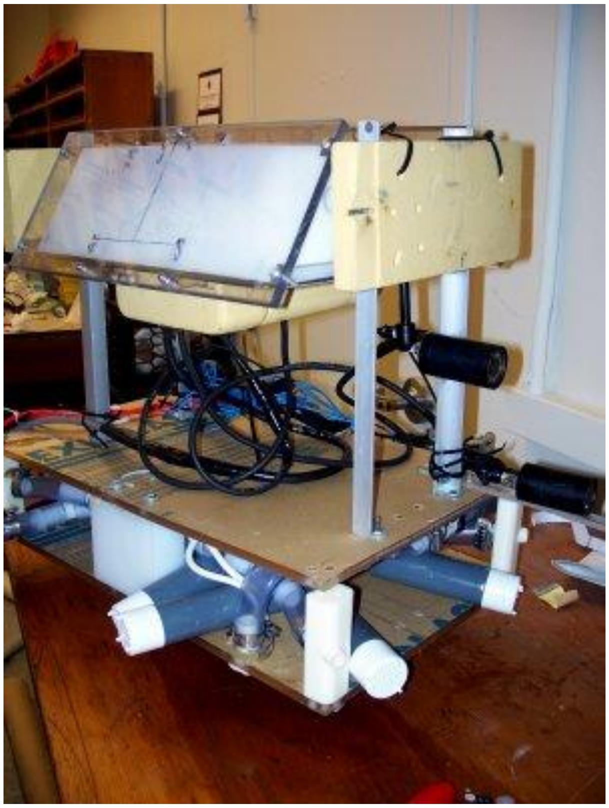
The MIT ROV Team

presents



Cuddlefish

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

Team Members: David Anderson, Michelle Chang, Stephanie Chin, Rangel Dokov, Matthew Gildner, Robert Han, Abigail Koss, Chris Merrill, Rachel Price, Pranay Sinha.

Mentor: Jordan Stanway
Faculty Advisor: Prof. Franz Hover

Abstract

This year, the MIT ROV team designed our ROV, *Cuddlefish*, not only to compete in the MATE competition, but also to be used afterwards for both didactic and practical purposes, a goal we have been working towards for the last few years. The emphasis was on extending electronic and software designs prototyped in the form of our 2007-08 ROV *Tim the Sixth,* as well as making the ROV much more versatile, compatible with different power systems, tethers, mission specific modules and sensors and most importantly, more reliable. These objectives, along with the size and maneuverability constraints we had set ourselves led us to design and build a vertical twin-body ROV, with powerful jet thrusters, capable of using on-board batteries as well as tether supplied power and fiber-optic data lines as well as standard Cat 5/5e cables. The design also reuses in its entirety the frame from *Tim the* Sixth for the upper module, electronics, power tether and software. Our mission modules include a motorized fork to open the escape tower hatch, passive hooks to carry ELSS pods and the air line and a passive system to open the air valve and hatch. The ROV also incorporates a transfer skirt made to specifications of the escape hatch on the mock submarine. Overall, this ROV can not only complete the MATE competition in a successful manner, but will also provide a good platform for future development.

The 2008-09 design cycle provided the team with many invaluable experiences. From getting dirty in the machine shop to attending black-tie receptions at the MIT museum to talk about the continuing MIT involvement with the sea and teaching school children about the role of ROVs in the energy sector, it has been an incredible year of pushing the envelope all round.

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Appendices

Design Rationale

In the past few years, the primary goal of the MIT ROV Team has been to produce a modular, extensible robot with components that could be upgraded individually. The driving force behind this was to enable the vehicle to be reused multiple times with varying mission profiles. While the team saw some success in this endeavor, we realized that the designs of some of our main systems needed drastic improvements if they were to work in this fashion. The critical areas identified for improvement were the propulsion system, which had always been prone to failures and the frame, which needed to be bigger to accommodate necessary mission modules and needed to be more stable.

Changes to the bottomside electronics system saw the addition of more motor control ports, while the topside system remained the same. Mission modules were designed with the specific missions in mind rather than to serve multiple purposes beyond the competition as in the past. The focus was on passive systems to increase reliability.

Structural Frame

Rather than designing and building a completely new frame, this year the team sought to simplify the process by incorporating the majority of last year's frame into the design of the new vehicle. This year a vertical frame design was chosen that would displace the vehicle's center of buoyancy and gravity from each other making it very resistant to pitch, heave and roll. Additionally this designed simplified process of the trimming the vehicle and provided more space for mounting the subsystem components.

The frame is made up of two main components: the trapezoidal frame used for last year's vehicle containing the control box and a base where the propulsion system and mission tools are attached. The top of the frame (essential last year's frame inverted) is made up of two angled polycarbonate plates held together by crossbars. A watertight polycarbonate control box is set between these plates and held in place by additional crossbars. The base of the frame is made up of two 30.5 x 46 cm acrylic plates separated by 11 cm tall Delrin blocks. The outside surfaces of these plates are used to mount the mission tools and cameras to the vehicle while not being the way of the propulsion system. The space between the two plates is used to house the propulsion system's pumps. The base and top parts of the frame are connected by 4 33 cm L-bars. Foam is attached on the frame's top giving it a slightly positive buoyancy. The completed frame can be seen in figure 1.

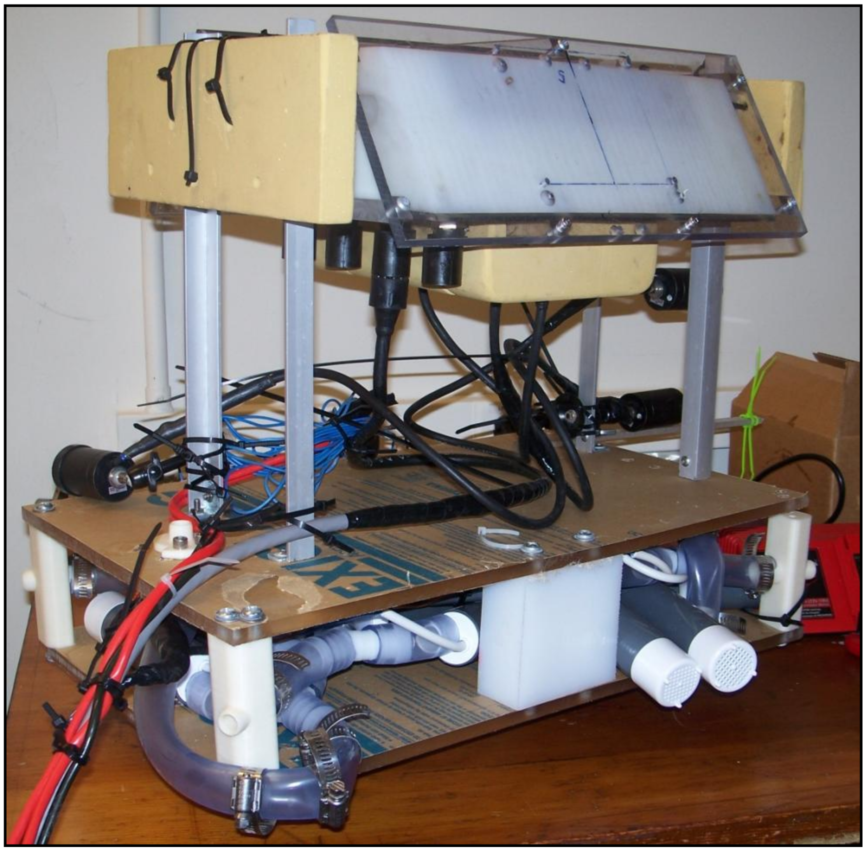

Figure 1: ROV frame with propulsion system and control box attached.

The stability of this frame results from the separation of the center of buoyancy and mass. The air-filled control box located at the top of the frame attributes to pulling the center of buoyancy upward along the height of the frame while the pumps at the base pull the center of mass downward. This separation provides the vehicle with a large righting moment whenever it is in pitch, heave or roll.

Propulsion System

The implementation of an innovative propulsion system has been a strong design goal in the past several iterations of MIT's vehicle. In the past this goal manifested itself in the form of in-house designed counter-rotating and 3D printed propellers and custom waterproof motor housings. This innovative tradition continues with this year's use of a water jet propulsion system.

In the past thrusters have historically been the most problematic subsystem of the vehicle. Leaks and friction in motor housings have resulted in a less than satisfactory performance. The design of this year's propulsion system attempted to avoid these problems while still creating a novel system. Rather than utilizing a high performance DC motor requiring a complicated waterproof housing, submersible pumps power the system thus significantly reducing the risk of leaks. Additionally thrust is provided by nozzles rather than propellers, eliminating the any problems relating to shaft friction.

To optimize the design of the water jet system extensive research and testing was performed before choosing a pump and nozzle geometry. Research showed that utilizing two 12V LVM Congo pumps in parallel would provide the most power for the space considerations[1]. These commercially available pumps are cylindrical in shape and take up less than 190 cm^3.

Once these pumps were chosen a frame was constructed to test the force produced by different nozzles. Mounted on the frame were the pumps and the test nozzle. This frame was then suspended in a water tank. Attached to a cross beam above the tank were two rods on which the frame could slide and a force sensor. The force sensor was connected to the frame by a threaded rod which screwed into the sensor and a Delrin block on the frame. A diagram of the frame setup can be seen in Figure 2.

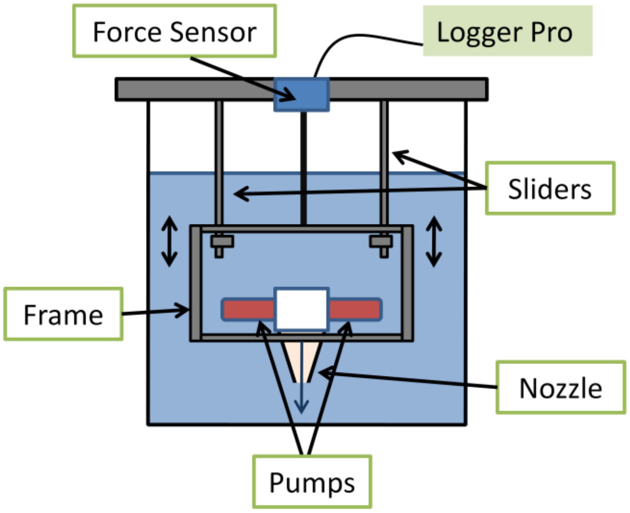

Figure 2: Testing Setup

Each test nozzle was designed in Solidworks and manufactured using a 3D printer. Force measurements were taken at 12V and 18V. A maximum thrust of 6N was obtained using a nozzle with a 1cm output diameter at 18V. This nozzle design was then incorporated into the modeling of nozzles for the final vehicle.

The vehicle makes use of eight nozzles each connected to two parallel pumps. Each nozzle has an input diameter of 1.5 cm, an output diameter of 1 cm and length of 52.3 cm. One nozzle is placed at each of the four corners of the ROV base. Each corner nozzle is integrated

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[1] http://www.bose.com/controller?event=VIEW_STATIC_PAGE_EVENT&url=/index_2.jsp

into a column which attaches to the base's corners. The nozzles are attached at 25˚ angles from the vehicle length to allow for strafing.

The four remaining nozzles are used for vertical movement. These nozzles are inserted into holes in the base of the ROV and attached by flanges incorporated into their design. Three nozzles are placed on the bottom of the ROV base to provide adequate thrust to lift the ELSS pods. The last nozzle is placed on the top of the base to propel the vehicle downward. A corner nozzle can be seen in figure 2 and a vertical nozzle can be seen in figure 3.

Figure 3: Corner Nozzle

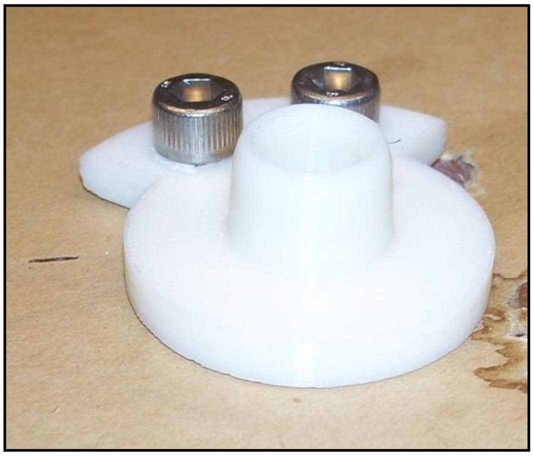


Figure 4: Vertical Nozzle

Nozzles are attached to the pumps using clear plastic ¾" tubing and y-connectors. The pumps and hosing are placed between the two acrylic plates which make up the vehicle's base. The pump pairs are connected to the control box using wet-pluggable connectors. Each pair is then PWM controlled to provide variable thrust. In Figure 5 the completed propulsion setup can be seen.

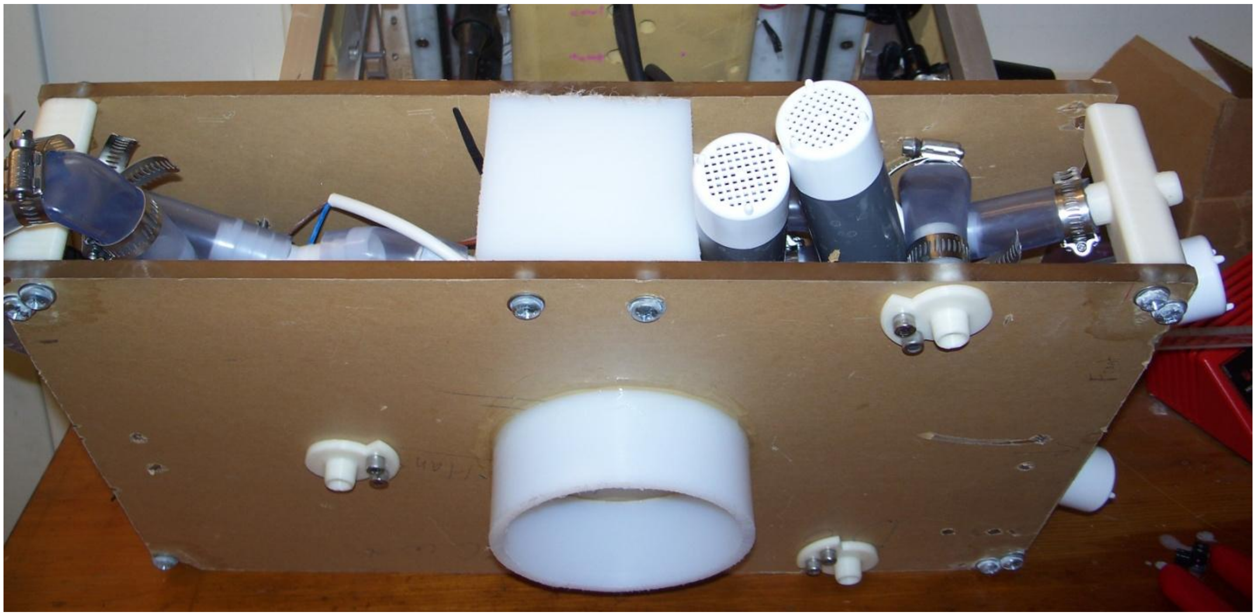


Figure 5: ROV base with vertical, corner nozzles and pumps.

Bottomside Power, Control and Sensor System

The schematic representation of the control system is shown in Figure 6. The central part of the control system is the Microchip PIC18F4431 microcontroller, which communicates with the topside computer and actuates the thrusters and servos on the ROV. The microcontroller receives commands from the surface by a serial RS-232 connection. A Texas

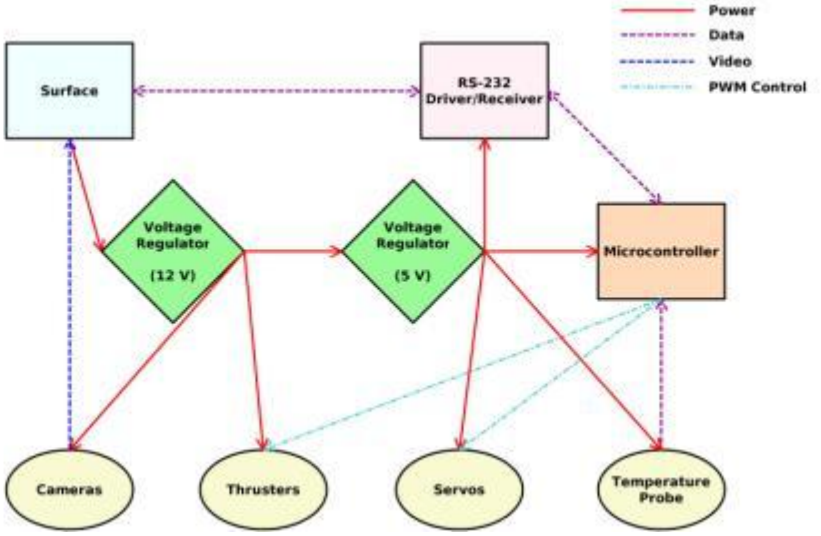


Fig 6: Schematic representation of bottomside control system

Instruments SN75C1406 chip is used to convert between the RS-232 voltage levels used by the topside computer and the TTL voltage levels used by the microcontroller. The control of the actuators is done through PWM signals that control both the thrusters and the servos. For the thrusters an STMicroelectronics VNH2SP30-E H-bridge is used to amplify the PWM control signal generated by the microcontroller to the current level needed for thruster operation. Figure 8 shows the detailed schematics for the bottomside control board.

This year, due to the large number of PWM outputs needed for the pump system, we decided to have three bottomside boards all listening to the same serial line from the topside control system. The serial commands contain an ‘address’ to identify which board should respond, and each command also contains the ‘address’ of the PWM port to be used on the identified board. Thus, each board only responds to the topside commands meant for it.

Power: The two on-board voltage regulators provide a stable source of both 12V and 5V with a wide range of input voltages from the surface. The 12V source is based on a National Semiconductor LM5030 switching regulator, that can handle the large currents necessary to run the thrusters. It can be operated either with a topside source through a tether, or with on-board battery supplies. The 5V source is provided by an STMicroelectronics LD1084V50 linear regulator, which supplies only the microcontroller and the servos, so it has a fairly low current requirement. Figure 12 shows the electrical schematic for the vehicle.

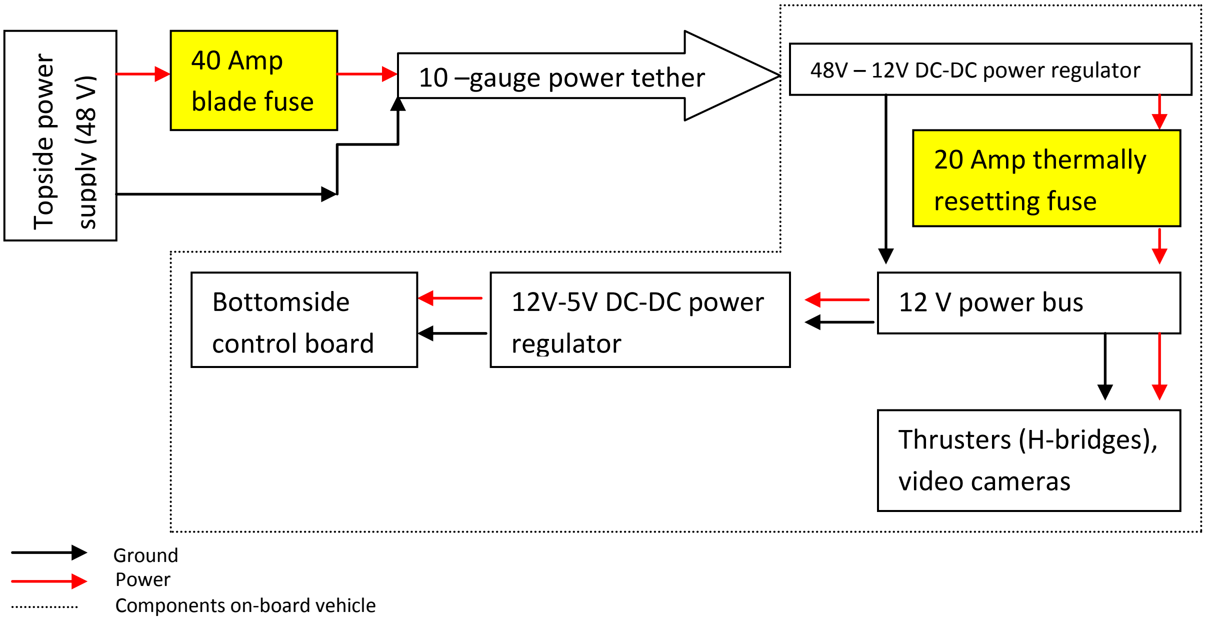


Fig 7: Electrical Schematic

Temperature sensors: Temperature sensing is performed by using a thermistor probe, which changes its resistance based on temperature. A high precision resistor voltage divider and an Analog Devices AD622AR instrumentation amplifier are used to convert the resistance change to an analog voltage signal which is read by the microcontroller's analog to digital converter.

Video: In the current design the video signals from all five cameras are sent directly to the surface through the tether. For compatibility with our fiber optic tether that only has two video channels, a video switching system is maintained in the control electronics, that allows any two of the four cameras to be send through the tether.

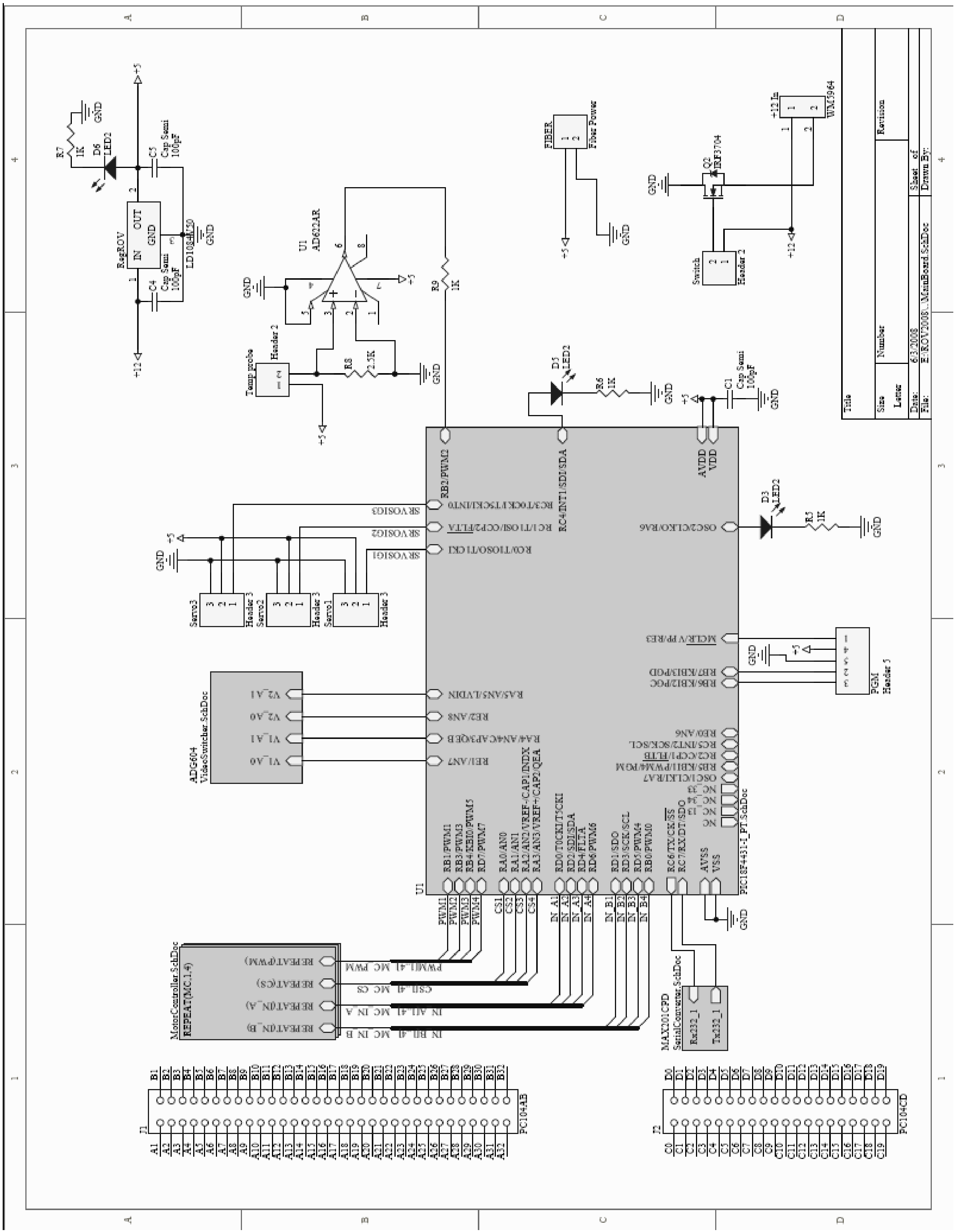
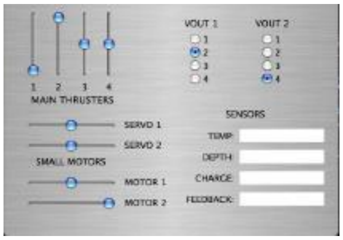


Fig 8: Bottomside control board schematics

Topside Control System



VOUT 1: ○ 1 ● 2 ○ 3 ○ 4

VOUT 2: ○ 1 ○ 2 ○ 3 ● 4

Fig 9: Screenshot of topside controls

Topside controls are driven by a custom JAVA application on a Windows laptop (See Figure 9). Algorithms for this application were taken directly from kROV 5.0, the team's previous topside software version (developed by K. Stiehl). 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.

JAVA usb drivers were authored by independent developer George Rhoten and are open source.[2] The drivers and the application can be used on linux and Windows platforms.

Mission 1

The first mission involves a survey of the submarine and identification of five points of damage marked by the letters A through E. To accomplish this mission, and indeed to allow optimal control of the vehicle, the ROV has five waterproof color cameras mounted at different locations. The primary drive camera provides an unrestricted view in front of the vehicle. The rear camera allows a view of the tether to prevent tangling. The starboard camera focuses on one of the passive lifting hooks for the ELSS pods and the port camera focuses on the air line hatch arm. The bottom camera provides a view of the docking hatch and the escape tower hatch opening mechanism. Views from these cameras allow the identification of targets all around.

Mission 2

The second mission involves rotating a wheel to open the ELSS hatch, opening the hatch itself and then transporting ELSS pods from their receptacle to the hatch. We plan to accomplish this by using a simple fork connected to the wrist joint of our 2007-08 manipulator arm and mounted with the prongs pointing vertically downwards to rotate the locking wheel and hooks on arms on the starboard side of the vehicle to lift and drop off the pods them selves.

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[2] http://sourceforge.net/projects/javajoystick/ [May 31, 2008]

Mission 3

Early on in the design phase, we realized that the arm that would be used to manipulate the life support pods could be used to turn the valve for the airline insertion task. Our design plan was to produce a fast method of completing the door opening and airline insertion, by creating a passive system with minimal precision maneuvering. Our door-opening mechanism had the primary goal of passively opening the door when facing it head-on. The largest target on the door in that direction was the plastic mesh. Zip ties were used as a simple whisker system to ensnare the mesh, allowing the pilot to reverse and open the door. Once the door is open past a certain point, the whiskers can be pulled from the mesh. The key to speed with the inlet was making the effective target as large as possible. The airline insertion point is mounted to a large plastic triangle, angle downward 45 degrees and angled outwards at 30 degrees. Coupled with the long arm on which the zip tie whiskers are mounted, the arrangement allows the pilot to “crash” the ROV into the inlet: as long as the tip of the triangle is on the bottom of the pipe, and the arm is on the outside of the milk crate, forward thrust should drive the insertion point into the inlet passively. This passivity does lend some challenges, however. Most notably, our passive system is very sensitive to changes in the mission props; the door mesh size, the inlet placement, and the resistance of the door hinges. Using zip ties that are slightly larger than necessary helps with the first and third problems. Should our door opening system be entirely unsuitable for the mission props at the competition, the am on which the zip ties are mounted is thin enough to hook the door handle, though this requires approaching the door from the side. Issues of inlet placement, however, delayed construction as we tried to get the most precise measurements possible. This sensitivity also makes testing difficult, as props need to be constructed to get any meaningful testing data.

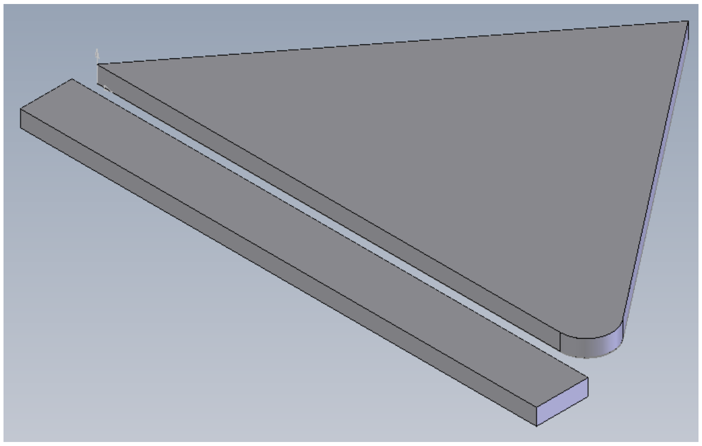

Figure 10: Mission 3 parts CAD

Mission 4

Mission 4 involves docking with the submarine mock-up. To achieve this, we have a skirt built to specifications provided by the MATE Center mounted to the bottom of the frame, with a camera providing an adequate angle of view to allow docking. The system is completely passive and depends on the pilot maneuvering the vehicle into position, descending, holding station and the ascending.

Tether

There are two kinds of tethers our vehicle is designed to use. If powered by on-board batteries, we prefer to use a single strand of fiber optic cable for purposes of maneuverability. It passively spools out of a disposable 500 meter long coil. 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.

The second kind of tether provides power as well as data transmission capability to the vehicle and will be used for the MATE International ROV Competition. It consists of two insulated 10 gauge wires for power transmission and a standard Cat 5 cable for data transmission. 5 lines on the Cat 5 are used for video transmission; two are used to transmit serial data to and from the topside controller and the last line is reserved for emergency use in case of breakages. The cables are housed in a water-resistant sheath and the tether has a usable length of 30 m.

Description of a Challenge

Our decision to redesign our propulsion system and move to a jet propulsion design provided several challenges. The first was the actual design of the nozzles. It was relatively simple to design an optimal nozzle cross-section, though not trivial either. The main issue was mounting the nozzles to the vehicle and the actual manufacture of the designed cross-section. Our first idea was to use a CNC lathe to machine the nozzles from a cylindrical blank. However, this did not solve the problem of an adequate mounting mechanism for the nozzles to the vehicle itself.

The solution we came up with was to incorporate the nozzles into structural frame elements that could be bolted into place. This had the additional advantage of saving space on board, but would mean that each nozzle would have to be designed separately. We did this, but then had the problem of actually manufacturing the complicated shapes. We experimented with making the structural elements – pillars for the frame for example – on a CNC mill, and then using a lathe to carve out the nozzle within it. This, however, provided finished products of a quality not acceptable, as the uneven shapes of the structural members did not allow their mounting on the lathe chucks in a centered manner.

The solution to this was using a 3D printer to manufacture the nozzles, which we did. We then had to ensure using destructive testing that the parts were strong enough to withstand the structural loads they would have to withstand as integral parts of the frame. This step was necessary as the 3D printing material is not as strong as a solid block of ABS, which would have been our material of choice.

Fortunately the parts passed testing and were ready for integration, leading to our final challenge on this subsystem – layout of the necessary plumbing. Lack of experience and availability of plumbing software tools led to our having to layout the pipes needed to connect pumps to their respective nozzles by a process of trial and error. After a few attempts, we were successful and had a fully functional jet propulsion system.

Troubleshooting Technique

As in any technical endeavor, many of our systems do not work the first time they are plugged into the vehicle. This is especially true if individual subsystems and components have not been tested along the way. One of the most frustrating malfunctions that one can have is to command the vehicle to carry out some operation and find no response at all, something which happened to us during our first outdoor test session at the MIT Sailing Pavilion on the Charles River.

Using our standard troubleshooting methodology, we went about systematically checking each section of the ROV that could lead to a no response condition. The first step was to look through the transparent cover of our control box to establish whether the vehicle was receiving power. The red power input LEDs on each of the control boards was illuminated, indicating that we did indeed have power. LEDs on the cameras were also aglow, indicating that that system, on a branch power loop, was also powered up.

The next thing we tried to determine was if the control boards were receiving any data. To do this, we simply looked at the data transmission LEDs on the control boards. These green LEDs blink if communication is occurring, but this time they stayed off. This could have several implications, from faulty connectors on the vehicle to a break in the tether to faulty cable soldering within the control box to something as simple as our not having plugged in the data tether to the topside computer.

Our topside control software has the option to display as text any data received through the Rx pin on the serial port. Our tether has a loop which carries a copy of all signals transmitted down the tether back up to the computer immediately after the serial plug at the topside end. The lack of any read-back on this mirror system indicated that the tether did not have any data being transmitted, which led us to believe there was a problem with either the software or the hardware topside. Replacing the tether serial plug with a simple mirroring circuit plug (i.e., with the Tx pin connected to the Rx pin) allowed the system to pick up read-back data. This meant that the issue was with the serial plug on the data tether. Opening the plug led to the discovery of a Tx wire that had not been properly soldered. Once this was rectified, everything worked properly.

Thus a systematic problem identification approach, aided by markers meant to indicate proper vehicle functioning, allows quick troubleshooting of issues.

Lesson Learned

By Chris Merrill

After initial introduction to the team all the new members were put through a training course meant to familiarize them with use of basic tools used by the team. This included sessions on SolidWorks, MATLAB, and Altium Designer 6 for electronics, machine shop training and training on the Edgerton Center's Laser cutter. After training however, came the biggest and best portion of the learning experience – we were asked to choose and develop a subsystem for the actual competition robot even though we were freshmen!

I chose mission 2 and developed the rotating fork to open the hatch wheel. This allowed me to put to use my SolidWorks training and also build the fork in the machine shop. In addition, it forced me to think about the design in advance, including the sizing of the motor required, the waterproofing necessary for the motor and whether we could reuse components already owned by the team to save on cost. I was able to complete this module with help and advice from the senior members whenever I needed it. It was an awesome feeling to have been allowed to play an important part in the design process and to see my design come to life.

In all, in think all the freshmen learned and gained a lot from the experience of being on the MIT ROV Team, not just in terms of skills such as use of software and machinery, but also in terms of what it takes to complete a design-build cycle successfully. I hope to stay involved in what is a fun, interesting and challenging project.

Future Improvements

Our plans for the future are not much different this year than they were over the last two years. The basically reflect those portions of our standing objectives that we have not yet been able to achieve.

Inertial Guidance

One of our objectives is to be able to use ROVs of our design for monitoring the environment in small rivers. These are often murky, rendering cameras nearly useless. In order to operate in such environments, we would like to implement a cheap but accurate inertial guidance system, including COTS MEMS accelerometers and gyroscopes, in addition to depth sensors.

Autonomous Operation

Since the payload includes two PC-104 boards, there is a possibility that our vehicle could be used in an autonomous or semi-autonomous mode, similar to WHOI's new HROV. *Tim VI* 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.

Submarine Rescue System

The UK Submarine Rescue Service, run by James Fisher's Rumic division in Scotland, is a fully equipped rescue system operated in the northern European waters. This commercially operated service can handle a number of submarine emergencies with its transfer under pressure capabilities, portable handling system, LR5 manned submersible, and other rescue devices, including the Scorpio 45 ROV[3].

Figure 11: Scorpio 45, ROV of the UK Sub Rescue Service[6]

The Scorpio (Submersible Craft for Ocean Repair, Position, Inspection and Observation)[4] is an ROV designed for use in the oil and general operations industry. Notably, it is used by both the US Navy and the British Royal Navy in their submarine rescue systems. The Scorpio 45 is the British navy's vehicle.

Equipped with a large array of tools, the Scorpio 45 is capable of handling many rescue situations remotely, in situations too dangerous for manned vehicles. To accomplish such tasks, the ROV is outfitted with multiple cameras, sonar systems, sensors, and manipulator arms. The Scorpio 45 is built to cut wires and clear debris, to pump mud, and to carry and release payloads.[5] Specifically, the vehicle

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[3] "Submarine Rescue." *JFRumic Limited*, 2004. 22 May 2009. <http://www.jfrumic.co.uk/SubRescue/UKSRS.html>

[4] "ROVs and Trenchers." Perry Slingsby Systems, 2008. 22 May 2009. <http://www.perryslingsbysystems.com/rovs_trenchers.html>

[5] "Case Study." *JF Rumic Limited*, 2004. 22 May 2009. < http://www.jfrumic.co.uk/SubRescue/Case%20Studies/Scorpio_CS/Scorpio1.html>

is able to carry canisters of "life support", oxygen, food, and medical supplies, to a submarine's escape hatch.[6]

The ROV made it to the headlines in August 2005, when it was involved in the rescue of the Russian submarine Priz. Trapped in underwater cables, the Priz was rendered immobile more than 600 feet deep off the coast of Siberia with seven men inside. The Russian Navy called for help after its own attempts to surface the submarine failed. The Scorpio 45 was able to cut the cables entangling the submarine, and the crew were all able to exit the sub themselves.[7]

Reflections on the Experience

Apart from all the engineering challenges and activities that the MIT ROV Team undertakes, perhaps our most rewarding experiences are those of educating students and adults alike about Ocean Engineering and its importance and benefits to mankind. This is especially important in order to aid incoming freshmen at MIT make an informed decision about which major they wish to pick for their undergraduate studies.

The MIT ROV Team participated in the Discover Ocean Engineering pre-orientation program in August 2008 as part of out outreach efforts. We helped students build and test sea-perch ROVs in the MIT swimming pools and also off the dock at the Woods Hole Oceanographic Institute. It was an excellent experience to see the freshmen enjoy this activity, redesign and provide their sea-perches with additional capabilities and learn about ocean science and engineering.

Participation in the program also had a very pleasant side-effect; we managed to recruit two very enthusiastic new members with amazing skill sets and great personalities. They have been invaluable to the team not just as engineers but also as people – boosting morale and egging everyone along whenever needed.

All in all, we plan to keep participating in this event every year, and hope to influence students as well as learn from them as much as we can.

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[6] "Scorpio 45: The UK's deep-sea rescuer." *BBC NEWS*, 7 Aug 2005. 22 May 2009. <http://news.bbc.co.uk/go/pr/fr/-/2/hi/uk_news/4128728.stm>

[7] "Scorpio 45: The UK's deep-sea rescuer." *BBC NEWS*, 7 Aug 2005. 22 May 2009. <http://news.bbc.co.uk/go/pr/fr/-/2/hi/uk_news/4128728.stm>

Acknowledgements

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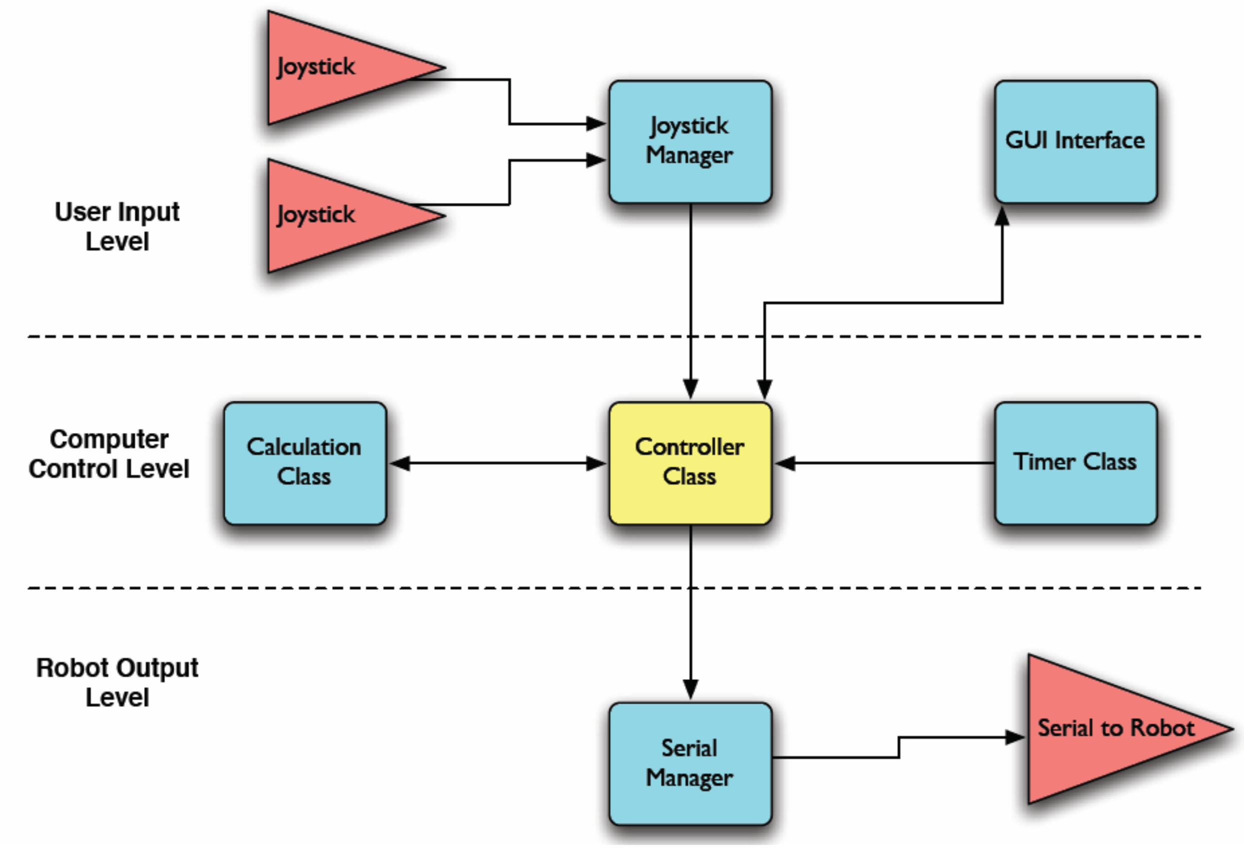
MIT Center for Ocean Engineering
MIT Department of Mechanical Engineering
The Edgerton Center and Student Shop
The MATE Center
MIT Sea Grant College Program
Prizm Advanced Communication and Electronics
Altium
Fiber Instrument Sales, Inc
The Ocean Engineering Teaching Lab
The MIT Museum

Prof. Franz Hover
Jordan Stanway
Lauren Cooney
Dan Walker

Appendix A
MIT ROV Team Budget – FY2009

Category	Itemized Expenses	Total Expenses	Sponsors	Projected Funds
MATE Robot		$ 3,400.00	**Mechanical Engineering Dept.**	$3,500.00
materials	$ 600.00		**Chevron-MITEI**	$5,000.00
pumps	$ 1,500.00		**Exxon Mobil (Edgerton)**	$6,000.00
nozzles	$ 200.00			
electronics	$ 1,100.00			
Tools, hardware	$ 700.00	$ 700.00		
Food	$ 500.00	$ 500.00		
Media (poster, t-shirts)		$ 350.00		
presentation poster	$ 150.00			
t-shirts	$ 200.00			
Lodging		$ -		
double/night	$ 180.00			
no. doubles	0			
no. nights	0			
Travel		$ 300.00		
Car Rental rates plus gas	$ 75.00			
no. cars	1			
no. days	4			
Total		$ 5,250.00		$14,500.00

Appendix B
Topside Control Flowchart[8]



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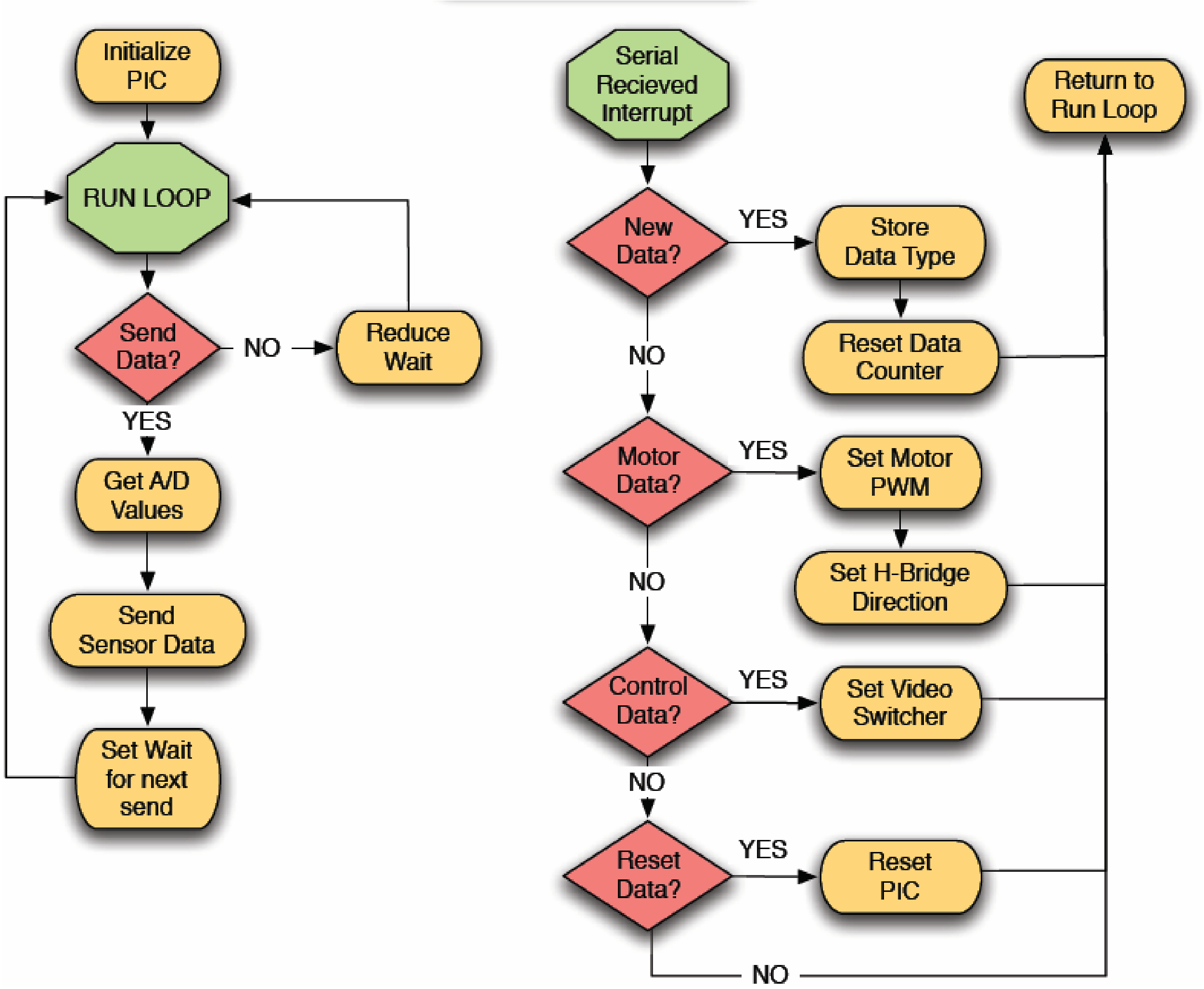
[8] Based on control scheme design by Kurt Stiehl, MIT ROV Team 2006-07

Appendix C
Bottomside Control Flowchart[9]



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[9] Based on control scheme design by Kurt Stiehl, MIT ROV Team 2006-07