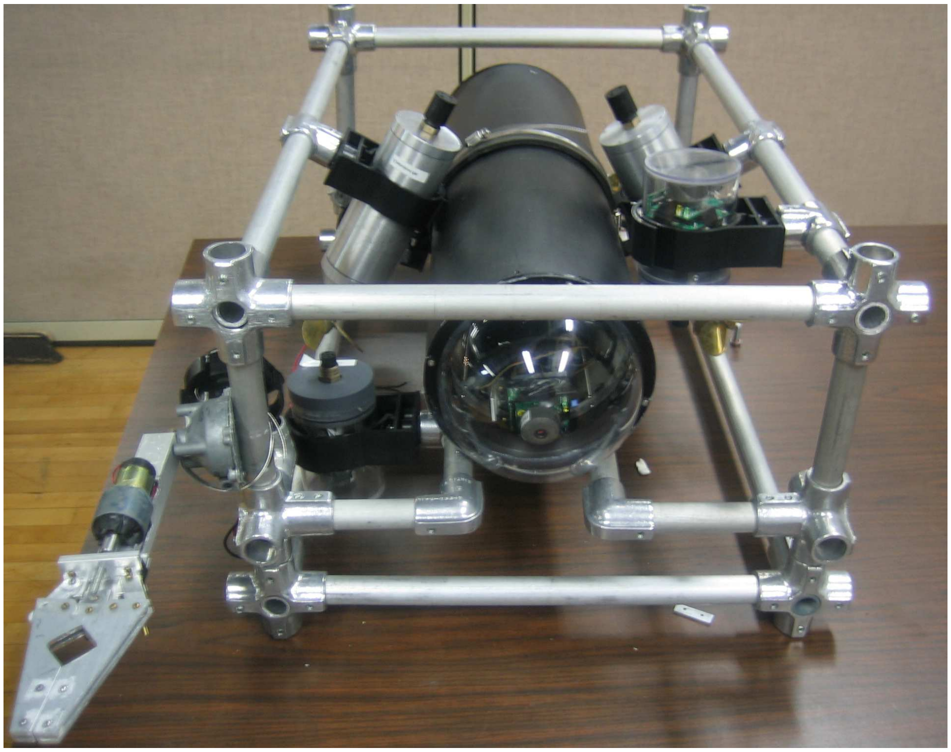
“PantheROV III”

ROV Team
at
University of Wisconsin-Milwaukee
Explorer Class

MATE International ROV Competition
Spring 2007



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Abstract

The main goal of this project is to engineer a Remotely Operated Vehicle (ROV) capable of operating under simulated polar conditions at the Marine Institute in St. Johns, Newfoundland, Canada. The ROV must complete three missions with tasks that resemble those in industry. First, the ROV must attach a messenger line to a buoy anchor for retrieval. Second, the ROV must complete several oceanographic tasks including obtaining biological samples and deploying a Passive Acoustic Sensor (PAS). Lastly, the vehicle must perform a task seen in the oil industry; replacing a gasket on an underwater wellhead.

PantheROV III is a redesign of last year's entry, PantheROV II. The main aluminum dry hull is now anodized for corrosion protection; the thruster housings are adapted from relatively problematic dynamic seals to strong magnetically coupled systems. The frame is upgraded from PVC components to corrosion resistant aluminum piping with SpeedRail(R) interconnects. The main internal pan-tilt camera mount is now a servo driven, two ring design, rapid prototyped from ABS plastic. A mechanical arm with a single shoulder joint and all purpose gripper is used for all object manipulation.

The electronics underwent a major system redesign. The major fallback to PantheROV II was its under designed motor drivers and lack of internal electrical protection which led to catastrophic failure. Our solution is a well designed and tested opto-isolated control and motor driver circuit which operates reliably under similar conditions where the old circuit failed. The vehicle brain remains a Rabbit microcontroller.

Design Rationale

Thruster:

The thruster design for the PantheROV III revolves around the use of a magnetic coupling to reduce friction and eliminate the possibility of a dynamic seal leak. In previous thruster housing designs, a spring loaded lip seal was used to seal the drive shaft. This seal generated large amounts of friction because of the rubber contacting the steel shaft. This seal was also susceptible to leaking if a shaft is mis-aligned. The magnetic seal eliminates friction from contact and also can adjust for 3 degrees from parallel and up to 0.6cm of misalignment between each half of the couple.

Figure 1 – Magnetic Couplings

The thruster housing is a pressure can with an o-ring seal on each end cap. Astroflight Cobalt 40 electric motors are mounted in the pressure can with one half of the magnetic couple attached to the motor shaft. The other half of the couple is bolted to the main drive shaft, which is attached to a propeller.

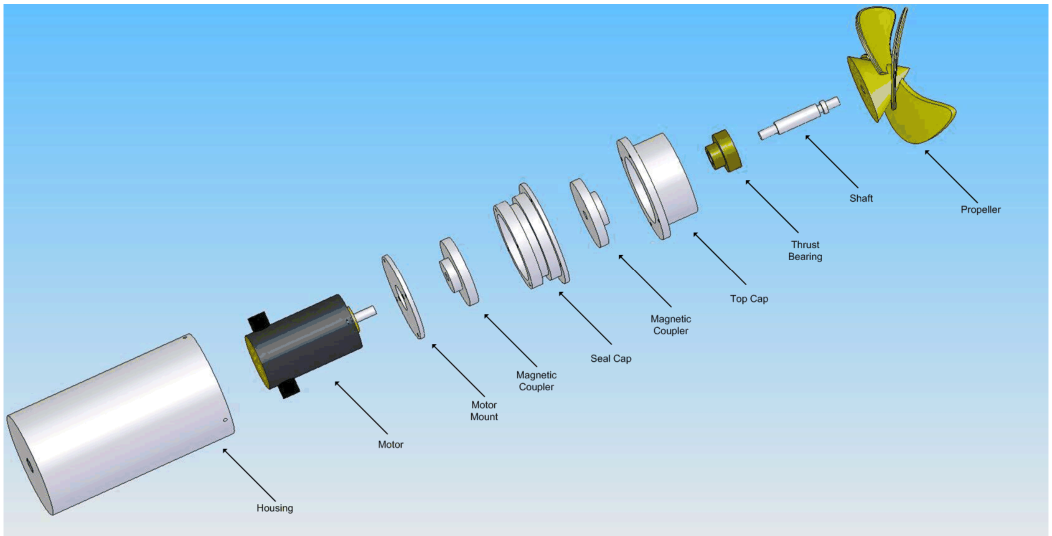

Figure 2 – Exploded View of Thruster Housing

To maximize the torque transfer through the coupling, the distance between the two halves must be the smallest distance possible. The total distance between the two thrusters is 0.3cm with only 0.15cm of aluminum between them. The couples can handle up to 96 in-oz of torque, which is greater than the ~14 in-oz. of torque the motors create. The motors create 1.99in-oz per amp, and are running at ~7 amps.

Another feature of the magnetic coupling is that it acts as a clutch. This can be problematic upon initial acceleration or reversing thrust, but it is corrected with a gradual acceleration in the control system. Slower acceleration rather than an abrupt activation allows the magnets to catch and transmit power. The benefit to this clutch system is that if something gets caught in the propellers, the propeller will stop without stalling the motor. Motor stall is the point at which the motor will draw maximum current, which could exceed the current restrictions and/or damage the motor drivers. By allowing the motor to continue to spin, the stall condition is avoided.

The Astroflight Cobalt 40 motors (100) are high power motors capable of running on 12-24V. While loaded in the water the motors draw ~7amps. (101)

The propellers are used in opposite pairs to help counter torque from the spinning propellers. They are a four bladed 100mm diameter brass propeller manufactured by Harbor Models (102).

The bulkhead connectors used are manufactured by Impulse Enterprises(103). They are wet-pluggable connectors, allowing a connection to be made even if both ends of the connector are wet. These connecters are rated for 1360 atm.

The pressure can and all end caps are machined aluminum because of the heat transfer and oxidation resistance that aluminum offers.

The top cap of the thruster housing is machined as a straight cylinder because this allows a good area for the cowling to mount on. The cowl is a contoured cylinder around the propeller to help direct water flow as well keeping objects out of the props. The cowl is designed to imitate the Kort 37, a design for forward and backward operation.

The cowl is designed to behave as a kort nozzle to aid in thrust. A kort nozzle utilizes Bernoulli’s principle to generate thrust because of the difference in pressure between slower and faster moving fluids. This pressure difference creates a resultant force in the direction of travel. This is the same mechanism as an airfoil that allows airplanes to fly.

Figure 3 – Matched Pair of Brass Propellers

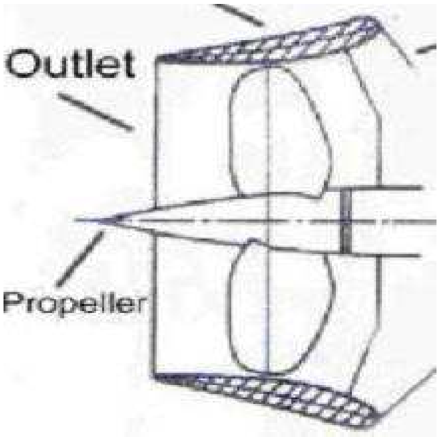

Figure 4 – Kort Nozzle

Manipulator Arm:

The objective of the PantheROV III manipulator is to perform the wide array of tasks presented at this year’s competition. These tasks include transportation and manipulation of the messenger line, collection of an O-Ball “Jelly Fish”, transportation of the passive acoustic sensor, transportation and manipulation of the wellhead gasket and transportation and manipulation of the hot stab.

Since all of these tasks involve similarly sized items, it was decided that a single versatile capable of completing all these task would be designed, rather than an individual manipulator for each mission. The manipulator system is based off a simple claw design which has flat area near the tip of the claw for manipulation of small objects such as messenger line and an open area in the center of the claw for holding onto larger objects such as the hot stab. The claw is constructed of 3.175mm aluminum plate held together with stainless steel fasteners.

Actuation of the claw is achieved through the use of a small DC gear motor. This motor turns a threaded shaft inside of a threaded block of aluminum to which the claw linkages are attached. As the shaft spins it pulls the threaded block forward or back which in turn opens or closes the claw. This system was selected for a number of reasons; first, the system cannot be back driven, meaning that unless the motor is turning the claw cannot be opened or closed manually. Second, the high gear reduction of the motor allows for relatively high torque at low speeds and low power requirements. This translates to the claw being able to grasp things firmly while maintaining a high degree of control and using a low amount of power. The claw has a maximum opening range of 5in.

The claw is mounted on the end of an arm made of square aluminum tube which is connected to a high torque, low RPM 12v DC motor. This motor acts as the manipulator arm’s shoulder joint. It allows the arm to pivot nearly 360°. This range of motion allows object manipulation above and below the vehicle as well as in front. A benefit of the freely rotating arm is that it allows the arm to be stored alongside the body of the ROV when not in use, rather than sticking out the front, potentially getting in the way during tight maneuvering.

Aluminum was selected for the construction of the majority of the manipulation system due to it’s superior physical and mechanical properties. It’s high strength to weight ratio allowed for smaller pieces and ultimately less mass at the end of the arm, resulting in lower power requirements to move the system. Due to its oxidation resistance, it was a natural choice for use in submerged applications.

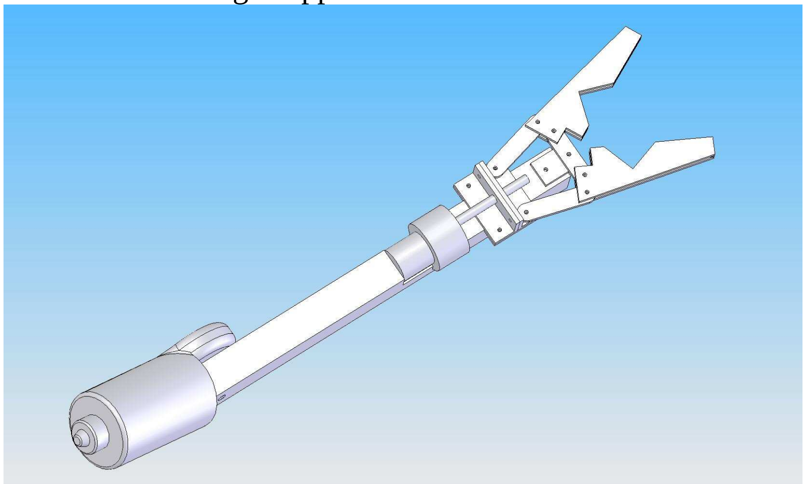

Figure 5 – Manipulator Arm Design

Hull and Frame:

PantherROV III is designed with superior corrosion resistant alloys and anodized for further protection. The frame is built using 2.54cm IPS T-6063 aluminum alloy pipe. Speed Rail fittings made from 535 aluminum alloy, one of the most corrosion resistant aluminum alloys, are used as interconnects. Tees, elbows, and double side outlet crosses are needed to create the frame. All of these parts, especially the double side outlet cross, provide modularity and flexibility in mounting external equipment such as cameras, lighting, and thrusters.

The hull is a 203.2mm OD, 6.35mm wall thickness anodized aluminum pipe. There are two anodized aluminum end-caps with single o-ring seals. The front end-cap has a silicon sealed acrylic dome for the main pan and tilt camera. Impulse (3) bulkheads are mounted on the back end-cap. A 3-ring internal frame with an ABS plastic shelf attached centrally allows internal components to be mounted securely.

Electronics:

Power:

During the competition, power will be supplied by the 24VDC source available at the mission location. All components in the vehicle require 12VDC or less, however the length of the tether will cause a large enough voltage drop that use of the higher voltage supply is necessary. The resistance of the power conductor in the tether is 0.3Ω. At the maximum allowable current of 40A, which our vehicle will approach when all motors are running, the voltage drop would be $0.3\Omega \times 40A = 12V$. Therefore use of the +24V supply is necessary to guarantee reliable operation. DC to DC converters and optocouplers will provide electrical isolation between high power components and sensitive low power electronics.

Control:

The PantheROV III thruster motor control and thruster motor driver systems are defined as separate systems that interact with each other through an interface. The control system consists of "low power" electronics (including the microcontroller- the heart of the ROV electronics system) that provide direction and speed control logic, operating at standard transistor to transistor logic (TTL) voltage and current levels. The driver system consists of circuitry that connects the motors to their power supply and must be capable of withstanding up to 24VDC and currents approaching 40A. The driver system used in PantheROV II during the 2006 MATE International ROV Competition was not able to tolerate the high current levels, and the overheating of several power MOSFETs led to their destruction. The damage cascaded through the sensitive electronics and to the microcontroller, destroying critical hardware and eliminating PantheROV II from the mission portion of the competition. Preventing this type of damage has been a matter of designing a more robust motor driver system, with an interface that allows it to be electrically isolated from the control system.

The control system is located on a separate printed circuit board, designed using ExpressPCB software. This system consists of a Rabbit Semiconductor 3700 microcontroller, along with various integrated circuits that allow the Rabbit to interface with devices on the vehicle. All microcontroller input/output pins that are unused in the original design are brought out to headers on the circuit board to allow for possible design additions or changes.

Each of the six motors (four thruster motors and two arm motors) are driven by their own driver printed circuit board, also designed using ExpressPCB. Each of these boards is capable of connecting directly to the +24V power source, and conducting up to 10A of current. The design is an H-bridge circuit implemented using SPDT relays and power MOSFETs. Reverse biased diodes provide protection against the flyback effect (large voltage spikes over the motor coils when the motor is rapidly switched on and off). Speed is adjusted by changing the duty cycle of the pulse width modulation signal which switches the MOSFETs. This changes the effective voltage that the motors recieve, and thus adjusts their speed. The use of extra components (MOSFETs, diodes, and relays) in parallel allows the large currents to be split up, thereby reducing the power dissipation of the devices and providing a robust system.

The interface between the control and driver systems is an HCPL-2530 optocoupler integrated circuit. Pulse width modulation signals enter the input side of this IC, causing an internal LED to light up during the “high” part of the signal. The light from the LED turns on a phototransistor on the output side. The optocoupler has an open collector output that is connected to the logic “high” level with a pullup resistor. This results in the output signal being an inverted copy of the input signal. This output signal drives a 74HCT14 inverter IC with Schmitt Trigger inputs (for fast switching) to re-create the original signal.

Test Results:

Several tests have been conducted on the motor driver PC board. A motor housing and propeller from PantheROV II was used for all testing. In test number one, a motor was run with a steady 7A current, while the temperature of the MOSFETS and flyback diodes was recorded. The ambient temperature was 23°C. After five minutes of steady use, the MOSFETs increased temperature by approximately 20°C relative to ambient, and the diodes increased by approximately 40°C relative to ambient. The maximum operating temperature for the MOSFETs and diodes is 175°C, so both devices were operating well within their safe limits.

Test number two measured the current drawn by the circuit while changing the PWM duty cycle.

Battery Voltage	PWM freq	Duty Cycle	Current Draw
12	500Hz	15%	200mA
12	500Hz	20%	800mA
12	500Hz	25%	1.5A
12	500Hz	30%	2.9A
12	500Hz	35%	4.1A
12	500Hz	40%	5.6A
12	500Hz	45%	7.2A
12	500Hz	50%	8.9A

Table 1 – Motor Current Draw Test Results

The third test measured the inrush current that the motor draws when started from a dead stop at different PWM duty cycles.

Battery Voltage	PWM freq	Duty Cycle	Inrush Current Draw
12	500Hz	20%	1.0A
12	500Hz	30%	3.2A
12	500Hz	40%	6.3A
12	500Hz	50%	10.3A

Table 2 – Inrush Current Test Results

Control/Feedback System

The control and sensor systems of an ROV are what make it possible to control a vehicle without having it physically visible. Therefore, it is vital that these subsystems provide a great amount of usable feedback that a pilot can use to operate the vehicle with ease and precision.

There are two disparate systems of PantheROV III that make control possible. A topside laptop is the center for control and feedback to the pilot. It is here where commands are sent to the ROV and where a graphical user interface (GUI) provides feedback to the pilot. On the ROV, a Rabbit RCM 3700 microcontroller receives and processes commands from the topside computer to control the four thrusters, robotic arm motors, and pan-tilt camera control. Also on the ROV is a network of cameras to provide visual feedback.

These two systems are interconnected in an IP-based network – in which each device in the system has a different IP address. This makes interaction between devices simple. An overview of the communication system is shown in Figure []. The specific subsystems are described below.

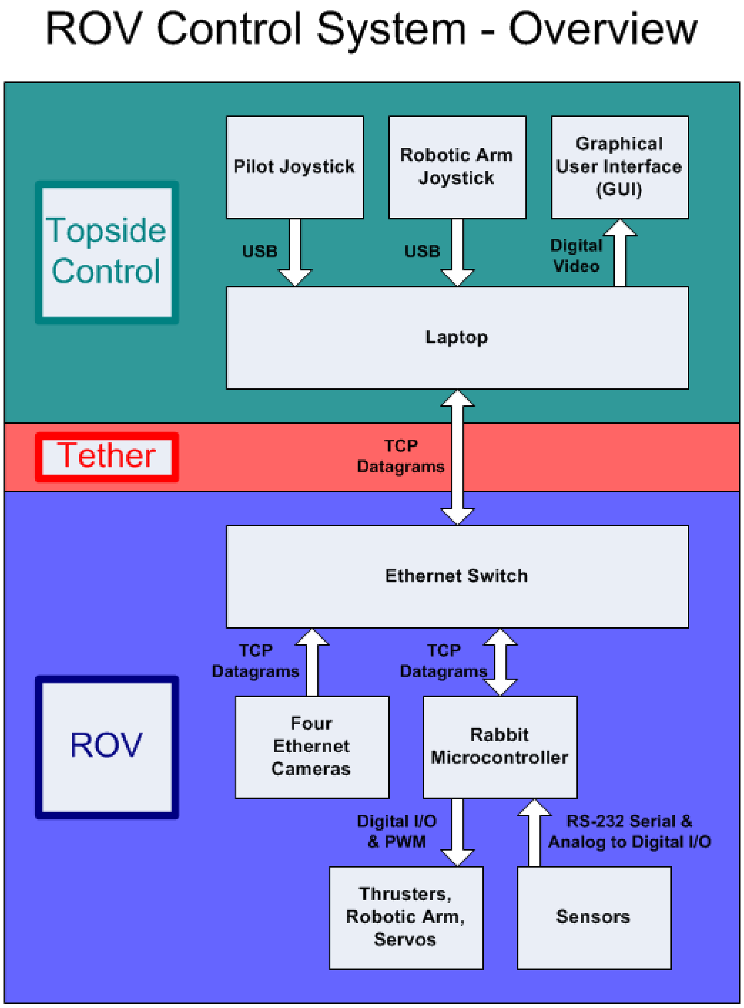

Figure 6 – ROV Control System Overview

Topside Control:

The topside laptop computer is the center for command and feedback. To control the vehicle, two USB joysticks are operated by two different pilots. One controls the navigation of the vehicle and one operates the robotic arm. The two joysticks are interfaced in a GUI written in Java 1.5 Programming Language. Java is an object-oriented programming environment known for its flexibility, portability, and abundance of method libraries making the development process easier. To control the ROV, the Java program waits for an interrupt from one of the joysticks, it determines which button, hat, or analog stick moved and also what action needs to be taken. The program then assembles a packet with instruction information and sends it to the ROV.

The topside computer also receives feedback from the ROV. Voltage, current, humidity, ambient temperature, compass, and pitch/roll are measured by PantherROV III and transmitted to the topside computer for graphical display.

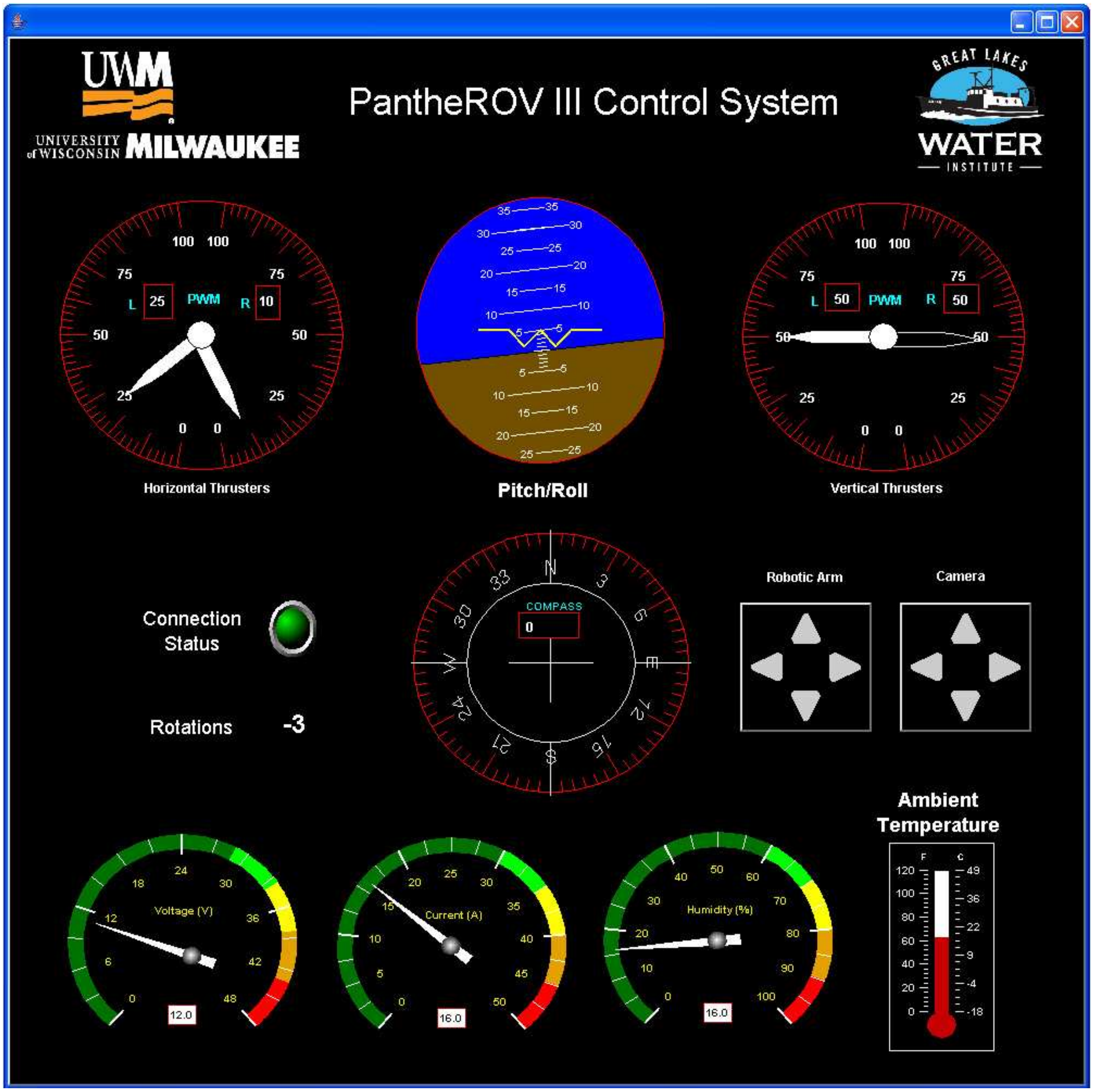

Figure 7 – PantheROV III Graphical User Interface

ROV Microcontroller:

The commands transmitted by the topside computer are processed and executed by the Rabbit RCM 3700 microcontroller. It was chosen because of its flexible design, which includes 31 digital input/output lines and an Ethernet controller. Some of the digital I/O lines can also be configured to be used as Pulse Width Modulation (PWM) ports and serial ports. To program the microcontroller, a programming language called Dynamic C is developed on a PC. The language itself is much like the standard C programming language, with the addition of libraries and keywords that are specific to the Rabbit hardware. In order to transfer a program to the RCM 3700, it is *cross-compiled* over a serial programming cable. The act of *cross-compiling* converts the machine code from the architecture of a PC to one that the microcontroller processor can understand.

Communication Protocol/Medium:

To interconnect the disparate systems, a single Category-5 shielded twisted-pair cable (Cat-5 STP) is utilized. Transmission Control Protocol (TCP) datagrams are exchanged between laptop and ROV, and between laptop and Ethernet-enabled cameras. This method of information exchange is highly reliable – It is the method utilized by many Internet information exchanges. TCP is a connection-based protocol, which means that a connection must be established before commands can be sent. This allows for the use of built-in flow and congestion control, which prevents against losing packets of information. It also employs the use of acknowledgements and Cyclic Redundancy Check (CRC) checksums, which aid in detecting transmission errors. With all of these built-in safety features, a highly reliable control system can be constructed without spending extra time developing a proprietary transfer protocol.

Software Flow:

The main goal of the two systems is to maintain a consistent connection and transfer data and commands reliably. To achieve this, both the laptop and the ROV implement “keep-alive” style methods to keep data concurrency, i.e. tell each that things are working properly and that the connection is still valid. The main reason for this safeguard is to prevent the robot from acting uncontrollably if the connection is broken. Instead of simply sending a “keep-alive” message, a packet with all of the control parameters is sent – addressing the problem of a consistent connection and data concurrency simultaneously.

Besides the automatic transmission of “keep-alive” messages, the normal commands and sensor data is assembled and transmitted as it changes. Then when it arrives at its destination, the computer uses an “If-Then” style decision structure to decide functions need to be executed.

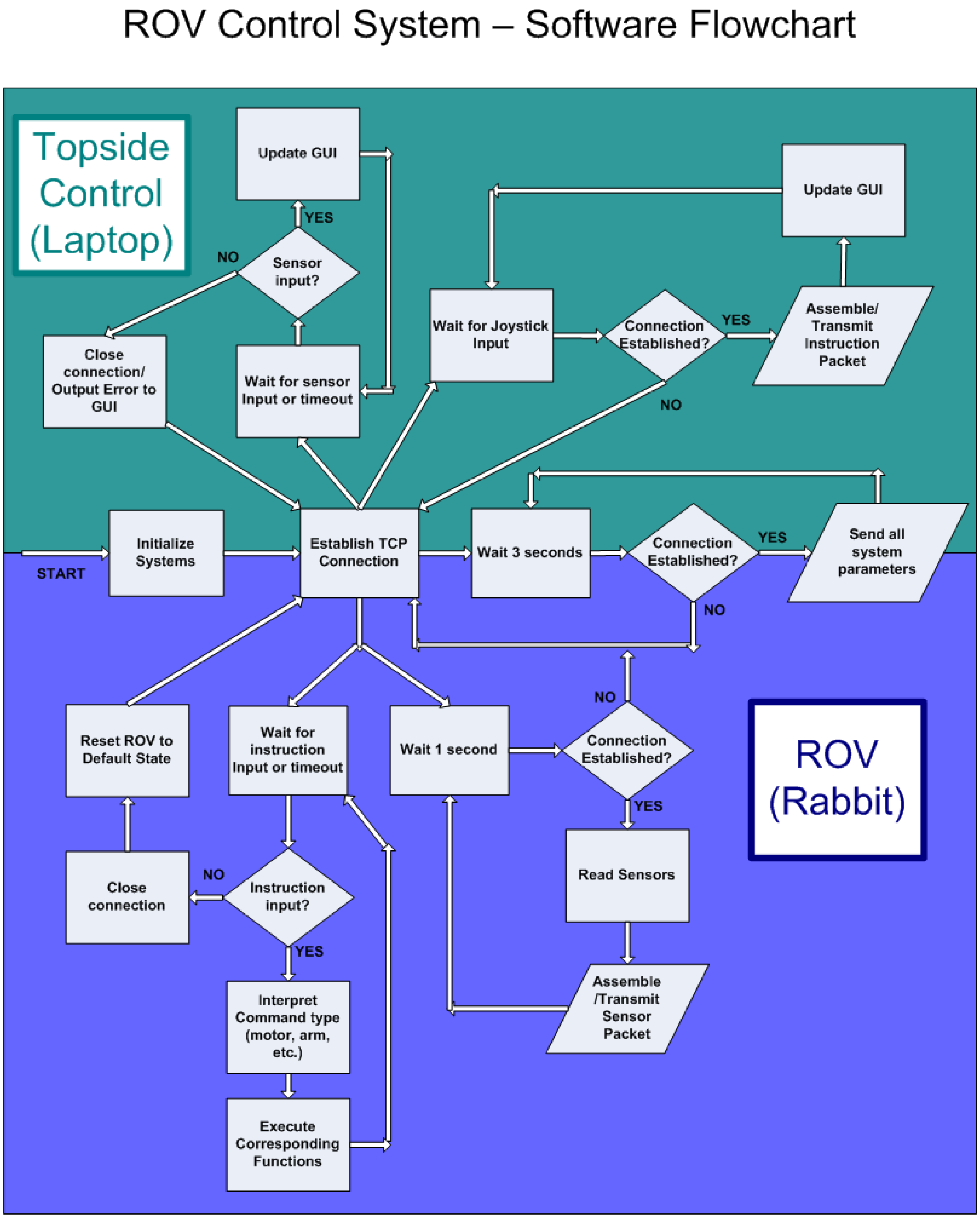

Figure 8 – PantheROV III Software Flowchart

Vision System:

The vision components are one of the unique aspects of our vehicle. We designed the system so that it has many viewing angles, because this is the only form of feedback we will receive when the ROV is in the pool. Another design goal is to create a tether that is thin and reliable. With four DLink DCS-900 Ethernet-enabled web cameras (6), we can accomplish our visual goals through a single Category-5 cable. Contrary to using analog cameras and running separate coaxial cable lines for each camera, our vision design connects all of the cameras to a single Ethernet switch with patch Category-5 cabling and a single shielded Cat-5 cable is sent to the surface. Each camera communicates over the reliable Transmission Control Protocol (TCP) with a computer on the surface, sending Motion JPEG (M-JPEG) formatted files. The camera works by taking pictures at approximately 20 frames per second, and sends them to a connected computer, which uses software to reorganize the pictures into a motion picture.

One of our cameras is mounted inside the front of the hull, pointed out through a clear acrylic dome, and attached to two servos. These servos allow the camera to tilt and pan, giving us a 180-degree viewing angle. The other three cameras are each encased in a 76.2mm diameter acrylic tube and mounted on the outside of the vehicle (Figure 19). One end of the tube, where the camera lens is located, is fashioned with a clear polycarbonate faceplate for a flat viewing surface.

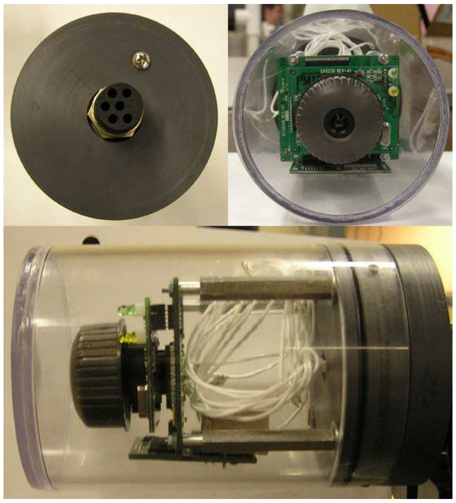

Figure 9 – Camera Housings

This end is sealed with clear acrylic cement. The other end of the camera tube is a removable end cap, constructed from Delrin, a plastic often used as a metal replacement. The end cap includes an o-ring seal, set screw groove, pressure release screw, and a 6-pin wet-pluggable Impulse connector. Each one of the cameras is connected to PantheROV II with an Impulse-constructed cable and is mounted to the PVC frame.

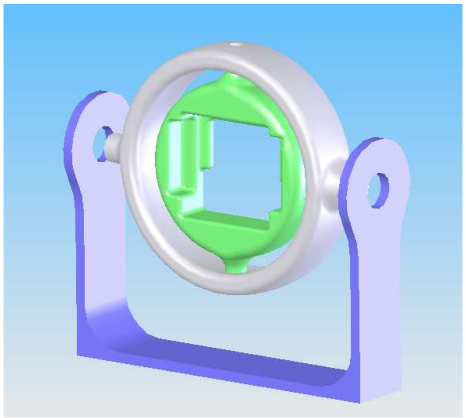

Figure 10 – Main Camera Assembly

Troubleshooting

Troubleshooting for the PantheROV III began almost immediately after the 2006 competition. The power electronics used to drive PantherROV II thruster motors failed less than a minute into the mission portion of the 2006 competition, a careful analysis was needed to determine why. The first step was to determine, by inspection, which components failed. This required physically taking apart the motor driver circuitry and inspecting each component to see if it had been damaged. In some cases the damage was obvious, but in other cases (such as FETs and diodes) components had to be carefully continuity tested, and then tested in a prototype circuit to reveal whether they were functioning as expected. The damaged components were then identified in the circuit schematic. The design appeared to be fundamentally sound, so the next step was to walk through the entire design and attempt to justify the choice of each component, based on voltage, current, and other circuit parameters. Careful analysis of component datasheets and relevant calculations revealed that the circuitry was unable to handle its current load for more than a few seconds, and this led to the damage that eliminated PantheROV II from the competition. For the 2007 competition, the circuit was carefully redesigned and exhaustively tested to be certain that it would function as expected.

Challenges

The biggest managerial challenge the team faced was purchasing parts using the funding granted by the UWM Student Activities Office (SAO). To utilize the funds parts either have to be purchased by a team member, with reimbursement on approved purchases, or a list of parts and vendors had to be sent through the SAO to be approved and then purchased. It often took several weeks to have the orders processed through SAO. Some of the orders were quite large, beyond the means of the students on the team. This challenge was solved in two ways; First, long term planning and organization had to take place so orders could be placed well in advanced with the SAO. Second, Mentor Tom Consi was gracious enough to assist in several larger purchases. This enabled the team to purchase the parts that were needed to complete the vehicle.

Lessons Learned

The team members this year learned a lesson in management of time. At the beginning of the school year, the goals for the Fall semester were to design and build a working ROV platform that could be tested and troubleshooted before the competition scenario was released. The spring semester could then be used to develop mission critical systems and practice completion of the mission. Unfortunatly there was little progress in the Fall semester. Some major work was completed such as the re-designed motor driver circuit and the initial design of the magnetically coupled thruster housings. Work started gaining some speed during the spring semester, however not as fast as hoped. As the semester ended the team began to utilize time more efficiently and manage time so that projects were being completed. If as much time management had been practiced at the beginning of the school year as at the end, much more testing and piloting practice could have been accomplished.

Future Improvements

Every system has to be continually updated to maintain usefulness. PantheROV III is no exception and several improvements are being planned. One improvement that is underway is to use the data from the pan and tilt sensor to create an automated stabilizer system. As the vehicle tilts or rotates, the pan tilt sensor would send a signal to the software, which would then fire a thruster to correct for the tilt of the vehicle. This would be particularly useful when the vehicle is operating in unstable environments or if the ROV is carrying a load, which could throw off the center of balance. The implementation of this improvement would make piloting the ROV far easier, allowing the pilot to concentrate on other aspects of a mission. There are many issues to work out with this system such as what happens when lateral thrust with the vertical thrusters is used, which inherently tilts the vehicle. It may be necessary to reconfigure the thruster configuration for a system like this. Considerations like this must be made when designing an improvement and beginning to implement the changes.

Reflections

This year was a great year of building off of the experience learned at the last (2006) competition. Using these lessons, a superior, more robust vehicle has been designed and created. The hands on experience has been more help in the "real" world than a years worth of classroom time.

- Greg Oswald

I joined the ROV Team at UWM in the winter before the 2005 competition because it sounded interesting even though I was not an engineer. I quickly found myself taking a leadership role and became the team leader. Throughout this time, I have proven myself as a quick learner and dedicated team member. As a result, I was offered a job at the WATER Institute working on GLUCOS, a scientific buoy array. I have also published a student paper for Oceans 2006 and have an abstract submitted for Oceans 2007. Because of this competition and all of the engineering knowledge I have gained, my career was jumpstarted, much before graduation.

- Korey Verhein

My participation on the ROV team at UW-Milwaukee led directly to getting an engineering internship at the UW-Milwaukee Great Lakes WATER Institute, an Oceanographic and Limnological research facility. I believe that the vast majority of career relevant electronics knowledge that I posses has come as a direct result of my involvement with the ROV team and my internship.

- Don Murray

Polar Exploration

Humans have always been explorers and extreme environments have been the most challenging and enticing. During the early 20th century Antarctica was "the last unexplored continent on earth," and several explorers from Europe took on the challenge of leading a scientific expedition to the South Pole. Two celebrated explorers attempted separate expeditions. A British man named Robert Falcon Scott led the scientific expedition *Terra Nova*, while Captain Roald Amundsen, a Norwegian, secretly planned the *Fram* expedition. Both explorers arrived on the island of ice in January of 1911. Using superior dog-drivers Captain Amundsen became the first recorded human to reach the pole on December 15, 1911. Unfortunately for Scott, his mechanical equipment failed and the ponies could not handle the extremes. The *Terra Nova* team finally reached the pole on January 17, 1912, only 33 days later. They ultimately gave their lives for the sake of discovering a place that humans had never encountered.

Even today, the pioneering spirit has not been lost and the new frontier is space. For the International Polar year (IPY), scientists from many backgrounds are studying the polar regions of Earth and comparing them to similar places in the universe. NASA's Mars Program is conducting the Phoenix mission to study the poles of Mars which are a close analogue to Earth's Antarctic region. "Because of the interest in tracking life forms to the most extreme environments, the knowledge gained from examining atmospheric, chemical, and mineralogical processes in this pristine region of Mars will be highly complementary in understanding similar regions on the Earth."

Figure 10 - NASA's Mars Polar Lander : Phoenix

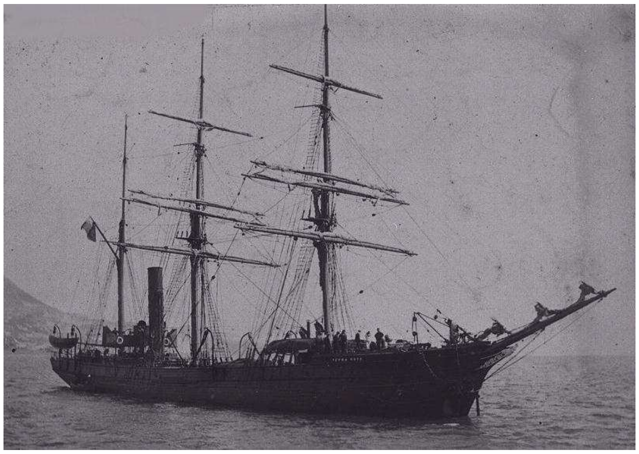

Figure 11 – Robert Falcon Scott’s Earth Polar Lander: Terra Nova

Acknowledgements

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University of Wisconsin-Milwaukee:
College of Engineering and Applied Science at UW-Milwaukee
Mike Brown - UWM Machine Shop

Companies:
Impulse Enterprise, Inc.
IGUS, Inc.
Edmund Optics, Inc.
Speed Rail
Generic Logic

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2932 Spafford Street
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(530) 757-8400
http:/www.rabbitsemiconductor.com/

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3311 Beach Ave.
Marina Del Rey, CA 90292
(310) 821-6242
http://www.astroflight.com

(3) Impulse Enterprise
8254 Ronson Road
San Diego, CA 92111
(800) 327-0971
http://www.impulse-ent.com/

(4) Express PCB
http://www.expresspcb.com

(5) D-Link Corporation
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Neihu District,
Taipei City 114,
Taiwan, R.O.C.
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Figure 2-www.mcmaster.com
The race to the pole
Sian Flynn
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Phoenix Mars Polar Lander Proposal
http://classic.ipy.org/development/eoi/details.php?id=1053

Phoenix Mars Lander: Getting Down and Dirty On the Red Planet
Leonard David
http://www.space.com/businesstechnology/060404_phoenix_tech.html

Budget

Purchased Vehicle Components				
Description	**Vendor**	**Quantity**	**Unit Price**	**Total**
Magnetic Thruster Couplings	McMaster	8	$49.00	$392.00
Closed-Cell Foam	US Composites	1	$54.00	$54.00
LED Array	Superbright LEDS	4	$14.95	$59.80
Load Cell	Omega	1	$69.00	$69.00
Pan-tilt Sensor Parts	OceanServer	1	$249.00	$249.00
Robotic Arm Materials	Various	1	$55.00	$55.00
Robotic Arm Motors	Meci	2	$12.95	$25.90
Spare Thruster Motors	Astroflight	2	$129.95	$259.90
Spare Microcontrollers	Rabbit Semiconductor	2	$59.00	$118.00
Humidity Sensor	Digikey	1	$34.01	$34.01
Current Sensor	Digikey	2	$10.64	$21.28
Servos	HobbyPeople	2	$26.99	$53.98
Glues/Epoxies	Various	1	$50.00	$50.00
Aluminum Frame Tubing	SpeedyMetals	1	$50.00	$50.00
Motor Driver Printed Circuit Boards	ExpressPCB	1	$221.25	$221.25
General Electronic Components	Jameco	1	$135.00	$135.00
Frame Interconnects	Holliander	1	$200.48	$200.48
			Total:	$2,048.60

Reused Purchased Components				
Description	**Vendor**	**Quantity**	**Unit Price**	**Total**
Waterproof Connectors	Impulse	1	$ 817.00	$ 817.00
Dlink DCS 900 Webcams	Buy.com	4	$ 82.99	$ 331.96
Linksys Ethernet Switch	Buy.com	1	$ 42.99	$ 42.99
Thruster Motors	Astroflight	1	$ 129.95	$ 129.95
203.2 mm Aluminum Hull	SpeedyMetals	1	$ 63.06	$ 63.06
Propellers	Harbor Models Inc.	4	$ 34.95	$ 139.80
RCM 3700 Microcontroller	Rabbit Semiconductor	1	$ 59.00	$ 59.00
			Total:	$1,583.76

Travel Expenses				
Description	**Vendor**	**Quantity**	**Unit Price**	**Total**
Flight - MKE to YYT	Air Canada	5	498	$2,490.00

Donated Parts/Services		
Description	**Vendor**	**Quantity**
38 m Shielded Twisted Pair	Igus	1
38 m 4 Conductor 10 AWG cable	Igus	1
Thruster Motors	WATER Institute	3
Software Widgets	Generic Logic	1
Shipping of Vehicle	WATER Institute	1

Appendix – Electrical Schematics

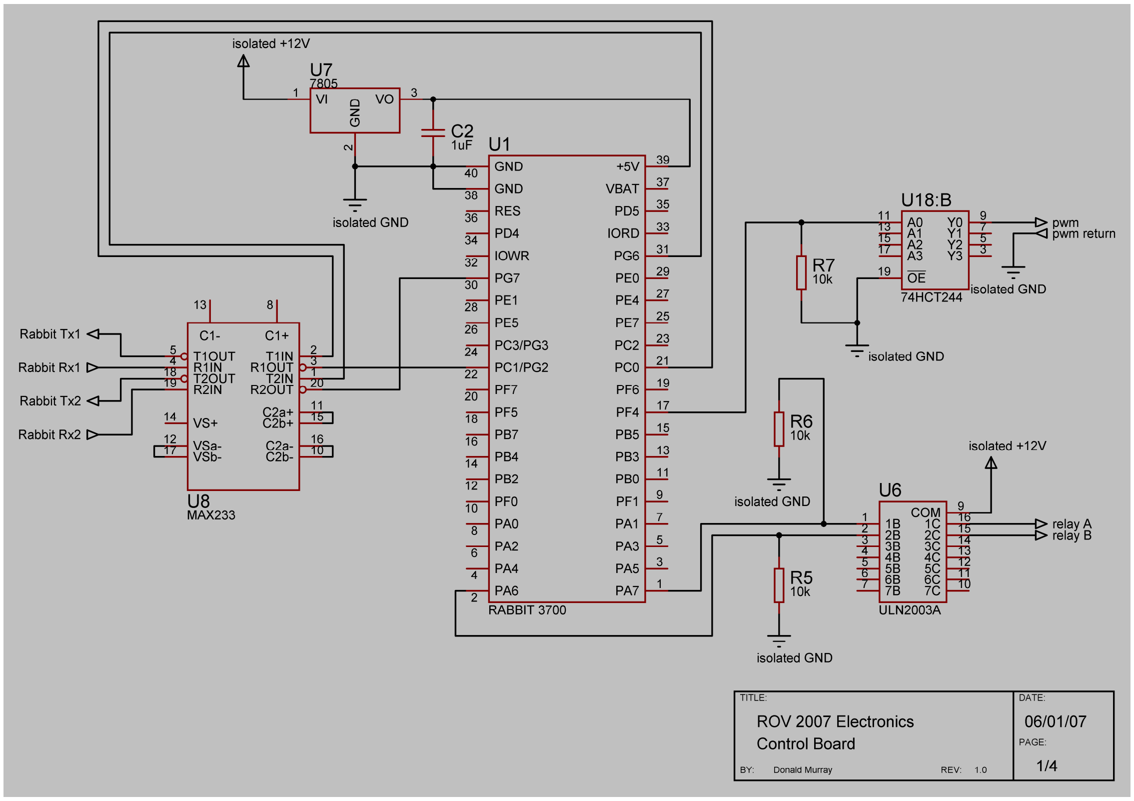

Figure A – Control Subsystem

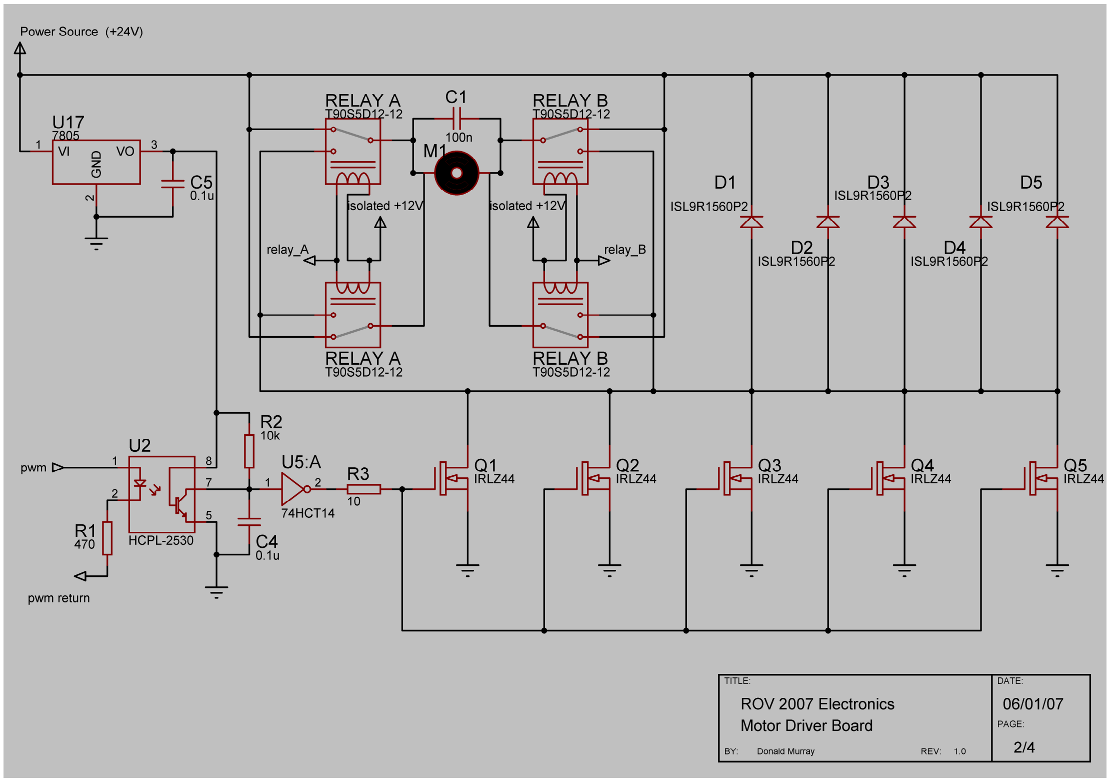

Figure B – Motor Driver Subsystem

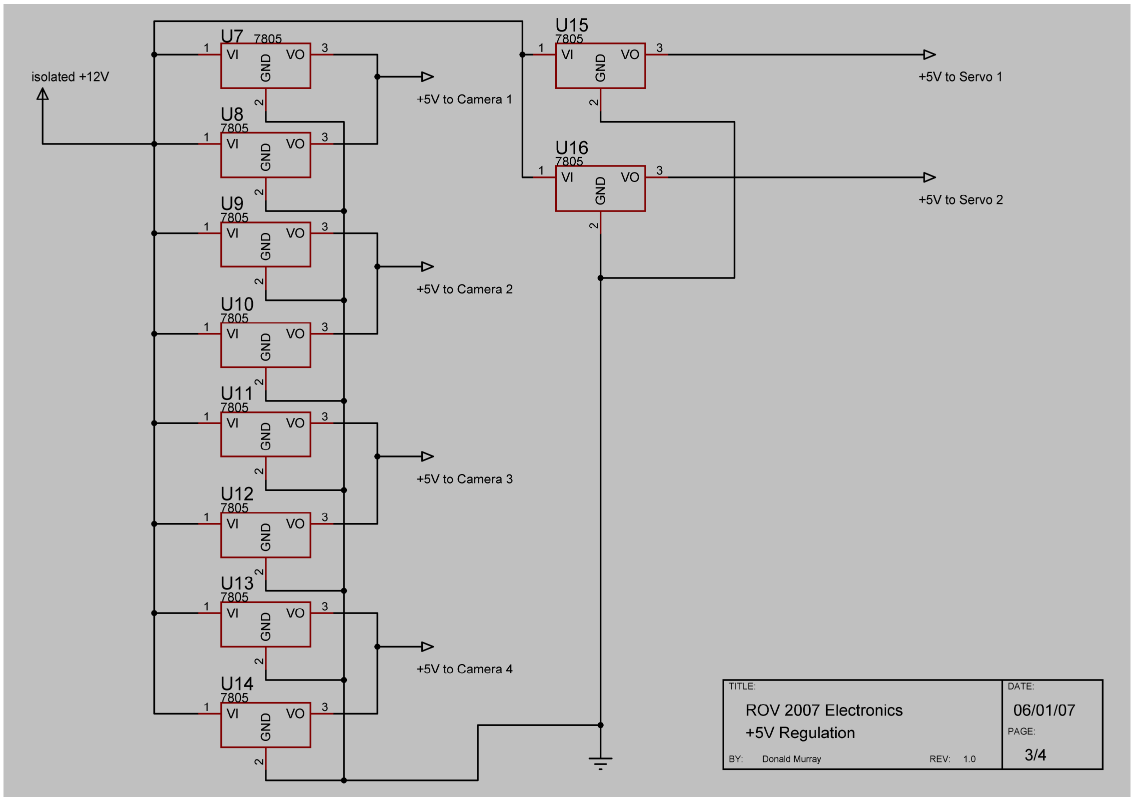

Figure C – Voltage Regulation

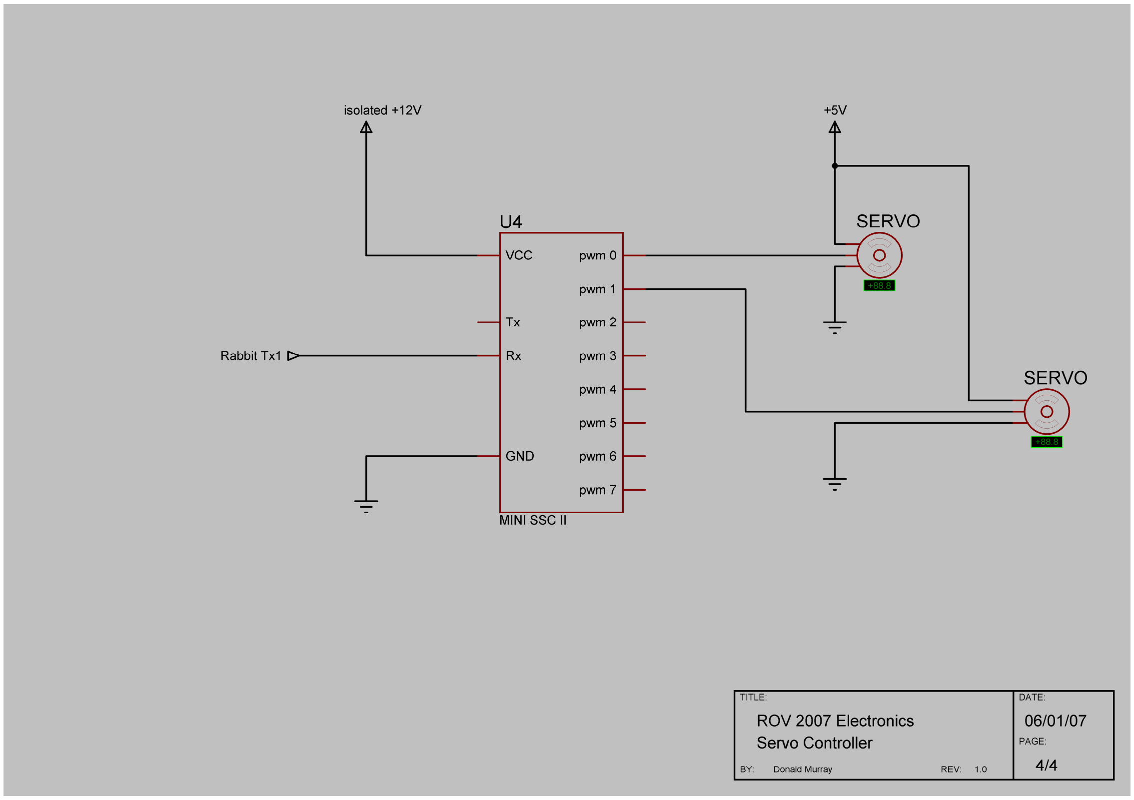

Figure D – Servo Control Subsystem

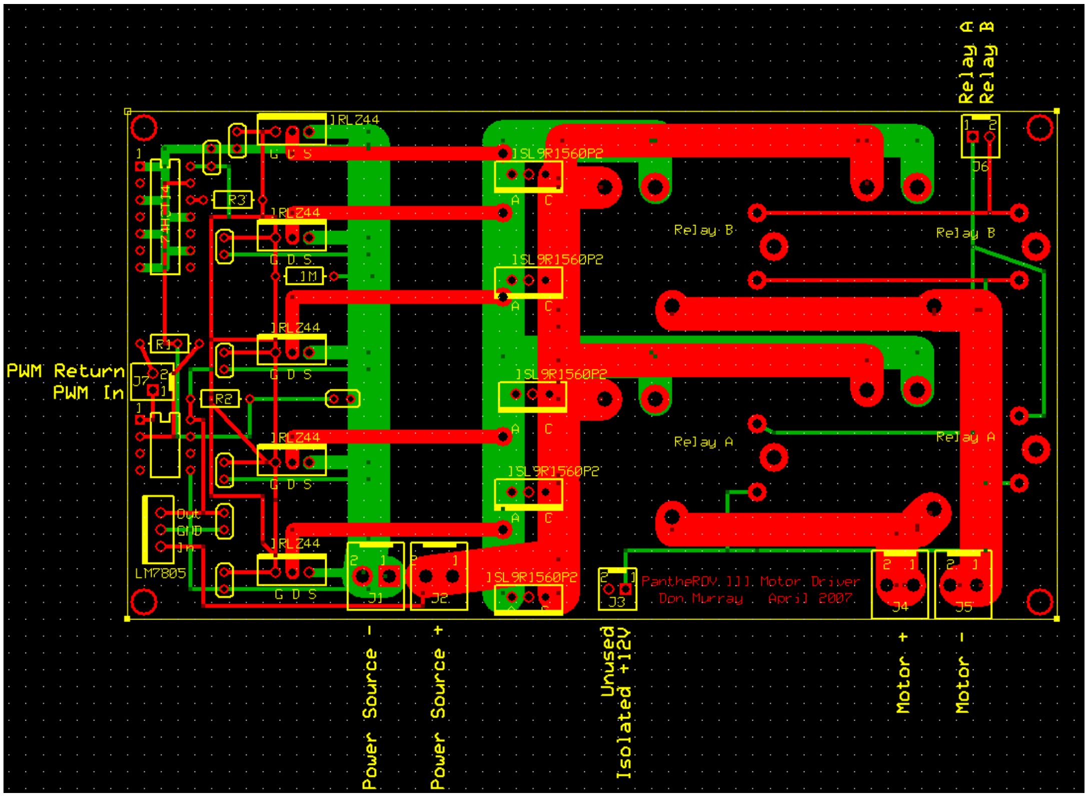

Figure E – Motor Driver PC Board

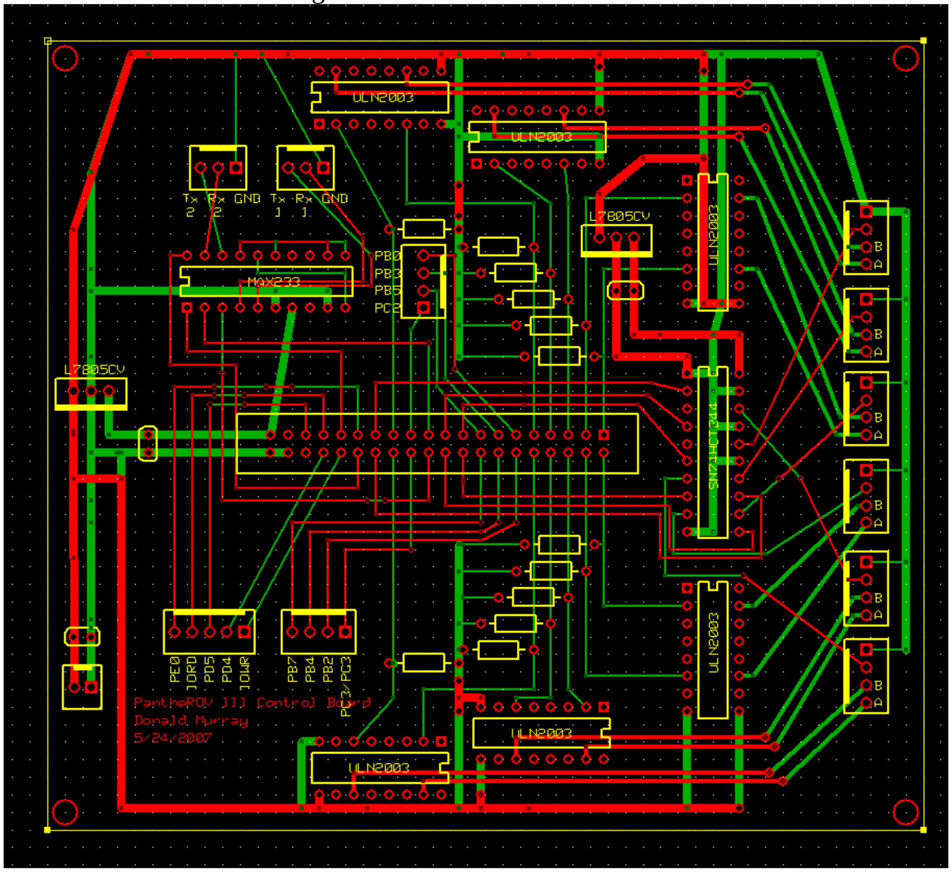

Figure F – Control Subsystem PC Board