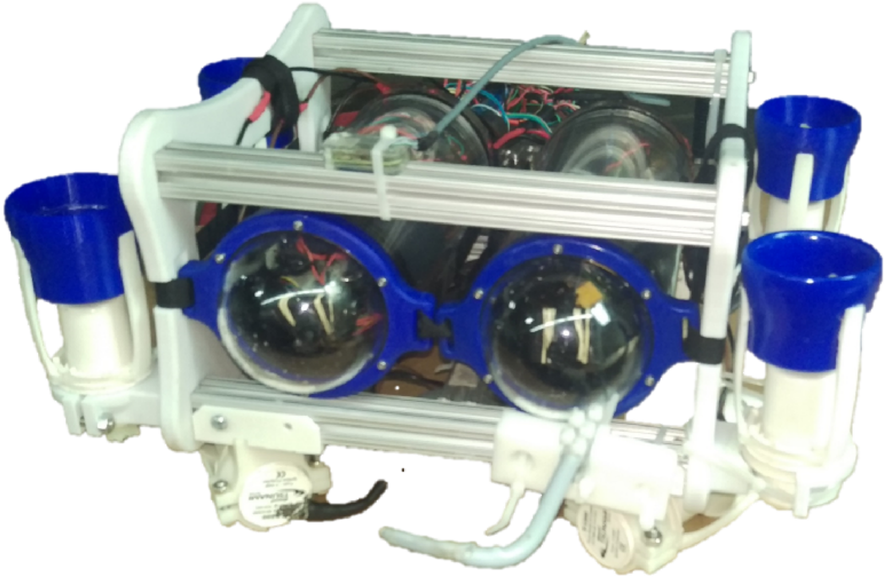
MSOE Underwater Robotics

Milwaukee School of Engineering, Milwaukee, Wisconsin

The Systems and Design Philosophy of *Mosquito*



Fully intact ROV, *Mosquito*

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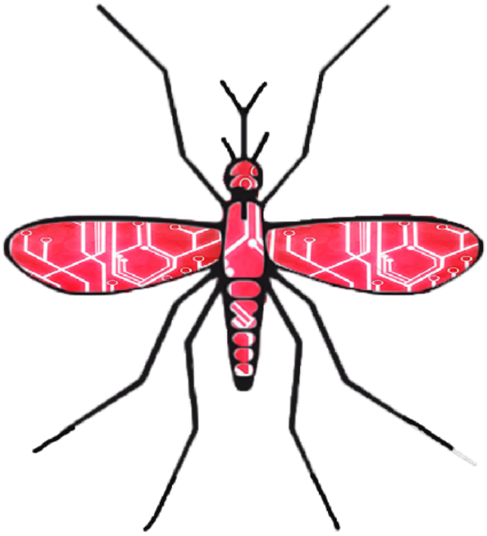
Milwaukee School of Engineering Underwater Robotics

Abstract

The MSOE ROV team is a fourth year company and student organization at the Milwaukee School of Engineering. The company is made up of 9 engineers, 5 returning from last year while 4 are completely new to the world of ROV. Last year, the team did not attend the international competition; instead, it was decided to focus on a completely new ROV. This allowed for development of this year's ROV to start early and get the new members involved with the design straight away.

The ROV, *Mosquito,* was designed specifically to be compact and light to allow for easy transportation to remote parts of the world. The system is broken down into subsystems that could easily interface and synergize with each other to accomplish all of the needed tasks related to the mission to Europa, including collecting cube sats and oil samples, studying coral, and converting oil rigs to reefs, all while diving deep. Many parts of Mosquito were created using 3D printing, including the frame and gripper, which allowed for more freedom in the design and to not be dependent on commercial products. This, combined with each member's drive to create the best ROV possible, allowed the team to create an ROV that is out of this world.



MSOE ROV Logo— The Mosquito

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Company History and Growth

The MSOE Underwater Robotics team was started in 2013 with 3 members and no sponsors. Now in 2016, it currently has 9 members, and has qualified for 3 international competitions (and attended 2). The team moved from working in dorm rooms and basements to the team's own official on-campus MSOE workspace. The ROV has been an approved senior design project, and the team was recognized in an official Congressional Record, available on the Library of Congress: http://thomas.loc.gov/cgi-bin/query/z?r113%3AE01AU3-0046%3A%2F. Over the years, the team has also gained many business contacts for monetary and component support, and has been mentioned in many company whitepapers and reports. Also, various professors and school faculty have helped the team grow the last few years.

Team Organization and Management

Google docs was used to track progress, goals, to-do lists, and ideas which also allowed for easy collaboration and document storage. Goals were set before the 2015-2016 school year to allow the team to hit the water swimming. The team began meeting with the actual robot/parts weekly from the first weekend before school started to increase team motivation and bonding with the extrinsic motivation. Such a team setup and environment is only possible with the egoless team structure that was present, where everyone on the team had a similar knowledge level and equal say in the ROV's design.

No Gantt chart was used because it was decided that it would take too much time to itemize the complex ROV project tasks into a Gantt chart, which ultimately takes away from actual development. Instead, the team used a combination of larger goals and a simple "to-do" list to show workflow. A to-do list is better fit for handling dynamic situations encountered since new items are easily added. It's easy to get lost in the management/bureaucratic of a Gantt chart; to-do list focuses on one thing: getting stuff done.

Item	Deadline
Tether	Early October
Thrusters	Mid November
Frame	Mid January
Control Electronics	Mid January
Functioning ROV	Late January
Payload Tools	Late March
Testing and practice	February - June

Table showing major team deadlines

To hold team members accountable and to make sure the ROV would be ready when, major, semi-informal, deadlines were set over the course of the year (as seen above). This organization method was advantageous to the team because it easily takes into consideration other life and school events that all team members were quite busy with all year. Through the ROV's development, the team stayed on track and was often ahead of where they wanted to be, all thanks to the efficiency and fluidness of the MSOE ROV's team structure.

Safety

Workplace safety was verified and held to strict standards by a third party auditor. That provided additional incentive to maintain a safe work environment with no electrical hazards or trip hazards. If the team didn't comply with the strict standards set, they would no longer have lab access. The team referenced the Oceaneering safety manual that is published on the MATE website.

The entire electrical system is galvanically isolated from the 48VDC power supply (up to 1000V) allowing for increased handling safety in a pool since onboard ROV power cannot flow to an Earth ground (such as the water). Also, this improves electrical reliability by reducing the effects of unwanted outside EMI from the power supply or environment. All external wire connections are sealed using marine grade liquid electrical tape, and are then covered with a thermoplastic heat-shrink, creating a waterproof seal that is resistant to abrasion and cracking from standard use. All large capacitors have direct bleeder resistors to discharge capacitors during a power shutdown. All motors stop moving within 3 seconds of power being disconnected. After 3 seconds, there is enough voltage present to dimly lit the

LEDs which indicates that there is still voltage present, but not enough to move the motors. All lights are completely extinguished within 8 seconds. All thrusters stop motion if they receive no command within 500 milliseconds which prevents unwanted motion. This is accomplished with the motor controller hardware, eliminating room for software error. All PCBs are coated with a dielectric conformal coating to protect against undesired connections from loose parts of moisture/humidity. There are fuses in place on the +48V input with reverse input protection. All electronics and electrical connections are mechanically secure and have no exposed electrical connections. This reduces the possibility of unwanted connections or shorts from occurring. From a mechanical perspective, the entire design is rigid. The motor guards prevent items from touching the propellers or getting tangled. Everything is securely mounted to the vehicle and can easily withstand vibration and mechanical shocks. For general safety, the team made sure to wear safety glasses when needed, and only worked on the system when it was powered down and dried off.

Design Rationale

All design designs are a combination of: Efficiency, economics and practicality and every decision made always has a trade off with a set of pros/cons. It's much better to have something that is less than ideal but has been fully tested. Practice/testing will overcome pitfalls.

There were two distinct design/build phases: the stable base system and then the customized and tuned system. The first phase, which mainly took place before the mission manual was released, focused on building a reliable, stable, base ROV. The second phase focused on customizing the ROV for the mission. The team also optimized/fine-tuned any base ROV systems as needed to improve performance or increase reliability. A reliable/well tested ROV is arguably the most important factor in successfully completing any task. It encourages a more robust/modular design that can be easily adapted and added to in the future

It also allowed the second design/build phase to focus on how to best complete the mission without the distractions/stress of finishing critical ROV systems. That allows for more complete focus/attention on mission specific payload tools. The system might not be as tightly integrated as possible, but will be more robust, more thoroughly tested, more modular, and better thought out overall since more undivided time is dedicated to each subsystem

Testing

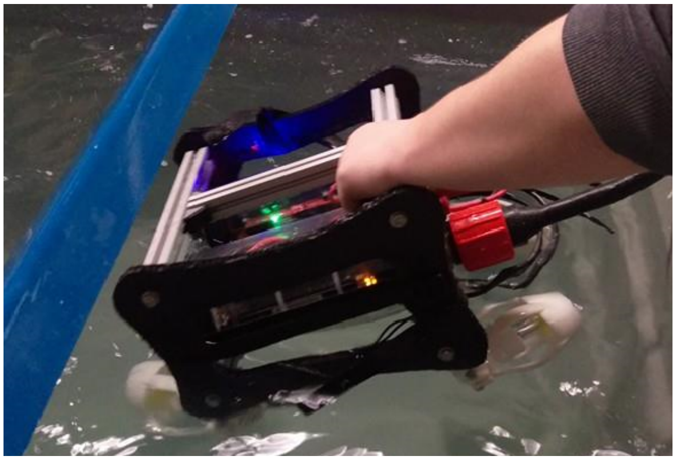
Design verification and testing were important parts of the development process this year. Previous years had suffered from rushing to build things at the last minute, not getting enough practice or system uptime in, and choosing the faster route instead of the better route. Starting development earlier and putting emphasis on ensuring that each subsystem and component was reliable on its own, has allowed for the extreme reliability and stability in this year's ROV

Pressure test chamber used for testing dry housing seals

The dry housing was tested to a simulated 37 meters of water for 30 minutes to verify seals before any electronics were put in them. The dry housing seals are regularly tested before critical runs, or after opening the tubes (which could potentially damage the O-rings, have hair get in the way, not have enough grease, scratches on the tube, etc.). That was accomplished with a vacuum pump attachment connected to the vent cap, and a handheld vacuum pump. This test started with drawing a near vacuum (usually -65kPa, or a simulated 6.5 meters of water) on the tubes, noting the value on the pressure gauge, letting the tubes sit for at least 15 minutes, then rechecking the gauge to see if the pressure decreased. A decrease in readings means there is a leak on the system and all seals need to be inspected. With careful maintenance and protocols around seals, there was never a leak.

Corrugated Plastic Model of the ROV's frame

Before doing the costly print of the ROV frame, it was first modeled out of corrugated plastic and examined by everyone on the team. Of course, this was in addition to the SolidWorks models that were used to design the frame and majority of the ROV. The team strongly believed that there was additional value in seeing the final design as a to-scale model to get perspective and see things in a new way. Once a final design was chosen, the frame was then cut out of cheaply available corrugated plastic to better visualize and test fit all of the subsystems on the frame. 3D printers were also backlogged which delayed the printing of the ROV's frame. The temporary corrugated plastic frame allowed for ROV development to move forward and provided an exceptional model for realizing what improvements could be made to the design.



ROV in the team's 1400L test tank, kept in the lab space

The ROV electronics were tested and had signal integrity and power stability verified on an oscilloscope. The electrical system was stress tested by running four motors from full forward to full reverse in 250 millisecond intervals, allowing for maximum system power draw and noise generation. The test ran for 10 minutes without any issues. The 5V microcontroller power supply showed less than 50mV of ripple and the 12V main power bus showed a 275mV drop when motors switched direction. The entire ROV was tested in a pool to verify that all systems worked together, passed the Explorer demonstration without any issues, and has had lots of additional pool time honing in on mission tasks while constantly improving payload tools and piloting techniques.

New vs. Reused

A complete system/component was never completely reused, but was instead broken down to the raw components and improved in design. Nearly all quality engineering projects have some basis to start with since a large part of engineering is improving an existing system. Only the raw components have ever been reused which helped to reduce costs by reusing two of the most expensive component, the PAF700 DC/DC regulators and the SubConn bulkhead connectors. Circuit boards were redesigned with new features, protection circuits, and filters for the PAF700 regulators. Screw caps were added to the tether bulkheads for improved reliability and reduced wire lengths to minimize wire runs and size of the bulkheads. The old 6 awg power wires from the tether could have been reused but another option was found to be significantly better. That allowed the team to recycle the 6 awg wire. Various scrap materials/components (wire, pieces of HDPE, screws, bolts, epoxy, hot glue, raw electronics, etc.) that have accumulated over the tears were able to be reused on the ROV and helped keep costs down. Reusing is also an important part of conservation (reuse, reuse, recycle) and reduces electronic waste and wasted funds/budget.

Conservation

Scrap material from cutouts and previous years was reused whenever possible while unusable copper wire and metals were recycled. Additive manufacturing was used for building many components to reduce waste from machining parts. All materials used were ensured that they were nonreactive and non-hazardous in chlorinated, fresh, and saltwater.

Weight and Size Management

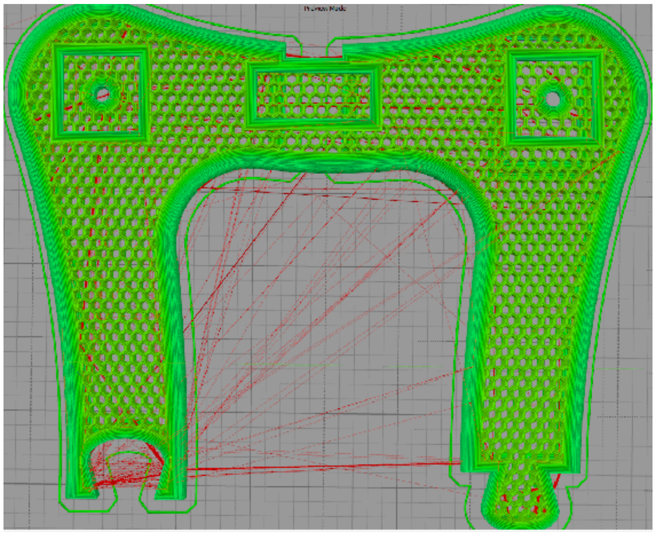
To accommodate for the weight and size limitations, the team used SolidWorks to get an idea of a tool's mass. Also, a spreadsheet was regularly updated with mass estimates for every subsystem. Everything possible was accounted for, and visually seeing the masses allowed the team to regularly optimize and re-engineer the subsystems in order to reduce weight.

The frame for the ROV was designed to be as minimal as possible, and designed to provide exactly enough room for mounting all of the desired thrusters and tools. The frame was redesigned 5 times while attempting to reduce weight and size.

For thrusters, the original plan was to use 12 of them, four in each direction. The team instead opted to use eight thrusters, with the horizontal thrusters arranged in a vectored setup. The vectoring arrangement allows for similar maneuverability as the original 12 thrusters while also reducing system weight. Thanks to all of this careful design process that kept track of weight, the final ROV was able to have a low dry mass of 15.8kg, including the tether and all necessary payload tools to complete the mission.

Frame

Since design and planning of the ROV started well before the mission release, the original frame was large and needed to be optimized once the mission details were out to ensure that the size requirements were met. Compacting the design into a frame that only incorporates the necessities keeps the weight down and increases utility. Polycarbonate was used to print the first rendition of the frame, however the frame began to crack after a month of testing and usage. The final frame was printed in ABS which has a lower density of 1.05g/cm3, compared to PC's density of 1.22g/cm3, thus saving weight while gaining performance. With ABS being more elastic than PC, the frame is able to better hold up to the rough handling that the ROV experiences on a regular basis. The final improvement made to the design was for it to be printed with a sparse filled honeycomb pattern, which keeps the frame rigid while saving 0.8kg of mass.

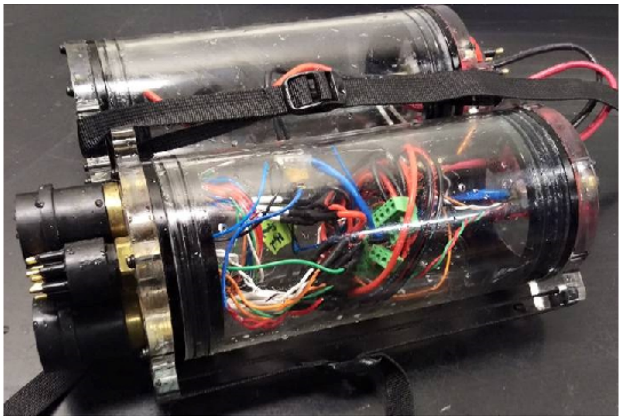


3D model of the newest frame, featuring the weight-saving honeycomb structure

Original 3D Printed frame, printed at 100% fill in PolyCarbonate

Dry Housing

On past ROVs, the team had previously used rectangular boxes with success, but did have minor issues with the box compressing at a depth greater than 3 meters and changing ROV buoyancy. With having to go deeper this year, it was necessary to move to a stronger enclosure capable of withstanding greater pressures. It was decided to use a cylinder dry housing because cylinders are much more capable of withstanding pressure and the circular seals work better due to the circular seal with no corners. Cylinders also have much better hydrodynamic properties with their lower drag coefficients compared to a rectangular prism. That allows for faster acceleration while also reducing the effects of undesired currents pushing the ROV around. The only downside is that they require more focus on organization and planning in order for all the electronics to fit.



Assembled dry housing, after a pressure test to verify seals

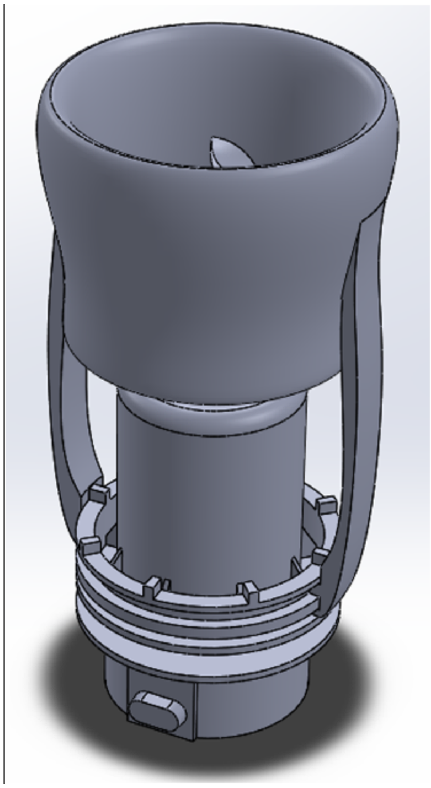
The team decided to go with 2 customized 10cm acrylic tube enclosure from Blue Robotics that has been tested to depths of 100 meters. The electronics are split among both tubes to reduce total ROV size. The 2 tubes displace 3.5 liters of water (20 Newtons) compared to the 12 liters (120 Newtons) from the old box dry housing. That change allows for a great reduction in added weight to the ROV, and much less surface area, both allowing for greatly increased acceleration. The clearness of the tubes allows for verifying that no water has entered the enclosure and that the system is running with the status LEDs. The enclosure has a vent to hold the two caps in place with pressure differential, and uses a dual o ring system for sealing. Two straps were added to prevent the caps from coming off in the event of a bulkhead getting caught on something. The straps also double as a way to secure the tubes to the frame.

Buoyancy/Ballast

The goal for buoyancy was to keep mass low in order to keep acceleration/maneuverability high (Newton's law, F=ma). Extra mass or flotation was only added to balance the ROV and make it neutrally buoyant in water. The team aimed to keep all naturally negatively buoyant items towards the bottom of the ROV and all positively buoyant items towards the top to keep the center of gravity towards the bottom and to keep the ROV in tension.

Thrusters

The team had considered using a brushless system like the past 3 years, but since there have been nothing but hardships with them, a more reliable/familiar brushed bilge pump solution was chosen. Opening a bilge pump showed a quality shaft seal that should increase in sealing performance under pressure and a motor that filled the entire space given as the motor case is modeled around the motor. That allows for an excellent power/size ratio and a reliable seal.

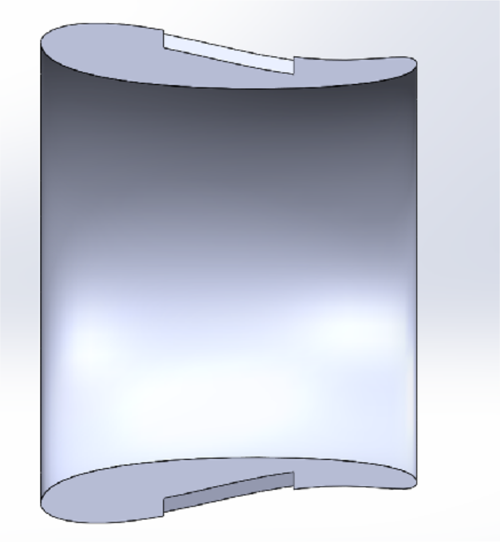


SolidWorks Rendering of a modified bilge pump with a Kort nozzle as a propeller shroud.

Eight Tsunami 1200 GPH bilge pumps were used, four vertical, and four vectored horizontally. The thrusters were mounted at 37.5 degrees to create a best case combination of agile turning and quick forward/backward movements. While a 45 degree angle would improve lateral thrust, it would also reduce the more commonly used forward and backward thrust. This form of vectored thrusting eliminates the need for lateral thrusters, allowing for reduced weight. They were placed so the water flow is as unobstructed as possible, while allowing for a balanced application of the force.

Thruster Guards

Designing the thruster guards was walking a fine line between safety and efficiency. The original design was made to cover the thruster props and provide an efficiency boost using a Kort nozzle design to aid in thrust performance.



Cross section of the modified Kort nozzle profile

The guard would then be attached to the bottom of the modified bilge pump with a compression zip-tie on extruded arms. These arms were designed to flow with the basic shape of the guard while providing the least amount of resistant to water flow as possible. The guard originally had a honeycombed mesh to prevent unwanted objects, such as fingers, to be sucked into the prop, however was removed do to a major drop in efficiency because of the decreased water flow. This problem was fixed with the finalized design by increasing the clearance between the prop and the guard and moving towards a modified Kort nozzle design to improve thrust. This modified Kort nozzle was engineered to act similar to how airfoils work for aircraft wings and incorporate the design into a safe but efficient model for improving thrust. The final design was tested and verified to provide a 60% increase in thrust, for a measured thrust of 3.15 kgf.

Bulkheads

The team started with reusing the SubConn bulkheads since development began without size or weight in mind. But because of their stiffness and weight, the team decided to explore another option, the Blue Robotics cable penetrators. The penetrators were considerably smaller and a better fit for the team's electrical needs (the SubConn bulkheads were oversized for the electrical currents needed). The penetrators reduced wiring bulk and saved a significant amount of weight. After installing the new penetrators, the team found (by using a vacuum pump) issues with leaking that were not able to be fixed completely. Before reverting back to the original Subconn bulkheads, a lot of troubleshooting was done to attempt to find the source of the leak. The first thought was that air might leak through the penetrators, but water might not because of water's greater cohesion and surface tension properties that would group the water molecules together and thus need a larger hole to enter the dry housing. This effect should also have been magnified as a hydrophobic sealing agent was used on the all of the connections. However, a simulated pressure test in water (to 6 meters of water depth) showed that the penetrators still leaked in water. Fortunately, the team still had the reliable SubConn bulkheads available for electrical connections, that have continually proved themselves.

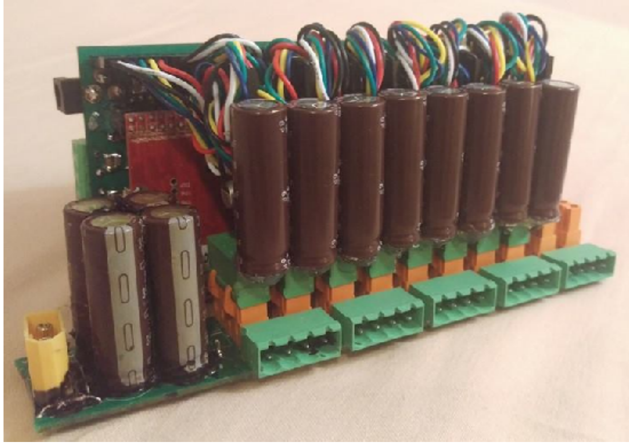
Vacuum pump test setup for doing easy tests of the dry housing's seals

The lightly corroded nuts on the bulkheads were replaced with new stainless nuts, and the O-rings were replaced with new Buna-n O-rings. The old nuts corroded because they were zinc plated and zinc has a 0.85 V galvanic difference from the brass on the bulkheads. The stainless only has a 0.10 V galvanic difference, resulting in a lower chance for corrosion. To help reduce weight and better manage wiring internal wiring in the confined space, the wires coming from the bulkheads were shortened to the exact lengths needed. Since the tether bulkheads are regularly removed, screw caps were added to guarantee a quality electrical connection and to eliminate the chance of the tether becoming unplugged during the ROV's operation.

Electronics

PCBs

Whenever possible, PCBS were used in order to improve system reliability and reduce hand wiring that can lead to errors. They also allow for neater electronics organization since there are a lot less wires to run plus a more modular design makes replacing parts easier. The PCB were coated with a conformal coating to reduce damage from the high humidity environment and improve mechanical shock performance.



Main control PCB, showing 8 Pololu motor controllers (with capacitors), a Tiva C microcontroller on the backside, and a yellow XT60 connector for input power

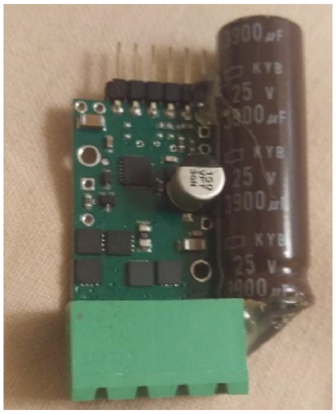
Wiring

NASA wiring specifications were used as a reference: http://www.hq.nasa.gov/office/codeq/doctree/87394.pdf. The wiring was kept neat, bundled, and wire groups were twisted together while keeping distance between power and signal wires. The twisted power wires reduces parasitic inductance. The wires were also kept at a minimum length to reduce resistance and weight, and help reduce the amount of wire management needed. A lot of wiring of the control electronics was eliminated with the use of custom PCBs

Microcontroller

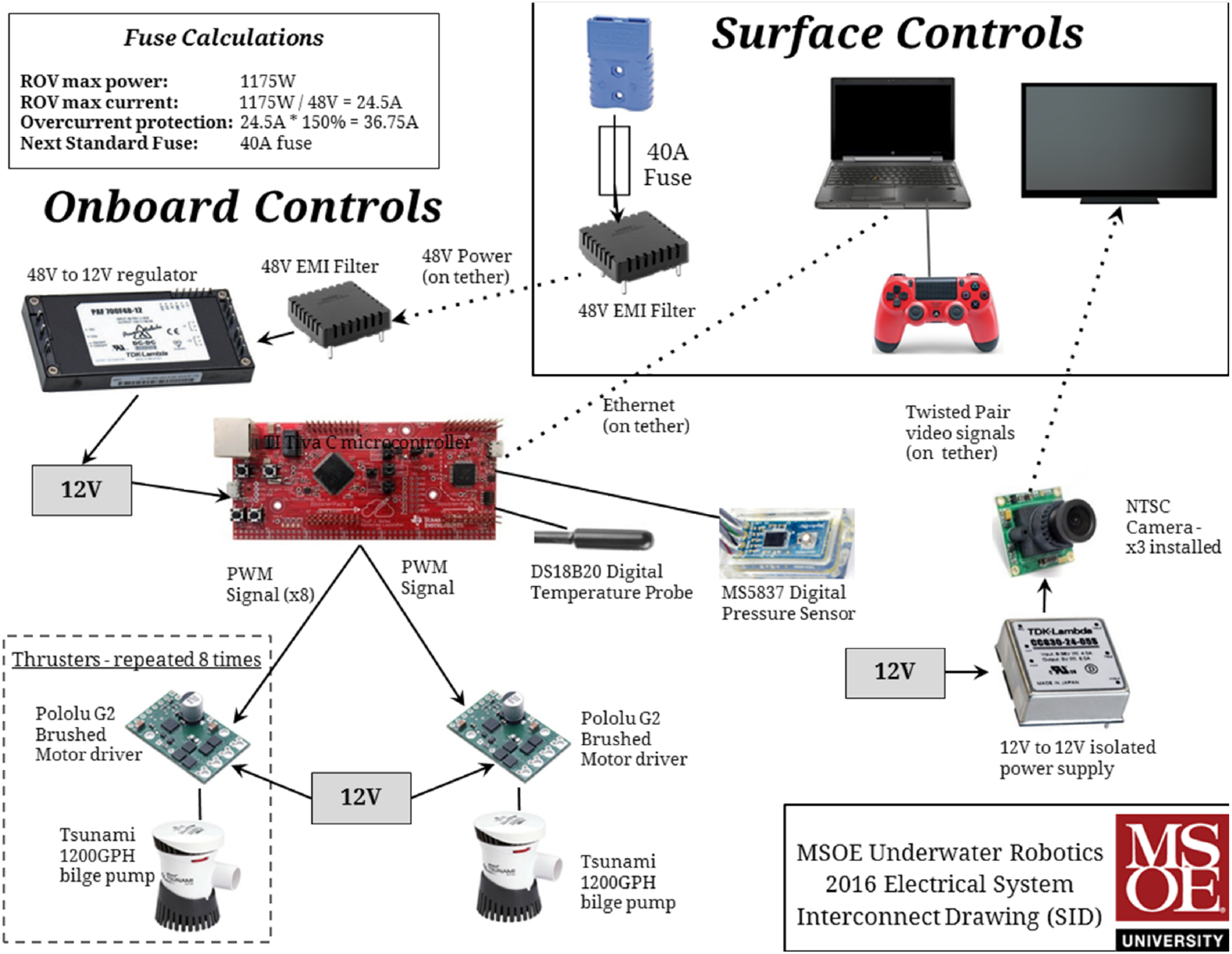
The Tiva C is the connected microcontroller used on the ROV. It's low cost, high performance, with a 120MHz ARM processor (with 150 million instructions per second), 90 GPIO, and a built in Ethernet port. The processor has a floating point unit that is useful for performing kinematic calculations and running control loops. That eliminates the need and extra development time to transfer calculations to fixed point integer math. It also contains a high precision, integrated 12-bit ADC that provides a precise way of monitoring current and voltage currents without needing to add additional components. There is a team-designed/built breakout board that adds buffering to all outside connections, reducing the chance of the Tiva C from getting damaged. Output buffers also improve signal quality with the increased current capacity, and provides the necessary logic level shifting to bring the signals to 5V over the Tiva C's 3.3V logic. Signal degradation to servos and sensors has been an issue that has been faced by the team in the past, and the output buffers fix that.

Motor Controllers



Pololu motor controller, showing team selected PCB connector and an additional 3900uF bulk capacitor, for line filtering/stabilization

Polulu simple motor controllers provide a reliable brushed motor controller with a lot of features for adjusting PWM frequency, acceleration/deceleration, under and over voltage cutoffs, temperature monitoring, thermal shutoff, and motor braking/regeneration. They also provide a large variety of input possibilities (UART, RC PWM, analog, USB, etc.). The team uses a 115200 baud UART connection to each driver. It's more reliable and more precise than a RC PWM signal (has CRC error checking and then receives exact numerical values instead of depending on reading pulse lengths to sub microsecond precision). UART data gives an integer motor control range of -3200 to 3200. Extra precision allowed for enhanced precision modes that restrict the range. Each motor controller receives its own



Fuse Calculations

ROV max power:	1175W
ROV max current:	1175W / 48V = 24.5A
Overcurrent protection:	24.5A * 150% = 36.75A
Next Standard Fuse:	40A fuse

MSOE Underwater Robotics
2016 Electrical System
Interconnect Drawing (SID)

UART signal instead of chaining the controllers together on one daisy chained UART bus. It's a more reliable design that allows the ROV to partially function in the case of a single point of failure. Each UART command utilizes an 8-bit cyclic redundancy check (CRC-7) to verify the integrity of the transmitted command and data. That eliminates any erratic behavior that can occur from signal noise and failed transmissions. There is also a built in watchdog functionality that disables the motor if a command hasn't been received in the past second. The motor controllers themselves are physically compact, and thoroughly tested. The team was also able to retrofit a connector to plug into a power breakout board to reduce wiring needed.

Internal Connectors

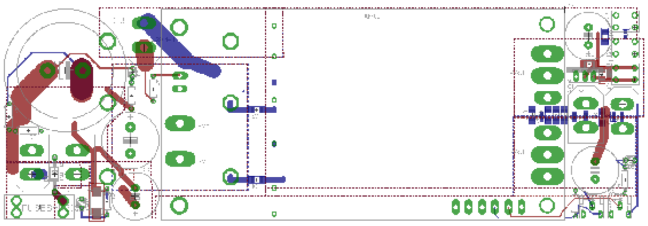
An IP68 inline Ethernet connector was used for video signals while XT60 connectors were used for all high current connections. Removable screw terminal blocks were used for motor connections which allows for easy disconnection of motor controllers. Motor controllers are connected to their PCB with a removable connector allowing a motor controller to be easily replaced and serviced if needed. The microcontroller (Tiva C) is connected to a breakout board via header pins and provides spring terminals for outgoing signals. Spring terminal blocks were used for signals and low power. That also increased modularity of the system allowing for parts to be easily removed/replaced if needed.

Electrical Connections

All electrical connections that are submerged in water are sealed using marine grade liquid electrical tape and then covered in a standard heat shrink. The liquid electrical tape forms a flexible waterproof seal while the heat shrink covers the cured liquid electrical tape to prevent the seal from getting damaged.

Voltage Regulators

For any load greater than a few watts, a switching regulator is used since they are much more efficient than an alternative linear regulator. The switching regulator use are two TDK-Lambda PAF700s operating at an efficiency of 90%, and an input voltage range of 36-72V allowing for spikes and drops on tether voltage. The PAF700 also has electrically isolated outputs which provides additional safety and helps to reduce the possibility of external noise from interfering with the ROV. PAF700 regulators have been with the team for several years (hand delivered by engineers of TDK-Lambda) and are still one of the best performing regulators on the market. They were found to have no water damage, and have new PCBs made to fully utilize all of their features that have been discovered over the past few years. The PAF700 regulator is turned to 13.8V, from its nominal 12.0V, allowing for the electrical system to get 15% more power out of the Tsunami 1200 GPH bilge pumps. Slightly boosted voltage also helps to account for voltage drops through wiring, motor controllers, and LC filters. It provides a steady voltage as long as the input voltage is within operating range. The small overvoltage applied to the "12V" rail is still within specifications for all devices connected to it. Using a regulated source on the ROV allows for more predictable operation under varying surface power supplies and power conditions. It also gives the onboard electronics and motors a close low impedance power source that doesn't suffer from the somewhat large tether resistance/inductance. Voltage stays constant as a result of not changing under load form the resistive losses through the tether as current increases.



Eagle rendering of the team designed PAF700 breakout-board, with LC filters, voltage tuning circuitry, and input/output connectors

Electrical Filtering

A lot of LRC calculations were done during circuit design assuming the worst case conditions with motor and power supply noise. This allows for the highest system reliability and stability in any environment. An EMI filter for the main input voltage was used for reducing power supply noise and any noise picked up from the 23 meter tether run. Small capacitors of 0.1uF are always added in addition to the large electrolytic caps. The small ceramic caps are much better at filtering the high frequency noise than the larger caps are. A large input capacitor bank (15,000uF) on the 48V is used to reduce voltage ripple and transients from environmental noise from the 23m tether that acts as an antenna, along with potential power supply noise and ripple. Size of the capacitors were calculated using the capacitor equation, $I = C\,dv/dt$ or by following manufacturer recommendations in datasheets and application notes.

The motor controller breakout board has RC snubbers for motor transients, and an LC low pass filter at the input to prevent high frequency noise from reaching the rest of the system. It is set up with a 1.5μF automotive grade inductor (rated for 45A continuously), and 18mF of capacitance which creates an LC low-pass filter with a -3dB point of 968Hz, which is below the motor switching frequency. The motor board also has a 10μF and 0.1μF ceramic capacitors near the power connection of each motor controller which provides additional high frequency filtering.

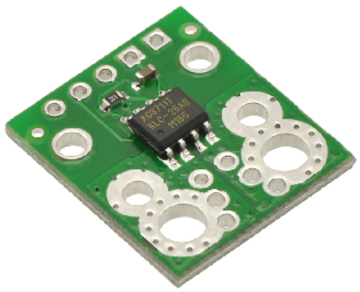
The 12V rail has over 150mF of electrolytic capacitors to account for the large current spikes when several motors switch directions quickly which indices a large back EMF to the system followed by a very large current draw (over 60A form 4 motors). This problem could have alternatively been solved by adding acceleration/deceleration ramps for slower starts and direction switches, but would have impacted ROV performance negatively. See technical issues for data collected from 12V rail capacitors.

All power supply outputs are sized with bleeder resistors so the system in nonfunctional in 3 seconds. LEDs indicate that voltage is present and the system is unsafe to work on. While all motors stop moving after 3 seconds, power supply LEDs are dimly lit for slightly longer than the 3 seconds. They take up extra space and add some cost, but overall increases system performance and reliability.

Sensors

Current Sensor

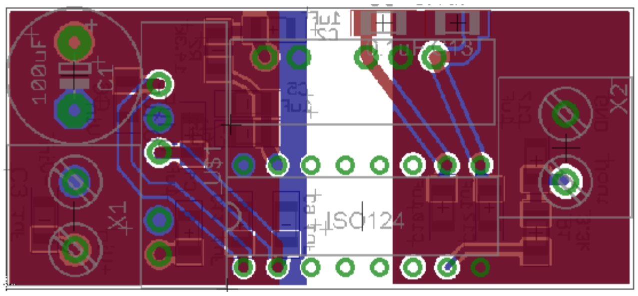
The team uses the Allegro ACS711 Hall Effect based current sensor. It's rated for 31A RMS (100A peaks) and is electrically isolated (thanks to the Hall Effect based operation). It provides an output sensitivity of 45 mV/A, allowing for the Tiva C's 12-bit ADC to have 18mA resolution. This allows the team to see small energy usage changes. The sensor has an internal resistance of 0.6mΩ, allowing for low operating temperature even at high currents while minimally affecting the power input to the system. It is used in conjunction with a voltage sensor for measuring input power on the 48V input to determine system power usage.



Breakout board for the Allegro ACS711 current sensor

Voltage Sensor

The ISO124 isolation amplifier is used with a voltage divider and isolated power supplies for reading the 48V power supply. The main input power (48V) is isolated from the main ROV power system (12V) to reduce negative effects from poor power supplies or rogue voltages in the water. This allows for verification of proper operating voltages on the input, allowing for the system to monitor if the input voltage approaches the minimum operating voltage of the main power regulators.



Eagle rendering of the team designed voltage isolator circuit

12V Line Sensor

The 12V rail shares the same ground as the Tiva C, eliminating the need of a voltage isolator circuit. The voltage is monitored by a voltage divider to bring the 12V down to an appropriate voltage for the Tiva C's ADC. Thanks to the Tiva C's 12-bit ADC, the 12V rail can be measured with a 4.0mV resolution after accounting for the 5.23 linear scaling factor applied by the voltage divider.

Temperature Sensor

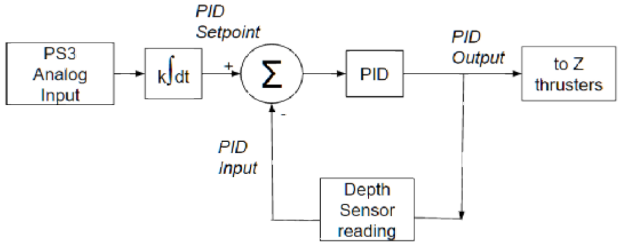
The team uses the DS18B20 temperature sensor that is sold in a waterproofed package by SparkFun. It uses the minimal OneWire communication interface which reduces the amount of wiring needed. Only one line is needed for communication, plus a power and ground connection. The sensor uses an 8-bit Cyclic Redundancy Check (CRC) to verify data integrity and to allow the system to detect any read errors. It has an absolute accuracy of ± 0.5°C with 12-bit resolution giving it a precision of 0.0625°C. Thus, the sensor meets and exceeds the required temperature sensor specifications of ± 2.0°C.

Depth Sensor

The depth sensor, the MS5803, provides feedback for depth PID algorithms. It also provides an accurate way to measure the depth of the body of water the ROV is in, along with taking relative measurements by recording two separate depths. Using the sensor's internal summation ADC, the sensor has a resolution of 0.2 mBars, which correlates to approximately 0.2cm in a standard body of water. It's capable of accurately reading depths of up to 500 meters.

Depth Control

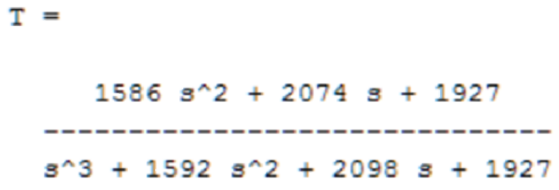
The system's onboard depth sensor is valuable for taking accurate depth and vertical distance measurements, and can be doubled as a device for stability control. One of the most challenging tasks as a pilot is controlling system motion in 3-dimensions, instead of the more familiar 2-dimensions. Adding in the ability to hover a constant depth, is useful for creating a 2D plane for the pilot to move on while allowing the ROV to compensate for items picked up that would have otherwise made the ROV move vertically.



PID diagram showing the high-level depth control implementation

Controls are managed using several PID loops tuned to get the desired behavior. The control loops are ran at 140 Hz, resulting in new thruster values being generated approximately every 7 milliseconds. These loops are able to update and react much faster than even some of the best pilots. Signal latency is reduced as well because the control loops are ran onboard the ROV. This eliminates the video display, controller input, and reaction time latencies that a human has to deal with when adjusting motor values in reaction to external stimulus.

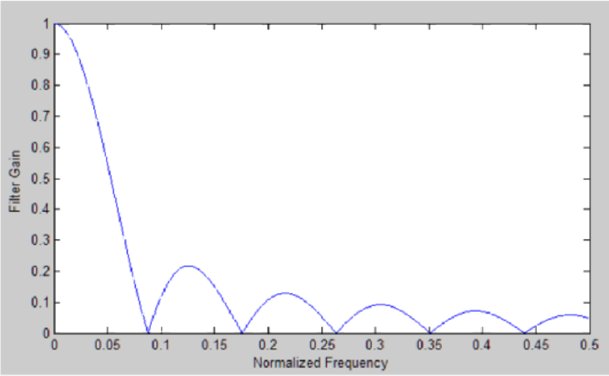
Depth control is managed in a "fly by wire" manner, where the pilot does not directly control the vertical thrusters. The analog trigger(see controller appendix...) is integrated over time to change the depth. With this, pressing the trigger fully would represent the max vertical speed of the ROV. This form of depth control is very intuitive to a pilot, and virtually eliminates undesired overshoot behavior that would naturally occur when piloting the ROV vertical thrusters manually. As soon as the depth trigger is released the ROV will hold the precise depth of when the trigger was released. This form of control eliminates the need to manually enter and exit a depth hold mode and provides seamless interaction and allows the pilot to better focus on the tasks at hand instead of stabilizing the ROV.



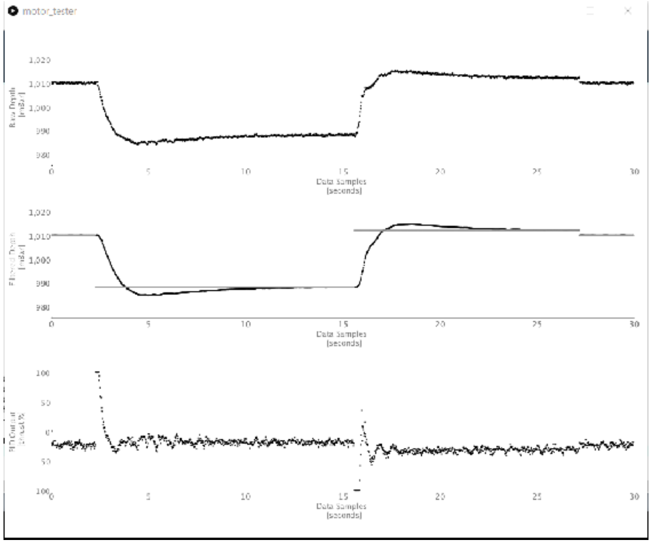
```
T =

     1586 s^2 + 2074 s + 1927
  ------------------------------
  s^3 + 1592 s^2 + 2098 s + 1927
```

Step response derived transfer function, using Matlab, that aided in setting PID gain values

The team designed and created an interface to log and display the ROV's response to the inputs, displaying the value sent to the thrusters, and the measured depth. This allowed for precise tuning of the PID gains, and the ability to approximate a transfer function of the ROV system for more in depth analysis using computer tools like Matlab.



Matlab frequency response graph of the exponential averaging filter used on the depth sensor



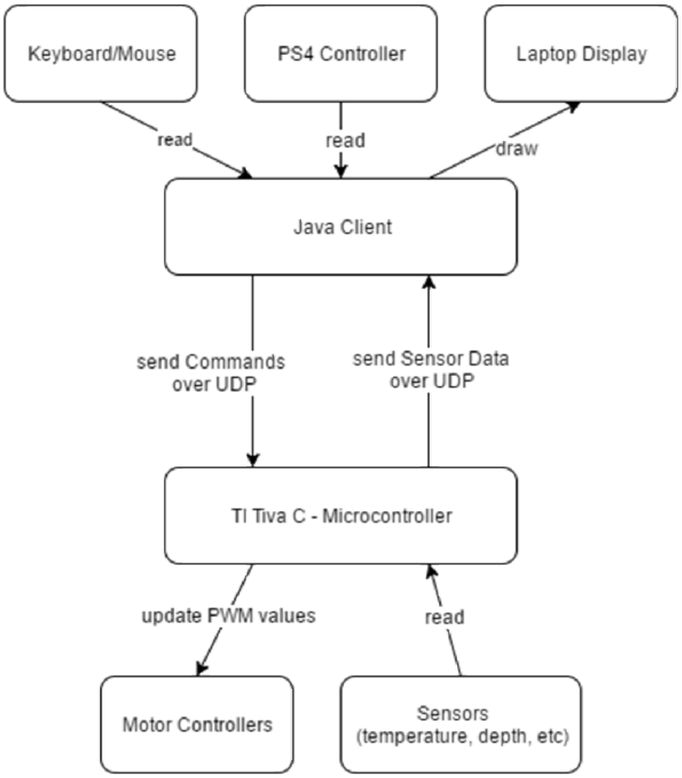
Step response of the ROV moving 75cm in depth, using the control loops. Top two graphs show the depth sensor data (unfiltered and filtered), and the bottom graph showing the PID thrust output

It was important for the tuning of the PID gains that the thrusters would not be in an oscillating or “thrashing” state. Thruster oscillation would heavily load and stress the motor controllers and motors themselves. To solve this we discovered that scheduling with two different sets of gains, and aggressive and a conservative set of gains, were needed for the system to have fast and stable response while previously holding a steady state value. With gain scheduling enabled, the conservative gains are enabled when the ROV is within 8mm of the desired set point.

Our final tuning gains allow the system to respond to a 75 cm depth step/change within 3 seconds, with only 4 cm of initial overshoot and a final steady state jitter of 0.8 cm.

Software Management

Git and BitBucket were used to manage software, allowing for advanced versioning and backups. Using git allowed the team to easily revert to older working versions if a change was made that breaks system functionality. Git’s branching functionality was also used to keep development and stable branches separate, the development branch was used to try out new features, while the stable branch was always available as a fallback option. The software was broken down into different files for each feature, allowing for clear organization and enhanced readability, while also keeping individual file sizes down to eliminate confusion.



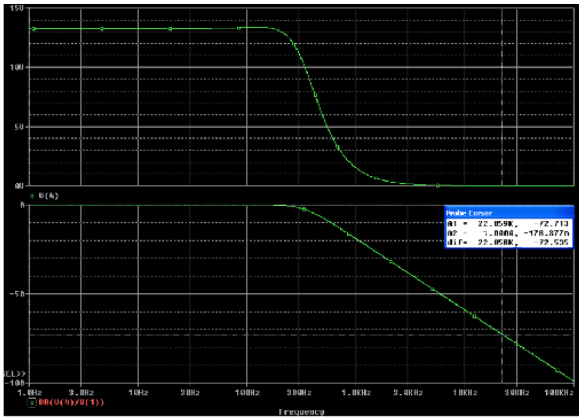
Basic flowchart showing general flow of the ROV’s team designed and created software components

Human Machine Interface (HMI)

Java code running on laptop provides feedback from the ROV from the sensors and set thruster values. Whenever possible, the PlayStation 4 controller is used to provide input to the system. The PS4 controller was chosen for its ideal joystick placement, large amount of buttons available for input, and its widespread use. It’s comfortable to hold and familiar to the team members. Its able to be read over USB, providing enhanced stability in noisy environments, or Bluetooth, allowing pilot to move around which was especially handy in testing. The HMI connects to the ROV via a UDP stream that is updated at 50Hz. UDP allows for efficient data transfer with minimal overhead, though some packets might be dropped occasionally.

Cameras

For cameras, the team was tempted to use an IP solution, but went with an analog video system because it is well proven, cheaper, and smaller. Video signals are transmitted over UTP wire using impedance matching baluns. The cameras only receive power from dry housing while all video signals are passed straight to the tether through an inline IP68 Ethernet plug. Power is filtered with an RLC filter to help isolate cameras from system noise (like motors) and to produce a cleaner picture. The video multiplexer is on the surface to reduce amount of electronics and wiring needed on the ROV, and allows for some setups to have multiple displays. Initially the team looked into waterproofing cameras individually with a housing or epoxy, but mission needs for the ROV were re-evaluated and it was determined that all necessary vision needed from a camera would be possible from inside the clear main dry housing. This decision reduced costs and development time, while producing a simpler design that could be easily adjusted if needed.



Bode plot of the LRC filter to use on the cameras power supply

Tether

Maximum power transfer analysis for different wire gauges

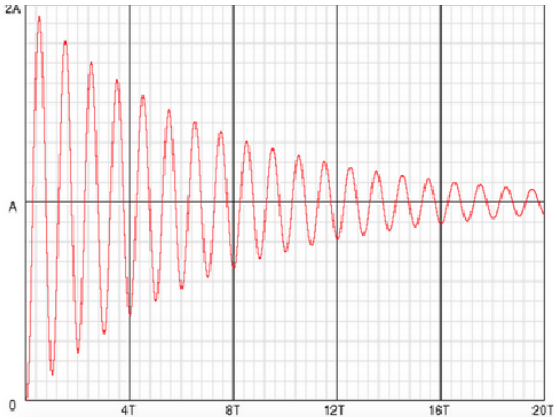
Wire AWG	Max Current [A]	ROV Voltage [V]	Worst Case Efficiency	Max Power [W]	Safety Factor	Mass [kg]	Cost [USD]
6	40.0	45.5	94.5%	1820	3.64	8.0	$0
12	40.0	38.1	79.4%	1524	3.04	2.1	$84
14	32.0	36.0	75.0%	1152	2.30	1.5	$56
16	20.1	36.0	75.0%	724	1.44	1.1	$50
18	12.5	36.0	75%	450	0.90		

The above table shows analysis comparing 5 different power wire options for the tether.

The standard operation of the ROV uses a maximum of approximately 500W. With this information and an estimated tether length of 22 meters, voltage drops and power carrying capacities can be calculated, assuming a 48V power supply is used. 16 gauge wire is then the smallest gauge wire that can be safely used to meet the power demands of the system. A large voltage drop is found acceptable for the system due to all of the onboard systems running off of regulators designed to accept a wide range of voltage inputs. 16 gauge wire used on the ROV is a high flex silicone covered wire made up of 208 strands, and has an ampacity of 35 amps.

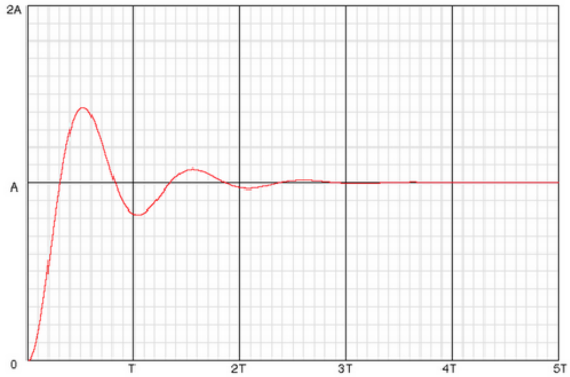
There's a careful balance of being able to transfer the necessary power while keeping cost and weight down and staying within the budget. It leverages efficiency of using a higher transmission voltage. Less mass means less flotation will be needed, and will require less force to move. The voltage drop is only relevant for determining power transfer efficiency since all on board electronics are powered off high performance regulators that maintain steady output voltage as long as the input voltage is between 36-76V. This allows for a lighter, cheaper and more flexible tether to be used. If ROV systems were directly powered off of the 48V input a voltage drop of less than 10% would be desired. ROV performance is more important than total electrical efficiency. Lighter tether also means a reduced need for total power and is cheaper, while using less natural resources. On hand 6 gauge wire is efficient and quite capable electrically but is very heavy, bulky, stiff, and difficult to work with which has been a problem in the past. To help compensate for the increased electrical resistance and inductance a large capacitor bank and EMI filter is added on board of the ROV to provide instantaneous power

Transient analysis based on wire inductance, EMI filter inductance, tether inductance/resistance, minimal added capacitance, and other parasitic components show:



Transient analysis of a power on, w/o onboard bulk capacitance, highlighting the excessive ringing and dangerously high overshoot.

Adding bulk capacitance in the form of one 12mF capacitors greatly reduces overshoot and settling time of the system's transients and helps to provide a cleaner more stable power source during steady state operation on the ROV. The max calculated maximum RLC transient input spike is within steady state voltage specifications, leading to a reliable product that isn't stressed. This calculation accounts for tether inductance and resistance, EMI filter inductance, and bulk input decoupling capacitors but doesn't account for power supply resistance which would further damp transient overshoot.



Transient analysis of a power on, with onboard bulk capacitance, showing an acceptable overshoot and minimal ringing.

Cat7 STP cable is used for all signal transmission. One for Ethernet communication and one for video signals. The tether is detachable for easier transport and ability to add future tether extensions to accommodate deeper areas. All of the separate wires are kept together with 12.5mm nylon cable mesh. Tether strain relief is provided to securely attach tether to the ROV and prevent tether from applying unnecessary force to bulkheads

Communication and Control

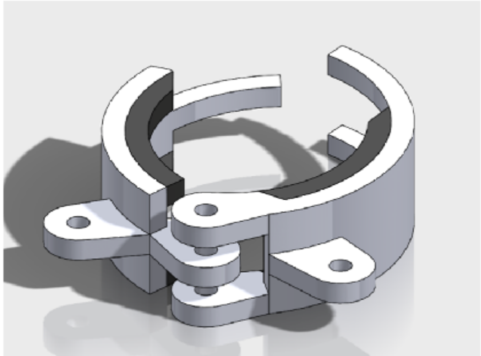
For communication from the shore to the ROV, Ethernet is used. Ethernet is the standard in harsh industrial applications where reliability and transmission speed are important. UDP (User Datagram Protocol) transmission has the least overhead, but provides no guarantee of data arrival. Communication protocol keeps this in mind by not relying on all data to arrive. The data stream is a continuous feed of all variables that are updated every 1/60th of a second. Receiving the current data points is more important than an older data point, which is the ideal use case for a UDP. To implement, any standard controller that can be connected to a PC. We used the PS4 controller because it is comfortable in the hands and has many button options for analog motor control.

Payload Tools

Manipulator

Upon initial review of the mission requirements, the ability to grip cylinders of 90mm and 25mm diameters was identified as a crucial design goal. Additionally, it was agreed upon that one well-designed gripper would allow for a high-mobility ROV to complete all of the missions. Use of 3D printed parts was also identified as a priority, as gripper parts were expected to undergo repetitive and stressful motions, and likely would need replacing as testing and practice occurred.

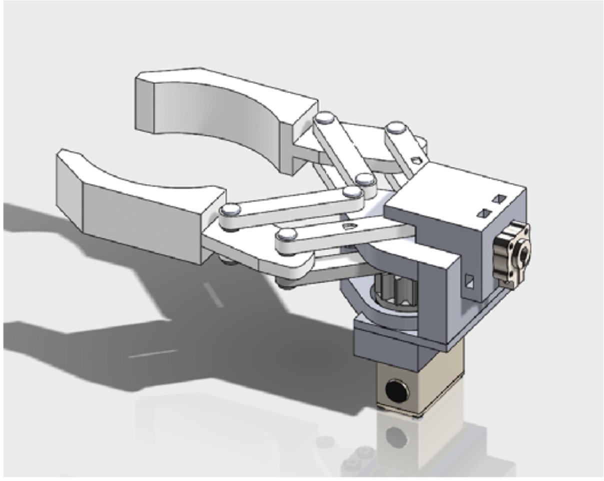
The first method of achieving these gripping abilities was to use two arc-shaped claw pieces with interlocking "finger" extensions. These claws would rotate about a shared pin, causing them to grab and release in a wide arc pattern. The motion of the claw pieces was to be controlled with a waterproof servo motor, which was deemed ideal due to the need for less than 180° of motion, allowing the motor to directly drive the claw piece. This first claw design was abandoned prior to 3D printing due to a desire for a more conventional claw design which relied on parallel beam linkages for claw piece motion.



Initial gripper concept, with interlocking claws

The parallel beam linkage concept drove the gripper design revisions once the first version had been rejected. This concept involved using two pairs of identical beams to connect each claw piece to a common base. The length of these beams was optimized to allow for the original 90mm and 25mm gripping requirements to be met while also allowing the claw pieces to remain parallel throughout their entire motion pattern. The use of parallel beam linkages also allowed for a section of the claw pieces to achieve full contact gripping, greatly improving the ROV's ability to grip smaller objects.

The gripper designs which employed the parallel beam linkage concept were revised mainly to accommodate different methods of position/torque control. Using the waterproof servo from the first design, a 2:1 torque gear chain was designed in order to allow for higher torque application to the claw pieces across their entire motion. The claw piece that was driven by this gear chain also had a 1:1 gear connection with the other claw piece, allowing for symmetry of motion. Both gear chains were contained within a single piece base platform. The gears in both gear chains were created using gear generating software and some manual SolidWorks editing.



Revised gripper, with parallel beam linkage

The first major edit to the parallel beam linkage concept was the removal of the 2:1 torque gear chain between the servo motor and the driven claw piece. Instead, a direct drive and magnetic clutch system was designed and constructed. The clutch consisted of two cylindrical pieces, each containing four (later increased to six) neodymium magnets arranged in a circular pattern and oriented to attract the other cylinder piece. This clutch helped protect the servo motor from excessive stress on its internal gears while still smoothly transferring torque. This change required a change to the common base platform, which was redesigned to employ four piece construction and a different servo motor location. This design was the first to be 3D printed and performed adequately to complete select missions.

A shift away from coplanar rotational control of the claw pieces and the waterproof servo motor prompted a final redesign. It was decided that a bilge pump motor (same type used for propulsion) would be a more suitable gripper operator due to its better torque potential. The bilge pump motor was implemented with a threaded rod and threaded nut setup which allowed for much stronger gripping strength.

Retrieval Basket

To reduce time wasted making repetitive trips to the surface, a retrieval basket was purchased and modified for easy transportation of items. Several missions required the bringing of items from the pool bottom to the surface for collection, so it was decided that time could be saved by eliminating trips. The lightweight and collapsible construction of the basket along with the addition of a simple handle made for easy deployment and transport.

Depth sensor

See "Electronics->Sensors->Depth sensor" for details on this specific payload tool.

Temperature Sensor

see "Electronics->Sensors->Temperature sensor" for details on this specific payload tool.

3D Printing

Upon this year's release of the mission details and requirements, the team was tasked with coming up with a lightweight and small design without decreasing the ROV integrity. After many frame revisions and brainstorming session, a final design was configured and assembled in SolidWorks making sure all measurements and placement of components were precise. After the compact design was finalized, determining the material and printing process was needed to get the most of the 3D printed parts. The parts of the ROV that were printed included the frame sides, thruster guards, and thruster clips for the top and bottom attachment. Originally the thruster guards were to be printed using 3D Systems Accura 25 Stereolithography (SL) a resin type printing technology that is able to print at under 100 Microns per layer. This material mimics properties of a ABS and PolyCarbonate blend and the SLA process produces parts with exceptionally smooth surfaces, an ideal property for flow. However, testing found the material too brittle for the ROV as a bump . The material was switched to Polylactic Acid (PLA) a Fused Deposition Modeling (FDM) material printed on RepRap printers.

Using a sparse fill honeycomb pattern without a top and bottom allows for water to pass thru the frame without affecting buoyancy. The honeycomb pattern still provides a structural frame and the ABS allows for flexing with its high elasticity. This is why the frame was not printed in PLA were the material is more rigid and tends to break and strain when exposed to stress. The thruster clips have been through a wide variety of materials and designs, tending to be the failure point on multiple occasions. Where the Accura 25 and the PLA being too brittle to handle the load of nuts and bolts, the polycarbonate and ABS clips stood up to the stress and vibration of the motors quite well. The first iteration of the frame had the bottom clips attached onto the frame as one piece, however with the ABS frame separate clips were made and plastic welded together, as well as attaching all pieces to the structural 8020 Aluminum rails. This year's mission requirements made the team rethink the design of the ROV from the previous 3 years. Having such a strict weight and size requirement made designs go through multiple iterations even on the simplest parts. Material properties of prototyping plastics were used to pre-calculate density and optimizing components to use the least amount of material and take up less space. Using 3D printing to our advantage, we were able to create a well structured, lightweight, and iconic looking ROV.

Budget

All finance information is available on the team's Google Drive with up to date account balances, purchases made., and receipts. This allows for full team financial transparency, and the ability to have multiple team members verify balances and log purchases made. Over the course of the entire year, the team was able to stay within budget for building the ROV, though at this time the team is still seeking sponsors for covering travel costs to the competition. An accurate budget is available at the end of this document.

Business/Community Relations

The team communicated directly with many company sales reps to get discounts and donations on parts. A Facebook page was maintained with up to date information on the team's progress. Also, occasional emails on the team's progress was sent out.

Lessons Learned

One important lesson the team learned is the importance of starting development early and getting as much done when school class load is as low as possible. That lesson has been learned over the past 4 years of the team's existence. This year the team finally was able to get the ball rolling immediately at the start of the school year.

Technical Issues

Motor twitching

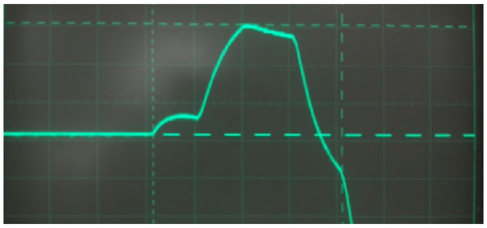
Motors occasionally twitched on previous hardware models. It was caused by a small amount of jitter in PWM pulses sent to motor controllers since pulses are generated in software with interrupts instead of with a hardware PWM module. Pulse size only needs to change by 1-2 microseconds to produce a small amount of motor motion. The solution was to move all servo PWM to hardware PWM modules, and run motor controllers off of UART.

Cameras

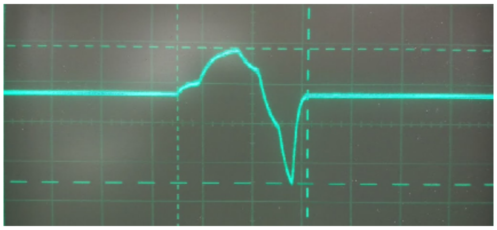
Cameras behaved poorly when motors were running which was a result from EMI induced noise from the running motors. The motor controllers have a switching frequency of 22kHz so a 2nd order RLC low-pass filter was designed and put in series with the camera power to eliminate the high frequency motor noise and spikes causing picture issues. The designed low pass filter has a simulated (with parasitic resistances accounted for) and theoretical attenuation of -72dB at the 22kHz switching frequency which would reduce even the largest inductive motor voltage spikes to a few millivolts.

Regulators

Problems arose with the regulator due to quickly reversing the direction of the thrusters. The motors would cause an overvoltage condition in the regulator. This was initially hot-fixed with software; however, a more permanent solution was needed. An active solution was considered by adding an analog comparator and burn off resistor to dissipate the excess energy. A passive solution was found to be more efficient. The motors initially had fly back diodes and a 0.1μF capacitor across the motor. This was not enough to take care of the overvoltage. Thus an 85mF capacitor bank was added to absorb the energy and prevent the regulators from hitting the 16V cutoff point.



Oscilloscope capture showing the 12V regulators shutting off, with no significant bus capacitance



Oscilloscope capture, with 85mF of capacitance, showing a small 50ms, 0.5V spike, with the regulators continuing to function

Interpersonal Issues

There was trouble finding an on campus workspace since there was no real defined process of obtain workspace for a student organization. Most of the present student organizations have been established for years. There was a lot of back and forth; however, a faculty advisor was able to petition on behalf of the ROV team for a work space. Issues emerged within the group as well. Balancing ROV, work, and coursework was challenging for team members. Keeping all members engaged with work during meetings and build sessions did present some problems due to the many different varieties of knowledge each team member had to contribute.

Future Improvements

Switching to a brushless thruster system would allow for weight and size to be reduced, while increasing thruster force and reducing electrical consumption. Past three years of the team have tried using brushless motors without much luck but it is still a possibility for the future.

Having a professionally built tether that is neutrally buoyant, or slightly positively buoyant would greatly add to the value of the ROV. While the team's current tether is more than adequate for most ROV things, it would still be better off with a thoroughly researched and designed special purpose tether.

Troubleshooting

Due to the problems the ROV team had last year, the team decided to implement a more stringent troubleshooting process. Because the ROV is so delicate and intricate in nature, it was extremely important to be able to solve problems in a consistent and logical way. In an effort to be prepared, the team created a troubleshooting plan to use when issues arose. This plan carried over from the previous year. The plan included writing down the issue, brainstorming possible solutions, discussing the pros and cons of each choice, choosing the best option, and finally implementing the new idea. If the team still had issues after the newest iteration was implemented, the process began again. This is to ensure that the team found the best solutions possible. The team hoped to find the best possible solution the first time, but experience has shown that this was not always the case.

Reflection

"Being my last year on the team that I started four short years ago, I wanted to make sure I pushed the team to do their best, and I was blown away by the results. None of this project would have been feasible without everyone's effort and dedication, and I'm glad to have been a part of it. The past 5 years of being on MATE ROV team's has flown by, and has really helped shape me to be the engineer that I am today. My biggest regret is that I won't be able to be a member of a team next year, though I very much look forward to being an ROV team mentor or MATE competition volunteer!" ~ *Seth Opgenorth, CEO and team founder*

Acknowledgements

None of the work done on the ROV would have happened without the hard work done by the MATE Competition and associated volunteers. Additionally, this ROV was made possible by material and monetary donations from the following:

Advanced Circuits—Donation of PCBs

MATE—Hosting a terrific competition and for being a great resource

Midwest ROV, LLC—Technical support and monetary donation

MSOE—For providing excellent facilities and faculty mentors/advisors

Milwaukee Tool—For donation of a wide variety of hand and power tools

OpenROV—Donation of a depth sensor/IMU

SolidWorks—Donation of licenses for the team

MacArtney/SubConn—For providing an exceptional discount on bulkhead connectors

TDK-Lambda—Donation of 3 DC/DC regulators

UWM Freshwater Science—For technical support and use of facilities

Yaskawa—For monetary donation

Safety Checklist

	Required Action
	Put on safety glasses
	Make sure dry housing latches are engaged and screws properly torqued
	Ensure all wires, motors, propellers, and materials are securely fastened
	Double check tether's strain relief connection to the ROV
	Check that there are no exposed sharp edges on the ROV
	Ensure that motor guards are in place and are guarding the propellers
	Verify that all hydraulic hose connections are secure
	Make sure that bare wires are not exposed
	Uncoil tether
	Check that 40 amp fuse is in place
	Double check the point of attachment to power source
	Double check the point of attachment to ROV

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Stackpole, E. (2013). *OpenROV*. Retrieved from http://openrov.com/

Steven, M., Bohm, H., & Jensen, V. (2010). *Underwater Robotics: Science,Design & Fabrication. MATE.*

ROV Budget

Date	Item	New/ Used?	Part Donation	Monetary Donation	Price	Account Balance	Fair Market Value
2013	Three PAF700 Regulators	reused	$1,065.00				$1,065.00
2014	Subconn Bulkheads	reused	$3,500.00				$4,565.00
-	2014-2015 Starting Balance			$1,142.46		$1,142.46	$4,565.00
7/14/2015	Test Bilge Pump	new			-$28.31	$1,114.15	$4,593.31
7/31/2015	TDK-Lambda EMI Filters	new	$66.00			$1,114.15	$4,659.31
8/12/2015	PCB Conformal Coating	new			-$14.07	$1,100.08	$4,673.38
8/14/2015	12 Tsunami Bilge pumps	new	$360.00			$1,100.08	$5,033.38
8/16/2015	Propeller set	new			-$102.56	$997.52	$5,135.94
8/17/2015	XT60 Connectors	new			-$11.96	$985.56	$5,147.90
8/17/2015	Motor controllers	new	$107.90		-$291.79	$693.77	$5,547.59
8/17/2015	Bulkhead O-rings	new			-$18.80	$674.97	$5,566.39
8/18/2015	PCB Shipping	new			-$19.63	$655.34	$5,586.02
8/18/2015	PCBs	new	$66.00			$655.34	$5,652.02
8/18/2015	Resistor Kit	new			-$14.88	$640.46	$5,666.90
8/19/2015	4" Acrylic Enclosure	new			-$165.00	$475.46	$5,831.90
8/19/2015	Pololu Laser Cutting	new			-$56.95	$418.51	$5,888.85
8/20/2015	14 awg Tether Wire	new			-$60.04	$358.47	$5,948.89
8/22/2015	Depth Sensor Module	new	$120.00			$358.47	$6,068.89
8/25/2015	Assorted Electronics	new			-$175.41	$183.06	$6,244.30
8/25/2015	Tether Sleeving	new			-$23.10	$159.96	$6,267.40
9/14/2015	Misc. Electronics	new			-$53.28	$106.68	$6,320.68
9/17/2015	Donation from Midwest ROV			$1,000.00		$1,106.68	$6,320.68
9/21/2015	Hardware and O-rings	new			-$77.79	$1,028.89	$6,398.47
10/4/2015	Dry housing and parts	new			-$110.50	$918.39	$6,508.97
10/7/2015	New Dry Housing Lids	new			-$84.95	$833.44	$6,593.92
10/16/2015	Tiva C Boards	new			-$51.29	$782.15	$6,645.21
10/16/2015	Milwaukee Tool Donation	new	$490.00			$782.15	$7,135.21
11/20/2015	Plastic	new			-$20.50	$761.65	$7,155.71
11/29/2015	Voltage isoltation electronics	new			-$42.20	$719.45	$7,197.91
12/6/2015	Sensors	new			-$39.12	$680.33	$7,237.03
12/13/2015	40A AGU Fuses	new			-$8.80	$671.53	$7,245.83
12/14/2015	New Dry Housing Lids	new			-$46.95	$624.58	$7,292.78
12/14/2015	Blue Robotics penetrators	new			-$110.00	$514.58	$7,402.78
12/19/2015	Vacuum Pump	new			-$43.00	$471.58	$7,445.78
12/27/2015	Connectors and Heatshrink	new			-$43.56	$428.02	$7,489.34
1/16/2016	Mission Props	new			-$122.08	$305.94	$7,611.42
1/23/2016	100ft Hose	new			-$43.06	$262.88	$7,654.48
1/31/2016	100ft - 16awg silicone wire	new			-$35.21	$227.67	$7,689.69
2/3/2016	Gripper Parts	new			-$35.17	$192.50	$7,724.86
2/13/2016	PS4 controller	new			-$69.52	$122.98	$7,794.38
2/17/2016	FPV Camera and valve	new			-$47.88	$75.10	$7,842.26
2/18/2016	New Tiva C PCB	new			-$23.58	$51.52	$7,865.84
3/9/2016	PC-11 Marine Epoxy	new			-$21.99	$29.53	$7,887.83
3/9/2016	Acrylic Cement and Sticks	new			-$15.95	$13.58	$7,903.78
3/11/2016	Clutch 1 Parts	new			-$22.54	-$8.96	$7,926.32
3/15/2016	Yaskawa Donation			$1,000.00		$991.04	$7,926.32
3/16/2016	Digikey Tiva C Parts	new			-$131.81	$859.23	$8,058.13
3/17/2016	Two Sub Micro Servos	new			-$46.68	$812.55	$8,104.81
3/17/2016	30A current sensor	new			-$33.80	$778.75	$8,138.61
3/17/2016	Laser cut dry housing lids	new			-$77.12	$701.63	$8,215.73
	Final estimated ROV Cost						**$8,238.53**