MSOE Underwater Robotics

Milwaukee School of Engineering, Milwaukee, Wisconsin

The Systems and Design Philosophy of *Mosquito 2.0*

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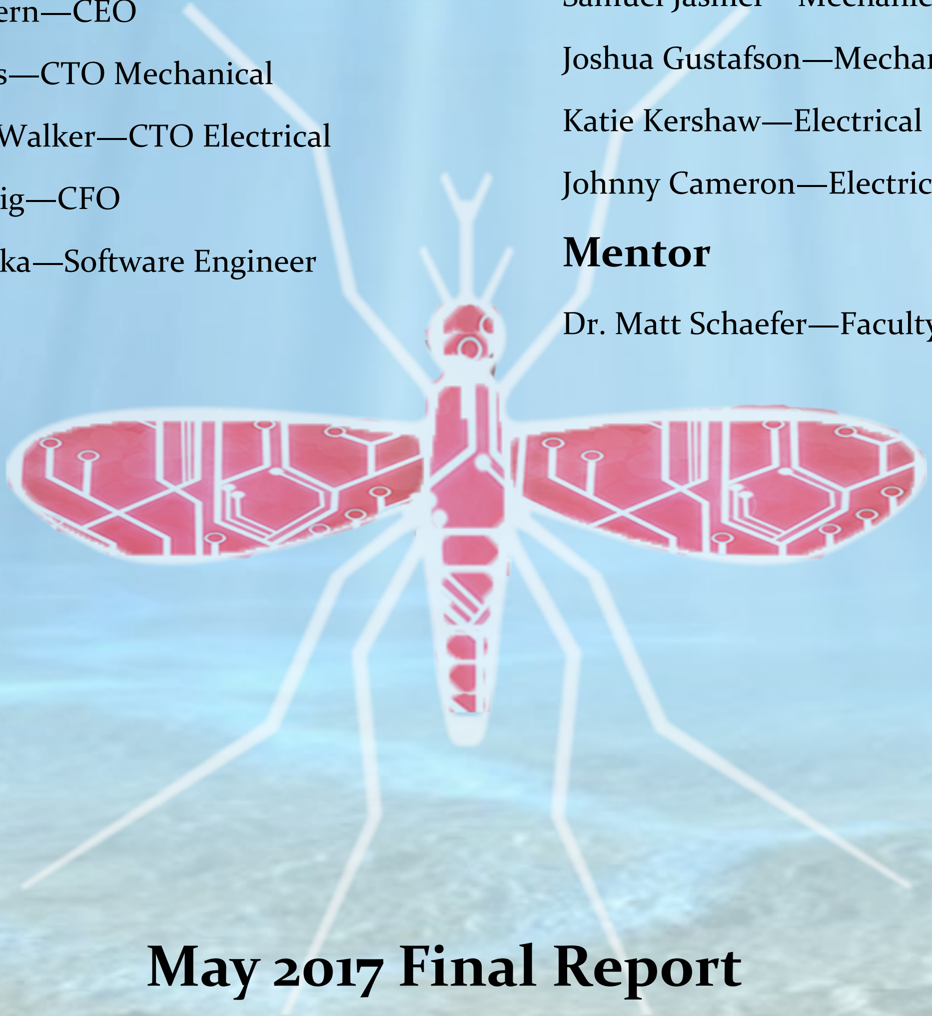

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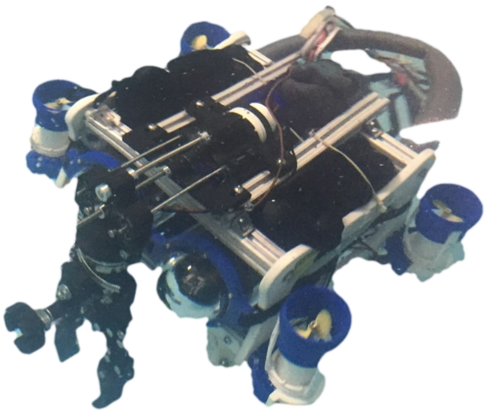
Abstract

The MSOE ROV team is a fifth 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 new to the team. Last year, the team attended the international competition at NASA's Neutral Buoyancy Laboratory and placed fifth attracting the attention of the new students and faculty members.

The ROV, Mosquito 2.0, was designed specifically to be compact, practical and modular, focusing on adaptability and stability to be able to complete any scheduled task, while being able to change critical systems for future endeavors. It's ideal for a company in need for a flexible tool. A subsystem approach to design allowed a lot of collaboration to happen since each part of the ROV could be worked on separately and brought together with ease. Many parts of the Mosquito 2.0 were created using 3D printing. This provides the multiple benefits of being economically friendly to a small team and allows for freedom and adaptability in our designs; That allowed the team to create the best ROV possible while staying in the realm of possibility for a small but dedicated team.



Fully Assembled ROV—The Mosquito 2.0

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Team Organization and Management

Google docs was used to track progress, goals, task lists, and ideas which also allowed for easy collaboration and document storage. Constant communication, especially during design stages, is necessary, so the team used GroupMe to stay on top of team tasks and discuss ideas. Goals were set before the 2016-2017 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. MSOE's practical teaching method is ideal for an interdisciplinary team structure. Allowing students to brings skills from all over to create a product that everybody on the team knows inside and out, independent on their specific major/ background.

Being comprised of mostly Juniors and Seniors, the team is constantly trying to balance the complex work life. A functional organization group structure had tasks divided up between technical officers and allowed a lot of slack between informal-deadlines. This is not the best structure for a complex operation, but for a small team it allowed flexibility around school, work and extracurriculars. 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.

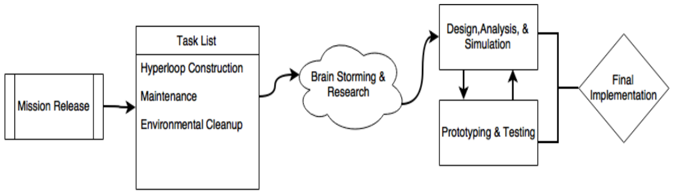
Safety

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, lab access would no longer be granted. 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 heatshrink, 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 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. Our design process was heavily influenced by 3D printing, allowing our designs to be quickly developed from brainstorming to implementation in less than a few days and sometimes produce a turn around in a few hours.



Flow Diagram Showing the Team's Process

The design process above gives a broad overview of how our team iterates through our designs. The team first assesses the needed task to be completed from the competition manual. We broke these major tasks into major deliverables and started the brainstorming process. Thinking through ideas we determined if we could build it ourselves or get it donated; that design would take precedence. Simulation is critical to the modern day engineer. Simulating the electrical and mechanical systems using a wide variety of programs such as MultiSim, Simulink and SolidWorks allowed the team to make analysis oriented design decisions and spending less time trial and error. However, all the simulated analysis in the world does not take the place of prototype testing driven by hard data. Thrust and gripper testing was completed in a laboratory setting using force sensors to gauge power needs and achievable thrust. Electrical designs were tested on breadboards and scopes. Once a reliable design was established final implementation onto the ROV would take place. The modular design allowed the team to work on each subsystem independently testing and prototyping then bringing the system together for final implementation.

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

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.

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

Last year's complete redesign of the frame, dry housing, electronics, and tether created an easily modifiable platform. Considering this, limited modifications were made to frame other than necessary items such as the gripper to accomplish mission critical tasks. The gripper was custom built to meet the tasks of manipulation and turning of the nozzle. The complete redesign of the electrical system also created many problems a main focus of this year was on creating a stable system both in hardware and software. After an analysis of the electrical systems, it was determined the only component needed to be replaced was the motor controller. Attempts were made to make a custom solution for the motor controllers; however, several Pololu 18v25 motor controllers were ultimately purchased.

Weight and Size Management

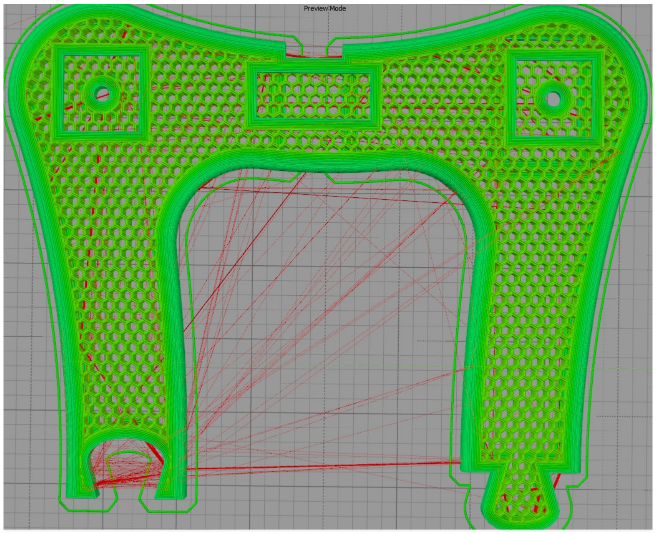
To accommodate for the weight and size limitations, the team used SolidWorks to get an idea of a tool's mass. Also, a spreadsheet was regularly updated with mass estimates for every subsystem. Everything possible was accounted for, and visually seeing the masses allowed the team to regularly optimize 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 about 19kg, including the tether and all necessary payload tools to complete the mission.

Frame

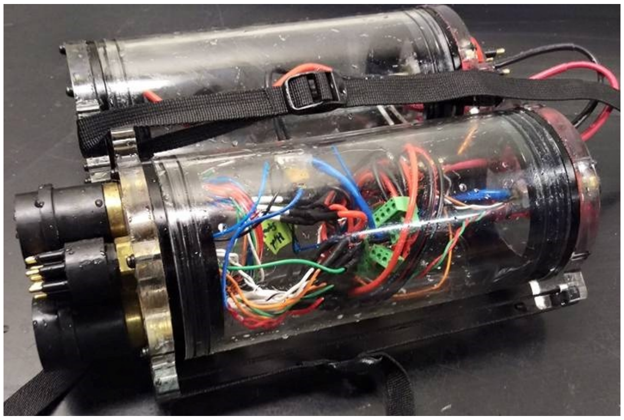
Compacting the design into a frame that only incorporates the necessities keeps the weight down and increases utility. The frame was printed in ABS which has a lower density of 1.05g/cm3, compared to PC's density of 1.22g/cm3, thus saving weight while gaining performance. With ABS being more elastic than PC, the frame is able to better hold up to the rough handling that the ROV experiences on a regular basis. The sparse filled honeycomb pattern keeps the frame rigid while saving 0.8kg of mass.



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

Dry Housing

It was decided to use a cylinder dry housing because cylinders 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

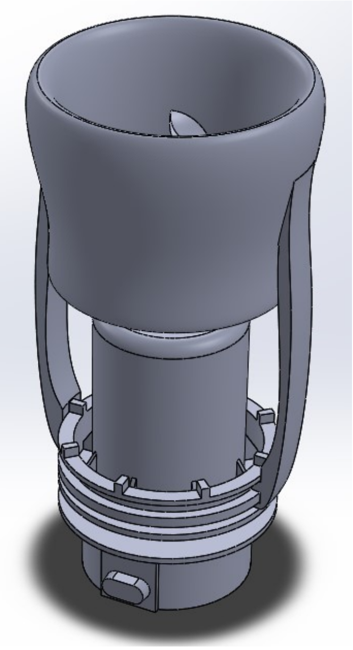
The team decided to go with 2 customized 10cm acrylic tube enclosure from Blue Robotics that have been tested to depths of 100 meters. The electronics are split among both tubes to reduce total ROV size. The 2 tubes displace 3.5 liters of water (20 Newtons) compared to the 12 liters (120 Newtons) from 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 used the reliable/familiar brushed bilge pump solution. 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.

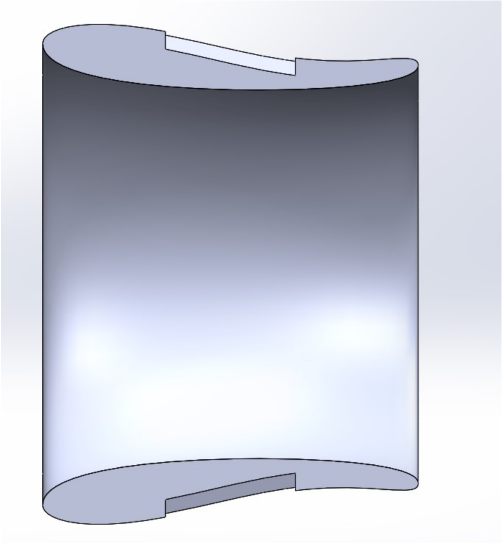


SolidWorks Rendering of a modified bilge pump with a Kort nozzle as a propeller shroud.

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 uses the SubConn bulkheads which have never leaked and have proven themselves over and over again over the years.

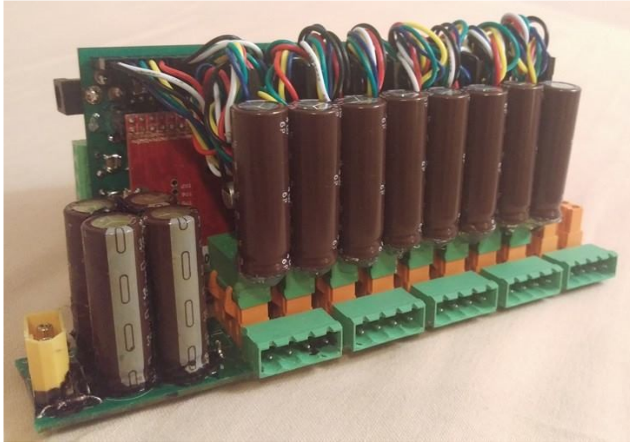
Vacuum pump test setup for doing easy tests of the dry housing's seals

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

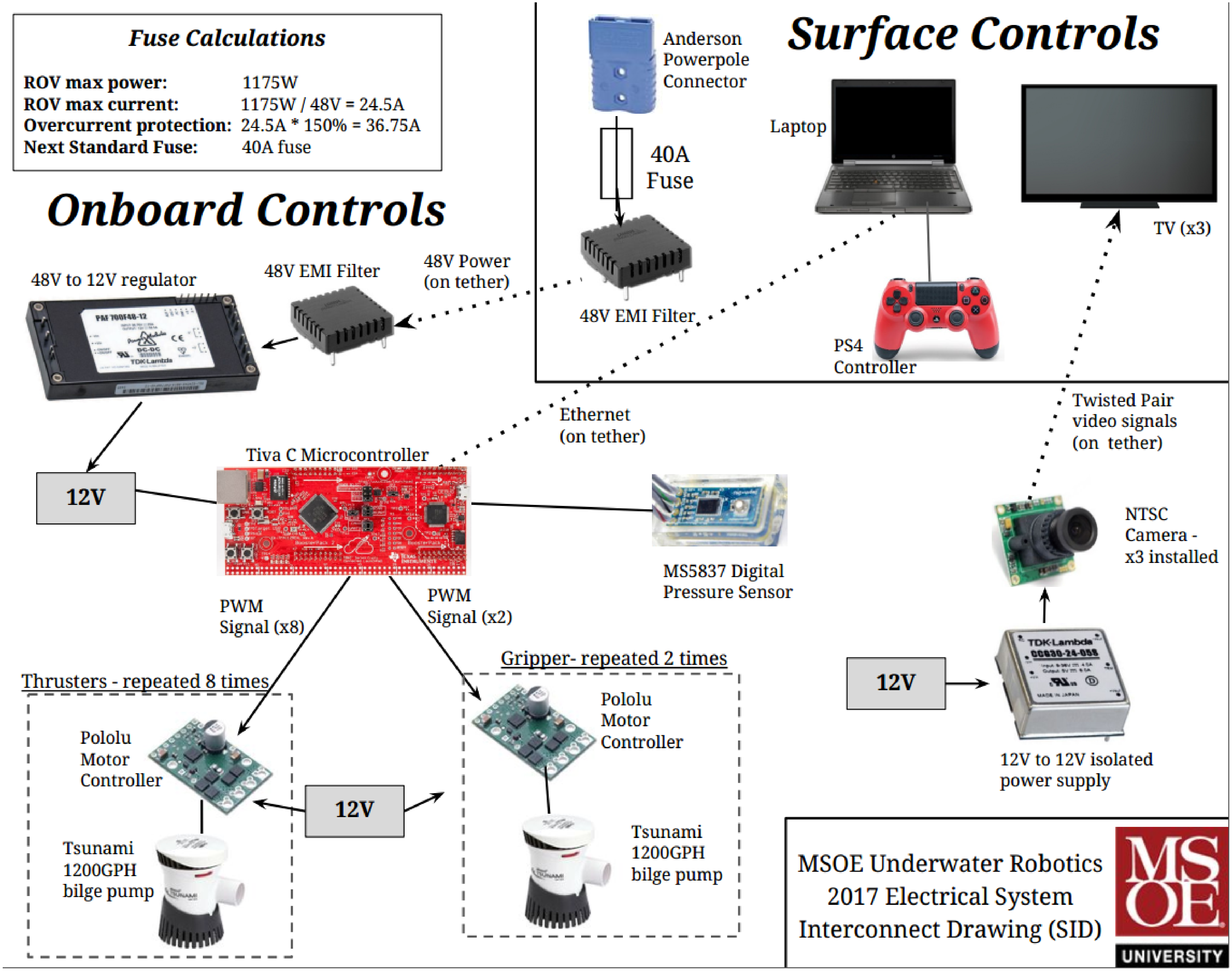
Microcontroller

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

This year the team decided to try our hand designing our own H-bridge motor drivers using high power mosfets and a prepackaged H-bridge fet driver IC. This design was going to be implemented to allow us to replace our current regulator, which was taking up an entire tube on the robot, to a much smaller regulator by using the 48V provided by the tether instead of a stepped down 12V. Accomplished by adjusted duty cycles and some very heavy filtering across the motor to smooth out the spikes in voltage.

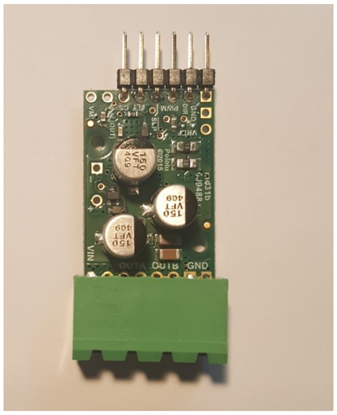
During prototype testing the driver was able to output the expected voltage of 12V when in a static power applied mode. The major issue was with switching direction; as the driver was switching the motor direction a large amount of shoot through current went through the all the mosfets in the driver causing components to be destroyed. The team then re-evaluated the time it would take to get a competition ready controller, and we decided to change to a commercially available controller.



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
2017 Electrical System
Interconnect Drawing (SID)



Pololu High Power H-Bridge Motor Controller

The Polulu G2 18v25 High Power 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. The drivers are controlled using PWM . Each motor controller receives its own PWM signal instead of chaining multiple controllers together. It's a more reliable design that allows the ROV to partially function in the case of a single point of failure.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. This controller drastically reduced space as well by having far less wiring and filtering capacitors, retrofitted connectors for a breakout board, and much smaller discrete components.

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.

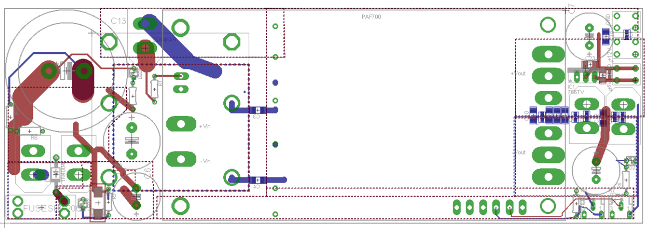
Electrical Connections

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. 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.

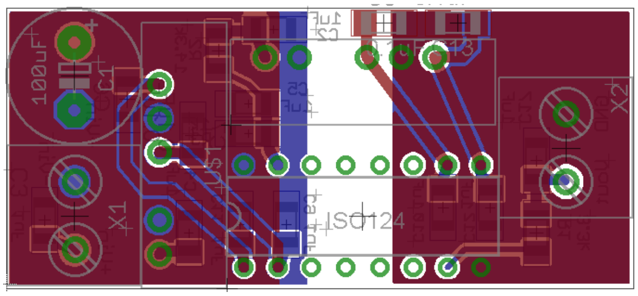
The 12V rail has over 150mF of electrolytic capacitors to account for the large current spikes when several motors switch directions quickly which indices a large back EMF to the system followed by a very large current draw (over 60A form 4 motors). This problem could have alternatively been solved by 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

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

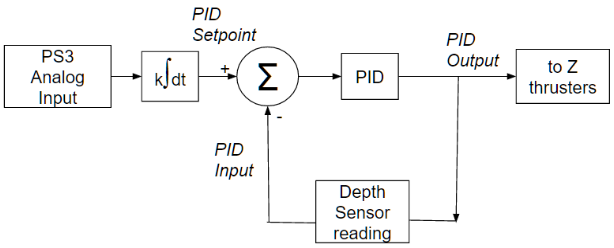
The 12V rail shares the same ground as the Tiva C, eliminating the need of a voltage isolator circuit. The voltage is monitored by a voltage divider to bring the 12V down to an appropriate voltage for the Tiva C's ADC. Thanks to the Tiva C's 12-bit ADC, the 12V rail can be measured with a 4.0mV resolution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

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.

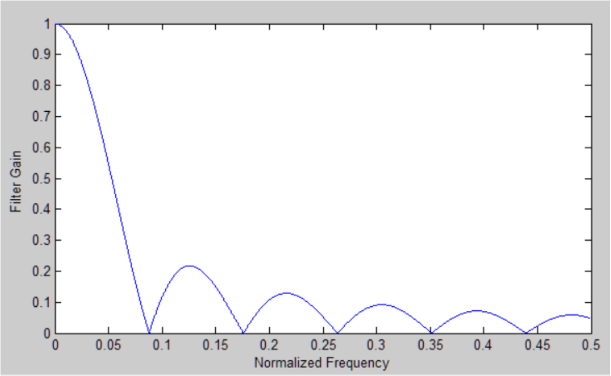


PID diagram showing the high-level depth control implementation

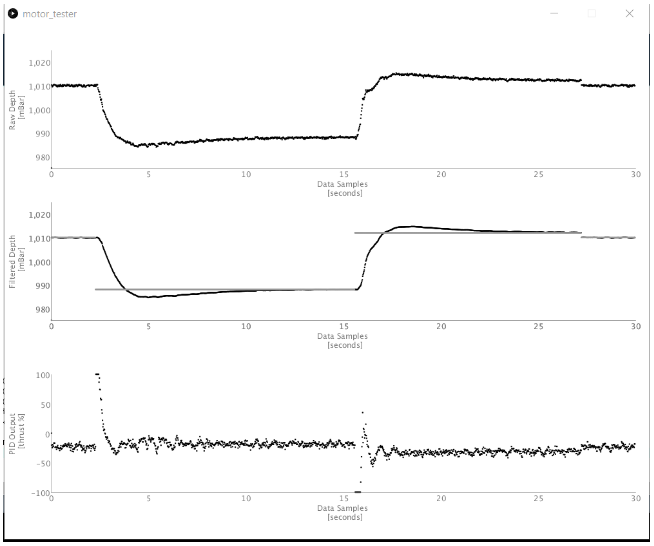
Controls are managed using several PID loops tuned to get the desired behavior. The control loops are ran at 140 Hz, resulting in new thruster values being generated approximately every 7 milliseconds. These loops are able to update and react much faster than even some of the best pilots. Signal latency 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.

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



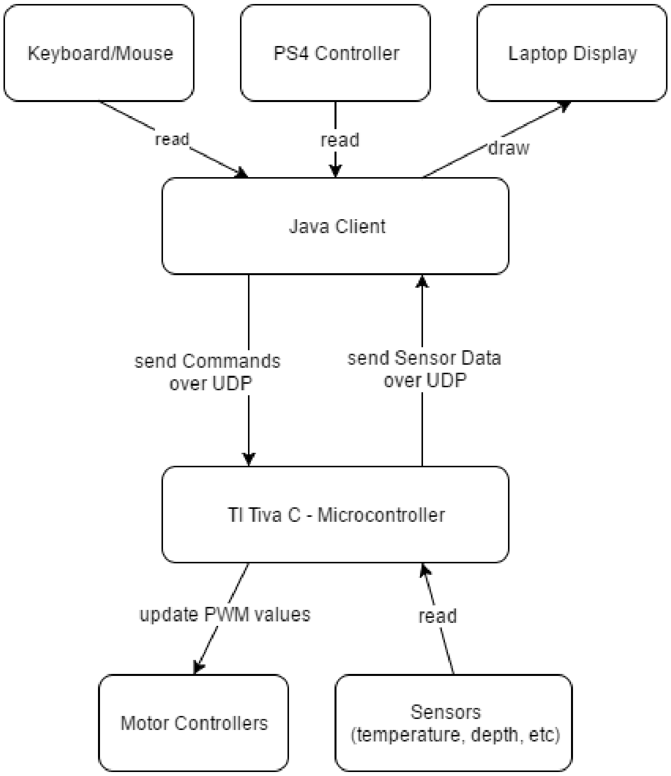
Step response of the ROV moving 75cm in depth, using the control loops. Top two graphs show the depth sensor data (unfiltered and filtered), and the bottom graph showing the PID thrust output

It was important 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.



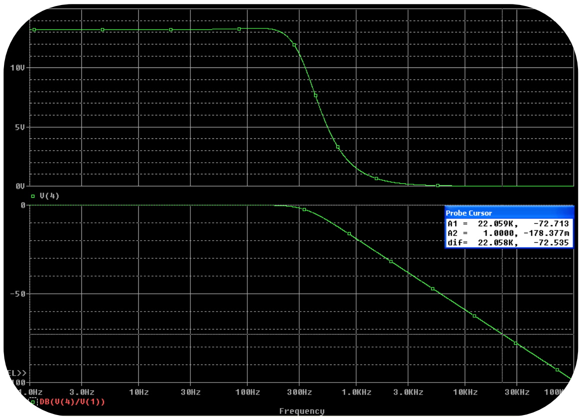
Basic flowchart showing general flow of the ROV's team designed and created software components

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.

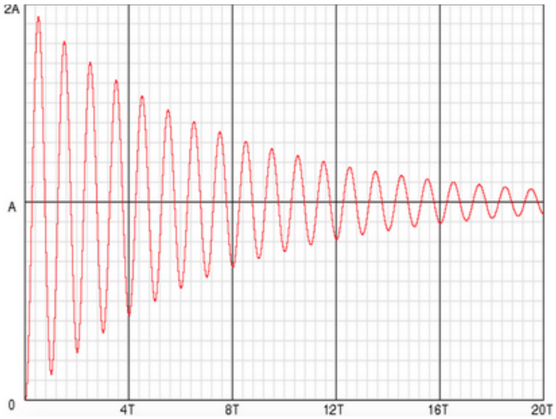
Wire AWG	Max Current [A]	ROV Voltage [V]	Worst Case Efficiency	Max Power [W]	Safety Factor	Mass [kg]	Cost [USD]
6	40.0	45.5	94.5%	1820	3.64	8.0	$0
12	40.0	38.1	79.4%	1524	3.04	2.1	$84
14	32.0	36.0	75.0%	1152	2.30	1.5	$56
16	20.1	36.0	75.0%	724	1.44	1.1	$50
18	12.5	36.0	75%	450	0.90		

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.

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

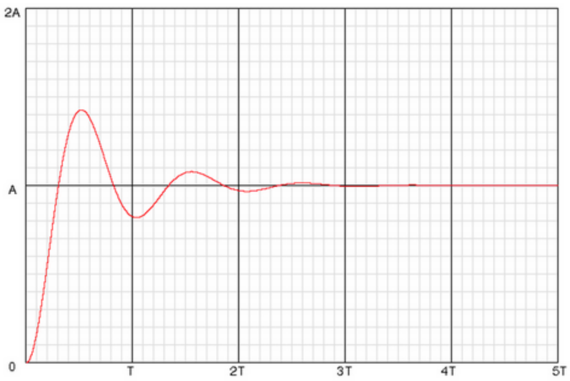
For communication from the shore to the ROV, Ethernet is used. Ethernet is the standard in harsh industrial applications where reliability and transmission speed are important. UDP (User Datagram Protocol) transmission has the least overhead, but provides no guarantee of data arrival. Communication protocol 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.

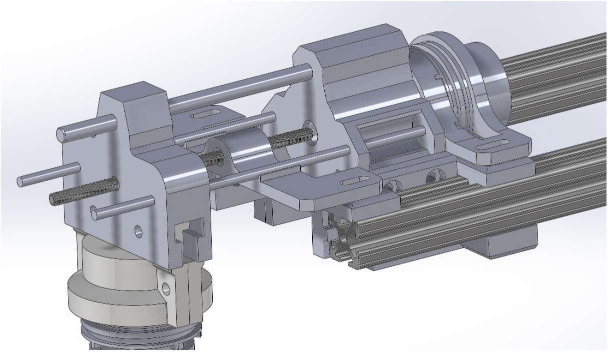
Manipulator

Since the base ROV was being used from last year the focus was mainly on the payload tools. This led to a full redesign of how the gripper system works while keeping the base design intact. Upon review of how last year's system, we knew we needed to reduce the chance of key gripper mechanism breaking down during use. We used a 3D printed gear box to get a specific reduction of 7.5:1 on the previous gripper. This suited our needs, however was prone to breakage after repeated use. The team decided to transfer over to a more compact ceramic and metal gearbox made by Matex that would deliver a 5:1 reduction from the bilge pump.

Matex Gearbox

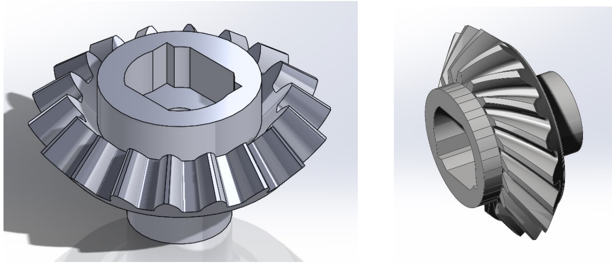
We still needed a speed reduction so that the gripper could maintain a usable close speed. This was achieved by using a higher pitched ACME lead screw that transmitted the gripping strength. Moving from 12 threads per inch to 16 threads per inch would give us a grip time we needed. Next we moved to making the gripper more adaptable to the mission tasks. This required an overhaul of the gripper motion. Initial team brainstorming theorized that having the ability to move the whole gripper would reduce the need to reposition the ROV around the mission props. This was implemented by adding another bilge pump motor to drive a forward and backward motion lead screw shown in the image below. This plays well into our design rationale of wanting a modular design, by having the gripper assembly slide onto this upper assembly the gripper could be easily replace by another tool that needed the same motion.





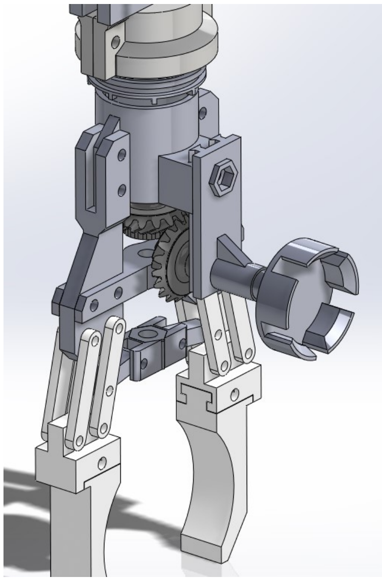
Top Slider

The whole assembly can then be put into a folded traveling mode, where the gripper is detached and the slider is pushed to the middle of the ROV. This saves space during transportation and storage. A lot of the mission tasks have the ROV grabbing circular objects, so the gripper claws were designed with this in mind. However, in the future we did not want to be tied down to this claw design, so we made them interchangeable as well. During brainstorming and planning we found that the opening and closing the valve during the fountain removal would be the hardest part of the competition, however based on our gripper orientation which was suitable for the majority of the tasks, it was unable to turn the valve efficiently in its current state. A spur bevel gear design was proposed and prototyped to work well however slipping occurred during power transmission to the valve. To reduce the possibility of slipping occurring, we moved to a helical bevel design shown in figure below.



Spur bevel gear vs helical bevel gear design

This design once again was designed to be modular and can be replaced with a different mission tool. Overall the gripper redesign was a success and the added motion pared with the control system will make the ROV more reliable and adaptable to mission tasks.



Final Gripper

Budget

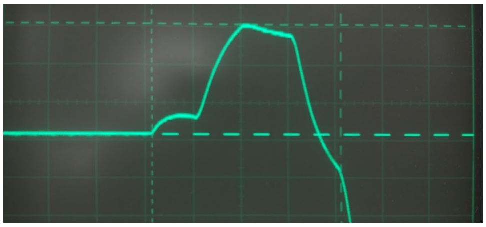
All finance information is available on the team's Google Drive with up to date account balances, purchases made., and receipts. This allows for full team financial transparency, and the ability to have multiple team members verify balances and log purchases made. Over the course of the entire year, 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.

Lessons Learned

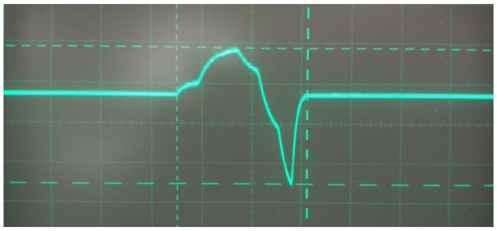
Technical Issues

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

An important lesson learned this year was academic year diversification among team members. While we have a diverse major group, previous troubles in team member retention and engagement have resulted in academic year gaps and lack of manpower for certain tasks. A good mixture of freshman, sophomores, juniors, and seniors should be established. To solve this resources are being allocated in individual involvement and recruitment.

Reflection

Overall, this year went fairly well. At the beginning, it took some time to get going since the former CEO and founder graduated last year. But once the new leadership was established, everything else started falling into place.

Future improvements to the team include getting the freshman from this year ready to take over the team after this year's juniors graduate next year. Making the transition of leadership as smooth as possible will help the team stay alive even after key members graduate. Also, the team should better take into account what can be accomplished while considering time commitment and knowledge level of the current members.

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

Polulu—For giving the team a generous discount on the motor controller

UWM Freshwater Science—For technical support and use of facilities

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

References

MATE. (2012). *Marine Advanced Technology Education*. Retrieved from http://www.marinetech.org/

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

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

2017 ROV Budget

	Date Purchased	Item	Supplier	Part Donation	Monetary Donation	Amount
	9/6/2016	Starting balance in account	n/a	n/a	n/a	$878.08
ROV Parts	10/26/2016	H-Bridge Parts	Digikey	No	No	$37.55
	10/17/2016	97014A632 - ACME Threaded Rod 1/4" -16	McMaster- Carr	No	No	$43.57
	10/17/2016	6112K38 - Linear Motion Shafts 5mm	McMaster- Carr	No	No	$17.06
	10/17/2016	57155K375 - Stainless Steel Ball Bearings	McMaster- Carr	No	No	$15.84
	12/11/2016	4pcs - 5mm Linear Bearings	Amazon	No	No	$10.50
	12/12/2016	3pcs - 5:1 Metal Nylon Planetary Gear Box	Matex	No	No	$90.00
	12/13/2016	H-Bridge Driver	Digikey	No	No	$14.82
	1/9/2017	Hex ACME Nuts	McMaster- Carr	No	No	$13.62
	1/14/2017	Bluetooth module	Amazon	No	No	$16.98
	1/23/2017	MATE Registration	n/a	No	No	$250.00
	2/6/2017	Bearing 8mm	Amazon	No	No	$11.30
	2/6/2016	LED Driver	Amazon	No	No	$15.90
	2/7/2017	8mm collet	Amazon	No	No	$19.22
	2/12/2017	H-Bridge Parts	Digikey	No	No	$44.24
	4/1/2017	Electrical Misc	Amazon	No	No	$66.53
	4/29/2017	Gripper parts	McMaster-Carr	No	No	$17.97
	4/30/2017	Gripper parts	amazon	No	No	$14.70
	5/20/2017	Polulu Motor Controllers	Polulu	Yes	No	$400.00
Travel	5/1/2017	Wisconsin Space Grant Consortium (WSGC)	WSGC	No	Yes	$3,000.00
	5/14/2017	Hotel -Room - Long Beach	Hotel Current	No	No	$623.80
	5/25/2017	Hotel Room - way there	Super 8	No	No	$120.00
	5/25/2017	Hotel Room - way back	Super 8	No	No	$120.00
		Gas		No	No	$500.00
		Food		No	No	$500.00
				Remaining Balance		$1,714.48

Mosquito—2.0 Cost Calculation

Item	New/Resued	Cost	Quantity	Total Cost per Item
Cylindircal dry housing	Reused	$54.00	2	$108.00
Dome end cap	Reused	$59.00	2	$118.00
Flat end cap	Reused	$16.00	2	$32.00
Vent and plug	Reused	$8.00	2	$16.00
Polulu Laser Cutting	Reused	$57.00	1	$57.00
Hardware and O-rings	Reused	$29.00	4	$116.00
Subconn bulkheads	Reused	$2,000.00	1	$2,000.00
Other bulkheads	Reused	$4.00	2	$8.00
Bulkhead O-rings	Reused	$18.80	1	$18.80
Plastic for frame	Reused	$20.00	1	$20.00
Plastic for propeller guards	Reused	$1.25	8	$10.00
Aluminum rails	Reused	$1.00	60	$60.00
Gripper pieces	New	$1.00	15	$15.00
Metal rods	New	$2.00	15	$30.00
Propeller set	Reused	$102.00	1	$102.00
Misc. mechanical	New	$1.00	50	$50.00
Bilge pumps	Reused	$34.00	10	$340.00
FPV Camera	Reused	$15.00	2	$30.00
48V to 12V regulator	Reused	$300.00	1	$300.00
Tiva C Board	New	$51.00	1	$51.00
Motor controllers	New	$50.00	10	$500.00
Temperature sensor	Reused	$10.00	1	$10.00
Depth sensor	Reused	$120.00	1	$120.00
30A current sensor	Reused	$34.00	1	$34.00
TDK-Lambda EMI Filters	Reused	$66.00	1	$66.00
12V to 12V regulator	Reused	$40.00	1	$40.00
PCB Conformal Coating	Reused	$14.00	1	$14.00
Custom PCB	Reused	$86.00	1	$86.00
PS4 Controller	Reused	$70.00	1	$70.00
Monitors	Reused	$150.00	3	$450.00
100ft - 16awg silicone wire	Reused	$45.00	1	$45.00
Other Connectors and Heatshrink	New	$43.00	1	$43.00
PC-11 Marine Epoxy	New	$22.00	1	$22.00
XT60 Connectors	Reused	$12.00	1	$12.00
Misc. electrical	New	$100.00	1	$100.00
			Total Cost of ROV	$4,871.80