Infinite Monkey Gang

Technical Documentation

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1 Abstract

The Infinite Monkey Theorem states that a group of monkeys typing indefinitely will almost certainly produce the complete works of Shakespeare. The Infinite Monkey Gang believes that a team of high-school students innovating indefinitely will almost certainly produce the ideal Remotely Operated underwater Vehicle (ROV). 2018 is the Sammamish-based company's second year in the MATE ROV competition. The diverse strengths of The Infinite Monkey Gang's seven members – including software development, management, vehicle operation, and engineering – create a cohesive and efficient company. Together, they designed and built an ROV equipped to salvage wreckage, operate scientific tools, and install tidal turbines in the coastal waters of Washington State. Key features include: a versatile gripper for access into tight spaces; a motorized camera gimbal for view adjustment; a precision control system for fine-tuned motion; a built-in lift bag management system for heavy lifting; easily-accessible components for quick repairs; and customizable software for mission-specific requirements. Combined, these elements form an inexpensive, adaptable ROV capable of operating safely over extensive periods of time. When searching for aircraft wreckage, the vehicle uses its rotatable wide-angle camera to search the sea floor. The precision of the ROV's movement and gripper control provides safety and accuracy while positioning seismometer sensors, installing and maintaining ocean-bottom turbines, removing debris, and restoring eelgrass.

Upper row, left to right: Kevin Ehlers – CFO, Kaelin Laundry – Systems Engineer, Gabriel Gaetner – Missions Expert and Pilot, Oren Tropen – Systems Engineer.
Lower row, left to right: Natali Kendal-Freedman – COO, Koyha Kato – Mechanical Engineer, Silvia Calinov – CEO.
Photo: Tejus Krishnan

2 Project Management

2.1 Organizational and Planning Processes

Last year, the Infinite Monkey Gang competed as a team of 18 people from an after-school program. At the beginning of this school year, the seven people who wanted to continue the team outside of the school program met (2017-2018). The project manager kept her role and began figuring out the logistics of competing again this year. One major challenge we faced was becoming independent from our school, as it had a new team this year. We decided to meet in a team member's garage and declared ourselves unaffiliated. Our meetings were Wednesdays from 12 p.m. to 2:30 p.m. and Sundays from 1:30 p.m. to 3:30 p.m. If someone couldn't go, they let the project manager know ahead of time. Our team utilized the messaging app Slack for communicating amongst ourselves. We have a "general" chat for team announcements, as well as individual chats for reminders and system-specific work. In addition, there is a "random" chat for sharing non-work content and jokes. This channel facilitates team bonding while removing distractions from other channels.

2.2 Schedule Development and Maintenance

Our group is highly motivated to work on our ROV, as all our members actively decided to continue outside of the school program. Therefore, we did not need to create a set schedule when we started organizing in October. We began every meeting by creating a task list for that meeting, and generally completed the entire list. We delegated any unfinished elements to an individual member who completed them outside of meetings or made them the top priority at the following meeting. Typically, the reason we didn't accomplish a task was a lack of materials or tools. We remedied this before the next meeting by assigning a member to locate or buy those items in the interim.

2.3 Resources, Procedures, and Protocols

Whenever we design something new, we first turn to the whiteboard. We begin drawing individually and then look over each member's design collectively. Typically, the person encounters a major design flaw as they attempt to explain their idea. The entire team then works together to find a solution, creating an environment that fosters critical and realistic thinking. Figure 1 depicts a half hour discussion stemming from a few diagrams of possible structures. This photograph was taken last year as we created the initial design for the ROV. We utilize multiple colors to differentiate each member's input.

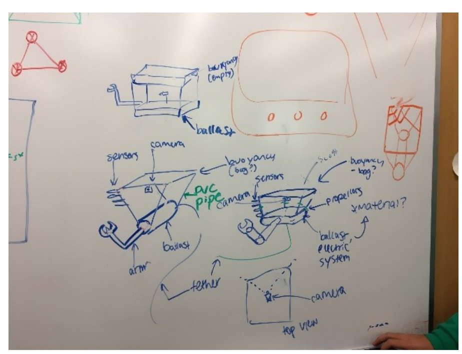


Figure 1: Whiteboard from one of our brainstorming sessions. Photo: Silvia Calinov

CEO	CFO	COO
Organizes meetings Ensures everyone is on task Handles "behind the scenes" communication with MATE Ensures team meets due dates	Excel and budgeting expert Records individual spending Completes budget- related calculations	Verifies viability and applicability of designs Completes mathematical calculations Edits writing components

Figure 2: Specific team roles and responsibilities: Leadership and operations

Mechanical Engineer	Systems Engineer	Missions Expert
Assembles structure Builds components Attaches motors, manipulator, and tube to structure Assists with electrical work	Designs majority of manipulation components Designs control system Programs ROV controls Solders electrical connections	Pilots the ROV Ensures thorough understanding of tasks Focuses design work on task specifics

Figure 3: Specific team roles and responsibilities: Engineering

3 Design Rationale

3.1 Thrusters

3.1.1 Layout

In order to deliver the turbines into their base mount or to manipulate a lift bag, having precise positional control is key. To this end, we organized our thrusters so that their individual output vectors are combined to produce motion in six degrees of freedom: up/down, left/right, forward/backward, roll, pitch, and yaw. The default configuration we use in product demonstration has one thruster at each corner of the vehicle, shown in Figure 4, plus two vertical thrusters. The four primary thrusters can be rotated depending on the task but generally are oriented at roughly 45 degrees (relative to the rectangular frame). To ensure quick ferrying of gear between the demonstration area and the surface, the two vertical thrusters have higher-torque motors.

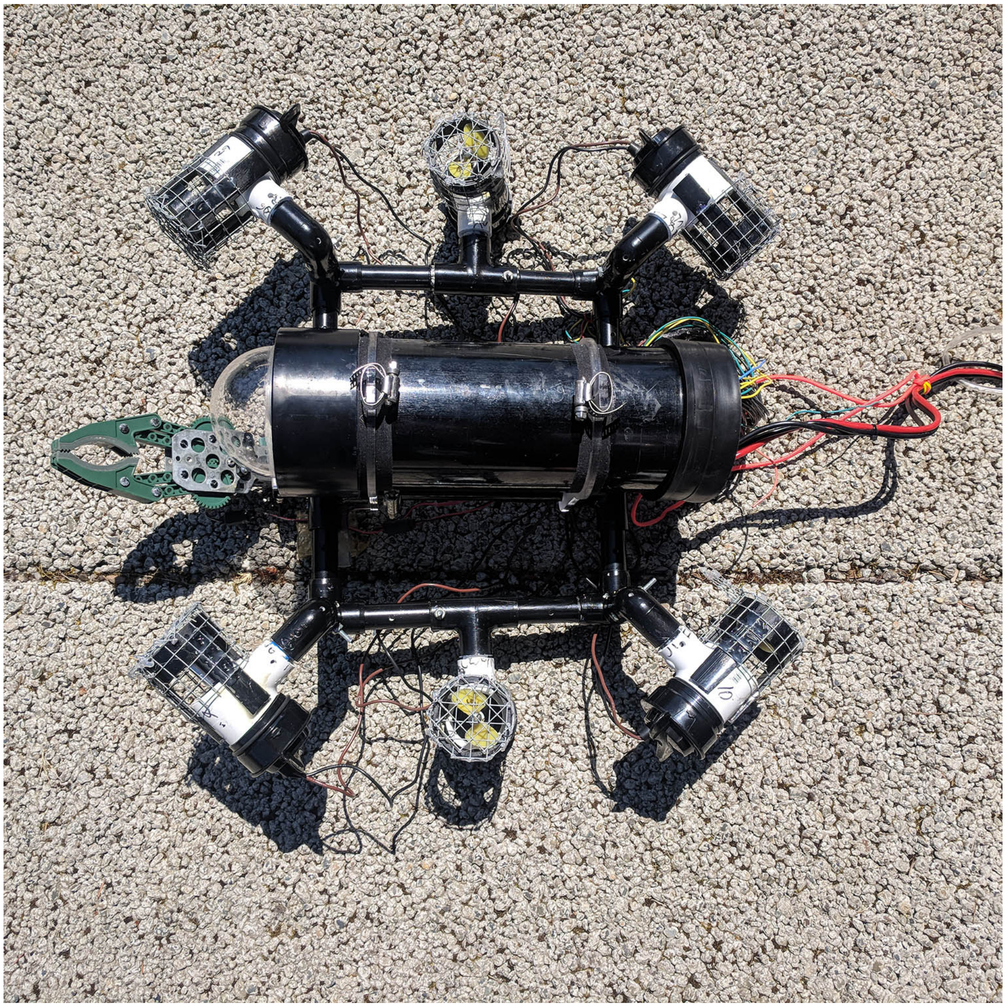


Figure 4: Top-down view of the ROV and its thruster layout. Photo: Silvia Calinov

3.1.2 Motors

In keeping our vehicle low-cost and accessible, our thrusters are operated by motors originally designed for bilge pumps. We have brushed DC motors rated at 500 Gallons per Hour (GPH) and 1000 GPH for the horizontal and vertical thrusters, respectively. Installed on the output shaft of each is a plastic 2-inch-diameter propeller.

Figure 5: A mounted thruster, complete with thruster guard. Photo: Oren Tropen

We decided to use these waterproof bilge pump motors instead of waterproofing our own because of the time, experience, and monetary risk (failure results in a total loss of the motor) involved for a very small reward. While these bilge pump canisters don't have the highest efficiency, they provide more than enough thrust for our application, and are easy and inexpensive to procure.

We custom-built "thrust directors" by cutting holes in the side of short lengths of 2in diameter tube. They aim water flow in the direction the motor is pointing, so that energy isn't dissipated by water moving "sideways."

We performed an experiment to understand how these additions affected thrust output; the results can be seen in Figure 6. Without the thrust directors, the forward thrust was only 4.2N, and the reverse thrust was around 3.4N. After adding the assemblies, a single thruster produces 5.8N of thrust forward and slightly more in reverse as well.

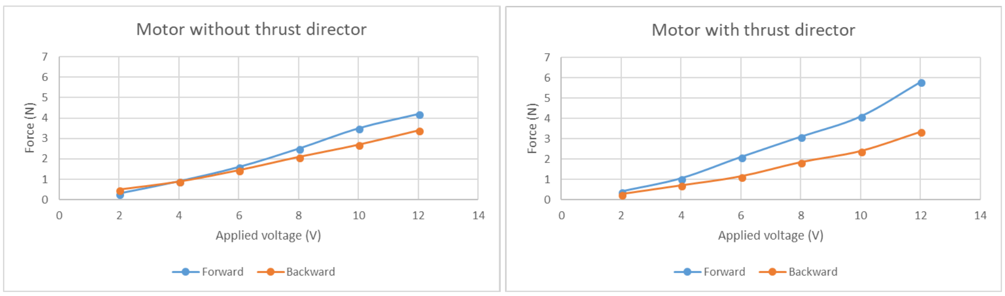


Figure 6: Experimental results from a test to determine the impact of our additions to a bare thruster motor.

3.1.3 Motor Controllers

Our system architecture calls for housing all motor controllers inside a water-tight tube onboard our ROV. By putting the motor controllers close to our motors — as opposed to in a surface control box — we ensure that only a single high-current line runs through the tether.

The DC motors we chose for our thrusters are rated for 12v and can pull up to 2.5A each for the low-power motors and 3.5A for the higher-power motors. This presented a challenge when choosing motor controllers to regulate the voltage applied to each motor. It's relatively easy to get motor controllers rated under 1A, but 2A and above are rarer. The ones that are rated for such currents are typically quite large. Given that a minimum of six motor controllers must fit onboard our vehicle, we needed the most space-efficient controllers available.

	Build a custom H-bridge	**Buy space-efficient 12V 4A+ motor controllers**	**Re-use last year's motor controllers**	**Buy Vex motor controller 29s**
Price	Low-medium	High	Low	Low
Size	Medium	Small	Large	Small
Implementation difficulty	High	Low	Low	Low
Primary challenge	Knowledge of analog circuitry	Expensive	Space and mounting in tube	Not rated for our power needs

Based on our analysis, the Vex motor controllers were the best option: they were inexpensive, small, and easy to integrate into our system. The primary issue was that they are designed for smaller motors operating on LiPo batteries, so they are not rated for 12V nor our 3.5A max currents. To test if they would work for our scenario, we ran a thruster motor off a benchtop testing set-up and validated that they operated for extended periods of time with motor resistance, in stall conditions, and at high voltages. We also tracked their temperature to confirm that the heat they produced would not be a risk to the electronics. The Vex controllers passed all our tests, corroborating others' claims that VEX motor controllers were heavily overbuilt and able to sustain 12v 3.5A loads with a safety margin left over. Therefore, we opted to use them for controlling our thrusters and arm.

3.2 Structure

Our vehicle's structural frame provides a solid mount point for our thrusters and secures the electronics tube to the rest of the ROV. Due to our thruster layout, our superstructure is a PVC rectangle with three-way perpendicular joints on each corner. Front-back struts run down the center of the larger rectangle to provide support for the electronics tube and manipulator arm. Two laser-cut acrylic plates are mounted onto the struts and extend upward to secure the electronics tube in place. Hose clamps tighten the "fingers" of each acrylic plate around the tube to ensure that it stays in place. The plate-based mounting strategy simultaneously improves control over its positioning and reduces the amount of extraneous PVC mounting hardware (compared to using only tubes).

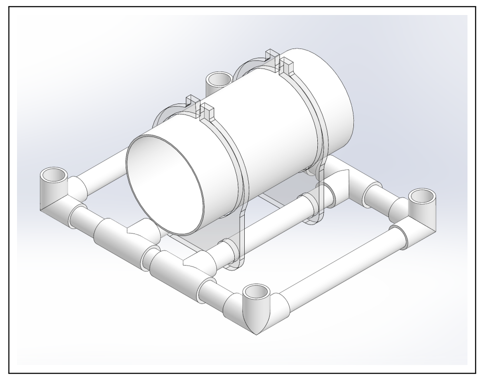


Figure 7: Screenshot of our 3D mechanical Computer-Aided Design (CAD) model. Made in SolidWorks.

While we have access to a laser cutter and other build materials, the use of PVC provides us with an inexpensive, easily interchangeable, and modular frame. All parts are commercially available, which allows us to make changes or repairs with a much quicker turn around time than more heavily customized approaches would. Finally, the PVC joints for the thruster mounts are secured with machine screws rather than glue, allowing us to pivot them inwards for compact storage, and outwards for maximum control due to the extended radius to the thrust vectors.

3.3 Tether communications

Our tether is primarily composed of two connections: a pair of 10-gauge wires for the 12V, <25A supply and a USB 2.0 cable for control system communications and video feed. Simplicity and reliability were important factors when designing our tether and communications system, so we opted for minimum cable count and well-supported protocols whenever possible. Because all motor controllers and voltage regulators are onboard, we only need a single power line from the surface. The USB connection is multiplexed onboard by a USB hub so that we can connect our control system and video feed to the same physical cable. The control system sends messages via a USB serial protocol so that control system software surface-side can interface with it via a virtual COM port.

The USB protocol is susceptible to failure when run over long distances due to noise and interference, even with shielded cables. To eliminate noise, a USB repeater placed half way along our 50-ft tether receives and then re-sends the data at full signal voltage. To ensure competition legality, the power line which normally runs from the surface-side USB connection to the repeater and beyond is cut. We instead supply power to the repeater from the regulators onboard our ROV. The ground line is maintained to provide a stable reference voltage for the surface control device's USB interface.

The final required connection is our main power source. One challenge with this element is the voltage drop due to wire resistance: thinner wires have more resistance, and wire resistance decreases the voltage available at the ROV end. Unfortunately, *thicker* wires are less flexible, inhibiting our ROV's ability to move freely. With 10-gauge wire, the voltage drop along our 100-ft (30.48m) round trip when carrying the full 25A is:

$$\Delta V = (25A) \cdot \left(\frac{3.277\Omega}{km} \cdot 0.03048km \right) = 2.497V$$

With thinner 12-gauge wire, it is instead:

$$\Delta V = (25A) \cdot \left(\frac{5.211\Omega}{km} \cdot 0.03048km \right) = 3.971V$$

A drop of almost four volts is a significant hit to our maximum thrust output, so we opted to use the less-flexible 10-gauge wire. Wire any thicker would be significantly more expensive and inflexible, making gauges lower than 10 unrealistic.

3.4 Onboard Electronics

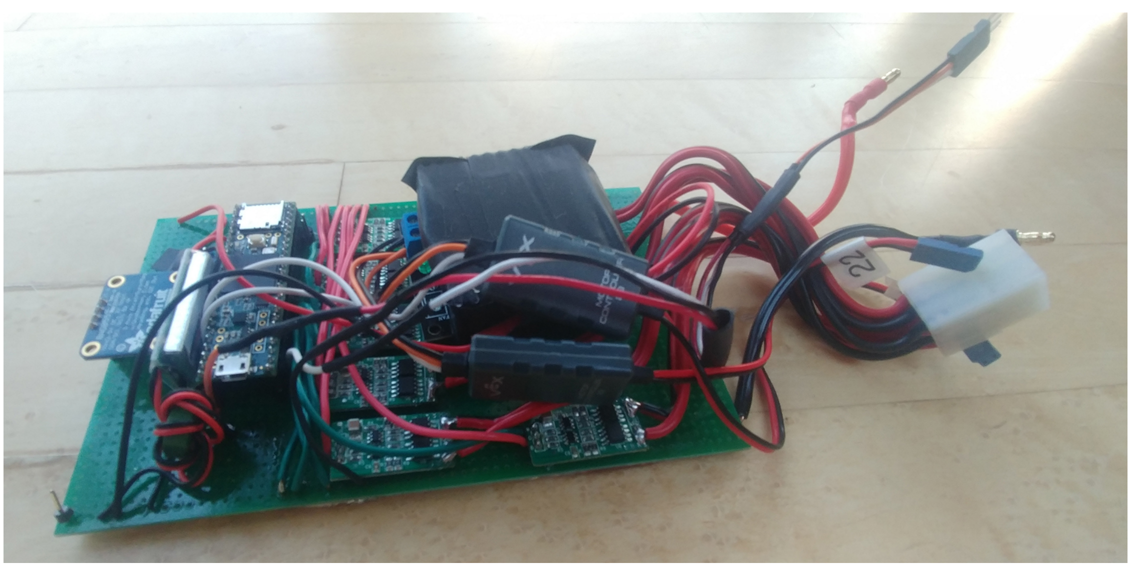


Figure 8: Electronics board when detached from the ROV. Photo: Kaelin Laundry

The control system is operated by a PJRC Electronics Teensy 3.6. The Teensy's 180Hz ARM processor is an order of magnitude more capable than an Arduino or other similar microcontroller. Compiled and deployed with a customized toolchain based on PlatformIO and GCC (GNU Compiler Collection), our onboard software is written in C++11 with access to the full standard library. The software that we run for control system operations is relatively complex, so having a powerful base and an easy to work with software platform is critical. We wouldn't be able to operate the control system as we currently do if using a less-powerful controller such as a standard Arduino. The Teensy has a plethora of digital and analog input/output options for interfacing with external sensors and other devices. The Teensy communicates with an onboard Inertial Measurement Unit (IMU) via the I2C protocol.

To power the Teensy, IMU, and USB repeater, we have an onboard voltage regulator with a maximum output of 1A. It regulates from 12V to 5V. An additional voltage regulator with a higher current throughput capability is configured to run at 8V and is used to operate our manipulator motors, which aren't designed for the full 12V used for our thrusters.

All our onboard electronics are soldered onto a 4in (10.16 cm) by 8in (20.32 cm) protoboard. Components are connected via soldered traces on the surface of the board. Last year, our electronics were individually mounted to an acrylic sheet and then wired together with jumpers. This setup made it difficult to ensure that everything stayed connected and cluttered the space inside the watertight tube. Our current control board eliminates these problems by having almost no cables separate from the board. Nothing can accidentally become disconnected, and it's easier to add individual components to the system as needed.

The board has multiple connectors which allow it to be disconnected from the sealed conduits exiting the back of the tube. One set of connectors is for main power, and a connector with a grid of twelve separate conductors is used for all our thrusters. The ability to remove the board from the main ROV structure and thrusters makes it easy to work on the control system and to add new components.

3.5 Camera

Our primary camera is a bare-board USB-based webcam. Rather than use a classic consumer camera with a plastic casing on the outside, we use a functionally similar device which is mounted to its exposed Printed Circuit Board (PCB). We chose this camera because it has no unnecessary casing to take up space and its PCB has holes for mounting with screws. We replaced the camera lens with a wide-angle fisheye lens so that our operator can see more of the area in front of the vehicle.

In addition to the wide-angle lens, our camera is mounted on a one-axis motorized gimbal. It rotates the camera vertically from straight up to straight down. The operator can control the angle dynamically based on what he/she is doing. It's mounted

Figure 9: Outside view of our mounted camera. Photo: Oren Tropen

roughly in the middle of our 180-degree clear acrylic dome to enable a full range of visibility.

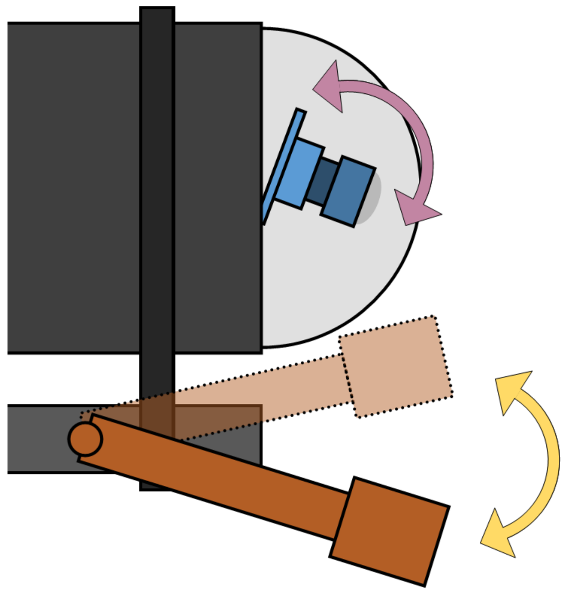


Figure 10: The motion of the camera and gripper. They can be controlled independently but are most useful when moved together. Made in Microsoft Publisher.

3.6 Control Console

Our surface-side operator console is extremely simple.
We use a standard consumer laptop to run our ROV control software and a connected Xbox controller. This simplicity minimizes unnecessary cost, improves ease of transport for the overall system, and increases operator precision. The alternative option was building or buying a frame, putting a microcontroller or mini PC inside, and wiring it to any control interfaces and a display. Doing so would require purchasing each of those components (likely hundreds of dollars at a minimum), transporting the device whenever we wanted to use our ROV, and relying on large amounts of customized driver software to interface with external components. By using a generic laptop and an easily-accessible Xbox controller, we eliminated those challenges entirely.

The USB connection from our tether plugs into the laptop and the game controller for user input. Both are then used by the control software we provide.

3.7 Auxiliary Sensors

3.7.1 Inertial Measurement Unit (IMU)

One concern we had after early testing of our vehicle was the possibility of disorientation while under water. This can happen when manipulating larger objects; if the vehicle is pulled

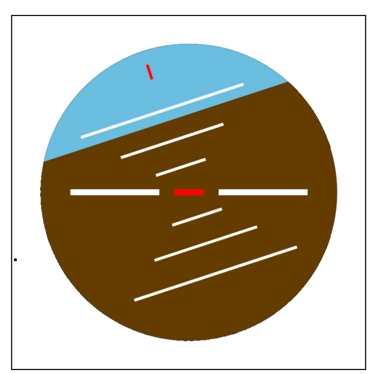


Figure 11: Screenshot of our artificial horizon.

in an unexpected way, it might end up facing a pool wall or floor, causing the operator to lose track of the direction they're facing. Similarly, when attempting to pick up or carry an item, the vehicle sometimes tilts forward; it can be difficult to recognize when it's tilting and what must be done to move in the intended direction.

The Inertial Measurement Unit is a sensor which combines a gyroscope, accelerometer and magnetometer to produce linear accelerations in three dimensions and absolute orientation in roll, pitch, and yaw. We only use the orientation information. To aid our understanding of how the vehicle is tilting, we render an aviation-style attitude indicator (or "artificial horizon") on our operator interface display. To give the operator an understanding of the direction they are facing, we display a compass-like gauge with a known heading marked as a reference.

3.7.2 Leak Sensor

Water exposure poses a danger to the electronics housed on our ROV. Chlorinated pool water and saline ocean water are particularly damaging; chlorine corrodes metal elements, and salt (a conductor) can short out sensitive devices. Putting our electronics in a submerged tube places our vehicle's heart at risk. To mitigate the risk of both small leaks and large breaches, we installed a conduction-based water sensor below the main electronics board. If water enters the compartment, it will be the first electronic item affected. If the sensor detects water, a warning appears on our operator interface to alert the operator and surface crew.

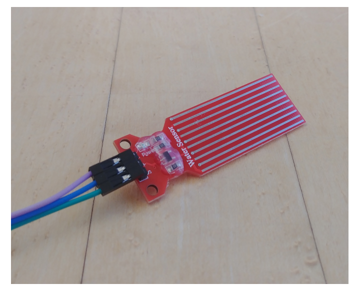


Figure 12: Picture of our water sensor, including custom sealant for the regulation electronics. Photo: Kaelin Laundry

3.8 Manipulator

Our manipulator is comprised of a VEX Robotics Claw with a 100 RPM electric gear motor 393, with an external torque ratio of 1:3. This structure is mounted on a pivot bracket with another identical motor geared for a torque ratio of 1:3. To waterproof the motors, we unscrewed the cases and then coated the internal circuit board in silicon and the gears in synthetic grease. After reassembling the cases, we sealed the joints in a plastic case using PL Premium construction adhesive, being careful to maintain a seal around the wire entry point. The final step is to press a greased O-ring onto the output shaft. We submerged the motors for 30 minutes at a depth of 4 meters to test the waterproofing. After several days, there was no sign of corrosion and the motors remained fully functional. Our integrated design is original; however, we utilized a commercially available claw kit for its powerful, secure, and optimally shaped claw. Waterproofing our motors cost about 25% less than purchasing waterproofed servos, making our equivalent to the cost of laser cutting an acrylic claw. Additionally, an acrylic claw would have required several hours of CAD work. Given the time constraints of the competition, using a claw kit was more realistic. While designing our manipulator support structure, we realized that pitch control would be beneficial for manipulating props at various angles and moving them within our field of vision, which drove us to add the rotational motor.

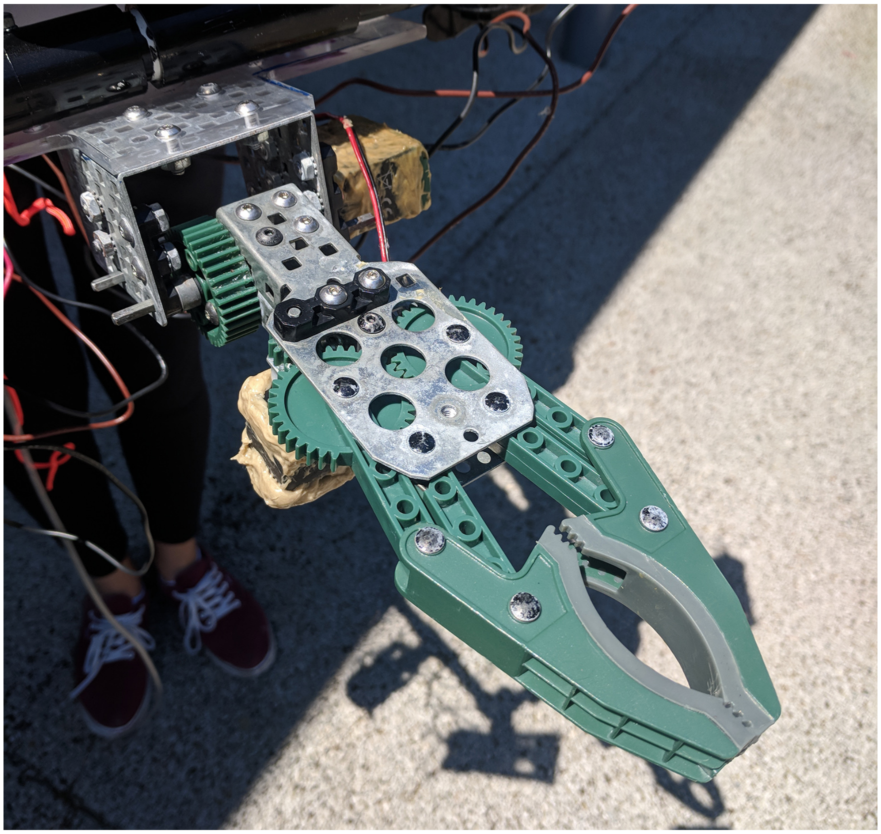


Figure 13: The gripper mounted to the front of our ROV. Photo: Oren Tropen

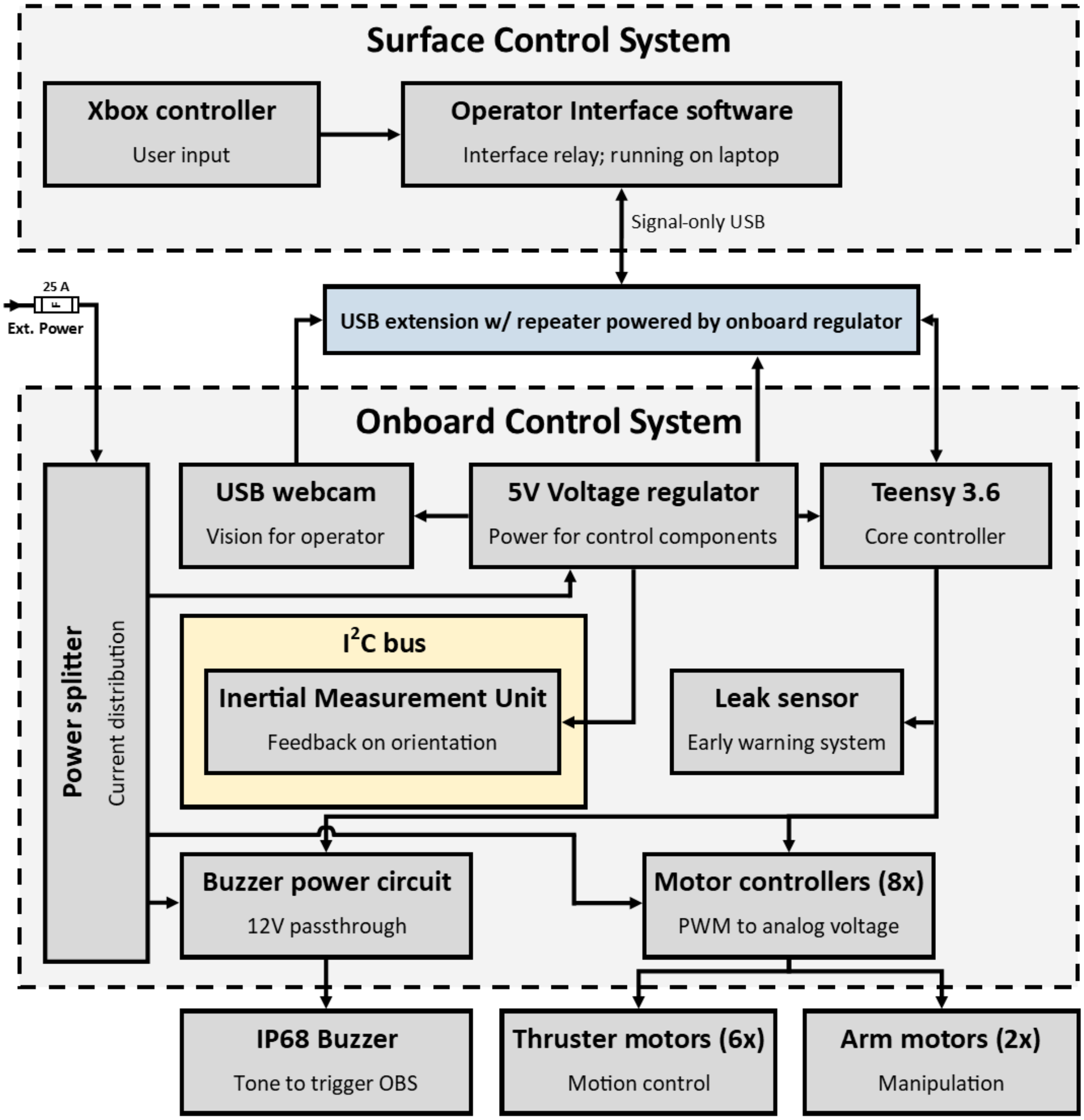
3.9 Component Sourcing: Build, Buy, New, Used

Our driving philosophy was centered around building as much as we could ourselves rather than purchasing pre-designed, pre-fabricated parts. Our ROV used no components from commercial ROV kits or companies. This enables more customization and dramatically reduces cost, which are both helpful for our performance as a company. With that in mind, we purchased bilge pump motors and fashioned our own guards and mounting assemblies. We similarly purchased off-the-shelf components which we then custom assembled for our gripper system. The frame was entirely custom (assembled with PVC pipe).

Some of our ROV's components were decided to be of the same type as last year, so we were able to re-use a subset of last year's purchases. In total, we re-used the power cabling from our tether, the Inertial Measurement Unit (IMU), four of our six thruster motors, and some of the parts for the gripper. These saved on recurring costs for this year.

4 System Interconnection Diagrams

4.1 Electrical



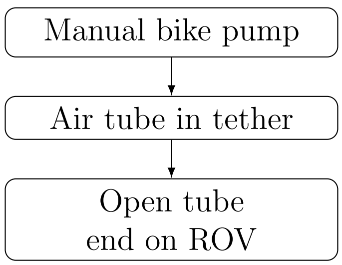
4.1.1 Fuse Calculation

Quantity	Description	Current per (A)	Current total (A)
2	High-power vertical thruster	3.5	7
4	Standard lateral thruster	2.5	10
2	Arm motor	0.4	0.8
			17.8 total

As shown above, nominal maximum current is $17.8A$. To decide on a fuse value, we apply a 150% safety factor: $I_{fuse} = 17.8A \cdot 1.5 = 26.7A$. For safety reasons, the maximum allowed fuse is $25A$; because our theoretical consumption cap is slightly over that, we use the maximum-allowed fuse value of $25A$.

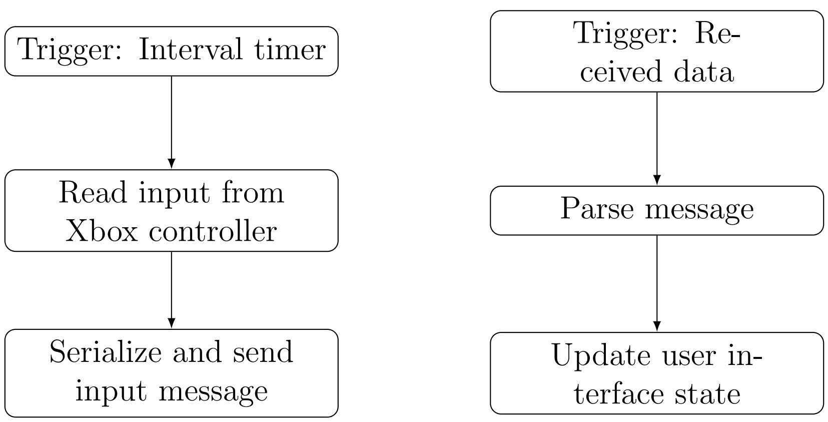
4.2 Pneumatic

We use only low-pressure manual pneumatic systems. The air hose through our tether is open on the ROV end.

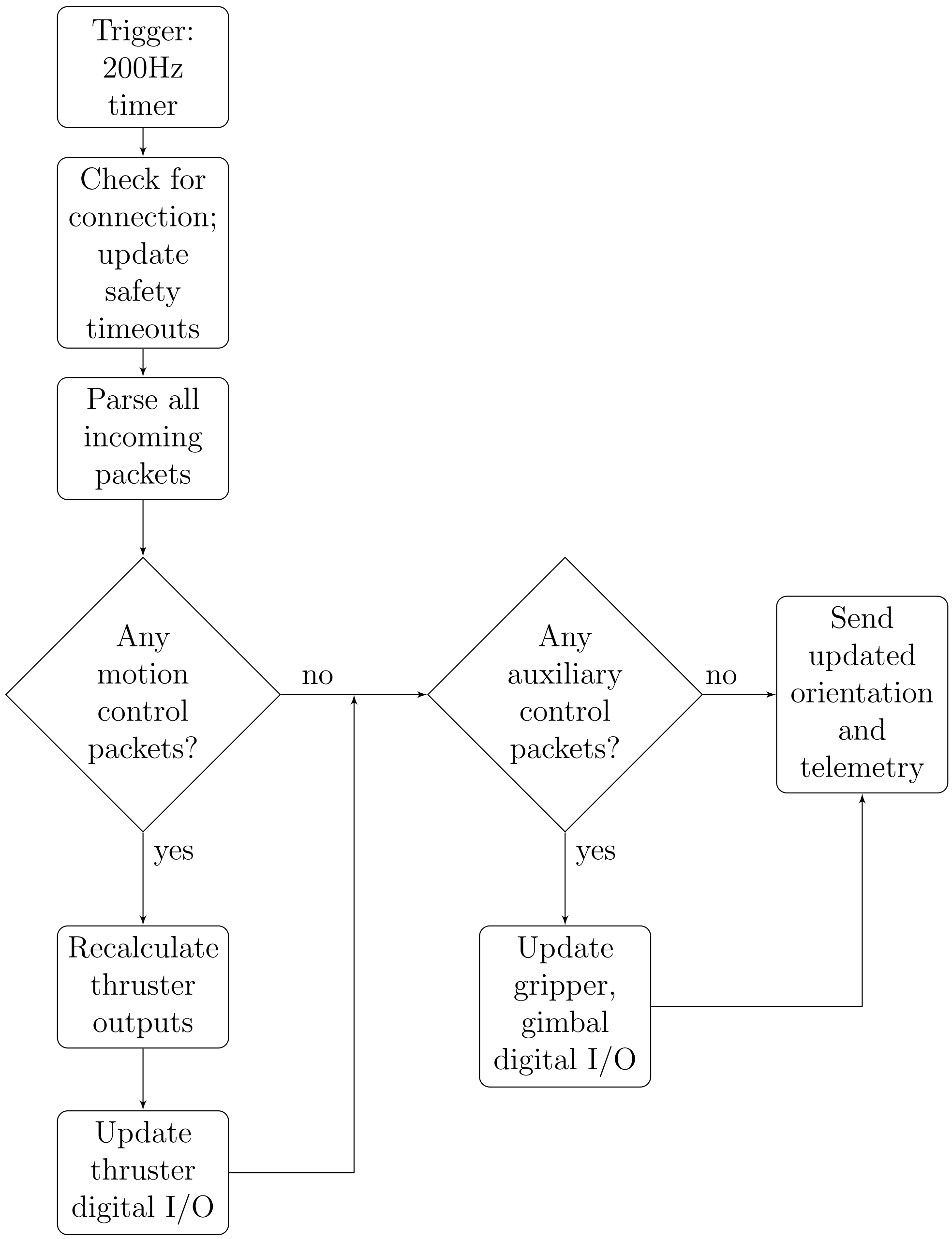


4.3 Software

4.3.1 Surface operator interface



4.3.2 Onboard control system



5 Safety

Throughout the construction and operation of our ROV, safety has been our highest priority. By employing safety protocols for using tools and requiring adult oversight during meetings, we work efficiently and ensure the safety of our team members. We brief all members on proper operation of power tools before they begin using them. When necessary, we require safety goggles, gloves, masks, and close-toed shoes in the shop. We maintained proper ventilation throughout the process and took the extra precaution of using PVC cement outdoors. To prevent accidents during fabrication, we cleaned all floors and organized all surfaces after every meeting. While testing, running on the pool deck was prohibited and all members (except the tether handler) worked away from the pool edge. In addition to safety precautions for fabrication and testing, we developed many safety features onboard our ROV to ensure the safety of vehicle operators.

To preclude harm to the ROV, user, and environment, we incorporated many safety features into our design. Crosshatched wire prop guards prevent stray fingers and debris from coming into contact with the propellers. Additionally, we clipped and melted all zip ties on the tether and ROV to prevent them from scratching or cutting the tether management team. All wires and connections outside of the ROV are potted and shrink wrapped to avoid shorting. We implemented a master enable/disable switch into our program, allowing the pilot to disable the ROV quickly during a malfunction. The initial condition is disabled, ensuring the ROV cannot run until the pilot enables it. The pressure-tested electronics tube and dome resist shattering and high pressures. We greased our manipulator servos, installed new O-rings where the shaft meets the body, and coated all seams on the servo frame in epoxy. Because our motors are repurposed bilge pump motors, they are already waterproofed. We use an O-ring friction fit between the end cap and tube as well as custom wire penetrators to prevent leaks from the end cap.

5.1 Safety Checklist for Workshop

1. Appropriate attire and safety goggles
2. Gloves and clean masks as needed
3. Open garage door for ventilation
4. No horseplay near bench
5. Power tool briefing before operation
6. Warning before power tool operation
7. Use proper clamps as necessary

5.2 Safety Checklist for Operation

1. Safety goggles & close toed shoes
2. Check integrity of prop guards, wire pots, and all wire connections
3. Check tether strain relief integrity
4. Uncoil tether
5. Check propeller angles
6. Check end cap seal

7. Check fuse
8. Ready up before power on
9. Enable command once in the water

6 Critical Analysis/Reflection

6.1 Testing and Troubleshooting

Our ROV is designed to salvage wreckage, operate scientific tools, and install tidal turbines quickly and safely. Our arm, located in front of the camera, moves roughly 120 degrees up and down. The gripper opens and closes, allowing us to manipulate objects such as the eelgrass, propeller array, and cable connector. Our control system allows for fine-motion control, firing short bursts of the motors for small adjustments. Fine-motion control is critical for tasks that require high degrees of precision, such as placing the cable connector into the OBS and placing the turbine in the turbine base. We included stronger vertical thrusters because many tasks, including eelgrass and lift bag recovery, require the ROV to return to the surface. By minimizing the time spent travelling to and from the surface, we create more time for the ROV to complete other tasks.

While building our ROV, we encountered glitches in both the electronics and the physical structure. When we encountered an electronic issue, we followed a general procedure designed to prevent injuries to our team members and damage to our ROV. First, we removed the ROV from the water. We ran the software in small, independent steps to determine if each system was functional. Once we ensured that the individual components worked, we combined the systems and tested their interactions. After checking the interactions, we returned the electronics to the ROV. Finally, we confirmed the seal after briefly submerging the ROV and continued underwater testing.

To preempt major issues with our physical structure, we spent several months discussing various designs for our ROV. We eventually decided on a PVC rectangle superstructure with three-way perpendicular joints on each corner. We utilize two vertical thrusters on either side of the electronics tube, in addition to four lateral ones which can be angled to enable pitch. Front-back struts run down the center of the larger rectangle to provide support for the electronics tube and manipulator arm. Two laser-cut acrylic plates are mounted onto the struts and extend upward to secure the electronics tube in place. Hose clamps tighten the "fingers" of each acrylic plate around the tube to ensure that it stays in place. Most of the structure is held together by screws instead of glue, so we can replace parts as necessary. Our new design addresses the flaws we found in our old ROV. Last year, we positioned the two vertical thrusters on the front and back of our ROV to enable pitch. However, this placed the thrusters under the electronics tube, making them extremely inefficient. This year, the vertical thrusters are located on either side of the electronics tube, which avoids interference with the electronics tube and enables roll. Additionally, our previous design forced us to waste time travelling slowly to and from the surface. To solve this issue, we increased the strength of our vertical motors. Another significant change was adding acrylic plates to secure the electronics tube more effectively.

As with any design, testing revealed unforeseen consequences we had to address. Originally, we used a very fine wire mesh for our propeller guards. We quickly realized that this mesh blocked water flow through the propeller, significantly reducing the speed of our ROV. We decided to increase the gap size of the wire mesh; however, the only accessible mesh was too large to meet safety standards. We solved this dilemma by crosshatching two layers to increase the gaps without compromising safety.

6.2 Challenges

Our motors' raw outputs are calculated by dynamically solving a system of algebraic equations as pilot input changes. Last year, we rotated our four lateral thrusters to enable both pitch and roll. This thruster configuration allowed for six degrees of freedom, and the matrix solved successfully. This year, we decided not to angle the lateral thrusters, eliminating pitch in order to maximize forward speed. However, this also eliminates a degree of freedom and creates an infinite number of solutions to the matrix system, causing unexpected results. It took multiple rounds of iteration to settle on our current control software implementation, which combines this algebraic scheme with ”bare” trigonometric calculations.

A less technical challenge we encountered at the start of the year was member truancy. Due to our busy and often conflicting schedules, we rarely had a meeting where all our members were present. Low attendance led to disorganization and missed deadlines. For instance, the team member originally assigned to wiring was unable to attend most meetings. We quickly realized that waiting indefinitely for that member was not an effective use of time. Absent members started sending memos detailing what needed to get done, and members who lacked jobs started picking up the slack. By being more flexible in our roles and improving our communication, we greatly increased our cohesiveness and efficiency. Likewise, some members initially lacked jobs for long stretches of time. We started assigning non-urgent tasks to these members, greatly increasing our productivity and simultaneously giving them an opportunity to learn and take on more time-sensitive work items.

6.3 Lessons Learned

This year, we added a gimbal to our camera to increase our field of view. The gimbal rotates up and down, allowing the pilot to keep the arm in sight without using pitch. (This was a major factor in our decision to disable pitch for our default competition configuration.) During implementation, we discovered that the gimbal didn't function as expected. When both our troubleshooting procedure and independent modifications of the servo failed to solve the problem, we began exploring other possible causes. We checked for everything from stripped gears to errors in the code. Eventually, we looked to validating the fundamentals of our circuit board and realized we accidentally had wired the servo motors to the 12V rail rather than the expected 5V. We rewired the gimbal before any damage occurred. Following that mistake, we were more careful when verifying specifications and adding wiring.

Our team attended our first MATE ROV competition last year. We discovered that despite all the time we spent building our ROV, there were some aspects of the competition we were unprepared for. We didn't have a solid setup routine for the product demonstration, so we rushed, got a wire stuck in the seal, and ended up flooding our entire electronics compartment. While we succeeded in salvaging it, we more importantly learned the value of remaining calm under pressure and creating a checklist to avoid easily preventable mistakes. Furthermore, we significantly underestimated the importance of marketing to the competition and put very little effort into it. Our marketing display scored the lowest of any team, significantly affecting how we placed in the competition. This year, we dedicated more time to marketing our vehicle and community outreach, which greatly improved our overall score at the competition.

7 Budget

The Infinite Monkey Gang originally estimated a total cost of $915 including design, construction, transportation, and presentation of the ROV. Including the OBS and Lift Bag, we estimated that new materials and tools would cost $445. The remaining $470 of our budget covered other costs, including registration for the competition, travel to the competition, and construction of practice props. As we are an independent team, we did not receive any contributions from local organizations or schools. Our organization's policy is to purchase any materials we need, record the costs of those materials, compile a list of the amount spent by each member, and redistribute the cost evenly after the final competition. Team members who initially payed less than average will reimburse the members who initially payed more than average (see Figure 14).

Funding

Team Members	Funds Provided	Average Cost/Person	$ needed to get equal funding		# People
Kevin	$ 129.77	$ 113.54	$ 16.23		7
Oren	$ 84.35	$ 113.54	$ (29.19)		
Silvia	$ 82.18	$ 113.54	$ (31.36)		
Kaelin	$ 226.82	$ 113.54	$ 113.28		
Gabe	$ 70.14	$ 113.54	$ (43.40)		
Kohya	$ 112.74	$ 113.54	$ (0.80)		
Natali	$ 88.76	$ 113.54	$ (24.78)		
			Need to pay = -		
			Need to be paid = +		

Figure 14: Funding

Another cost included in our budget is travel expenses to the competition facilities. As both the regional and international competitions are located nearby in Federal Way, we opted against staying the night in a hotel near the facility. Since the competition is nearby, driving was the most cost-effective option. Using Google Maps, we approximated the distance between Tesla STEM High School, a central location for all team members, and the competition facility at 40 miles. To safely transport our team and our competition materials to the competition, we required three cars. We divided the total mileage driven per car (240 miles) by the average fuel economy of the three cars on the highway (30 miles per gallon) to approximate the fuel consumption (8 gallons) for driving to and from the regional competition. To calculate the cost of driving to the competition we multiplied the fuel consumption by the average local price per gallon of gasoline. The regional competition cost us approximately $30 in gasoline (See Figure 15). After we learned we were continuing to the international competition, we looked for ways to lower our travel expenses. The most cost-effective solution is driving three cars to the competition each day, as staying in a hotel for three nights is far more expensive. Using the above method for calculating gasoline expenses, we estimated the total travel cost at $90 of gasoline for three cars driving 6 trips each. Combined, our total travel expenses for the regional and international competitions are approximately $120.

		Internal	Environmental Manipulation									Travel		
	Structure	Control	Propulsion	Manipulation	Camera	Tether	Tools	OBS	Lift Bag	Misc	Props	Regional	International	Registration
Cost Actual	$ 24.05	$ 104.17	$ 72.82	$ 14.99	$ -	$ 20.00	$ 25.02	$ 68.70	$ 12.00	$ 49.82	$ 174.39	$ 28.80		$ 200.00
Cost Budge	$ 70.00	$ 125.00	$ 100.00	$ 20.00	$ 20.00	$ 30.00	$ 20.00	$ 30.00	$ 10.00	$ 20.00	$ 150.00	$ 30.00	$ 90.00	$ 200.00
Remaining	$ 45.95	$ 20.83	$ 27.18	$ 5.01	$ 20.00	$ 10.00	$ (5.02)	$ (38.70)	$ (2.00)	$ (29.82)	$ (24.39)	$ 1.20	$ 90.00	$ -

Figure 15: Budget

7.1 Project Costs

Total Projected Costs: $915.00

Total Actual Costs: $794.76

Total ROV Projected Costs (Includes Lift Bag & OBS): $445.00

New ROV Materials Costs (Includes Lift Bag & OBS): $236.03

All ROV Materials Costs (Includes Donated/Reused/Pre-Owned Materials): $768.60

Travel Budget: $120.00

Remaining Funds (No International Competition): $120.24

Environmental Manipulation (Propulsion/Manipulator/Camera)				
Item	Quantity	Cost/Unit	Notes	Bought/Donated/Reused/Pre-Owned
Johnson Pumps of America Marine Pump Cartridge 1000 GPH	2	$ 31.67	Vertical Thrusters	Bought
Johnson Pumps of America Marine Pump Cartridge 500 GPH	4	$ 21.92	Horizontal Thrusters	Reused
VEX Claw	1	$ 19.99	Manipulator	Reused
VEX EDR 393 Motor	2	$ 14.99	Moving Manipulator	1- Reused 1 - Bought
Fisheye Lens	1	$ 10.00	Wider Viewing Angle	Reused
USB Circuit Board Camera	1	$ 15.00	Vision from ROV	Reused
2 Axis Gimbal	1	$ 10.00	Camera Movement	Pre-Owned
1/4 Inch Wire Mesh	1	$ 9.48	Motor Guards Version 2 Material	Bought
1/8 Inch Wire Mesh	1	$ 12.00	Motor Guards Version 1 Material	Pre-Owned

Internal Control System				
Item	Quantity	Cost/Unit	Notes	Bought/Donated/Reused/Pre-Owned
Teensy Microcontroller 3.6	1	$ 24.25	Onboard Controller	Bought
Vex Motor Controller 29	8	$ 9.99	Controlling Motors	Bought
Adafruit BNO055 IMU	1	$ 34.95		Reused
5V UBEC	1	$ 5.00		Reused
Voltage regulator	1	$ 18.86		Reused

Structure				
Item	Quantity	Cost/Unit	Notes	Bought/Donated/Reused/Pre-Owned
PVC (Joints)	N/A	$ 9.91	Constructing Structure	Bought
ABS Tube 4" x 12"	1	$ 5.00	Electronics Tube & Buoyancy	Reused
Acrylic Dome 4"	1	$ 18.00	Camera Viewpoint	Reused
4" Rubber End Cap	1	$ 12.00	Electronics Tube Seal	Reused
PVC (Pipe)	N/A	$ 5.20	Structure of ROV	Bought
PVC 1/2 inch to Motor Size	6	$ 6.00	Motor Mounts	Reused
Acrylic Sheet 1/8 Inch Thickness	1	$ 9.00	Buoyancy Tube Mount & Manipulator Mount	Reused
Stainless Steel Hose Clamp 4"	1	$ 2.00	Apply Pressure to Flexible End Cap	Reused
Stainless Steel Hose Clamp 1/2"	6	$ 1.49	Attaching Tube to Acrylic Plate & Plate to ROV	Bought
Stainless Steel Bars	2	$ 15.00	Ballast	Pre-Owned
Misc Screws	N/A	$ 5.00	Attaching Acrylic Manipulator Mount to Frame & Pinning Motors to Frame	Pre-Owned

Tether				
Item	Quantity	Cost/Unit	Notes	Bought/Donated/Reused/Pre-Owned
USB Cable with Repeater 50 Foot	1	$ 20.00	Camera & Control Signal	Bought
10 Gauge Wire 50 Foot	2	$ 25.00	Power & Ground Cables	Reused
Pool Noodle	4	$ 2.60	Buoyancy	Reused

Lift Bag				
Item	Quantity	Cost/Unit	Notes	Bought/Donated/Reused/Pre-Owned
Trash Bag	1	$ 0.50	Lifting Surface	Reused
Misc PVC Lengths and Joints	N/A	$ 6.00	Structure for Lift Bag	Bought
50' Air Tube	1	$ 16.00	Providing Air for Lift Bag	Reused
Double Action Air Pump	1	$ 15.00	Pumping air into lift bag	Reused
Hook	1	$ 6.00	Attachment point to Prop	Bought

OBS				
Item	Quantity	Cost/Unit	Notes	Bought/Donated/Reused/Pre-Owned
9V Battery Holder	1	$ 2.95	Holding Power for OBS	Bought
9V Battery Holder	1	$ 1.50	Power OBS	Reused
DC Barrel Jack Adapter	2	$ 1.90		Bought
Misc resistors	1	$ 7.95		Bought
Piezo Mic and Amp	2	$ 5.90	Detecting Acoustic Release	Bought
H-Bridge	1	$ 3.00	Amplifying Buzzer	Reused
Misc Capacitors	N/A	$ 4.00		Reused
Servo Motor	1	$ 10.00	Release from tether	Bought
Teensy 3.6 Microcontroller	1	$ 24.25	Microcontroller	Bought
Electret Microphone Amplifier	1	$ 7.95	Amplify Microphone	Bought

Props				
Item	Quantity	Cost/Unit	Notes	Bought/Donated/Reused/Pre-Owned
Misc Art Supplies	N/A	$ 18.65	Corrugaded Plastic/Foam Strips	Bought
Bricks	6	$ 0.50		Pre-Owned
PVC Joints/Tube/Caps/Reducers (All Sizes)	N/A	$ 109.45	Various Props	Bought
Rebar 2 foot x 1/2 in	1	$ 2.10	Prop Weight	Bought
ABS Cap/Pipe/Adapter	N/A	$ 16.66		Bought
Paracord	1	$ 5.14	Pulling Props out of Water	Bought
Bullnose Propellers	1	$ 2.49	Turbine Prop	Bought
Door Hinges	2	$ 2.86		Bought
Washer 1/4 Inch	4	$ 0.12		Bought
Chain (10 ft)	1	$ 5.30		Bought
U-Bolt 1 1/2 Inch	2	$ 4.20		Bought

Tools				
Item	Quantity	Cost/Unit	Notes	Bought/Donated/Reused/Pre-Owned
2 Part 5 Minute Epoxy	1	$ 18.45	Waterproofing	Bought
PVC Cement	1	$ 6.57	Attaching PVC Together	Bought
Hand Driill	1	$ 25.00	Drilling Holes	Pre-Owned
Screwdrivers	N/A	$ 15.00		Pre-Owned
Allen Wrench	N/A	$ 10.00	Tightening Arm Screws	Pre-Owned

Misc				
Item	Quantity	Cost/Unit	Notes	Bought/Donated/Reused/Pre-Owned
12 Volt 25 Amp Power Supply	1	$ 43.55	Powering ROV on Land	Reused
Misc Zip Ties	N/A	$ 20.00	Cable Management/Ties	Reused
Hydraulics & Fluid Power Quiz	1	$ 15.00	Enable Fluid Power	Bought
X-Box One Controller	1	$ 35.00		Pre-Owned
Food	N/A	$ 34.82	Birthday Celebration & Snacks	Bought

Travel						
	Regional					
	Miles to Driv	Approx MPG	Approx Gallons Used	AVG Price/Gallon (5/17)	Cost of Driving to Regional Competition	Miles to KCAC From STEM
1 Car 2 ways	80	30	2.7	$ 3.60	$ 9.72	40
2 Cars 2 Way	160	30	5.4	$ 3.60	$ 19.44	
3 Cars 2 ways	240	30	8	$ 3.60	$ 28.80	
						Total Cost Travel (1 car)
						$ 38.52
						Total Cost Travel (2 car)
	International					$ 77.04
	Miles to Driv	Approx MPG	Approx Gallons Used	AVG Price/Gallon (5/17)	Cost of Driving to International Competition	Total Cost Travel (3 car)
1 Car 6 ways	240	30	8	$ 3.60	$ 28.80	$ 115.20
2 Cars 6 Way	480	30	16	$ 3.60	$ 57.60	
3 Cars 6 ways	720	30	24	$ 3.60	$ 86.40	

8 References and Acknowledgements

8.1 References

Steven, W. M., & Harry, B., & Vickie, J., (2010). Underwater Robotics: Science, Design and Fabrication.
Other information was gathered from experienced mentors and supporters.

8.2 Acknowledgements

MATE: The MATE program

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