Tim the ROV

Designed and built by the MIT ROV Team

Team Members: Michelle Aquing, Heather Brundage, Lauren Cooney, Bridget Downey, Eddie Huo, Albert Kwon, Harry Lichter, M. Jordan Stanway, Thaddeus Stefanov-Wagner, Kurt Stiehl, Daniel Walker

Instructor: Dr. Franz Hover

Abstract

Developed for the 4th Annual Marine Advanced Technology Education Center's (MATE) Remotely Operated Vehicle (ROV) Competition, Tim the ROV was designed and built by MIT's ROV team to compete in the Explorer Class division. Capable of operating at depths of 40 feet and completing tasks such as fluid collection, temperature measurements, and object retrieval in under 30 minutes, Tim was designed to be small and highly maneuverable. To aid in maneuverability, Tim is equipped with on-board power which lets him use a passive-spooling, single-strand fiber optic tether to communicate with the surface. Tim's compact layout and powerful thrusters also contribute to the main design goal – a small, highly maneuverable ROV capable of completing the MATE ROV competition.

Figure 1 Tim the ROV

Design Rational

The MIT ROV team set out this year to develop a very small, highly mobile, and mission-capable ROV. This ROV would be capable of performing all the mission tasks set forth by the MATE competition scenario, including positioning a fiber optic connection, retrieving three science probes, collecting an undiluted fluid sample, and measuring the temperature of an upward current. It would be able to complete all tasks in under 30 minutes while at depths of up to 40 feet. From experience, it has become apparent that a small tether and a small vehicle are necessary for good mission performance. Making size and maneuverability a top priority, the team aimed to build an ROV that would fit into a twelve-inch cube and would run off a small tether.

In order to meet this goal, the team took a new approach this year - operating the vehicle off of on-board batteries. Though this meant stricter power restrictions, it allowed for significantly reduced tether size and eliminated power loss issues involved in low voltage powering through a long tether. Though on board batteries take up space and added significant weight to the vehicle, these were trade offs the team was willing to make in order to improve maneuverability. The decision to keep the ROV small and to use on board power affected the rest of the design of the vehicle.

Batteries

After researching small, efficient, 12-volt (a competition requirement) batteries, the team decided to use 10, 1.2 volt, 20Amp-hour Nickel Metal-Hydride (NiMH) battery cells (Figure 2). These are split into two waterproof Otter boxes (Figure 3), each with a 30 A slow blow fuse in order to protect the batteries. A 25 amp fuse on the entire power system is located in the control box in order to meet competition requirements (See schematic in Appendix C). Two sets of two battery packs were built in order to allow for charging, and each can easily be discounted from the main system using waterproof impulse connectors.

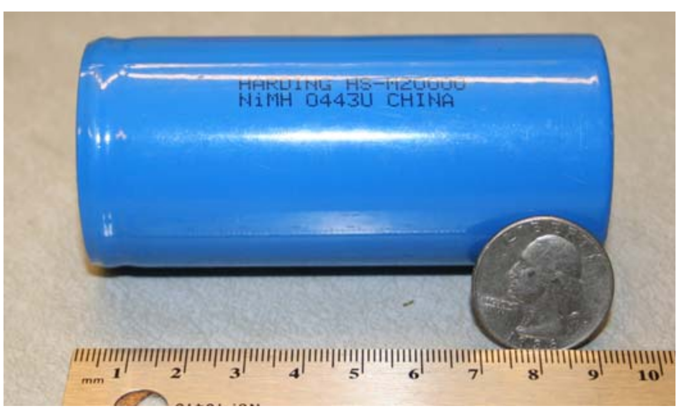


Figure 2 NiMH 20 Amp-hour battery

Figure 3 Battery pack, complete with fuse

Tasks 1 & 2 – Connect Communication Link and Retrieve Data Probes

When deciding on how to complete the mission tasks of retrieving the probes, the main goal was to design a passive system that would quickly retrieve all the probes. The team had hoped to find a way to descend on the probes, grabbing all three at once, and then ascending again. The mission specifications were not specific enough to design for this, however, and a relatively simple cork-screw design resulted. In order to keep the system simple and compact, the same method will be used to carry the communications link to the connector. This prevented the need to deal with more appendages on the vehicle that could stick out and get caught. It also decreased the complexity of trying to add manipulator to the vehicle.

In order to retrieve the probes, Tim first has to be open the drawer. Though many ideas were considered for the drawer opener, the goal of simplicity won out and a completely passive hook was designed to use the thrust from the ROV in order to open the drawer. This meant no more motors, that could allow for the hook to swing out when it was needed then tuck away when it was done, were added to the system to take up space and power and add complexity.

Task 3 – Collect a Fluid Sample

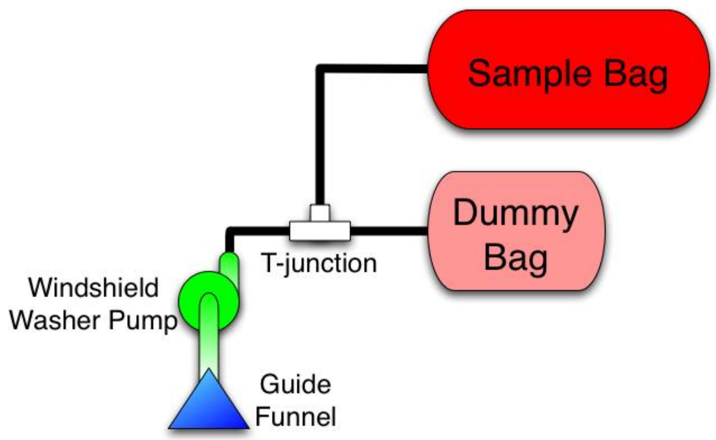


Figure 4 Fluid Collection System

Again, simplicity, size and power constraints guided the design for task number three – collecting a sample of fluid from the crevice. Similar to last year's system, the design is based on two flexible collection bags, so that there is no net change in buoyancy when the sample is collected. A funnel is used to aid in targeting the collection, and a windshield washer pump is adapted to suck the sample into the bags (Figure 4). This pump is an improvement over the bilge pump used in the past because it has 10% of the internal volume and therefore requires less fluid for priming. This means less dilution in the collected sample. To avoid any dilution in the actual sample, a passive rejection system is used. The sample flows straight through a t-junction into a dummy bag, getting rid of the water that initially fills the pump as primer. Once this dummy bag is filled, the fluid passes through the upward leg of the t-junction, and into the 500 mL sample bag. The system fills 500 mL in 20 seconds.

Task 4 – Measure Temperature

In order to fulfill this mission requirement of measuring the temperature of a venting fluid, Tim is equipped with a temperature sensor based on a resistance temperature detector (RTD) (Figure 5). An RTD changes resistance linearly with temperature, so it is easy to calibrate, and provides an easy to measure voltage output.

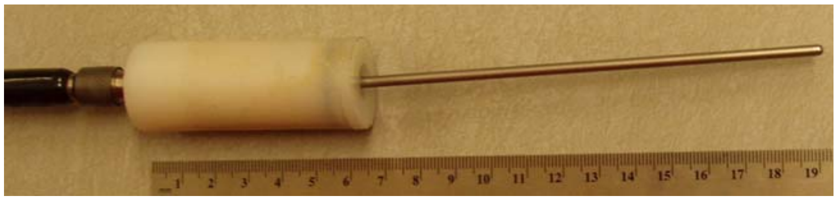


Figure 5 RTD sensor package

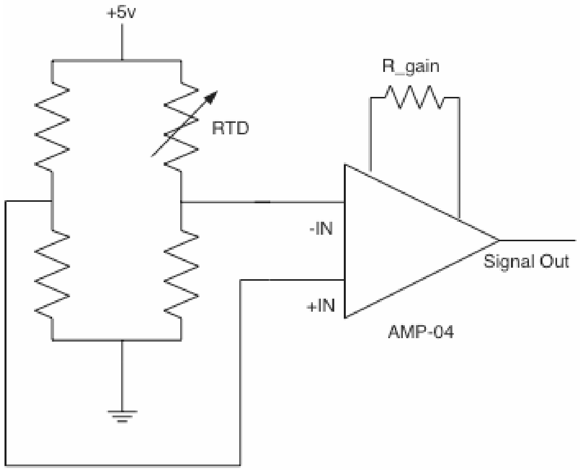
To cut out the baseline resistance of the RTD, it is fitted it into a Wheatstone bridge (Figure 6). The bridge is an analog circuit with four legs, each containing a resistive element. One, two, or four of these legs are active elements, corresponding to quarter-, half-, and full-bridge configurations. The temperature sensor is installed in a quarter-bridge, since only one active element is needed, the RTD.

Since the temperature liquid water is being measured, the RTD does not need to measure temperatures below 0º C. When all legs of a Wheatstone bridge have the same resistance, it is balanced. A balanced bridge outputs 0v across its measurement terminals. So, in order to cut the range below 0º C out of the measurements, the resistors for the other legs where chosen based on the RTD's resistance at 0º C. Resistors were carefully matched near the 0˚ C RTD resistance, and the end result was a sensor that measures down to -7˚ C.

In order to maximize accuracy, an instrumentation amplifier was also incorporated into the design. Since the analog to digital channels are 12 bits, an analog signal in is translated from 0-5v to an integer 0-2^12 (4096). This restricts the measurement to be within 0-5V, and the accuracy is inversely proportional to the range of temperatures in that 0-5V. Assuming the temperature of the vent would be no greater than 60º C, output measurement to that a 5V signal is amplified to corresponds to 61˚. The amplifier serves to provide a clean signal over the line from the sensor to the main electronics box.

Benchtop calibration was performed by starting with a container of icewater, a lab digital thermometer, and a water heater. The sensor was powered, and temperature was recorded from the thermometer while voltage was recorded from the sensor. Hot water was added and stirred in to raise the temperature between measurements. The data was plotted and a linear fit was generated. The result was a calibration line with an R^2 of 0.9845 (Figure 7). This calibration line gives the sensor readout in increments of 0.0167º C.

The RTD and its supporting circuitry are housed in a 2.54 cm (1 in) diameter polyethylene cylinder, sealed with an o-ring and filled with urethane potting compound for waterproofing. It communicates with the main electronics box via a wet-pluggable Impulse Enterprises cable and two bulkhead connectors (See Figure 5).



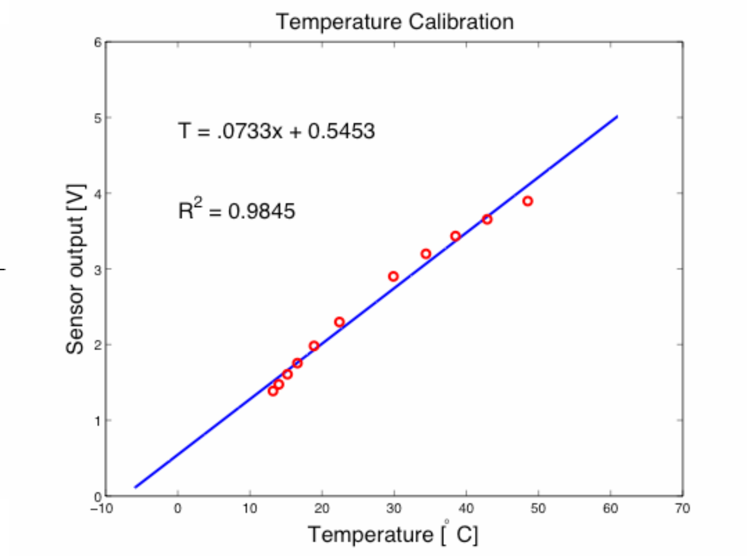


Figure 6 RTD in Wheatstone bridge and amplifier circuit

Figure 7 Temperature Calibration

Video

In order to complete these tasks and drive the ROV the team determined that four video cameras were needed. Though there were many camera's to choose from, the team decided to go with color cameras with built in LED light ring, as they are readily available, require minimal power, are small and easy to mount.

Since sending four channels of video to the surface would add unnecessary complication to the tether system, which can easily pass two video signals, and would require four video screens at the surface, a team member designed a video switching board placed on the ROV which allows any two video signals to be selected by the ROV operator and sent up the tether.

Tether

A major design change in this year's ROV is the use of a fiber optic tether. Since power no longer needed to be passed down the tether, a fiber optic tether could be used to send data to the ROV while providing minimal resistance to motion. After researching current technologies and talking to various companies, we were able to get a system donated to us which includes two multiplexing boards and a passive spooler that attaches to the ROV and allows even more maneuverability by removing some of the threat of getting the tether tangled around an object and needing to retrace steps (Figure 8). This will hopefully save us time during the competition. The small size of the boards, spooler, and fiber all aided our goal of keeping the ROV small and maneuverable.

Figure 8 Small fiber optic board and spooler

Control System

The ROV has two computers that make up its control system (Figure 9). The topside computer is a standard Windows laptop. The bottomside computer is a Microchip embedded microcontroller. The two talk to each other through a standard serial port language and speed, 8N9600. A laptop was chosen for the topside controller because it is easy to create a graphical user interface (GUI) with a laptop. This GUI lets the pilot display systems data and create custom flight routines. An embedded controller was chosen for the bottomside computer because of its low cost, small size, and selection of onboard analog, digital, and timed pins.

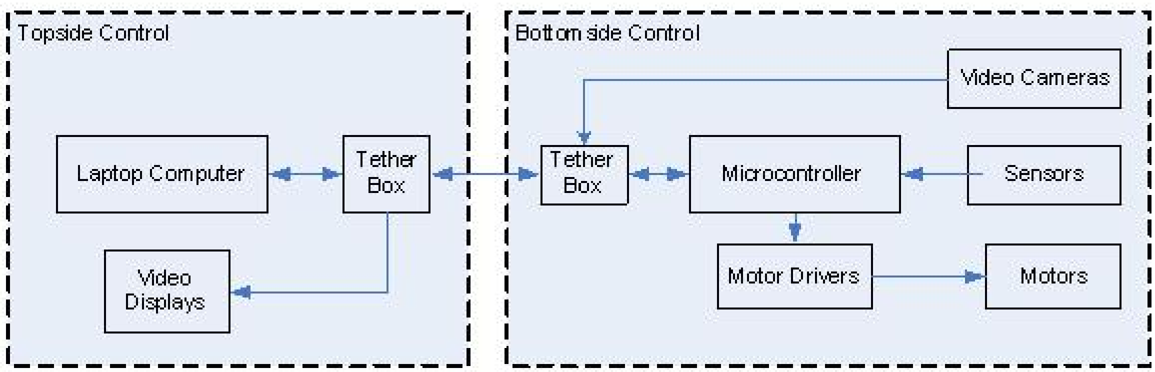


Figure 9 Control System Layout

Every 1/10th of a second, the bottomside controller tells the topside controller that it is functioning, and gives some useful data like depth, speed, and temperature. The topside control responds by telling the bottomside controller any new instructions from the pilot. This is called a master-slave arrangement; the bottomside controller is the master, and the topside controller is the slave. The bottomside controller was chosen to be the master because it is more important than the topside control: it needs to create motor signals, read sensors, and implement feedback. It does this much faster than the pilot and topside controller is able to give it instructions. As a result, it is more efficient to make the topside controller wait for the bottomside controller, rather than vice versa.

Thrusters

Two main thrusters provide lateral and vertical motion. The thrusters were designed to be small, streamlined, waterproof and powerful, again with the goal of increased maneuverability. The main components are the motor and gearbox, the front spindle, back cap, main tube, propeller, and cowling (Figure 10) . The motor and gearbox provide the necessary rotational velocity to spin the propeller in the water. The motor is a 150W drill motor from Black and Decker. The original case and clutch were stripped, leaving only the motor and gearbox. The front spindle is the bearing housing, and constrains the propeller shaft in all directions except inline rotation (Figure 11). It also couples the propeller drive shaft to the output of the planetary gearbox. This allows the propeller to spin without applying off-axis or thrust loads on the motor. The main tube and back cap form the pressure housing with the front spindle. The propeller provides thrust when spun, and the cowling decreases wasted thrust from the propeller.

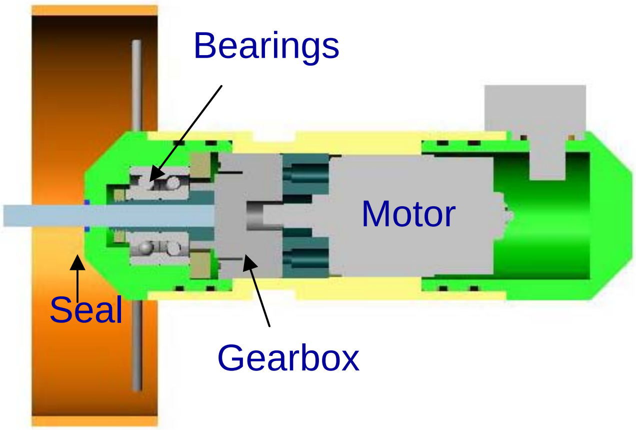


Figure 10 Main Thruster

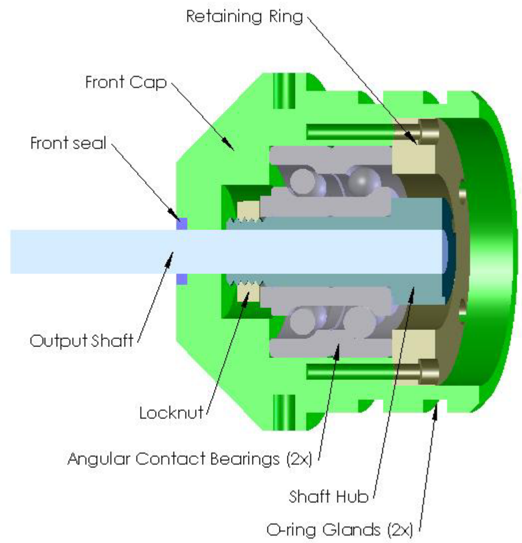


Figure 11 Section view of Front Spindle

Two smaller motors are mounted on the side of the ROV to provide translational motion. Though this adds complexity, it allows for another degree of motion which improves maneuverability and makes completing the mission tasks much simpler.

Pressure Sensor

Figure 10 Pressure Sensor

Though not required by the mission tasks, the team decided it would be advantageous to have depth measurements for closed-loop depth control as controlling the vertical motor by hand has proven difficult in the past. The pressure sensor selected for the ROV is a differential membrane/strain-gage type sensor which outputs a voltage proportional to the pressure difference across the membrane. One port of the sensor is left open to the control box, which is sealed at atmospheric pressure. In using a differential sensor this way, rather than an absolute sensor, the accuracy of the sensor increases, as its range is not partially used up by atmospheric pressure which is always present. This is called measuring in gage pressure. The sensor measures 0-206 kPa, providing useful readings up to a depth of 20 meters. Since it is part of a family of sensors, it can be easily traded to extend the operating depth of the closed-loop control. These sensors can be more expensive, however, and are less accurate over smaller ranges. Since it is input to the control system through 12-bit analog to digital channels, this setup provides depth measurements in increments of 4.9 mm.

Floatation

The method of buoyancy chosen for the ROV was a structural polyurethane foam. This foam was a donation from a project in the MIT Towing Tank, and came highly recommended for its easy "machinability" and low density. It is also meets the pressure requirements for the competition, as its depth rating exceeds the competition requirements.

To determine the quantity of foam needed, the buoyancy force was determined using Equation 1, where the density is the density of water and the volume submerged is the volume of the ROV that is underwater when floating on the surface.

$$F_B = \rho_{fluid} \cdot V_{submerged} \cdot g \qquad \textbf{Eq 1}$$

Once the weight of the ROV (the total mass * the force of gravity) was determined, the net force on the ROV was found. The net force on the ROV is equal to the buoyant force minus the weight of the ROV (Equation 2). Note that the density of the fluid is used to calculate the buoyant force, while the density of the object is used to calculate the weight of the object.

$$\begin{aligned} F_{net,obj} &= F_B - W_{obj} \\ &= \rho_f V_{sub}\, g - \rho_{obj}\, V_{obj}\, g \end{aligned} \qquad \textbf{Eq 2}$$

To determine the buoyant force of the foam, a team member placed piece of foam 0.15m x 0.089m x 0.051m (6.8*10^-4 m^3) in fresh water and found that the volume submerged was 1.28*10^-4 m^3. Knowing the density of freshwater to be approximately 1000 kg/m^3, the density of the foam was determined to be around 189 kg/m^3. By finding the mass of the ROV (Table 1) it was determined that approximately .005 m^3 of foam is needed to make the vehicle neutrally buoyant, though more will be needed, as the volume of the foam was not taken into account in the calculations.

In order to determine placement of the foam (and the subsystems) the distribution of mass was considered in order to keep a symmetrical balance along the centerline of the vehicle. Equation 3 shows the center of mass calculation performed to determine the x-coordinate of the center of mass.

$$x_{cm} = \frac{m_1 x_1 + m_2 x_2 + \cdots + m_n x_n}{M} \qquad \textbf{Eq 3}$$

Item	Quantity	Mass [g]	Total Mass [g]
Battery Case	2	259	518
Large Motor	2	67	134
Small Motor	2	34	68
Manipulator	1	10	10
Camera/Cable	4	26	104
Impulse Cables	13	5	65
Fluid Sampling	1	25	25
80-20 (per inch)	13	1.6 g/inch	20.8
Temp/Depth Probe	1	5	5
		Total Mass	944.8

Table 1 ROV Mass Calculations

Description of a Challenge

Since this is the third year our team has competed in the MATE ROV competition, we've had some time to build team-working skills and learn from our past mistakes. So this year, as we began reorganizing the team in December, we felt prepared, administratively, for the competition to begin, but events out of our control threw a wrench in what we thought were well laid plans. The past three years we have been able to get support from the Ocean Engineering Department at MIT. They gave us space to work in and some money to help us get started each year. Equipment and other resources were also readily available in labs, but on January 1st, 2005, the Ocean Engineering Department and the Mechanical Engineering Department merged. This meant that Professors and students alike were unsure of space and funding availability. The Department that had previously supported us no longer existed and the lab we usually worked in was forced into a smaller space that could not accommodate us. Thanks to the efforts of team members and the gracious donations of space and money from other sources, we managed to obtain adequate funding and space to build an ROV, but the initial uncertainty detracted energy and focus from designing and building an ROV. Looking back on this added challenge, we have learned the benefit of having separate project administrators and engineers. We also learned not to take support for granted, as well as how to find funding and other resources quickly.

Another challenge came in the form of a cap-stone design project many team members took part in during spring term. Many team members are junior Ocean or Mechanical Engineering majors who are required to take a two-term design/lab class starting the spring of their junior year that requires a great amount of time and energy on top of the normal MIT course load. Finding a balance between the two design projects – one for the class, and the ROV for a club – became a challenge both in terms of scheduling group meetings and finding any time to work on the ROV without compromising school work. Though we didn't perfect time or project management skills, we did learn about prioritizing multiple projects and the need to make schedules and set goals.

Troubleshooting Techniques

While building and testing the various systems things inevitably don't work. In order to fix them, the cause of the problem must be found. For example, after re-terminating an end of the fiber optic spooler the signal was not being received at the other end. First, the input signal was checked to ensure it was working and was connected properly. Next, the fiber itself was checked to ensure it was not crimped at any point. In a few places the fiber was wrapped too tightly and so was straightened out, but the signal was still not being received. Since both ends of the spooler had been reterminated, it was determined that one of the ends was not done properly. Since it was hard to determine which one was incorrect, one was chosen at random to be snapped off. Light was shone through the terminated end and was viewable at the un-terminated end, so it was clear that the original termination was inadequate and that end just needed to be retermined. After reterminating the snapped-off end, a signal was again sent through the spooler and this time there was minimal loss.

Systematically testing each step in the process is a general technique used to test all components. Starting from a known section that works, move forward to find the weak spot in the system, then correct it. Be it the fiber optic tether, or waterproofing components.

Skill Gained

In deciding to use a fiber optic tether, we didn't just get a more maneuverable vehicle, we also got the responsibility to learn about a new technology. Fiber optics are a new and evolving technology who's complexity and costliness creates a steep learning curve. In order to use a fiber optic tether, we had to research current underwater fiber optic technology, determine which, if any, option we should go with, and then find a way to integrate the fiber optic tether into our system. This would require converting data and video signals into optical signals and then reversing the process, as well as terminating tether ends. After two team members researched fiber optic technology and presented their findings to the team, we decided to actively look into systems options. We found out about a relatively new technology developed by Prizm, Inc. that consists of two boards – one top side and one on the ROV to turn - an a fiber spooler. In order to use this technology, we needed to understand it and be able to implement it. To this end, a team member spent a day at the company head quarters, touring the board manufacturing area and talking with the engineers. She also learned how to terminate the fiber optic tether, as the team would need to be able to do this during testing and possibly during the competition.

Fiber optics require a finely polished tip in order to minimize loss. Difficult to do on the bench, many ocean applications have avoided its use due to the added complication of polishing and re-terminating fiber optics while at sea. In the past year, new technology has been developed to aid in fast fiber optic re-termination. Called Unicams, these connectors have a pre-polished length of fiber already inserted. This means that the connecting fiber needs only to be well cleaved and connected through optical matching gel in order to make a good termination. After learning how to re-terminate by hand polishing and by using the Unicam connectors, the team ordered Unicam connectors to use for re-terminating the tether as needed. This new skill gave us more flexibility and independence in our ROV operation.

Future Improvements

In designing and building our ROV, we had many ideas we would have liked to pursue but could not due to our tight schedule. Some of these ideas, if realized, could improve or simplify our ROV greatly. Some of these ideas will be explored more fully in the future for more advanced iterations of our ROV.

It is generally better to reduce the number of actuators on any system, leaving less room for Murphy's law to act, but one of the other potential improvements we have discussed is equipping our cameras with pan and tilt capability. This could be done with small servos, but has never been a top priority, so will probably remain untouched until more beneficial improvements have all been carried out. Other generally useful improvements that have been on the low priority list include laser ranging/measurement, conductivity (salinity) measurement, light measurement, and an integrated compass.

Onboard power was a big change in our implementation for this year's ROV, but this system still leaves a lot of room for improvement. Designing a safe, reliable, quick-charge circuit for our battery packs would enable us to operate our ROV for a greater part of any given time, without the added cost of more batteries. This task will be among the first to be addressed in the future. The type of battery used on our ROV is another point for improvement. Using Lithium-Ion rechargeables instead of Nickel Metal-Hydride batteries would save us weight and volume, ultimately enabling a smaller vehicle with similar capabilities. This is largely due to the difference in energy density between the two chemistries. Li-ion chemistry yields 110-160 Wh/kg, while NiMH only yields 60-120 Wh/kg. That's a 25-45% improvement if Li-ion batteries are used. These would present difficulties, however. Li-ion batteries require a controlled charging circuit. They are also more prone to overheating.

Another point of potential improvement is in the thruster seals. The flexi-seals we use in this year's ROV work well and are designed for dynamic sealing like on our thruster shafts, but there is still a hole in the housing where water could get in if the seal wears out or becomes damaged. One other type of dynamic seal eliminates this entirely. Use of a magnetic coupling between the motor and the propeller of our thrusters would eliminate any chance of leaking because there would be no opening to leak through. Some further research and aggressive design work will be necessary to realize a reliable coupling small enough for our purposes.

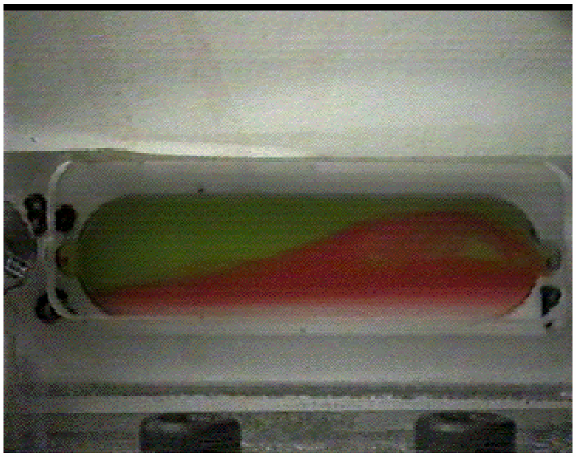
A further extension of that same principle would lead to a fully sealed, rim-driven propulsor. This is basically like a brushless DC motor with permanent magnets embedded in the tips of the propeller. The motor coil is housed in a shroud around the propeller, and drives it directly, without a shaft. These propulsors are generally more efficient than conventional thrusters, because they are inherently ducted and the motor housing is not blocking the flow to the propeller. They also require very precise tolerances and detailed engineering, meaning a *lot* of development time.

In order to simplify our ROV, it could be made with only two thrusters, each having freedom to rotate about two axes, thus enabling thrust to be produced in any direction. This concept presents some challenging issues in implementation and waterproofing, as well as requiring a complex control model to drive it. One of our team members is researching it as part of a senior thesis.

ROV's in Space: a career in fluids engineering

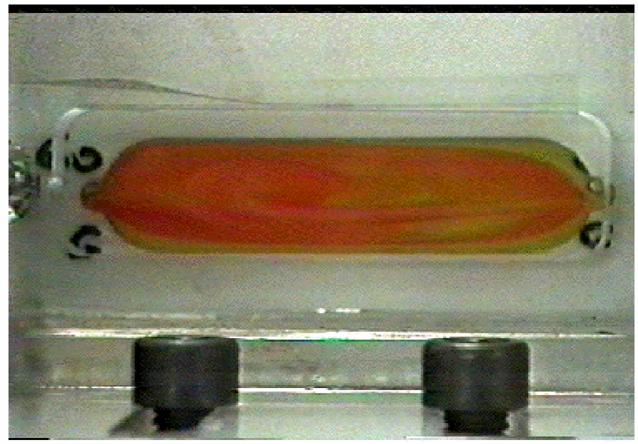
One career that is relevant to our mission specifications that of a space fluids engineer. Fluids engineering in space presents many new challenges and unknowns that fluids engineers on earth do not have to worry about. The most important factor to consider is the effect of micro gravity on fluid manipulation. Without gravity, many of the simplest phenomena that we take for granted while on Earth do not occur.

One of the issues that a fluids engineer faces is the loss of buoyancy forces. Imagine a lake where the boats can neither sink or float, but instead go up and down easily through the water. Buoyancy forces provide the backbone to some of the most fundamental systems on Earth, including refrigeration cycles and power plants. These systems rely on the fact that one fluid is denser than another fluid and is going to sink to the bottom as you see in Figure 1. In micro gravity (Figure 2), these forces are no longer in effect and mixing takes place much more readily. An aerospace fluids engineer has to pay close attention to this fact and has to use other factors such as electro negativity and catalysts to collect fluids. At the same time, engineers can use this to their advantage when trying to mix different fluids, as things that will not mix on earth can be held in a suspension for days at a time in space.



Mixing in 1-g

Figure 1



Mixing in μg

Figure 2

Another interesting part of a fluids engineer's job is dealing with fuel tanks in space. On earth, we rely on the fact that liquid fuel sinks to the bottom of the tank – meaning we only need one extraction point at the bottom of the tank to use all the fuel. In space, this is not the case. The fuel tanks have to be specially designed so that the fluid can always be captured or a gas type fuel is used instead. Another interesting problem cited by W. Teichert and M. Klein in their article about fluids in microgravity, is that the natural frequency of the fluid sloshing around changes. On earth, fluid will go back and forth in fuel tanks at approximately 1 Hz. In reduced gravity fields, the fluids move at a much slower natural frequency of .1 or .01 Hz. Some mechanical structures have the same low natural frequencies, which could result in failure of the system. Engineers must take this into account when designing spacecrafts that handle liquids.

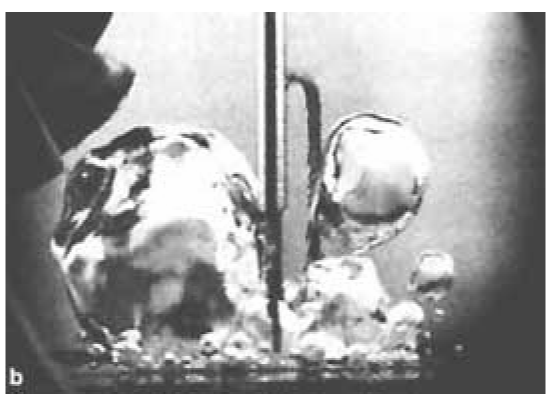


Figure 3 Boiling water in micro gravity

As you can see, a career in aerospace fluids engineering is extremely challenging and requires a lot of thinking outside of the box, but without this thought process, no long distance space flight would ever be able to make it to their destination. Even the simplest task such as boiling water is a much more complicated process in space (see

Figure 3). For our task, a fluids engineer would have to study the ROV's fluid collection system so that the sample was safely collected and could come back to earth in good shape. Also, if the control box or any of the components are filled with oil so that the ROV can go to great depths, a fluids engineer would have to make sure that the oil was safe for space travel and the issues cited earlier about fluid sloshing would not affect the controls. Finally, making sure that the ROV can work in the different gravity fields of Europa would require calculations in order to correctly model the gravity, making sure that the robot will complete the task successfully. A fluids engineer is essential to many space applications and without their input, no mission would ever be successful.

Sources:
Duval, Walter. "Numerical Study of Mixing of Two Fluids Under Low Gravity."
http://gltrs.grc.nasa.gov/cgi-bin/GLTRS/browse.pl?1992/E-7326.html
Rogers, Dr. Jan. "How Fluids Behave in Low Gravity."
http://science.nasa.gov/newhome/help/tutorials/fluid_behavior.htm
Teichert, Klein. "The Dynamic Behavior of Fluids in Microgravity."
http://esapub.esrin.esa.it/bulletin/bullet85/klein85.htm

Image of water boiling in space -

Figure 3.
http://media.nasaexplores.com/lessons/03-048/images/boiling5.jpg

Acknowledgements

We would like to thank the following companies, organizations and people for their generous donations of time, resources, and funds:

Dave Clifford and Prizm, Inc
Matt Greer and ExxonMobil
Professor J. Kim Vandiver and the MIT Edgerton Center
Professors M. Triantafyllou and N. Patrikalakis and
the MIT Center for Ocean Engineering
Professor Chryssostomos Chryssostomidis and MIT SeaGrant
Christiaan Adams and the MIT Ocean Engineering Teaching Lab
Fred Cote and the MIT Edgerton Center Student Shop
Phoenix International
Professor Alex Techet
Mike Davis
Jamez Kirtly

We would like to extend a special thank you to our instructor, Dr. Franz Hover.

Appendix A – Budget Expense Sheet

Expenses

Food			
01/01/05	Picante Grill	Planning Meeting	131.00
01/31/05	Royal East	1st Official Meeting	135.00
Team Shirts			
Estimated		Polo Shirts	525.00
		t-shirts	400.00
Capitol			
05/03/05	McMaster-Carr Supply	Capitol - Tools	412.31
Waterproofing			
03/24/05	Otterbox Inc	Waterproof Enclosures	78.43
03/29/05	Otterbox Inc	Waterproof Enclosures	88.97
02/03/05	Impulse Connectors	Waterproof connectors	453.00
02/03/05	Impulse Connectors	Waterproof connectors	1,000.00
04/26/05	Impulse Connectors	Waterproof connectors	514.48
04/26/05	Otterbox Inc	Waterproof Enclosures	66.98
05/13/05	Parker	Fiber through connector	122.98
Motors			
02/03/05	RoboCombat.com	Propulsion motors	100.73
03/07/05	robotmarketplace.com	more propulsion motors	138.67
04/08/05	Solarbotics	Manipulator Motors	55.75
04/20/05	RoboCombat.com	Backup Propulsion Motors	128.44
Fiber Optic System			
04/14/05	Fiber Instrument Sales	Fiber Optic Supplies	376.65
Power			
02/05/05	Rabbit Tool USA Inc.	Batteries	1,509.00
Random			
02/04/05	McMaster-Carr Supply		59.34
02/10/05	K&J Magnetics	Magnets for couplings	12.00
02/10/05	Newark	Fuses and electronics	53.99
03/05/05	McMaster-Carr Supply		2.06
03/08/05	Express PCB	Circuit boards	59.00
04/02/05	McMaster-Carr Supply		306.08
04/06/05	McMaster-Carr Supply		58.67
04/12/05	McMaster-Carr Supply		44.54
04/14/05	McMaster-Carr Supply		35.12
05/05/05	Action Automation	80/20 supplies	28.16
05/17/05	McMaster-Carr Supply		51.98
Travel			
Estimated		Housing	948.00
		Airfare	3,600.00
		Van rental	500.00
		Total Expenses:	11,996.33

Appendix B - Income Sheet

Income

01/01/05	Remaining Funds from Team 2003-2004		3,307.25
01/01/05	Funds from Ocean Engineering Department		3,000.00
5/11/2005	Funds from MIT Sea Grant		3,000.00
4/29/2005	Funds from ExxonMobil/Edgerton Center		6,000.00
	Funds from MATE Competition		500.00
	Expected: MATE Travel Stipend		1,500.00
		Total Income:	17,307.25

Appendix C – Electrical Schematic