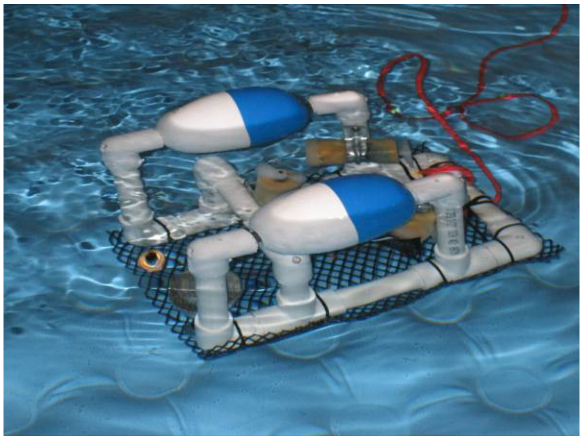
The MIT ROV Team

presents



MTHR & *JR*

Built by the MIT ROV Team
Massachusetts Institute of Technology
Cambridge, Massachusetts

Team Members: Heather Brundage, Lauren Cooney, Keith Durand, Eddie Huo, Pete Kruskall, Harry Lichter, Olayemi Oyebode, Pranay Sinha, Jordan Stanway, Kurt Stiehl, Thaddeus Stefanov-Wagner, Daniel Walker
Advisor: Dr. Franz Hover

Abstract

This year, the MIT ROV team designed our main ROV, *MTHR*, not only to compete in the MATE competition, but also to be used afterwards for both didactic and practical purposes. To this end, the team aimed to keep *MTHR* easy to operate and the sub-systems modular so that they could be improved or expanded upon, allowing *MTHR* to act as a test bed for new technology in the future. On top of this, the team also placed size constraints, in order to keep it maneuverable and easy to transport, and monetary constraints, in order to keep it affordable. These design considerations led our team to build a small, battery-powered ROV intuitively controlled through a fiber optic tether that utilizes counter-rotating propellers. In addition to *MTHR*, a second ROV, *JR*, was built to act as a flying-eye to aid in navigation during the competition. Working together, these two ROVs can successfully compete in the Annual MATE ROV Competition, while also providing a platform for future development.

Design Rationale

In past years, the MIT ROV Team has started by dismantling the robot from the previous year. There have been relatively few subsystems reused between years, and our primary goal for this year was to change that. We decided that we wanted to produce a modular, extensible robot using components that could be improved and upgraded individually. We identified three main subsystems we wanted to solidify this year so that they could continue to be used in future years: power, propulsion, and control. Other subsystems were necessary to construct *MTHR* and complete mission objectives. These systems were: structural frame, manipulator, and tether.

Besides *MTHR*, the team also decided to build a simple PVC ROV, *JR* to act as a 'flying-eye' for the mission. *JR* allows an overall view of the competition site, aiding in navigation and mission planning.

Power System

MTHR's power is provided by ten Nickel Metal-Hydride (NiMH) batteries connected in series with a 25-amp thermal resetting fuse. Each cell provides 20 amp-hours (Ah) of power at 1.2 volts, combining to make a 12 volt battery pack (See Figure 1). There are two battery packs, so that one can be used while the other is being charged. The batteries are housed in the same enclosure as the control hardware, to minimize the need for expensive, high-current, underwater connectors. *MTHR* uses batteries instead of surface-supplied power so that the tether can be smaller. Our robot is restricted to lower voltage because of its onboard power, but it was determined to be the better option. To support a 25 amp load at the end of a 30 meter tether, 14 gauge or thicker wire is necessary, not to mention dealing with the voltage drop and ohmic losses across the tether. It would be inflexible, heavy, and thick, compared to any tether that did not have to carry power to the vehicle. Furthermore, a longer tether would only make the problem worse. Choosing battery power enables *MTHR* to have a smaller, lighter tether, enhancing overall maneuverability while at the same time conserving energy by avoiding power loss over the tether.

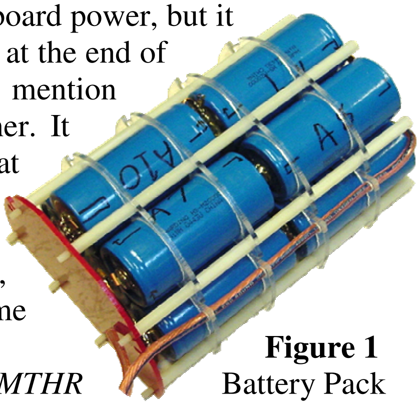


Figure 1
MTHR Battery Pack

Propulsion System

One of the aspects of ROV design that we have found most difficult in the past is finding reliable, efficient propulsion. Few commercial systems exist in the size required by our robot, and they are prohibitively expensive. We have used bilge pumps and trolling motors in the past, but found that they work well only in one direction and are very power-hungry, which is a big problem for a battery powered robot.. We've also been unsatisfied by the performance of model airplane propellers underwater. We decided to design and build a more efficient thruster from the ground up.

We took estimates of size constraints, operating speed, drag, and power available from the early stages of *MTHR's* design. From these estimates, we chose a design condition for the propulsor: propeller diameter - 11.43 cm (4.5 in.), inflow velocity - 1.03 m/s (2 knots), continuous current - 6 amps. This design point means that our propulsor will be operating at a fairly high thrust coefficient (C_t = 3.8 where it is 1 or less for most ships). To maximize the efficiency of the propulsor, we use contrarotating propellers surrounded by a duct. By rotating a second propeller in the opposite direction, energy lost to swirl in the flow can be minimized. Having two propellers also distributes the load, enabling more efficient propellers in the first place.

We conducted a full parametric study using computational tools, exploring different diameters, rotational speeds, duct loading, and numbers of blades. Hydrodynamic modeling with lifting line theory showed that our design should achieve 57% efficiency. The maximum theoretical efficiency of any propulsor at our operating point is 62%. Computational Fluid Dynamic (CFD) analysis (see Figures 2a & 2b) showed that our design almost completely canceled swirl, minimizing energy wasted in that way.

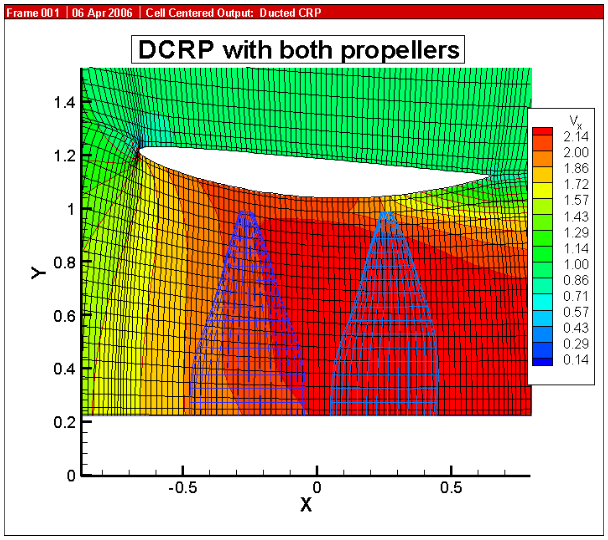


Figure 2a Axial velocities in the propulsor (thrust)

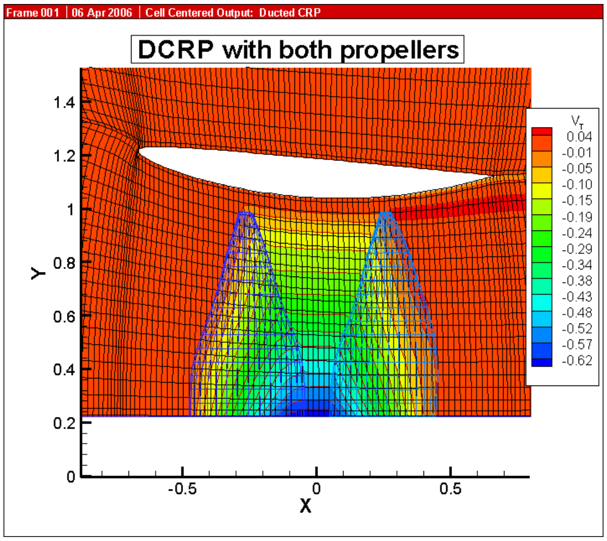


Figure 2b Tangential velocities in the propulsor (swirl)

The propellers were CNC milled and the duct was turned on a CNC lathe to keep the final products true to the hydrodynamic modeling. We matched small-diameter 12 volt DC motors to the propellers during the parametric study. We chose Maxon RE40 brushed motors with a 4.3:1 gearbox to give the appropriate torque at about 1000 rpm. They are housed in close-tolerance aluminum tubes to enhance cooling, and power is provided through Impulse Enterprises wet-pluggable connectors. The shaft is sealed by a Parker FlexiSeal spring-loaded PTFE o-ring. A custom miter gearbox is integrated into the propulsor hub to reverse the direction of rotation for one of the propellers. Two rows of stators hold the duct and protect the propellers from debris or curious fingers (important for safety and because *MTHR* has a small tether).

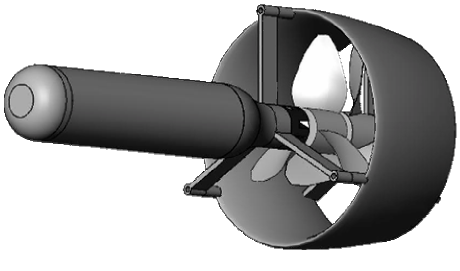


Figure 3 Thruster Model

Control System

The main control system is broken into two parts. The topside control system is based on a custom Cocoa application running on an Apple laptop. The applications is highly flexible and gives the user for very fine control on how the robot is manipulated. The bottomside is driven by a PIC 18F4431 via RS-232 serial communication. The serial commands are then sent to four motor controllers that drive the thrusters. Please refer to the appendix for the control system flow chart.

Bottomside Controls

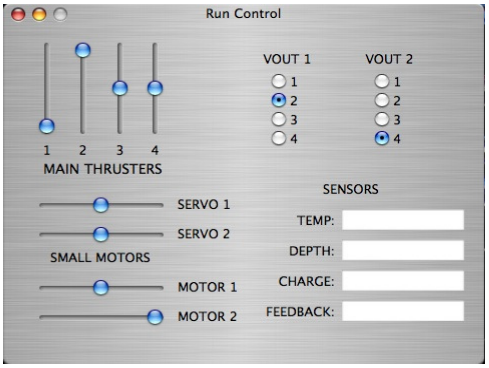
A PIC18F4431 microcontroller communicates with the topside controls through the tether. It actuates four ST Microelectronics VNH2SSP30-E integrated h-bridge motor drivers, defining the duty cycle for each propulsor by pulse-width modulation (PWM). It also drives two video multiplexers, allowing the operator to choose any of four cameras on either of two video channels. The system design was kept simple to increase reliability, ease of manufacturing, and simplicity of operation.

The bottomside controls and power system share a cylindrical, double o-ring sealed housing. This minimizes the use of expensive connectors and also takes advantage of the buoyancy inherent in the air cavity surrounding the control hardware. (The housing was designed to weigh approximately 1-2 lbs. submerged.) The housing is made of polycarbonate for lightweight strength and easy fabrication. It has room for the battery pack and up to four standard PC\104 boards. The main bottomside controls are on one board, the multiplexer for the fiber optic tether is on another, and two are available for payload. The PC/104 boards use stacking connectors to minimize wire clutter and signal degradation within the housing.

Topside Controls

Topside controls are driven by a custom Cocoa application on an Apple laptop (See Figure 4). The user provides input via joystick and buttons, which the application then maps to propulsor duty cycles and sends to the bottomside controller. Sensitivity settings can be changed by the user so that each pilot is able to customize the feel of the control to their own liking. It also has control for auxiliary motors and servos, along with calibration and display of sensors for depth, temperature, battery charge, and motor feedback. If a joystick is unavailable, the user can fly *MTHR* using the keyboard.

This application was developed to be portable and extensible. It can handle two ROVs at once if the user desires, driving each from a separate joystick.



Run Control

VOUT 1
○ 1
● 2
○ 3
○ 4

VOUT 2
○ 1
○ 2
○ 3
● 4

Figure 4 Screen Shot of Top Side Controls

Structural Frame

The frame was designed to use simple, similar parts in every case possible (See Figure 5). Two sideplates were laser-cut from acrylic and are connected at angles to seven crossbars, forming a strong trapezoidal frame. The sideplates and overall layout were designed to hold the vertical motors at a 30 degree angle so that they can provide sideways translation in addition to ascent and descent capability. The sideplates were cut out to be rid of excess material that would add drag and make them act as unwanted wings during ROV flight. Clear water in front of the thrusters is maximized, to reduce unwanted wake and unsteady hydrodynamic effects that could otherwise interfere with propulsive efficiency.

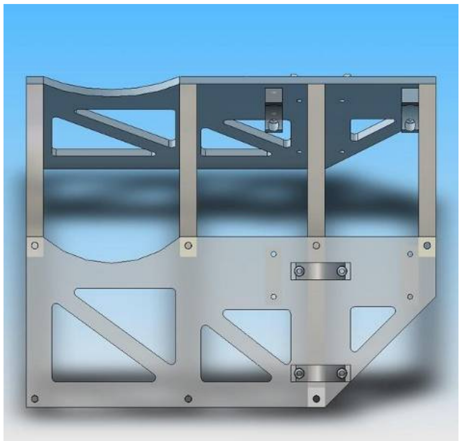


Figure 5 Frame Solid Model

Manipulator

We originally planned a complex 5-degree of freedom manipulator arm for *MTHR's* first payload. This would allow us to carry the science package to the trawl-resistant frame and insert the connectors. To provide simple control for this arm, we built a topside master arm modeled after the manipulator arm (See Figure 6). Each joint was fitted with a potentiometer to give the angular position at that joint. The arm on the robot would then use servos to move to the same position. We believed that this master-slave configuration provided the simplest method of controlling a complex arm.

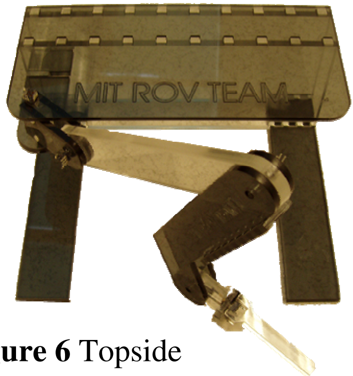


Figure 6 Topside Manipulator Controller

Unfortunately, time and manpower constraints prevented this manipulator from being completed in time for the competition. Instead, we are using a simple solenoid to draw the package flush to the bottom of our frame and will release the solenoid once the package is in place. A small, simple gripper is mounted at the bottom front of the frame to pick up the connector and place it in the science package.

Tether


Figure 7 Fiber Spooler and Mux

Our tether is a single strand of fiber optic cable. It passively spools out of a disposable 500 meter long coil (See Figure 7). If the tether becomes tangled during a mission, it can simply be cut and re-terminated for the next use. Signals are encoded and decoded by MiniMux2 boards, donated by Prizm Advanced Communication Electronics Inc. This setup provides *MTHR* with 2 video channels, 2 RS-232 serial channels, and one RS-485 serial channel. The tiny tether has negligible drag and weight, so it does not change vehicle dynamics, but care must be taken to avoid tangling or pinching the fiber so that communication is not interrupted or destroyed.

Video

MTHR has three cameras, but the video hardware can support one more as part of the payload, if desired. The color cameras include a ring of LED lights in the housing, providing good visibility with low power consumption. Two Analog Devices ADG604 video multiplexers on the control board choose which camera signals are sent up the two video channels through the fiber. The video is displayed, and can be recorded, on computer monitors topside at the pilot's station.

JR

JR is our "flying eye." Using a second robot as a support ROV for an external frame of reference should enhance our teams ability to perform any mission. Since we are using onboard power for *MTHR* and *JR* has a very simple function, we decided to make it surface powered. *JR* is actually just our version of the *SeaPerch* ROV that many of us have built as freshmen in the Discover Ocean Engineering Pre-Orientation Program (which is kept going partly due to heavy ROV Team involvement).[1]

JR is built on a PVC frame with pool floats and small 12 volt DC motors potted in wax. The tether is CATV cable, directly connecting each motor to the corresponding switch on the pilot's controller. Video is sent up a separate coaxial cable to protect the signal from interference. The goal of the SeaPerch design is a simple, cheap, robot that can be built in a minimum amount of time with a minimum amount of tools. We chose to make *JR* a SeaPerch because we have all the parts, it didn't need to meet any strenuous performance requirements, and it was a bit nostalgic for many of the team members.

Description of a Challenge

Our decision to design our own propellers came with a lot of extra headaches. The actual design didn't prove too bad; we used a series of existing propeller design tools, several custom MATLAB and Java programs, and our team knowledge of hydrodynamics and propeller design.

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[1] This design has also become the cornerstone of one of MIT SeaGrant's outreach programs, and they provide all the information necessary to build and operate one on their website at web.mit.edu/seagrant/www/outreach/seaperch/buildingsp/buildingsp.htm

The first big problem came with the last computational tool we were using. PBD 14.36 (Propeller Blade Designer) did not output a file of blade surface coordinates, which we needed for CAD and to machine the physical product. Unfortunately, the subprogram that translates one of PBD's outputs to what we needed was missing, and it would have taken a long time to rewrite. Fortunately, one of the Navy propeller designers at the Naval Surface Warfare Center in Carderock offered to process the files for us and send us CAD files of the blade surfaces. This wasn't the most streamlined process, but it was the best solution for our timescale, and it worked out well.

Once we finally had the necessary geometry coordinates from our model, we were able to generate a surface model. Unfortunately, we still couldn't make a full solid model because of some software subtlety. SolidWorks wasn't designed for complex hydrodynamic shapes and did not handle them well. We tried other CAD packages but were largely unsuccessful. Without an actual solid model, we couldn't have the propellers rapid prototyped or 3D printed. However, the surface coordinates did allow us to generate G-code for computer numerical controlled (CNC) machining.

The first plan was to make hard plastic/metal molds from the geometry, and then cast propellers in rigid urethane. This would save some trouble because each mold half only involved a single setup for machining much easier than realigning a part halfway. Unfortunately, we were unable to get sharp enough corners on the inside of the molds for it to close and fill properly. This was quite frustrating, as each mold half took about four hours to machine. Multiply that be a few iterations, and we had ourselves a major time sink.

The next idea was to make physical masters from plastic. In other words, we would machine the propellers directly, then either use as is, or create a soft mold for casting from the propeller. While this would involve multi-sided machining, it also would not require sharp inside corners, and reduced the CNC code to about 5000 lines per side (from 15000 to 100,000 for the molds!). The only problem was how to hold the propeller for the second side of machining. The first side is easy, just clamp the sides of the stock. In order to cut the second side, we made a jig that clamped the inside of the shaft bore, and added an alignment pin so we could have the part in the proper rotation. This way, we were able to manufacture the propellers, and implement our design on our robot.

Troubleshooting Technique

In any complex system, troubleshooting a problem can be challenging and time consuming. Rarely will you be able to build a system from the ground up and have it work the first time you try it, especially if you have not tested each part along the way. Electrical systems can be especially tricky, since the cause of an apparent problem can be difficult to pinpoint. One electrical troubleshooting issue the MIT ROV team had was getting the bottomside control boards to function properly. Though the correct serial signals were being sent to the bottomside board, the motors were not responding as expected.

In order to troubleshoot this problem, we looked at the system in parts – assuming nothing worked, we started from the input signal and followed the flow of control, checking each point along the way, until we found the source of the problem. Breaking down the problem and looking at each part gave us a systematical and efficient way of finding the non-functional part of the system.

We started by confirming that serial data was being sent to the bottomside board (using an oscilloscope), then, wrote a simple test code, utilizing LED indicators, to confirm that the PIC microcontroller was receiving the serial communications. Next, we checked that the PIC was handling the serial communications correctly by looking at the output of the specified pins. Finding all of these parts to be in working order, we next checked that the motor control chip was receiving the signals from the PIC. What we found was that there was an error in the PCB layout, which prevented a needed signal from reaching the chip. Once we compensated for this mistake, the boards operated as expected.

Had we not systematically gone about checking each point in the control flow diagram to make sure it acted as expected, we would have spent a significantly greater amount of time trying to troubleshoot our control system. Breaking down large systems into parts and checking each node along a pathway is a time (and sanity!) saving troubleshooting technique that we employed throughout the integration process to ensure a working system.

Lesson Learned

by Pranay Sinha

Electronics dominate every aspect of our lives today and yet, when I first came to MIT, this was one field which I had really not explored at all; had not even considered majoring in. Having enjoyed the Discover Ocean Engineering pre-orientation program, I decided to join the MIT Underwater ROV Team. This is where I first came received some hands-on training and actually got to work with circuits for a practical purpose for the first time. One of the circuits that I learned about was basic H-bridges for motor control. We needed to test these to see how well they worked with our thruster systems.

One of the seniors on the team, Jordan, took on the task of teaching me the basic concepts behind the design, functions and construction of the circuits. The preliminary layout was done using four transistors and resistors. Two of the transistors were of the PNP type while the others were NPN. We laid out the components on a proto-board and tested it using a power supply and motor comparable to the ones we were actually planning to use on our ROV. The circuit worked well after a little bit of debugging, something that did a world of good to my confidence in working with this kind of technology.

It is true that H-bridges are probably some of the simplest circuits one can make, but the same or remarkably similar concepts are used in switchgear of all kinds, simply because they provide full functionality, including coast and hard brake capabilities. They are generally very stable and if the ratings of the components used are right, they can take a lot of punishment before actually giving out. From a personal perspective though, I give H-bridges a place of great importance because they allowed me to truly understand how critical knowledge of such electronic systems is in the real world and how much fun their construction and application could be. I am such a firm believer in the necessity of learning about such systems that I am even planning to declare electrical engineering as a major. I am therefore truly grateful to the MATE ROV competition and the MIT Underwater ROV team, since without these entities, my education would probably not be headed in the exciting directions that it currently is.

Future Improvements

Though *MTHR* has incorporated many subsystems into a single working unit, there is always room for improvement. As mentioned earlier, we tried to keep our components modular for simplicity and to allow easier upgrades later. Some of the areas we've thought of improving are power, payload, autonomous operation, and pilot training.

Power

Although *MTHR* uses NiMH batteries this year, we have considered adopting a different battery chemistry. Other chemistries can provide more power with the same weight or volume. Since our primary concern with *MTHR* is volume, I'll focus on the potential improvements in volumetric energy density. Our current NiMH chemistry generally provides 100 W·h/L (360 MJ/m^3); Lithium ion chemistry, commonly used in laptop and cell phone batteries, provides 250 to 530 W·h/L (900 to 1900 MJ/m^3), that's almost 3-5 times the energy in the same volume! Using Lithium Ion batteries, we could greatly increase our mission time or reduce the size of our battery pack. There are drawbacks, however. Lithium ion chemistry requires more complex protective circuitry for safe charging an discharging. Lithium polymer batteries are also promising. With volumetric energy densities in the same range as lithium ion technology, these batteries could provide the same mission time or battery volume advantages. They have similar concerns during charging and discharging, but offer the added advantage of a less flammable (when compared to lithium ion) solid polymer electrolyte that can be molded to any desired shape.

Payload

MTHR's modular design allows for a wide variety of missions and associated payloads. Special payload sleds could be designed for a given mission and standardized to facilitate easy switching. For example, a water quality sled might include a CTD (which we have done some preliminary work on), a dissolved oxygen sensor, a turbidity probe, a pH probe, and other instruments. Its associated control and data logging hardware would be a 2-board PC\104 stack, housed in the main electronics enclosure. The first payload, the one that we built for the competition, is our manipulator setup.

Autonomous Operation

Since the payload includes two PC\104 boards, there is a possibility that *MTHR* could be used in an autonomous or semi-autonomous mode, similar to WHOI's new HROV. *MTHR* would be an ideal platform for testing new autonomous control systems, since it has a simple serial interface to drive the motors directly. This autonomous operation payload would have to include all the necessary navigational instruments (electronic compass, gyros, accelerometers, etc.) on the two boards, along with all the required computing power.

Pilot Training

Last but certainly not least, our team hopes to develop a pilot training program to improve our team members' capabilities in driving *MTHR*. An ROV can be the most advanced piece of equipment on a boat, but if the pilot is not proficient, the mission will suffer. Since we focused on making a generally capable ROV this year, we hope to have team members practice flying it during the term as we are developing the additions for next year, instead of dismantling it at the beginning of the term.

Ocean Observing system

An important organization involved with ocean observing is The National Oceanic and Atmospheric Administration (NOAA). A government organization responsible for monitoring oceans and atmospheres, NOAA is under the Department of Commerce and accomplishes its goal through six organizations: National Weather Service, National Marine Fisheries Service, National Environmental Satellite, Data and Information Service, NOAA Research, and Program Planning and Integration. In order to accomplish its tasks, NOAA works with governments on all levels: local, state, federal and international. NOAA uses its observations and measurements on the world's seas and atmospheres to generate information such as forecasts, weather warnings and weather advisories. They also monitor long-term trends as they study the issue of global warming and the ozone. NOAA also works in maintaining a balance in the ecosystems throughout the United States, such as fish.

NOAA is very active in research. They research issues related to weather such as hurricanes, tornadoes and other issues such as the marine ecosystem, the ozone, air pollution and ocean currents. For their information, NOAA relies on information gathered on its centers throughout the United States, partnerships with other government organizations as well as partnerships with academic institutions and various companies. NOAA releases some of its information, free of charge, to the public.

References

http://www.noaa.gov
http://en.wikipedia.org/wiki/Noaa

Acknowledgements

All the members of the MIT ROV Team would like to thank our sponsors and advisors for their support, without which we would not be able to continue our hands-on education in marine robotics.

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Fiber Instrument Sales, Inc
The Ocean Engineering Design Lab
The Ocean Engineering Teaching Lab

Dr Franz Hover
Christiaan Adams
Dr. Rich Kimball
Prof. Jake Kerwin
Thad Michael, NSWCCD

Appendix Table of Contents

I. MIT ROV Team Budget - FY 2006

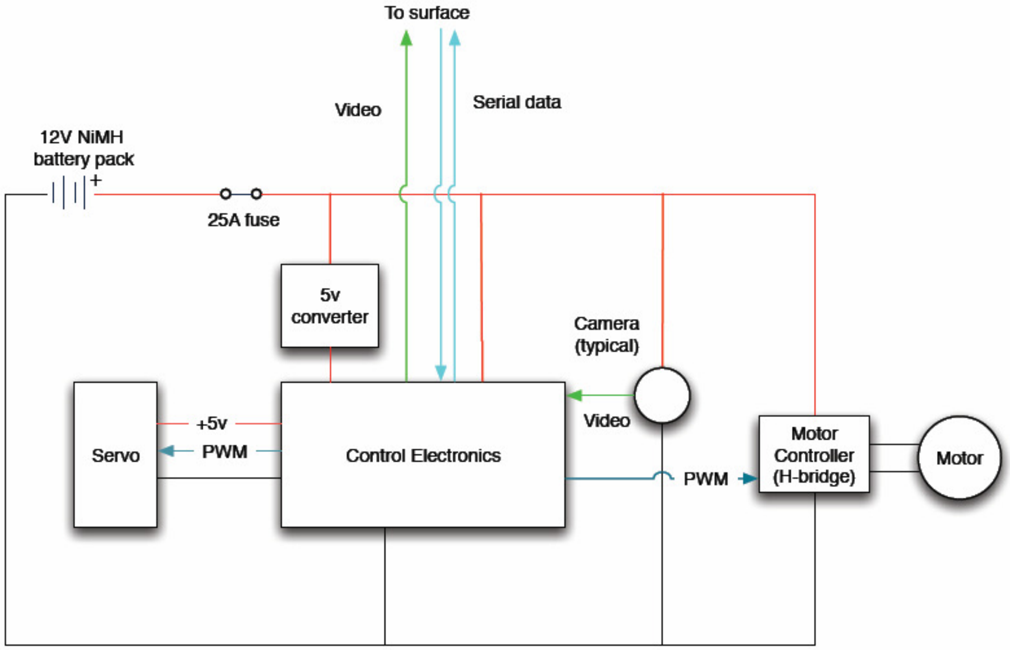
Team Expenses

ROV			
	Thrusters	505.51x4	$2,022.04
	Frame		$43.25
	Manipulators		$64.01
	Tether		$53.30
	Electronics		$379.04
	Overhead		$450.00
	JR		$75.00
Research			
	Manipulator		$600.00
	Thrusters		$1,500.00
	Electronics		$800.00
	Propeller		$200.00
Media			
	Poster		$150.00
	Paper		$50.00
	Resume book		$30.00
	T-Shirts		$302.94
Travel			
	Hotel		$1,545.60
	Vans		$1,000.00
	Shipping		$300.00
	Airfare		$3,571.80
Food			$543.24
Capitol			
	Laptop		$1,500.00
	Fiber Optic Tools		$900.00
Total outlay for this year:			**$16,080.22**

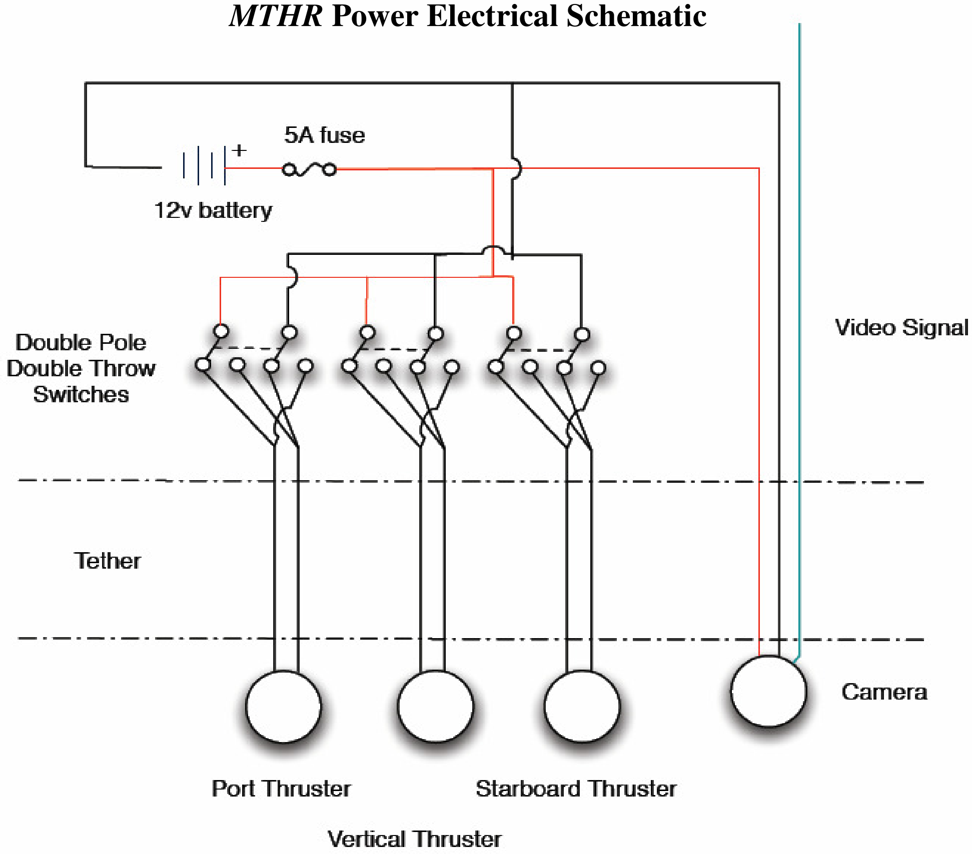
Resources

Monetary				
	MATE Travel Stipend			$1,000.00
	COE Contribution			$4,000.00
	ME Contribution			$4,000.00
	ExxonMobil Contribution			$6,000.00
	Sea Grant Contribution			$3,000.00
Total monetary resources				**$18,000.00**
Other				
	Prizm			
		Fiber spooler		$1,000.00
		Fiber Muxes		$10,000.00
	Altium			
		CircuitMaker		$12,000.00
	FIS			
		Fiber training		$299.00
		Fiber tools		$150.00
Total donated items:				**$23,449.00**
Re-used items				
	Cameras		200x3	$600.00
	NiMH batteries		22.65x20	$453.00
Total reused items:				**$1,053.00**

II. Power Electrical Schematics

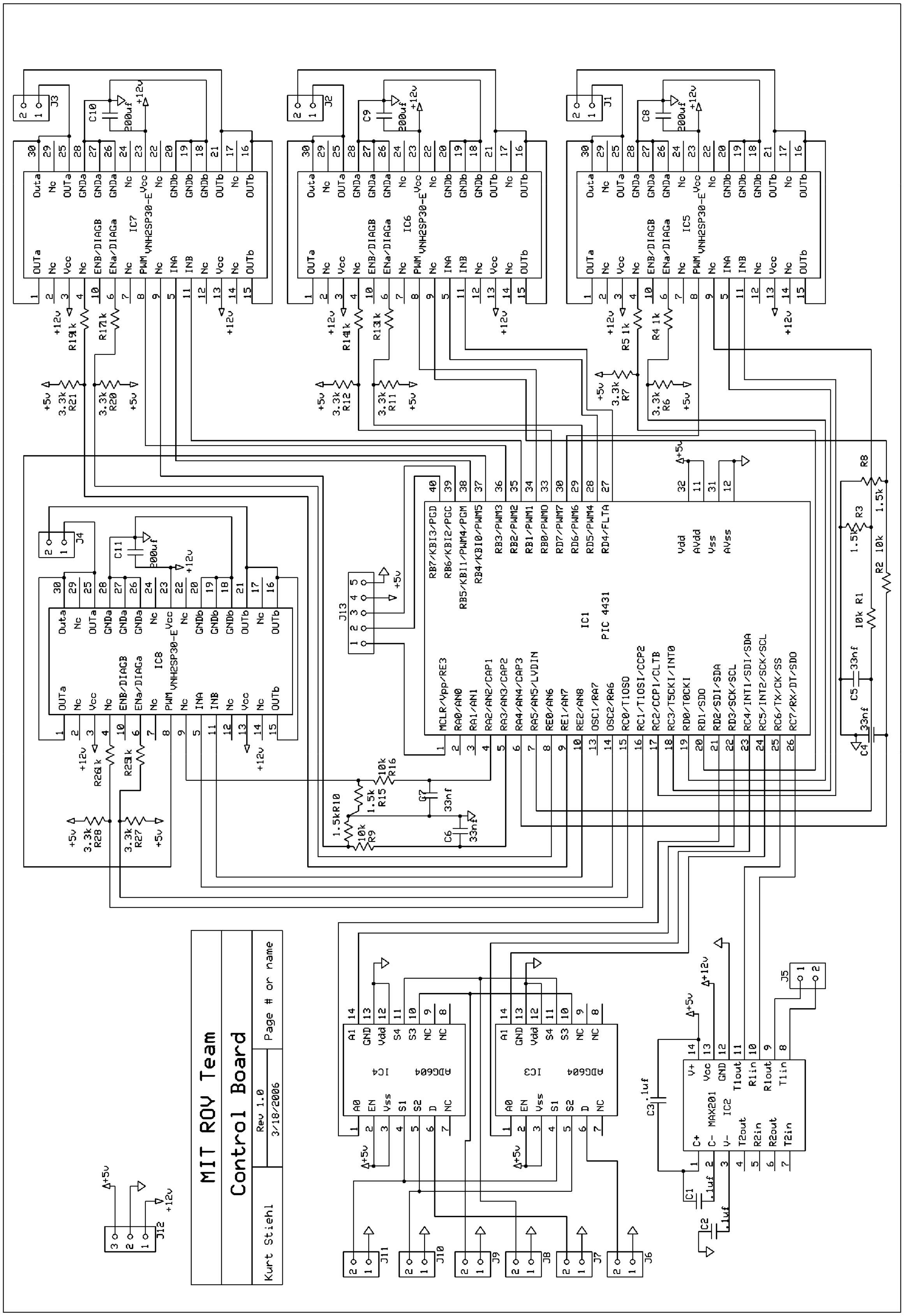


MTHR Power Electrical Schematic

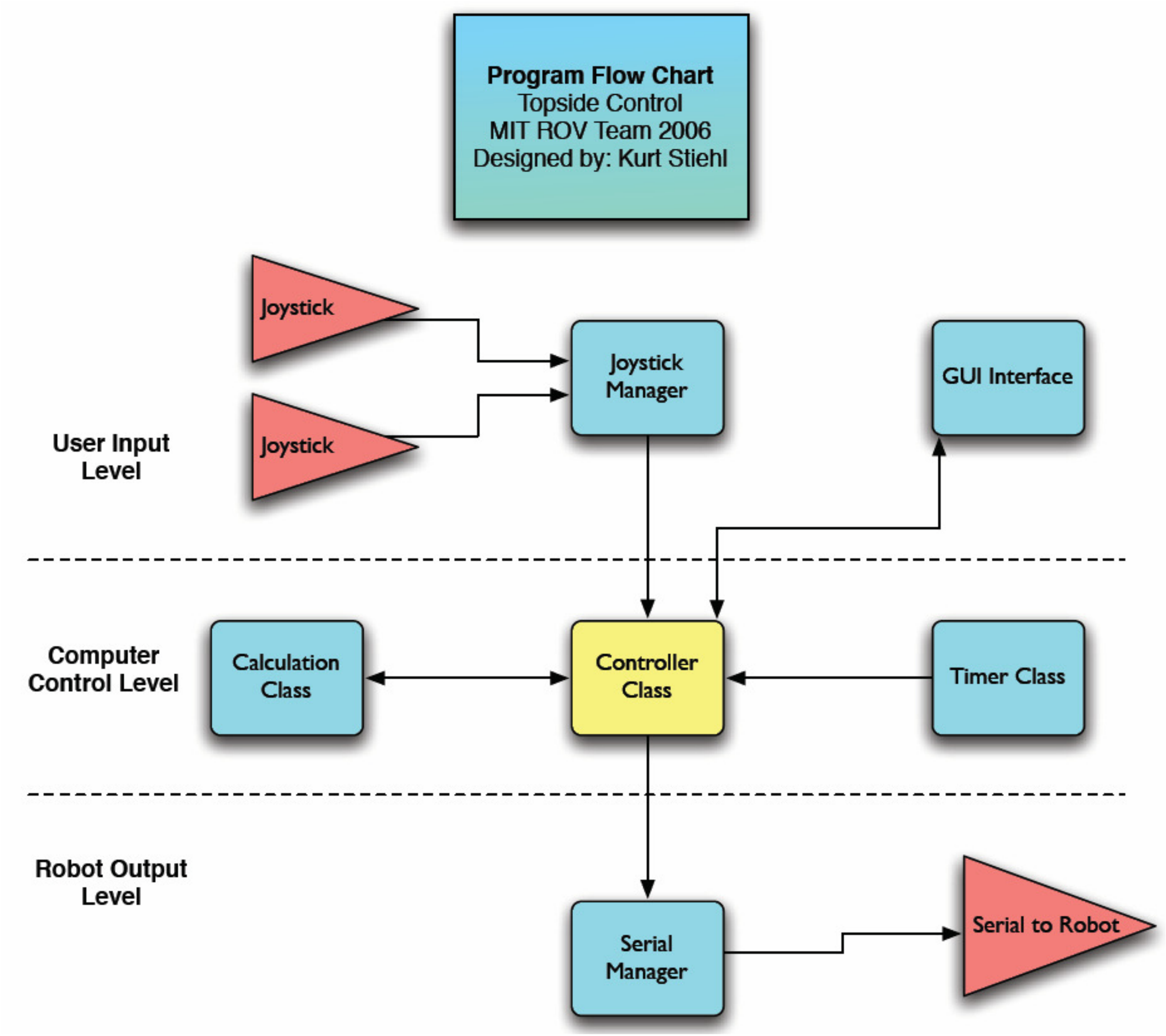


JR Power Electrical Schematic

III. Bottom Side Control Board Schematics



IV. Topside Control Flow Chart



V. Bottom Side Control Flow Chart