Small systems -can be used for other applications	-large amount of data -lots of equipment (camera, frame grabber, processor) -expensive -wouldn't work in murky conditions
Fish finder sonar	-Cheap -Easily obtained -Existing tutorial	-Requires reverse engineering fish finder -possible noise issues -Requires more design/engineering

DESIGN CONSTRAINTS

Primary Design Constraints

- Surface and subsurface operation
- Operation at pool depth (20-30 ft)
- Operable radius of at least 15 ft at max depth
- 3 degrees of freedom
- Cheap
- Small as possible
- Ability to fix in one position (neutral buoyancy)
- Obstacle detection
- Orientation detection

Microcontroller Constraints

- Digital inputs (8)
    - Control signal (1)
    - Obstacle detection sensors (3)
    - Orientation sensors (3)
    - Depth sensor (1)
- Digital outputs (4-5)
    - Motors/Servos (4-5)
- Built in PWM capability (read and write)

Appendix D- System Block Diagram