TIGERSHARK REMOTELY OPERATED VEHICLE

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ABSTRACT

The design and construction of a small inexpensive underwater Remotely Operated Vehicle (ROV) suitable for saltwater environments is described. The ROV is surface controlled using a laptop linked to an onboard microcontroller via an umbilical. Various sensors and devices on the ROV enable it to interact with its environment. Design considerations and methods of construction are detailed.

CONTENTS

ACKNOWLEDGEMENTS

I would like to thank Doyle Maleche for his electronics and extensive programming assistance. This project would not have been possible without his help. His extensive knowledge of the integration of electronics and mechanical systems helped guide me through the electronics selection process and through the integration and programming phase.

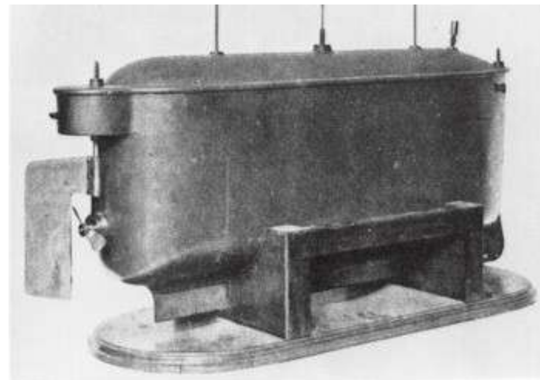
Thanks to Jeff Quast for his help in TIG welding dome ring mounting tubes and the use of his equipment.

I would like to acknowledge Subconn Inc./ M.J. Stewart Associates Inc. and thank Michael Stewart who generously donated the underwater connectors for pressure hull.

I would like to show my deepest gratitude to Dr. Brown at Olympic College for his support through this and previous ROV projects as well as for the use of the 3-D printer at the Olympic College Engineering Department.

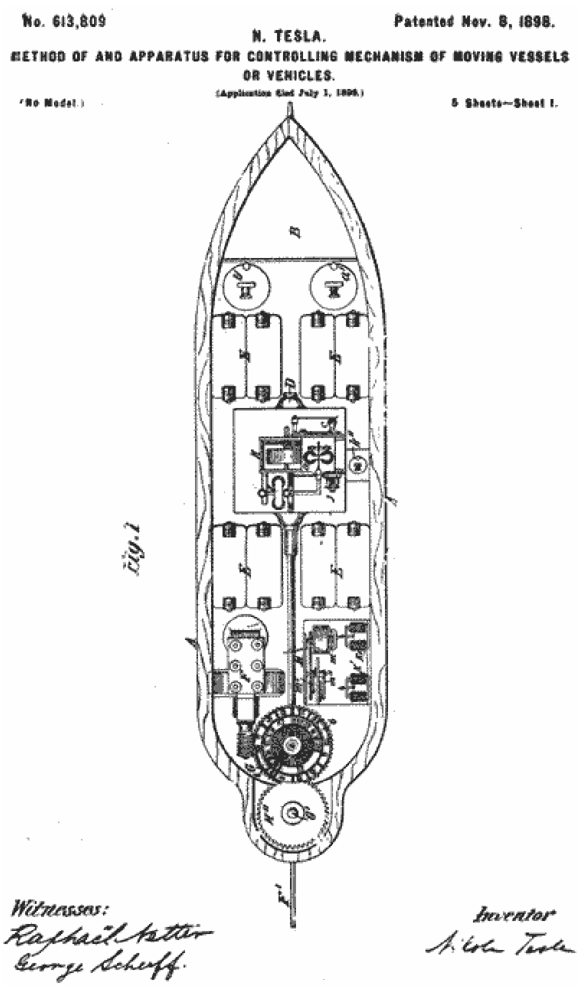
INTRODUCTION

Exploring underwater is a difficult and dangerous task. Diving equipment is expensive and requires special training to use. Time in the water is very limited at depths much below 60 feet and the danger increases greatly at deeper depths. To overcome these limitations when only observation or minor physical operations are required, a small remotely operated vehicle is suitable. Unfortunately these vehicles are generally very expensive, often many thousands of dollars, and out of reach of the average private user or small business.



Historical Background

The first remotely controlled vehicle was invented and patented by Nikola Tesla in 1898. The vehicle was a robot boat controlled by radio waves.



The first remotely operated underwater vehicle was the ROV POODLE built in 1953 for archeological exploration. Not log after the US Navy developed the Cable Underwater Operated Vehicle or CURV series in the 1960’s for retrieving torpedoes. In 1966 one of these vehicles was used to retrieve an atom bomb accidently dropped off the coast of Spain. In 1973 the first recue of human life with an ROV was performed when the CURVIII attached a rescue line to haul up the Pisces III Submersible near Cork, Ireland.

These early ROV’s relied heavily on hydraulic systems and were quite large and heavy. The first truly portable all electric ROV called SNOOPY was developed by the Navy in the early 1970’s.[3]

In the later 1970's and 1980's the offshore oil industry provided a real boom for the ROV market and commercial systems were growing in popularity. Currently ROV's are used in research, archeology, oil industry, cable industry, law enforcement, the Coast Guard and the Navy. Small ROV's are used for inspection, security/ police and fisheries.[3]

Currently the world record dive for an ROV is held by the JAMSTEC Kaiko ROV where it dived to 35,791 feet in the Marianas Trench.[3]

Project Description

The goal of this project is to provide a prototype of a small easily portable remotely operated vehicle that can explore the bottom of lakes and saltwater areas, capable of being operated from a small boat or dock with only a 12 volt battery source. The final outcome of this part of the project is to build a working system with basic operation which can be expanded upon by the user. Primary functionality is six degrees of freedom maneuverability, and video feedback. Other features will be planned for but not necessarily implemented due to project time constraints. Building a reliable platform to operate in the harsh underwater environment is a major challenge. This project will provide experience in the fields of Mechanical, Electrical, Software and Marine Engineering.

The mechanical design of the ROV will be performed using a 3-D design program (Inventor) and the electronics will be laid out using electronic design software (Multisim) and Visio. The pressure hull will be constructed of aluminum with machined parts. The ROV will have one camera, and provisions for adding a compass, pressure and temperature sensors will be made.

The ROV's microcontroller is an Arduino clone board called a FreeDuino. This board was chosen due to its low cost, open source hardware and software as well as user support. This controller allows the flexibility of using software to make changes to the operation of the ROV as well as some autonomous capabilities such as depth control, position holding, etc.

Primarily off the shelf solutions are used when possible to save development time and increase reliability. These solutions primarily relate to servos and motor speed controllers. Thrusters are made using bilge pump motors which are already sealed and have been proven to work at over 60 feet of water depth with minimal maintenance. Other possible thruster designs are presented but for the working prototype are not implemented due to time constraints.

The ROV's tether is composed of a Category 5 cable containing 4 twisted pairs bundled with a pair of heavy gauge power wires encased in a hollow buoyant rope. Power will be 12 volts initially, but possibly up to 48 volts at a later date. Different voltage options are discussed and the pros and cons of each will be explored.

Surface control will be provided by using a laptop and a joystick or game pad with mouse as backup. Video and sensor output will be displayed on the laptop. The software to run the ROV will be written specifically for this application in Visual BASIC which interfaces with the Arduino code on the ROV's microcontroller.

VEHICLE DESIGN AND CONSTRUCTION

Requirements

The environment which an ROV must be designed to work in has many challenging aspects that must be overcome. This ROV is designed to work in seawater or even in swimming pools which are both corrosive and electrically conductive environments. Pressure is also a large problem as water must be kept out of electrical parts and motors. Sealing a vessel at high water pressures requires more critical design requirements. The plans for this phase of the project are to make the pressure vessel suitable for depths of up to 1000 feet to allow for increased capabilities later on. In open water currents must be dealt with necessitating greater thrust requirements than in still water.

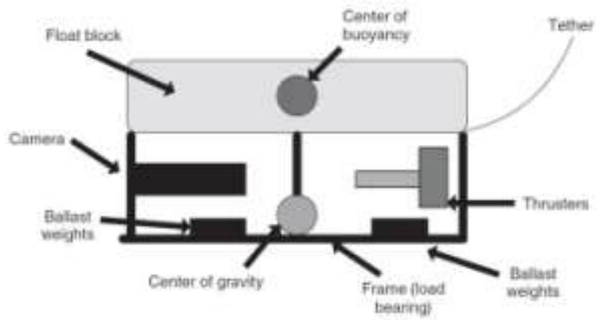
The ROV is designed to overcome these issues and have the capability to move around within its environment as well as provide other capabilities. The ROV's ability to move is accomplished through the use of thrusters. Thrusters are sealed motors with propellers. They are reversible and a minimum of three thrusters can provide up/down, forward/backward and left/right turning capability. Additional thrusters can be used to provide sideways motion or slew.

The most basic feedback requirement of an ROV is to bring vision of what is happening from the vehicles perspective. This is accomplished by a video link through a camera on the ROV to a display on the surface. This allows for the ROV to be navigated through its environment by the operator.

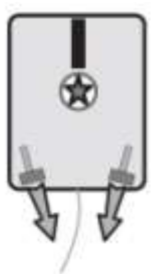
Design Considerations

The goal of this project is to build a low cost remotely operated vehicle for basic observation and interaction in underwater environments. Even with these simple goals it is major challenge to design something designed to work underwater at any depth reliably. The vehicle must balance underwater capability with cost, so compromises must be made in the area of depth capability, materials and components used. The most critical part of the ROV is the pressure housing. It is also the most time consuming to produce and has to be 100 percent reliable or the ROV will fail. With this in mind and with future plans for expanding the capability, a machined aluminum hull was decided upon with a commercially available acrylic ROV dome for the camera port. This provides a solid foundation to contain the electronics and the rest of the ROV is designed around this. The thrusters are made from off the shelf bilge pump motors to save cost and development time building sealed thrusters from scratch. The main electronic components are built from commercially available kits to reduce prototyping and troubleshooting time.

Overall Vehicle Structure



The structure of the ROV is based on the need to provide a location for electronics, thrusters and floatation. These three component sections need to be tied together to provide a solid unit that can handle the stresses of ocean current, propulsive thrust, ocean pressure and tension on the tether during retrieval. The design of this ROV is conventional and has the same components as most ROV's in use today. These main components are the pressure hull, the frame and the float. The location of the components must provide for static and dynamic stability.



The thruster mounting locations affect the dynamic stability and should be placed as far apart as possible to provide better turning ability. The thrusters are also canted inboard which accentuates the turning affect.

Pressure Hull

The pressure hull is constructed of .125" wall 4.5" outside diameter 6061 tubing with machined ends. The camera dome is mounted in one end and the electronics board and electronics board mounted to the other. The camera dome is a commercially available dome made for the VideoRay ROV. The pressure hull is capable of up to 1400 feet of water depth at which point the dome will fail as it is the weakest link.

The design specifications for the hull were carried out using DeepSea Power & Light's Under Pressure analysis software. The analysis was run twice once for the tube and end cap and again for the acrylic dome. The results of the calculations are in Appendix x.

6061 aluminum was chosen for its ease of machining and corrosion resistance. The housing has a total of six O-rings for the 3 connections. Each connection has both a compression and slip fit seal. The slip fit provides additional sealing before the pressure builds on the hull which pushes the compression seals tighter. This is a standard practice in the marine equipment industry and was the recommended method by Ted Brockett of Sound Ocean Systems, Inc.

The pressure hull ends were machined out of solid 6061 aluminum round using a small lathe. The machining was one of the most time consuming tasks of the project. Once the machining was complete a preliminary in water pressure test was performed by submerging the vessel in approximately 25 feet of water for several minutes. It is usually the first few feet of submergence that cause the most leaks and once the pressure build up on the outside of the vessel the o-ring seals become compressed and seal.

There were no leaks so the hull should be fine to its full depth rating. 

Connections to the tether and thrusters are accomplished through the use of two Subconn underwater connectors. These are designed to be used in the harsh underwater environment and provide further assurance that there will be no leaks into the housing.

Frame

A frame is used to tie the main components together and provide a solid mounting platform for additional components. The frame mounts to the float in four locations and has skids on the bottom to provide protection for the camera dome and components mounted on the bottom of the ROV should it come in contact with rocks or other unforgiving seafloor features. The frame also provides mounting points for thrusters, lights and movable ballast weights. It is important to keep the ballast as low as possible to provide the best stability and the frame design accomplishes this task. Initially the frame is composed of PVC pipe and components for ease of modification. Once further testing is completed a final version of the frame will be made using ½" stainless steel tubing which will add additional weight as well as durable protection to the ROV.

Float

Some floatation is provided by the pressure hull but more is needed to offset the thrusters and additional component weight. The float can also be designed to have a shape that provides the most stability without concern of the pressure resistance which is required of the hull. The float in this project is wide and flat which provides additional stability over a larger cylindrical pressure hull. The float is also hydrodynamically shaped to reduce the drag which primarily reduces the effect of ocean current as well as increase mobility.

Commonly available foam insulation board was chosen to make the float due to cost and the ease of shaping. The incompressibility of this foam should be adequate to depths of 1000 feet. Deeper depths would require far more expensive syntactic foam which is composed of resin and glass microspheres. Three layers of one inch thick foam are laminated and shaped to form the float.

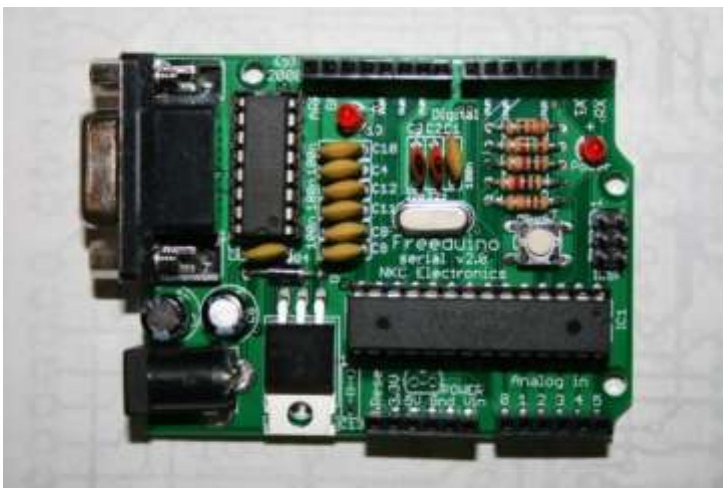
An aluminum plate is inset in the top to provide structural integrity and a mounting point for brackets that the pressure hull is mounted to. The hull has a layer of fiberglass to help seal it from water intrusion and provide durability. Fiberglassing was accomplished by using vacuum bagging which allows the fiberglass to be laminated and pulled down over the foam float form tightly and evenly.

Ballast

The float provides 12 pounds of additional floatation to the ROV which is offset by the weight of the components and ballast weights to obtain slight positive buoyancy. The ballast weights are movable to adjust the trim of the ROV so it sits level in the water. Ballast can also be removed to compensate for additional components added later. Primary ballast is provided by two 3lb dive weights. Additional ballast is provided by a number of small 6oz fishing weights. These will be replaced with movable lead slugs that fit into the frame once the stainless steel frame is built.

CONTROL

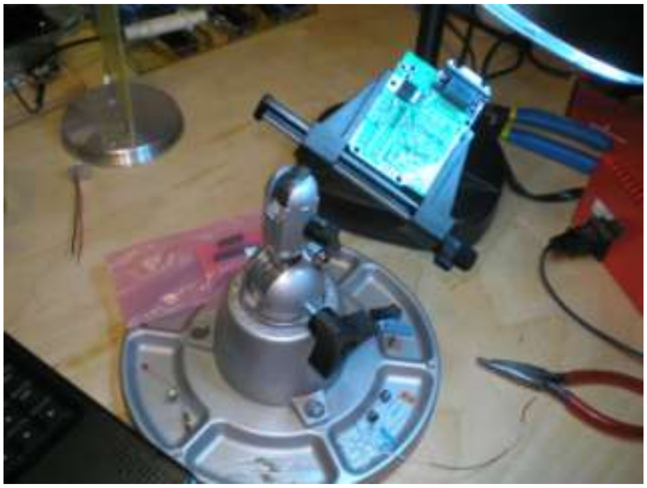
Control of the ROV consists of two main systems connected via the tether. The topside system is composed of the Laptop computer with joystick or mouse using a Visual Basic program to feed signals through the tether to the Arduino board on the ROV. The onboard microcontroller and software feeds pulse width modulation signals to the L298 speed controllers which in turn control the voltage and current feeding the thruster motors. This method was chosen as it provides software flexibility to add autonomous features later as well as the ability to have feedback and sensors output on the laptop display.



Electronics

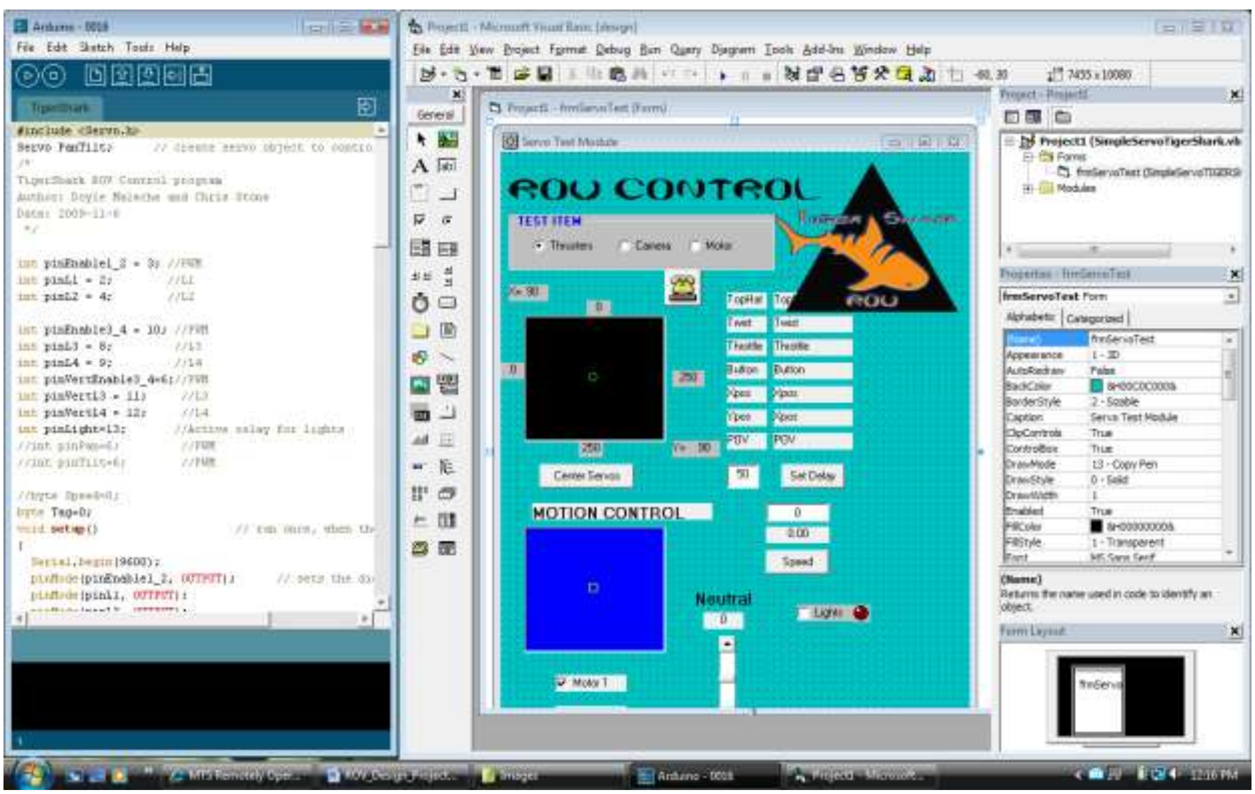
The ROV needs to have something to control the thrusters, camera and any sensors. The electronics were selected for their availability, reliability ease of use and programming as well as support. The Arduino family of microcontroller boards is becoming very popular for many applications and is a very low cost solution. The board meets many requirements for the ROV, compactness power requirement, expandability and interface. The Freeduino board was chosen as it is available with a RS-232 serial port that is easily converted to RS-432 which provides an error free signal over more than 4000' of cable with no amplification and through only two conductors. This frees up other conductors of the Cat5 cable for other devices.

All the electronics boards were kits and composed of etched printed circuit boards and the components. The Solarbotics L298 boards were modified by using different diodes and voltage regulators to increase the usable input voltage to 37 volts to allow the use of motors that are rated at higher voltage than 12 volts to increase the efficiency of the thrusters at a later date.



Software

The software to run the ROV is composed of two parts, the onboard software on the ROV and the topside software that communicates with the onboard program. On the ROV Arduino code is loaded into the ATmega chip and permanently resides there after loading. This program controls the L298 motor controllers by sending pulse width modulation signals. These PWM are controlled by the Visual Basic program running on the topside laptop. The Visual Basic program provides a visual display of what the controls are sending to the ROV. These programs are shown in their entirety in Appendix C.



Thrusters

Thrusters are built using off the shelf cartridge style bilge pump motors. They provide a low cost already sealed solution. These motors should be reliable at depths up to 60 feet or so provided the seals are re-greased periodically. Stephen Thone has tested and documented his findings on using these motors on his website [4]. Four 1000 gallon per hour pump motors are used to provide motion in the vertical and horizontal axis. The motors are mounted in housings formed on a 3-D printer of plastic. The two horizontal thrusters also feature Kort nozzles which provide additional efficiency in the forward direction. Both the vertical and horizontal thrusters are arranged with paired props that are counter rotating to counter the effects of torque steer discussed earlier. Two vertical thruster were chosen to provide more thrust and avoid the water flow path problems of a centrally mounted thruster.

Sensors

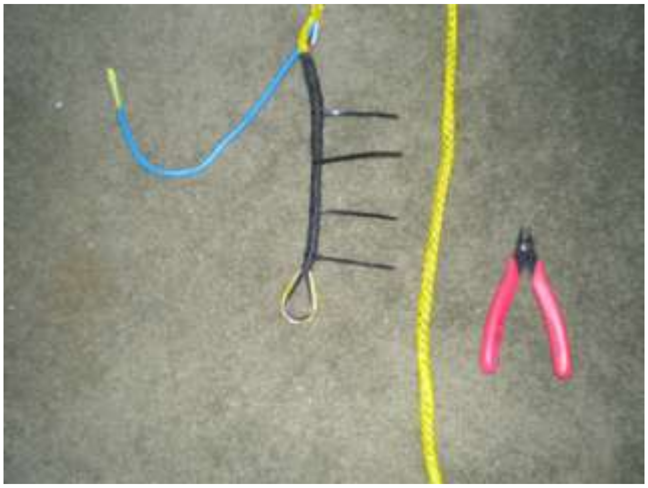
Sensors provide information and feedback to the ROV pilot on the surface. The ROV uses a color camera with pan and tilt servos to provide visual feedback for navigation of the ROV. Camera selection is very important as most cameras have very narrow field of view. The camera chosen for this project has a detachable 90° lens. This is adequate for a pan and tilt mounted camera and provides for 180° view in all directions. Two 5W high power LED's provide additional light for the camera. LED's provide high light output with low power consumption.

Tools

Tools allow the ROV to interact with its environment. Initially the ROV will be outfitted with a suction device utilizing a 500GPH bilge pump. This pushes water through a tube at an angle which causes a suction effect drawing objects into a sample container mounted on the frame. This can be used to clear mud from an area or suck up small objects and deposit them in the sample container.

UMBILICAL

The umbilical or tether provides a connection from the surface to the ROV both physically and electronically. Signals are passed up and down the tether and power is supplied through the tether to run the systems on the ROV. The tether provides a mechanical connection to the ROV so it can be retrieved or hauled to the surface in an emergency. Requirements for the tether are that it be strong tensionally, protect the electrical cables and be neutrally buoyant.

The tether is composed of a single category-5 cable and two conductors of 16 gauge power cable inside hollow braided poly rope. This provides some buoyancy to the cables, additional buoyancy is provided by small net floats. Category -5 cable has 4 twisted pairs of conductors suitable for sending digital signals as well as video. The tether terminates with an underwater connector that attaches to the ROV and an eye for the physical attachment. On the surface side the tether is attached to a modified extension cord reel to manage the winding process as well as provide connections to the surface electronics and power. 

CONCLUSION

This project was very extensive and there were many aspects of the design that had to be changed or figured out along the way. This was particularly due to many unknown factors in how all the components would fit and work together. Many of the components were not able to be designed in CAD easily and many parts were unavailable until further on in the process. The electronics and software had many unknowns as well. There were initially many choices to make in what components to use and once the microcontroller was selected this narrowed down the list. Several motor controller options were planned to be tested and a solution that wasn't in the original plan was chosen. Initially scratch built controllers using the L298 motor controller chip were to be the solution but after several unsuccessful attempts with bread boarded circuits that plan was dropped in favor of the Solarbotics L298 controller kits since time and reliability were of paramount importance. The power options were also unknown until later testing. It was decided to use 12 volt power to simplify the process but the motor controllers were built with components to allow the use of up to 36 volts at a later date with a few modifications.

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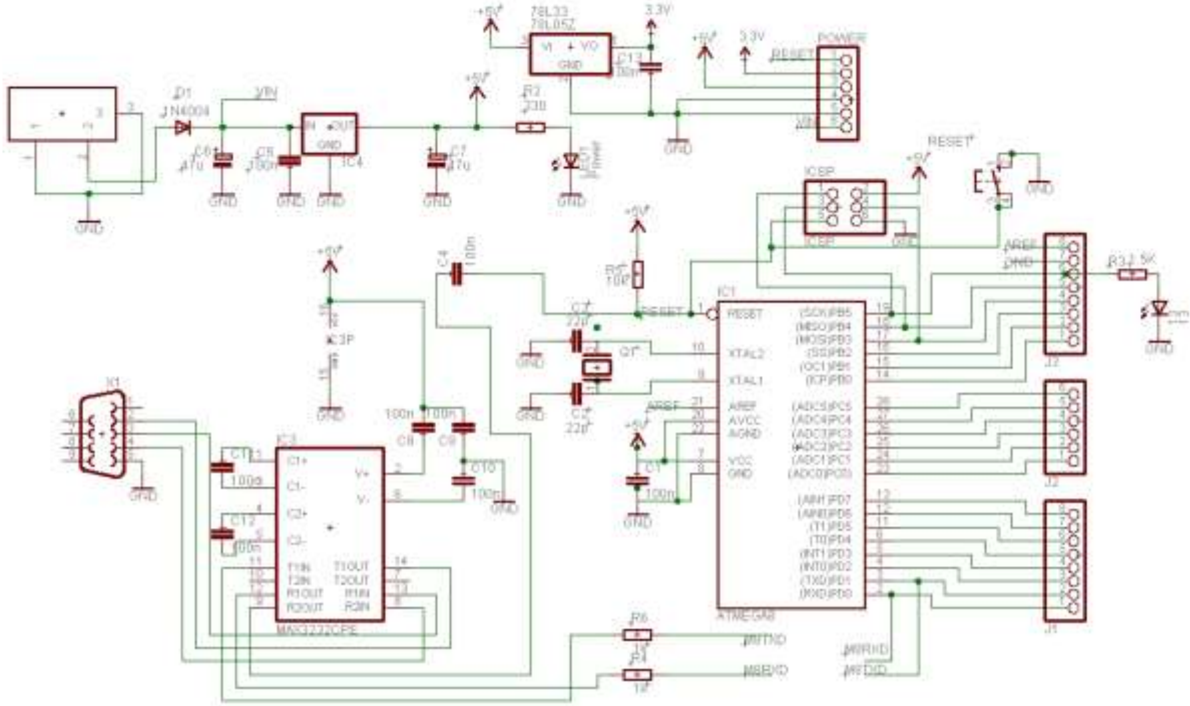
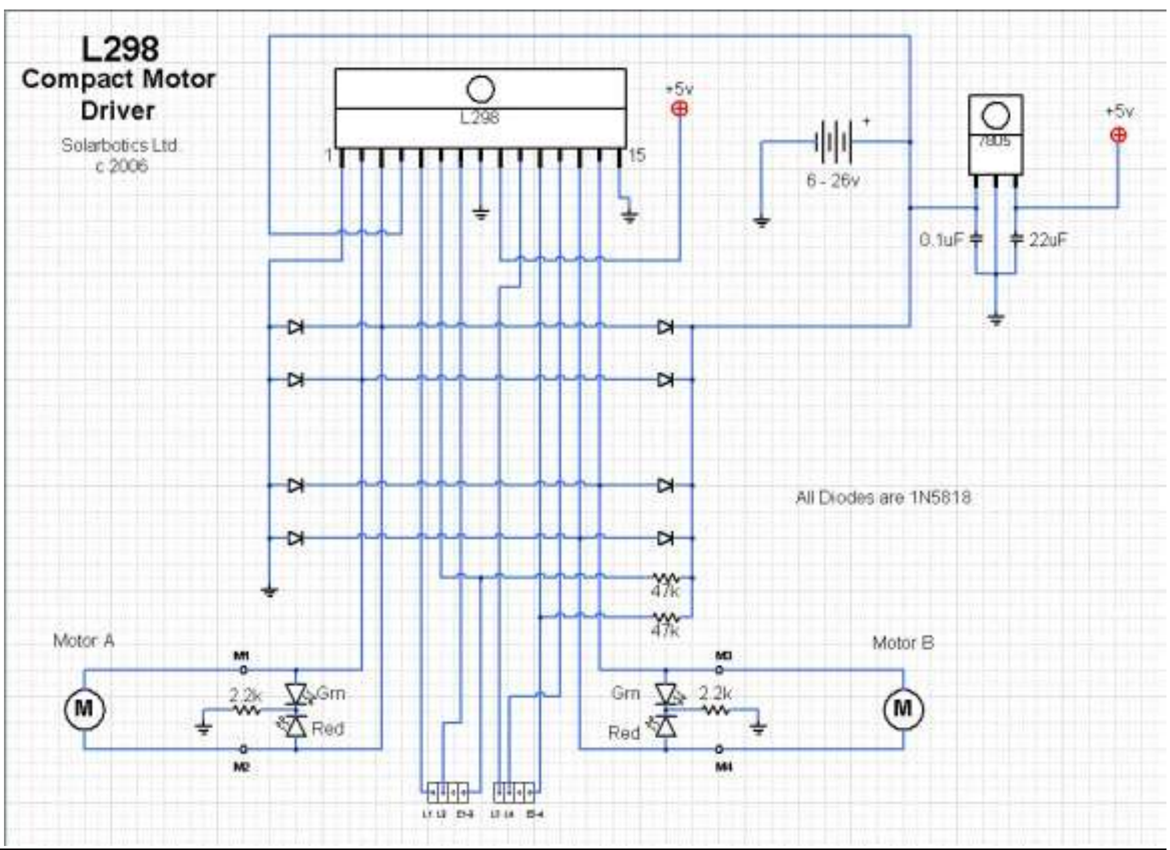
APPENDICES

APPENDIX A: CAD Drawings

APPENDIX B: Electronic Schematics





TIGER SHARK ROV WIRING CHART

ROV Connector

Location	PIN	Color		Polarity	Description
ROV		ORN		+	Port Vertical
ROV		ORN/BLU		-	Port Vertical
ROV		BLU/WHT		+	Starboard Vertical
ROV		BLU		-	Starboard Vertical
ROV					
ROV		RED		+	Port Horizontal
ROV		RED/WHT		-	Port Horizontal
ROV		GRN/WHT		+	Starboard Horizontal
ROV		GRN		-	Starboard Horizontal
ROV		WHT		+	Lights
ROV		BLK		-	Lights
ROV		GRN/BLK	GRN		Sensor
ROV		RED/BLK	RED		Sensor
ROV		BLK/WHT	BLK		Sensor
ROV		WHT/BLK	WHT		Sensor

Tether Connector

		Con	Cat5		
Tether	1	BLK		+	Main Ground
Tether	2	WHT		-	Main Power
Tether	3	RED			
Tether	4	GRN			
Tether	5	ORN			
Tether	6	BLU			
Tether	7	WHT/BLK		+	Camera Signal
Tether	8	RED/BLK		+	Audio Signal
Tether	9	GRN/BLK		-	Digital
Tether	10	ORN/BLK		+	Digital

APPENDIX C: Parts List

Tiger Shark ROV Project Parts List

MFG Part #	Description	Unit Price	Qty	Total
DEV-07914	Arduino Proto Shield Kit	$ 16.95	1	$ 16.95
PRT-08801	Breadboard Mini Self-Adhesive	$ 3.95	1	$ 3.95
COM-00100	COM-00100 Relay SPDT Sealed - Breadboard Mountable	$ 1.95	1	$ 1.95
PC-30	USB Video Capture adaptor	$ 10.79	1	$ 10.79
				$ -
	Aluminum 6061-T6 Extruded Tube 4.5" x 0.125" x 4.25" cut to 12"	$ 17.33	1	$ 17.33
	Aluminum 6061-T6 Bare Extruded Round 4.5" cut to 4"	$ 23.41	1	$ 23.41
	Aluminum 6063-T52 Extruded Angle 1" x 1" x 0.062" cut to 24"	$ 3.33	1	$ 3.33
	Aluminum 6061-T6 Bare Drawn Tube 0.25" x 0.065" x 0.12" cut to 12"	$ 2.82	1	$ 2.82
	Aluminum 6063-T52 Bare Extruded Angle Architectural 0.5" x 0.5" x 0.125" cut to 36"	$ 1.28	2	$ 2.56
	VideoRay ROV Dome	$ 10.00	2	$ 20.00
ARD-0013	Freeduino Serial v2.0 board kit Arduino Compatible	$ 16.99	1	$ 16.99
ARD-0019	Freeduino Protoshield Kit	$ 11.99	1	$ 11.99
				$ -
32903	1000gph Cartridge Bilge Pump, 3.2A @ 12V DC Draw	$ 25.89	4	$ 103.56
				$ -
GR230850	50mm, R Graupner Propeller	$ 4.30	2	$ 8.60
GR230851	50mm, L Graupner Propeller	$ 4.30	2	$ 8.60
	RS-232 to RS-485 converters	$ 8.00	2	$ 16.00
	100FT RJ45 CAT5 CAT5E ETHERNET LAN NETWORK CABLE 100 FT	$ 10.69	1	$ 10.69
9464K68	Viton® Fluoroelastomer O-Ring AS568A Dash Number 238, Packs of 5	$ 6.34	1	$ 6.34
3856T21	Diamond-Braided Polypropylene Rope 1/4" Diameter, 83# Work Load Limit, Orange 100'	$ 4.83	1	$ 4.83
	Braided PolyRope Yellow 100'	$ 5.99	1	$ 5.99
	100' 18 guage extension cord	$ 6.99	1	$ 6.99
				$ -
SW-P-DSCEX	DIY Color Security Camera w/ Bonus Wide Angle Lens	$ 39.99	1	$ 39.99
				$ -
HS-81	Hitec Micro Servo	$ 12.99	2	$ 25.98
				$ -
RB-Sbo-24	Solarbotics L298 2A 6V-50V Compact	$ 15.35	4	$ 61.40
RB-Spa-184	ATMega 328 chips	$ 5.50	4	$ 22.00
				$ -
703W-00/02	IDE Socket	$ 0.82	1	$ 0.82
516	Handle	$ 2.48	2	$ 4.96
24416	4mm standoff	$ 0.24	8	$ 1.92
SSI-LXH8080GD	LED Indicator	$ 0.47	1	$ 0.47

APPENDIX D: Equipment List

Industrial Equipment:

Grizzly Industrial G9728- Used for Machining of all pressure housing parts

Delta 6” Belt Sander- Cleanup of aluminum parts

DeWalt DW871 14” Cutoff Saw- Aluminum cutting

3-D Printer- Creation of thruster housings and mounts

Electronics and Test:

Durabook D13RY Semi-Rugged Laptop- Surface control and Display for ROV

Weller WLC-100 Soldering Station- Soldering of all electronic boards and connections.

Wavetek 16XL Multimeter- Testing and troubleshooting of electronics

Tektronix TDS220 Oscilloscope- PWM waveform analysis and troubleshooting 

Software:

Autodesk Inventor 3-D Design Software- Design of all machined parts

DeepSea Power & Light Under Pressure 3.01 Software- used for pressure hull analysis

MicroSoft Visual Basic v6.0- Surface control program

Arduino Alpha v16- ROV onboard program

APPENDIX E: Pressure Housing Analysis

TUBE plus ENDCAP values

Tube Inner Diameter : 4.2500 inches

Tube Outer Diameter : 4.5000 inches

Tube Wall Thickness : 0.1250 inches

Tube Length : 9.0000 inches

(Endcap Circular, Fixed)

Free Diameter : 4.2500 inches

Outer Diameter : 4.5000 inches

Endcap Thickness : 0.2500 inches

Combined Weight In Air : 2.29 lbs ; In Water : -3.30 lbs

Initial failure caused by Endcap failure at 0.9937 Ksi (2212.0 ft underwater)

aluminum 6061 T-6

Yield Stress : 35.0000 Ksi

Poisson's ratio : 0.3000

Density : 0.0980 lb/cu in

Elastic Modulus : 10.0000 Mpsi

TUBE CONFIGURATION

(External Pressure)

Inner Diameter: 4.2500 inches

Outer Diameter: 4.5000 inches

Wall Thickness: 0.1250 inches

Tube Length : 9.0000 inches

Weight in air : 1.52 lbs

Weight in water : -3.79 lbs

Failure mode: Thin wall collapse

Collapse pressure 1.5332 Ksi (3413.0ft underwater)

Thick wall crush at 1.8904 Ksi (4208.2 ft underwater)

Thin wall collapse mode : 3 nodes

aluminum 6061 T-6

Yield Stress : 35.0000 Ksi

Poisson's ratio : 0.3000

Density : 0.0980 lb/cu in

Elastic Modulus : 10.0000 Mpsi

Tube distortion values

Pressure	Depth	Stress	delta ID	delta OD	delta length
(Ksi)	(ft)	(Ksi)	(inches)	(inches)	(inches)
0.1000	222.6	1.7500	0.0007	0.0007	0.0003

0.2000	445.2	3.5000	0.0013	0.0013	0.0006
0.3000	667.8	5.2500	0.0020	0.0020	0.0009
0.4000	890.4	7.0000	0.0026	0.0026	0.0013
0.5000	1113.0	8.7500	0.0033	0.0033	0.0016
0.6000	1335.6	10.5000	0.0039	0.0039	0.0019
0.7000	1558.2	12.2500	0.0046	0.0046	0.0022
0.8000	1780.8	14.0000	0.0052	0.0052	0.0025
0.9000	2003.4	15.7500	0.0059	0.0059	0.0028
1.0000	2226.1	17.5000	0.0065	0.0065	0.0031
1.1000	2448.7	19.2500	0.0072	0.0072	0.0035
1.2000	2671.3	21.0000	0.0078	0.0078	0.0038
1.3000	2893.9	22.7500	0.0085	0.0085	0.0041
1.4000	3116.5	24.5000	0.0091	0.0091	0.0044
1.5000	3339.1	26.2500	0.0098	0.0098	0.0047
1.6000*	3561.7	28.0000	0.0104	0.0104	0.0050
1.7000*	3784.3	29.7500	0.0111	0.0111	0.0054
1.8000*	4006.9	31.5000	0.0117	0.0117	0.0057
1.9000*	4229.5	33.2500	0.0124	0.0124	0.0060
2.0000*	4452.1	35.0000	0.0130	0.0130	0.0063

* = after housing failure

ENDCAP CONFIGURATION - Endcap Circular, Fixed

Free Diameter : 4.2500 inches

Outer Diameter : 4.5000 inches

Endcap Thickness : 0.2500 inches

Weight in air : 0.39 lbs Weight in water : 0.24 lbs

Endcap failure at 0.9937 Ksi (2212.0 ft underwater)

aluminum 6061 T-6

Yield Stress : 35.0000 Ksi

Poisson's ratio : 0.3000

Density : 0.0980 lb/cu in

Elastic Modulus : 10.0000 Mpsi

Endcap distortion values (* = after failure)

Pressure	Depth	Max.Stress	Max.Shear	Max.Seat	C.defln
(Ksi)	(ft)	(Ksi)	(Ksi)	(Ksi)	(inches)
0.1000	222.6	3.5222	0.4250	0.9257	-0.0022
0.2000	445.2	7.0444	0.8500	1.8514	-0.0045
0.3000	667.8	10.5666	1.2750	2.7771	-0.0067
0.4000	890.4	14.0887	1.7000	3.7029	-0.0089
0.5000	1113.0	17.6109	2.1250	4.6286	-0.0111
0.6000	1335.6	21.1331	2.5500	5.5543	-0.0134
0.7000	1558.2	24.6553	2.9750	6.4800	-0.0156
0.8000	1780.8	28.1775	3.4000	7.4057	-0.0178
0.9000	2003.4	31.6997	3.8250	8.3314	-0.0200
1.0000*	2226.1	35.2219	4.2500	9.2571	-0.0223

1.1000*	2448.7	38.7441	4.6750	10.1829	-0.0245
1.2000*	2671.3	42.2663	5.1000	11.1086	-0.0267
1.3000*	2893.9	45.7884	5.5250	12.0343	-0.0289
1.4000*	3116.5	49.3106	5.9500	12.9600	-0.0312
1.5000*	3339.1	52.8328	6.3750	13.8857	-0.0334
1.6000*	3561.7	56.3550	6.8000	14.8114	-0.0356
1.7000*	3784.3	59.8772	7.2250	15.7371	-0.0379
1.8000*	4006.9	63.3994	7.6500	16.6629	-0.0401
1.9000*	4229.5	66.9216	8.0750	17.5886	-0.0423
2.0000*	4452.1	70.4438	8.5000	18.5143	-0.0445

* = after housing failure

HEMISPHERE CONFIGURATION

(External Pressure)

Inner Diameter : 3.5000 inches

Outer Diameter : 3.7500 inches

Wall Thickness : 0.1250 inches

Weight in air : 0.11 lbs

Weight in water : -0.40 lbs

Hemisphere collapse at : 0.6944 Ksi (1545.8 ft underwater)

Thin wall collapse at : 0.6944 Ksi

Thick wall collapse at : 0.9971 Ksi

Seat collapse at : 1.0311 Ksi

acrylic

Yield Stress : 8.0000 Ksi

Poisson's ratio : 0.4000

Density : 0.0430 lb/cu in

Elastic Modulus : 0.4000 Mpsi

Hemisphere distortion values

Pressure	Depth	Stress	delta ID	delta OD	seat
(Ksi)	(ft)	(Ksi)	(inches)	(inches)	(Ksi)
0.1000	222.6	0.7250	0.0039	0.0039	0.7759
0.2000	445.2	1.4500	0.0079	0.0079	1.5517
0.3000	667.8	2.1750	0.0118	0.0118	2.3276

0.4000	890.4	2.9000	0.0158	0.0158	3.1034
0.5000	1113.0	3.6250	0.0197	0.0197	3.8793
0.6000	1335.6	4.3500	0.0237	0.0237	4.6552
0.7000*	1558.2	5.0750	0.0276	0.0276	5.4310
0.8000*	1780.8	5.8000	0.0315	0.0315	6.2069
0.9000*	2003.4	6.5250	0.0355	0.0355	6.9828
1.0000*	2226.1	7.2500	0.0394	0.0394	7.7586
1.1000*	2448.7	7.9750	0.0434	0.0434	8.5345
1.2000*	2671.3	8.7000	0.0473	0.0473	9.3103
1.3000*	2893.9	9.4250	0.0512	0.0512	10.0862
1.4000*	3116.5	10.1500	0.0552	0.0552	10.8621
1.5000*	3339.1	10.8750	0.0591	0.0591	11.6379
1.6000*	3561.7	11.6000	0.0631	0.0631	12.4138
1.7000*	3784.3	12.3250	0.0670	0.0670	13.1897
1.8000*	4006.9	13.0500	0.0710	0.0710	13.9655
1.9000*	4229.5	13.7750	0.0749	0.0749	14.7414
2.0000*	4452.1	14.5000	0.0788	0.0788	15.5172

* = after housing failure

APPENDIX F: Software

Arduino Code