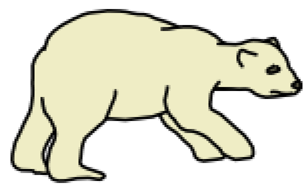
University of Alaska Fairbanks

Polar Submersibles



2010 M.A.T.E. ROV Competition

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Abstract

This is our 4th year competing in the MATE ROV Competition and our submersible is sleeker and lighter than ever before. We are Polar Submersibles, and we continue our tradition of low-cost, home-built underwater ROVs. We use sophisticated software and electronics that we write, design, test, and etch ourselves from home. We did not use any commercial ROV parts and even built our own thrusters from scratch. This year's ROV is our cheapest yet.

This year we split our electronics up into two parts to keep most of the complexity on land and to keep the electronics footprint on the ROV compact. These space savings translate to a smaller, lighter, and better-handling ROV. Agility and a compact size are especially important given the tight confines of the cave and the delicate nature of the tasks this year.

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The Arctic Penguin

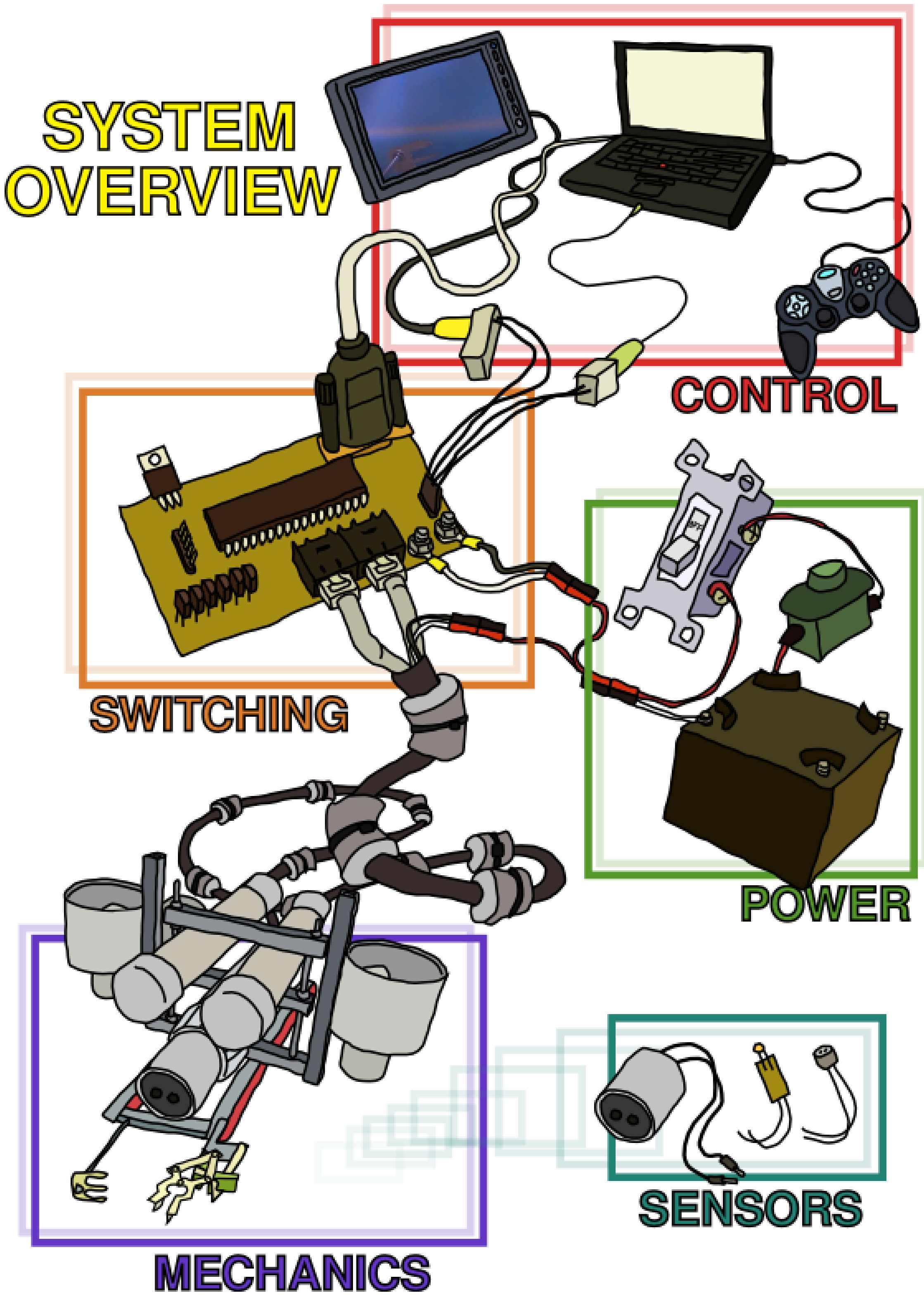
Design

Rationale

This year, ROVs must fit through the 80 cm square cave opening, and the tasks require fine control, not brute strength. Accordingly, we moved much of the electronic complexity out of the ROV and onto dry land. This decision kept the electronics housing small and modular, which met the space constraints better and freed us to test out different prototype designs. And because we only needed to move the electronics instead of eliminating them, we can still make use of proportional software control, which is even more important for these high-precision challenges.

We built many prototypes to test our ideas and track changes to our circuit designs and software using git for version control:
http://github.com/substack/underwater-rov-2010

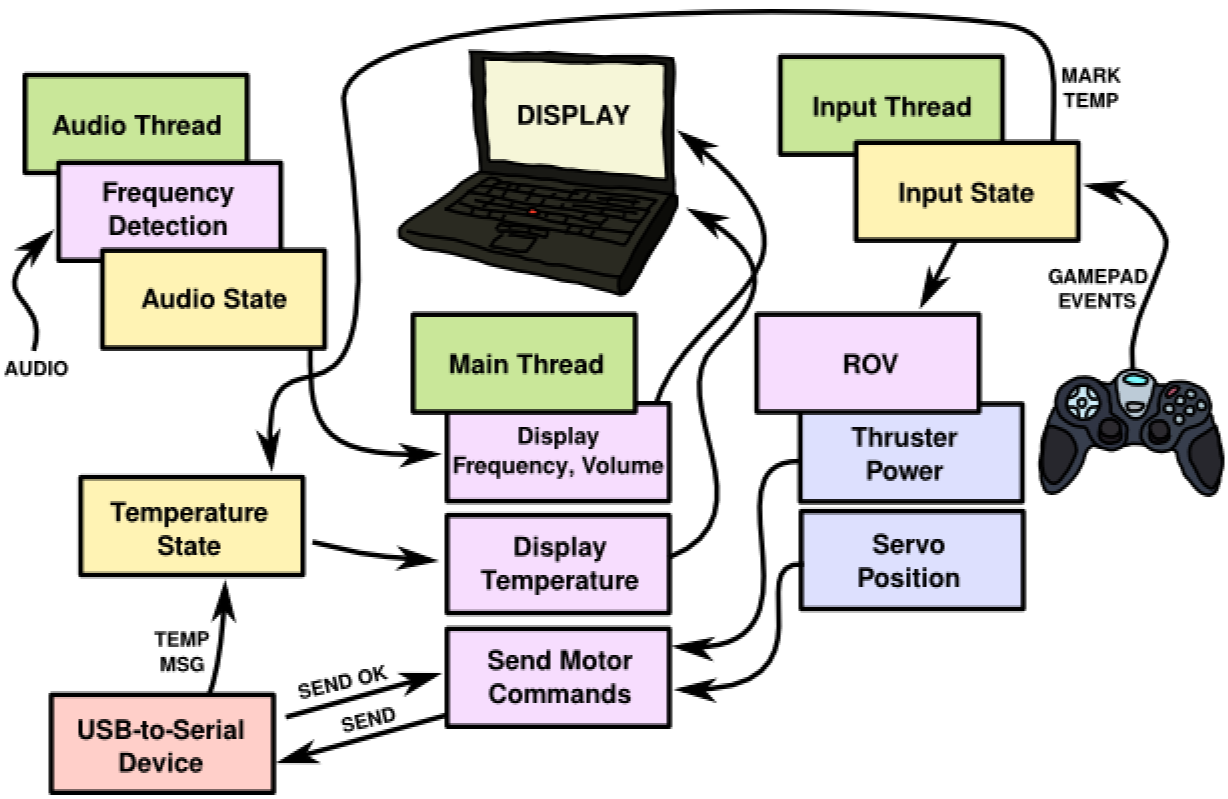
Overview



SYSTEM OVERVIEW
CONTROL
SWITCHING
POWER
SENSORS
MECHANICS

Control System

Control Software Data Flow Diagram



The software on the laptop computer sends motor commands based on user input from the gamepad, calculates the frequency of audio from the hydrophone, and records temperature information from the thermistor. The control software is written in Haskell, a purely functional programming language. Modules from Hackage, a repository of Haskell software packages, are used to handle concurrency, interface with the gamepad, read microphone data, and to calculate the dominant audio frequency.

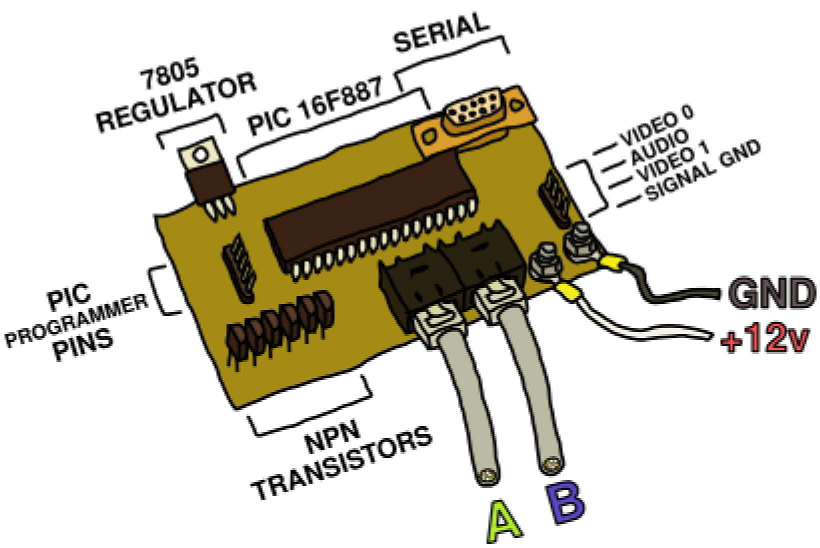
Meanwhile, a C program on the PIC 16F887 sets the PORTA register based on the motor power levels sent over the serial link from the laptop. Proportional control of the motors is obtained through pulse-width modulation on the motor signal lines. Surprisingly, the relays that switch the thrusters on and off can switch several hundred times per second.

Periodically, the PIC sends temperature data back to the computer over the serial link. The PIC obtains this data by querying the resistance on its E2 pin, which is wired to the thermistor across the tether. This raw value is interpolated to degrees Celsius by the laptop control software using experimental calibration data.

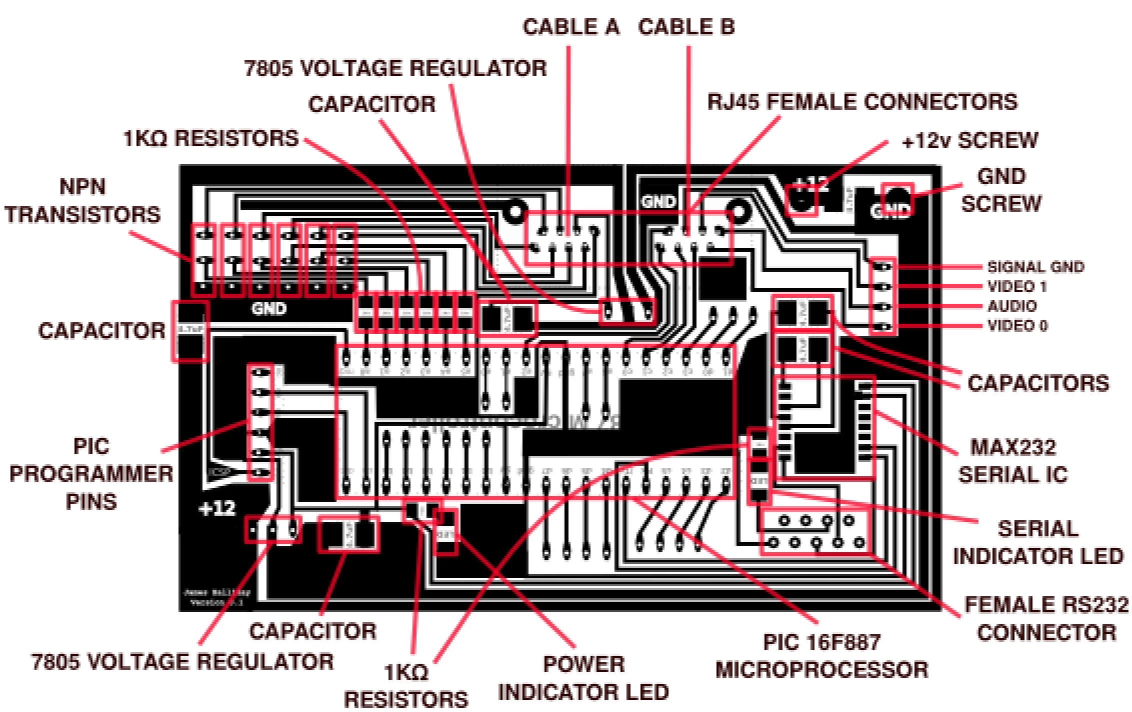
Switching

Topside Board

Topside Board Top View



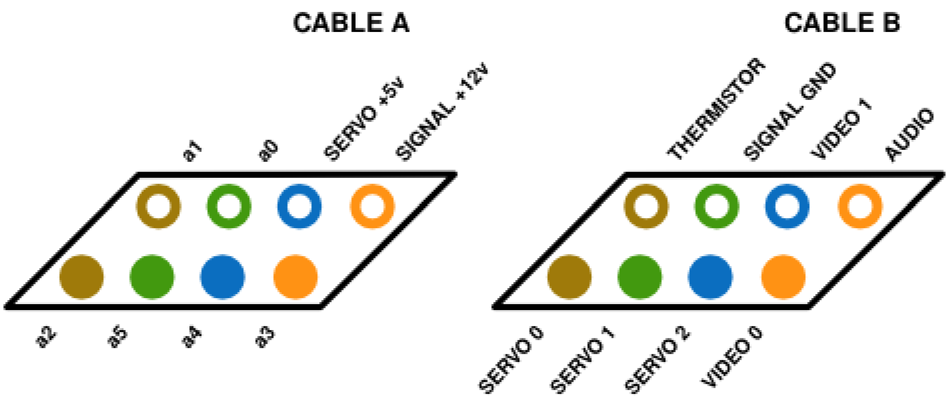
Topside Board Schematic



The topside circuit board sits near the laptop computer above the water and communicates with the computer through a serial-to-USB cable. Signals from the serial cable are managed by the MAX 232 serial chip, which is wired into the TX and RX pins of the PIC 16F887 microprocessor. The topside board has two female RJ45 connectors for the cat5 cables coming off the tether.

The PIC, MAX 232, and servos all need 5 volts, so two 7805 voltage regulators provide 5 volts from the 12 volt connection. The servos run on their own 7805 to isolate noise. Each of the regulators has a capacitor between GND and +5v to further buffer noise away.

Topside Cabling



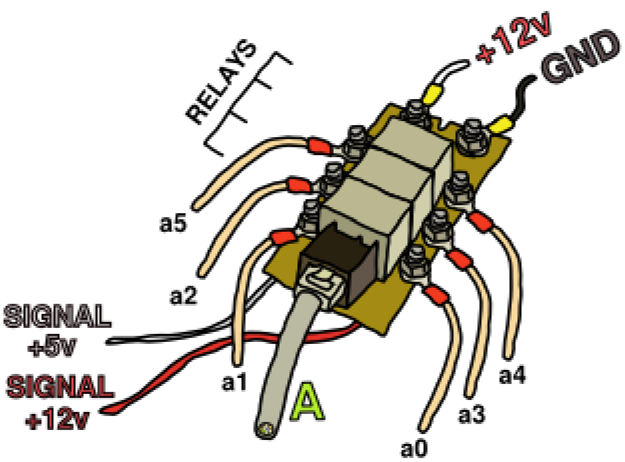
The a[0..5] wires on cable A map to the PIC's PORTA register. The PIC can't supply enough current to drive the relays on the ROV itself, so it signals a row of transistors through a row of 1KΩ resistors in order to step up the current on the motor control wires. The 6 motor control signals run alongside servo power and motor control ground on cable A.

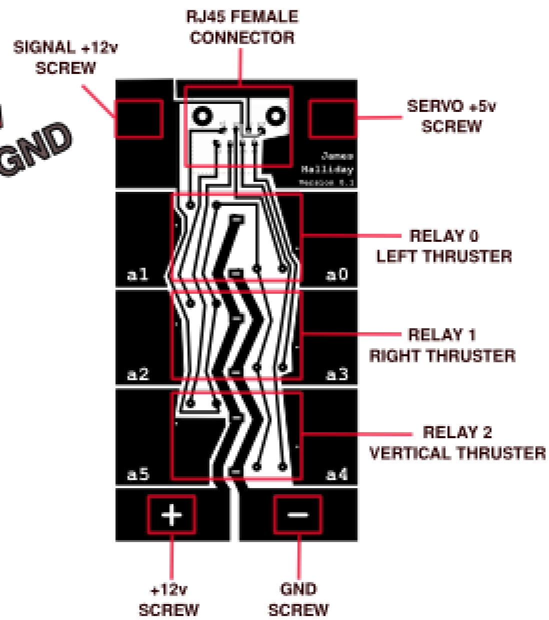
Cable B carries the servo control and sensor signals. As a consequence, the video flickers somewhat when the servos are running, but this effect is mitigated by an additional capacitor added between signal ground and signal +12v inside the electronics housing on the ROV.

Relay Board

Relay Board Top View

Relay Board Schematic





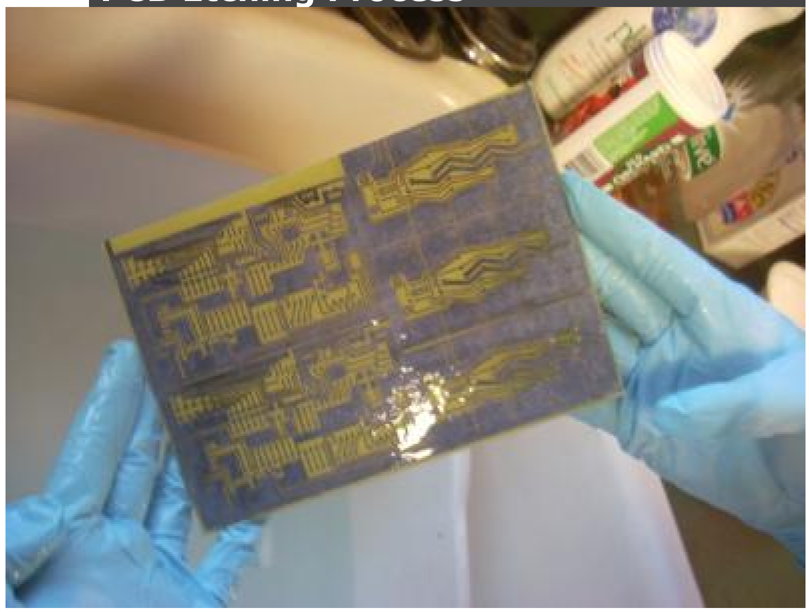
The relay board switches the thrusters for the motor control inputs on cable A. Each relay drives one set of thrusters bidirectionally. For instance, when a0 is off and a1 is on, the left thruster will spin forwards, and when a0 is on while a1 is off, the left thruster spins backwards. When a0 and a1 are both on or both off, nothing happens. The relays switch the +12v and GND at the bottom of the schematic. By isolating the motor power from all the other systems, more voltage could potentially be used at a later and the noise and induction spikes from the thrusters are kept away from the sensitive components.

Signal ground and signal +12v are patched off for use by the camera system and servos. A capacitor is soldered between these two leads off the board.

The relays are much cheaper and much easier to solder than the surface-mount automotive H-bridges we used previously in 2008.

Printed Circuit Board Design and Fabrication

PCB Etching Process



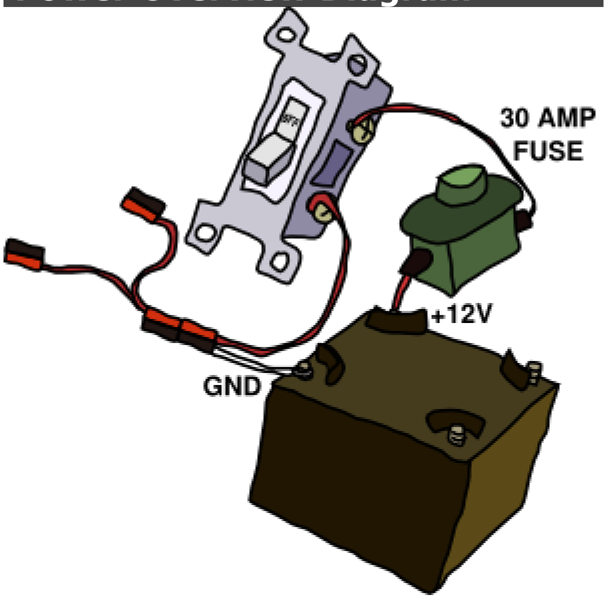
The circuit boards were made using the toner-transfer etching method known by our mentor as the "Gootee method". This method is cheap and has a fast turnaround time, but it is somewhat labor-intensive. The method follows.

First, draw a circuit board in a vector graphics program such as Inkscape with black regions where you wish copper to be. Next, print the design backwards onto a sheet of glossy paper with a laser printer. Magazine print seems to work very well. Next, iron the design onto the copper-side of a sheet of copper-clad fiberglass, pressing down with the iron and distributing heat evenly. After ironing, soak the sheet in water and peel away the paper, leaving only the toner. A toothbrush is useful to remove the few remaining bits of paper. With splash goggles and nitrile gloves, carefully immerse the board in a mixture of 2 parts 3% hydrogen peroxide and 1 part 28% hydrochloric acid, sold as muriatic acid in hardware stores. Gently rock the mixture until all the exposed copper is dissolved. Wash the board with water, then use acetone to dissolve the toner. The board is now etched!

Using this method, we were able to etch multiple relay and topside boards onto a single sheet of copper-clad fiberglass in an afternoon. Both the relay and topside board schematics in the previous sections minus the red labels are the actual images we used for etching.

Power

Power Overview Diagram



The power system is very simple. 12 volts DC powers both the topside board and the thrusters. Lower voltages are safer and less corrosive for our electrical traces if they get wet while powered up. A 30 amp fuse protects against shorts.

We recently purchased a DC-to-DC power brick that can convert the 48 volts at the venue into the 12 volts that our systems require. We looked into building this converter ourselves, but heat dissipation is a big issue.

Mechanics

Thrusters

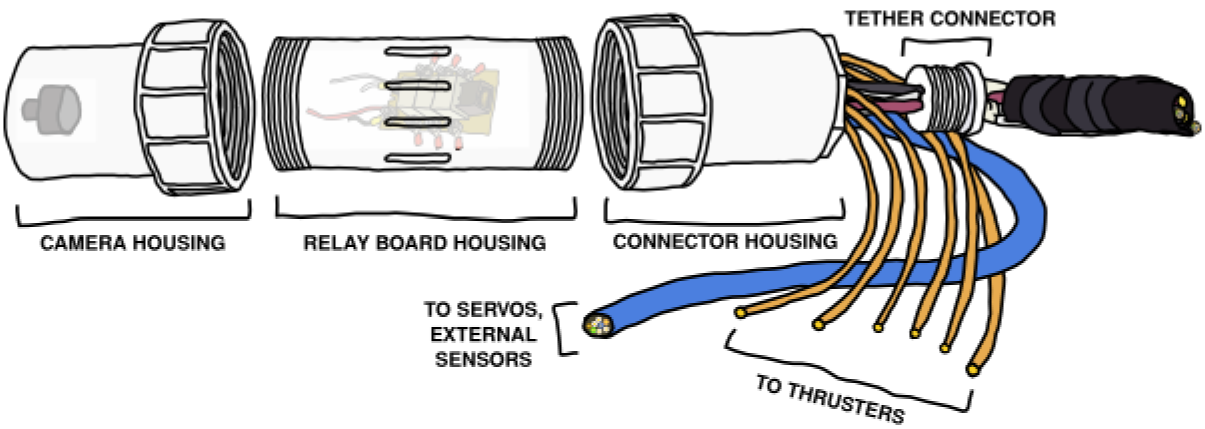
Our thrusters are from our 2008 design. They consist of 1250 Attwood bilge pump motors, homemade aluminum propellers, and PVC cowlings for increased thrust as well as safety. The bilge pumps are a cheap source of sealed electrical motors. We stripped away the bilge pump housings and attached our propellers with screws and epoxy to the rotors. We cut the aluminum propellers out of salvaged aluminum sheets and modeled the design after office fan blades. Two years later, the thrusters still work dependably.

Electronics Housing

The electronics housing consists of a PVC repair coupling with threaded ends and two PVC screw connectors. O-rings inside the screw caps hold a seal underwater, although the PVC screw connectors need to be very tight. The camera housing on the front looks out through a circular cut of lexan, the relay board housing stores the relay board and miscellaneous electronics, and the connector housing provides more room for cabling inside.

Owing to our simplified on-board electronics this year, we fit the camera and relay board all into one enclosure. The tether connector screws into the connector housing and wires along the outside ring of the connector housing run out to the thrusters. A blue cat5 cable runs from the electronics inside out to the servos, hydrophone, and thermistor. This cable was the source of a mysterious leak until we sealed both ends more properly.

Electronics Housing Diagram



Frame

The frame went through three primary iterations. The first was made from PVC which was easy to cut and work with to get an overall design. The main drawbacks of PVC were weight and cost. The structural weakness of PVC compared to metal meant that more was necessary, driving up the overall weight. The price of the many PVC fittings also drove the cost up.

The next frame was built out of aluminum. We chose aluminum for its light weight, low cost, and resistance to corrosion. We saved money by buying a large bulk stick of aluminum fro a local supplier instead of purchasing pre-cut pieces from a hardware store. Nuts and bolts didn't secure the frame well enough so we welded it together. However, gas-welding aluminum is difficult! With a little practice however we were able to fuse the metals well enough. Aluminum's low melting temperature and high heat transfer qualities proved difficult. The frame would bend unless we let it cool on a level platform. The aluminum would also sometimes melt away before a weld could form.

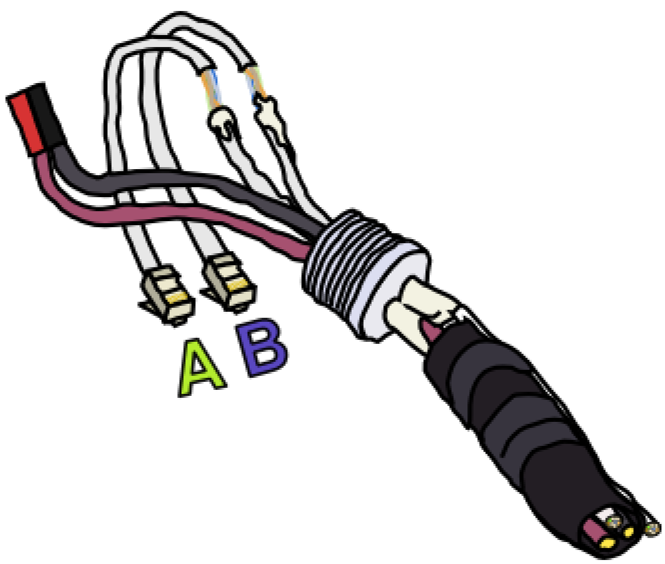
After building the second frame, we realized that much of the material was unnecessary. We looked at the components that had to be mounted onto the frame and concluded that a single set of cross members on two tall screws protruding from a base would cut the cost, decrease the weight, and make access to the main housing easier. We welded the third frame up using the techniques we developed welding the second one.

Buoyancy

Buoyancy is provided by two PVC tubes 5.1 cm in diameter and 50.8 cm in length with sealed end caps for static neutral buoyancy. Depth control is provided by just the thrusters. We cut the tubes extra long and trimmed them down until the ROV was neutrally buoyant.

Tether

Tether Screw Connector



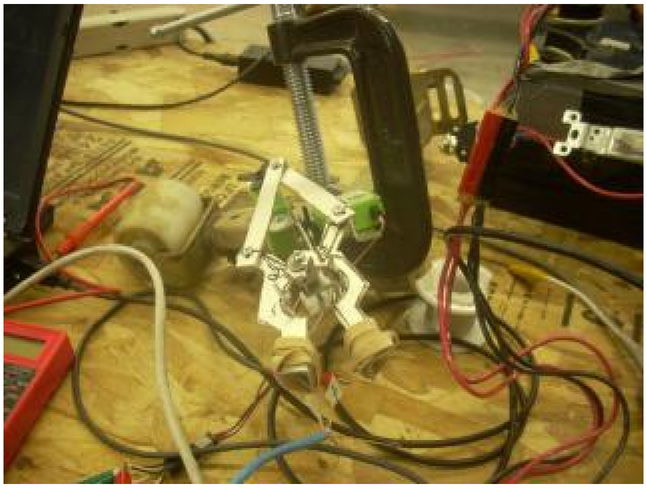
We used the same tether from previous years, but strung along an extra cat5 network cable along the outside. At somewhat regular intervals, we tied segments of buoyancy foam to the tether to maintain approximately neutral buoyancy. The foam segments also secure the extra cat5 cable along the outside.

The end of the tether has PVC screw thread that hooks into the electronics housing, where the cables are routed internally.

In order to stop leaks, we used epoxy and plumber's goop to seal the connector and the cat5 cables. We found that water flows well through cat5 cabling so our seals protect against small nicks in the tether.

Tools

Robotic Arm



We have two main mission tools at the time of this writing. A piece of cut aluminum in the shape of a fork is mounted to threaded rod on the front of our ROV. With this fork, we can quickly pull the J-bolts from the platform mission. On the other side, we built a manipulable arm out of two servos, sheet aluminum scraps, and some screws. This arm will help us collect the crustaceans in the cave and to carry the "T" from the undersea cable task.

We water-proofed the servos with epoxy along the outside. The wiring is in place for an additional servo should the need arise. This additional servo may prove useful for the bacterial mat task, which we haven't had time to implement yet.

Sensors

Cameras

Our camera system is contained in the electronics housing to keep everything simple. Due to our difficulties with failing cameras in 2008, we chose slightly higher quality cameras this year. Additionally, we chose cameras with wide fields of view in order to get a better feel for the whole course. The cameras are after-market back-up cameras normally used for trucks with trailers. The quality of the cameras are exceptional and the 160 degree wide angle gives the ROV pilot better view of the whole landscape. Two cameras were installed next to each other facing forward with one camera rotated 90 degrees. This created redundancy and increased the field of view with one camera's vision sweeping the horizontal 160 degrees and the other sweeping the vertical 160 degrees.

Thermistor

We are using the same thermistors to measure the temperature of the simulated hydrothermal vents, but this year we use our primary microprocessor on land to read the resistance of the thermistor directly across the entire length of the tether.

Hydrophone

A single line for audio extends the length of the tether into our laptop computer where the frequency and volume is calculated. Unfortunately, the microphones we purchased can only pick up the high-frequency source from several centimeters away underwater. We are still searching for better microphones.

Expenses

All prices in US dollars. We do not factor shipping or tax into the estimates.

ROV Unit Expenses

The price of materials in one ROV not including spare parts or excess materials.

Item	Unit Price	Quantity	Total Cost	Year
Thrusters	$35.00	4	$120.00	2008
Aluminum for frame	$2.95 / m	2.3 m	$6.78	2010
PVC coupler (main housing)	$8.00	1	$8.00	2010
Tether power cables	$3.28 / m	30.5 m	$100.00	2007
Tether mesh and buoyancy	$30.00	1	$30.00	2007
PIC 16F887	$3.00	1	$3.00	2010
MAX232 serial IC	$1.00	1	$1.00	2010

7805/7809 voltage regulator	$0.40	3	$1.20	2010
NPN transistors	$0.50	6	$3.00	2010
A4 Copper-clad fiberglass	$1.00	1	$1.00	2010
Muriatic acid (etching)	$2.67 / L	0.5 L	$1.32	2010
Hydrogen peroxide (etching)	$1.06 / L	1 L	$1.06	2010
Servo	$3.00	3	$9.00	2010
Relay	$0.50	3	$1.50	2010
DC/DC Converter	$86.00	1	$86.00	2010
Cameras	$30.00	2	$60.00	2010
Saitek gamepad	$6.00	1	$6.00	2010
Total			**$438.86**	

Research, Development, and Excess Material Expenses

Prices for experimental purposes and included excess materials and spare parts.

Item	Cost
Aluminum for framing	$30
PVC coupler	$16
Muriatic acid for etching	$10
Hydrogen peroxide for etching	$4
Total	**$60**

Travel Costs

Item	Unit Cost	Quantity	Total Cost
Airfare	$631.40	4	$2525.60
Lodging	$1,022.56	1	$1,022.56
Total			**$3548.16**

Troubleshooting Challenges

Leaks

We chose to use a PVC coupler for our electronics housing, as we had done before for previous ROVs. Based on our past successes , we hoped that we would not need to worry about leaks in the main housing, only the tether entry points and the camera view port. We took many steps to ensure these points of failure would not leak. However, the main housing developed an intermittent leak, which in some respects made the problem more difficult to diagnose.

We first tested each part of the housing separately in order to isolate which components might be responsible for the intermittent leak. At first, we suspected that the PVC coupler wasn't providing a reliable water-tight seal. To test this hypothesis, we submerged the sealed coupler underwater for extended periods and simulated stresses on the joints that occur during ROV operation. Our camera housings were tested in a similar manner. However, the camera housings and PVC couplers did not leak during these tests.

Next we lined the housing with paper towels in order to better locate the region of the leak in the assembled ROV. After submerging, we found slightly more wetness towards the back of the housing where the wires enter and exit. To narrow down which wires might be responsible, we pressurized the enclosure with an air compressor. The blue cat5 cable that carries servo and sensor wires very audibly leaked air during this test. The sealant we had applied to the cable was not effective.

Cat-5 cable has an outer casing around 4 pairs of wires with plenty of space for water to run through, even with our use of plumber's goop. Upon further experimentation, we learned that goop shrinks and retracts when dry, which created gaps in our seal. We depressurized the enclosure with a vacuum pump and used the vacuum to pull epoxy into the troublesome cable.

Electronics

We modified our electronics extensively after our circuit boards had been etched to solve problems as they arose. For instance, as soon as our microprocessor, transistors, and resistors were soldered to our topside board, we found that the relays weren't switching with a test program designed to switch them on and off at an audible rate. We measured the signal lines with a multimeter and saw the desired pattern, but finally noticed that the wiring was backwards along our bank of transistors in our initial design. The relay control wires need pulled down to ground, not pulled up to +12v. Rather than etch a new board right away, we saved time by cutting traces on our circuit board with a razor and jumpered over ground from a nearby trace. Before we did this, we verified with spare parts on a breadboard that this solution would work.

Project Conclusions

Future Improvements

A larger housing could allow more room for wiring and electronics in addition to providing buoyancy. This change would make the frame mechanically simpler too, since we wouldn't need to secure as many objects.
Further, a larger housing would also give more of a buffer if a leak did occur, since a larger housing would take longer to fill with water, and electronics could be placed towards the top of the enclosure.

When sealing the tether connection, it would be far simpler and more water-tight to use a single large hole filled with epoxy. We could also strip the wires through the length of the epoxy brick to prevent water from seeping inside the outer casing. This approach would have eliminated our problem with the leak through the blue cat5 cable.

Skills

This year we had access to a lathe in our workshop, which was useful for modifying the inside and outside diameters of tubing. We were able to use the lathe on a number of parts that had been made before but with cruder methods. We also used the lathe to build tools useful for ROV construction.

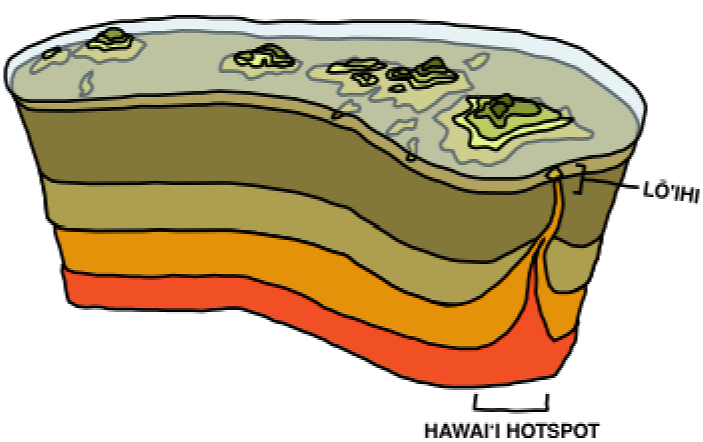
We gas-welded aluminum for this year's project and learned some of its caveats first-hand. In prior contests, we mostly used bolts to hold the frame and other parts together. This year, the welded frame provided greater strength and decreased clutter from bolts. We had to practice in order to create clean, functional welds, but the ability to weld will come in useful in future contests and other applications.

Reflections

Incremental development was critical for this highly experimental project. With so many unknowns, our assumptions needed to be tested early and often to counter the high levels of uncertainty. Our emphasis on rapid prototyping gave us partial functionality early enough that we were able to test out many of our ideas in the working system right away instead of making speculative design decisions or enduring long waits between choices and results. For instance, we made many improvements to the frame design by observing each model's operation in the water. We were also able to catch many electrical issues through continuous testing as we built and modified the circuit boards.

Lō'ihi Seamount

Lō'ihi Seamount Map



The Lō'ihi seamount is the newest volcano in the Hawaiian-Emperor seamount chain, which stretches from Lō'ihi all the way to the Aleutian Trench.

As the Hawai'i hotspot drifts southeast with respect to the Pacific Plate, new seamounts form and chemosynthetic microorganisms flourish along the hot, mineral-rich waters of the hydrothermal vents.

In 1996 when Pele's Dome collapsed, these large bacterial mats along with dissolved minerals and debris obstructed visibility for underwater cameras and submersibles sent to study the changes to Lō'ihi seamount. Lō'ihi's depth and subsequent low-oxygen environment results in high dissolved iron content. This dissolved iron is fed on by large communities of iron-oxidizing bacteria that form large jelly-like mats.

Resources

Etching Printed Circuit Boards the Gootee Way
http://www.cs.uaf.edu/2007/fall/cs441/lecture/10_11_pcb.html
(Mentor Orion Lawlor's writeup of the toner-transfer method)

Extremophiles from hydrothermal vents: Lo'ihi Submarine Volcano, Hawai'i
http://www.soest.hawaii.edu/HURL/extremophile.html

Loihi Submarine Volcano: a unique, natural extremophile laboratory
http://www.oar.noaa.gov/spotlite/archive/spot_loihi.html

Scientists Observe Collapsed Dome of Undersea Volcano Loihi
http://www.publicaffairs.noaa.gov/pr96/oct96/noaa96-69.html

Geomicrobiology of neutrophilic iron-oxidizing bacteria at Loihi Seamount
http://astrobiology.nasa.gov/nai/library-of-resources/annual-reports/2007/uh/projects/geomicrobiology-of-neutrophilic-iron-oxidizing-bacteria-at-loihi-seamount/

Acknowledgments

We would like to thank our mentor Orion Lawlor who let us use his shop, his tools, and provided guidance. In Alaska, warm places to work are hard to find, and without the shop our progress would have been far slower. Orion also invested much of his time helping us with this project. He even built us a small pond in order to test the ROV, and that's just short of moving mountains for us. Thanks Orion!