# PROVEN ROBOTICS

PURDUE ROV

## 2018 Technical Documentation

Jet City: Aircraft, Earthquakes, and Energy

## PURDUE UNIVERSITY

West Lafayette, IN USA

## ROV *CETACEAN*

Carries Equipment To Access Conductors, Earthquakes, and Aircraft Nautically

# COMPANY MEMBERS

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| Ryan McBee | Chief Operating Officer |
| Carolyn Lewelling | Chief Financial Officer/Power Head |
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# I. INTRODUCTION

## Abstract

Proven Robotics has developed a Remotely Operated underwater Vehicle (ROV) that satisfies the Applied Physics Laboratory's request. The vehicle can complete a wide range of tasks in both fresh and saltwater. These tasks include locating wreckage and returning parts to the surface, installing a seismometer, and installing a tidal turbine and scientific instrumentation. The 50-person company worked tirelessly throughout the year to produce ROV *Cetacean*, one of the smallest, lightest, and most technologically advanced ROVs in company history. This ROV is designed, built, and tested in-house to ensure it can complete every mission.

Proven Robotics is broken down into four departments: Mechanical, Electrical, Software, and Administrative. Each focuses on their respective areas within the company. Cross disciplinary project groups were utilized to focus on separate vehicle system, to improve communication between departments, and to coordinate over 7,000 work hours put into the ROV. Safety, scheduling, and budget constraints were taken into account throughout the year. Multiple iterations of each mission tool were designed and tested to ensure that each one could successfully complete their task.

Minimizing the size and weight of ROV *Cetacean* was a key design consideration. To do this, the ROV uses a new waterproof electronics enclosure system that significantly reduced the vehicle weight. It also uses custom printed circuit boards (PCBs), a waterjet cut frame, 3D-printed tool pieces, and eight Blue Robotics T200 Thrusters.

The following technical document discusses the design rationale and process used to create ROV *Cetacean*.


*Fig. 1 - Proven Robotics 2018 Team*

# II. Safety

## A. Safety Philosophy

Safety is of the utmost importance at Proven Robotics. Providing a safe work environment not only helps prevent workplace injuries, but also improves employee comfort and productivity. The safety of all employees, bystanders, and equipment is considered whenever an action is taken or a product is used. All employees must be trained before using heavy machinery, chemicals, or heating elements. New employees are mentored by more experienced employees to ensure they are working in a safe manner.

*Fig. 2 - Employees inspecting electronics in the lab*

## B. Safety Standards

Proven Robotics has several safety procedures that everyone must follow when working on ROV *Cetacean*. Personal protective equipment (PPE) is available to every employee in the workspace. This includes eye protection, dust masks, eye wash stations, shower stations, first aid kits, and fire extinguishers. Employees are required to use safety glasses when operating the drill press, the band saw, or the jig saw. Employees are also required to wear a dust mask if working with fiberglass. Proven Robotics' workspace is located on Purdue University's campus, providing safe access to all employees. In the event that an employee must work in another environment with different safety standards, such as an on campus machine shop, the stricter set of safety standards is followed (Ref 8).

*Fig. 3 - Operating the waterjet to cut the frame*

## C. Safety Features

There are several safety features built into ROV *Cetacean*. These include a master fuse on the tether, a strain relief cord for the tether, and smooth rounded frame pieces. Any time the vehicle is deployed, a safety checklist (Appendix A) is used to ensure all employees and bystanders are kept safe when the vehicle is running, and that the vehicle is kept safe.

Another safety feature on the ROV is protective shrouds on all thrusters. The 3D-printed shrouds are produced in-house and use a series of rings to block objects larger than 12.5 mm from entering the thrusters during operation. The area obstructed by the bars needed to be reduced as much as possible to minimize disruption to thruster flow while still providing safe coverage. The front shrouds were connected to the thrusters using snap-fit arms while the back shrouds were clamped to the thruster using the back nose cone.

*Fig. 4 - Shroud on the back of a Blue Robotics T200 thruster*

The ROV's software gives the pilot information on its systems so they can determine whether the vehicle is working properly before it is placed in the water. Once it has been determined that the ROV is working properly, the pilot instructs two poolside workers to deploy the ROV. Information about the thrusters and other systems is continuously updated on the pilot's screen, and if anything become unsafe, the pilot can quickly shut down the ROV. Any unexpected loss of communication will also shut down the ROV, which puts it into a safe mode with no moving parts.

# III. Mechanical Design Rationale

## A. Mechanical Overview

The mechanical components of ROV *Cetacean* were designed around the required mission tools and a new electronics enclosure system. Initial sketches were made for discussion before being fleshed out and finalized via SolidWorks models. Once computer-aided design (CAD) models were completed, a comprehensive design review was performed by the entire company to identify mistakes and avoid potential problems. Each design was iterated using the feedback from the review. Initial prototypes were then constructed using foam and 3D-printed parts to better visualize and test components that were difficult to machine. Different machining methods were used to most effectively make all the ROV parts. After completion, every watertight enclosure was repeatedly tested for at least 20 minutes at a minimum pressure of 85 kPa (8.66 m) using a vacuum pump or Proven Robotics' custom pressure testing vessel. For safety and reliability reasons, these test specifications exceed the expected mission time and depth. All mechanical systems were newly designed and built by Proven Robotics to ensure that the optimal solution was created. The resulting vehicle and tether has a mass of 14.69 kg and dimensions of 42.82 cm x 36.61 cm x 38.10 cm; therefore, both the size and weight are well within the smallest MATE requirements.

## B. Frame

ROV *Cetacean*'s frame consists of two main vertical side plates connected by two vertical front-facing plates and a horizontal ballast plate. The frame is joined by hybrid mortise and tenon joints firmly secured with bolts. The mortise and tenon joints reduce shear load on the bolts and perform well under tensile load. Similar to ROV *Cephalopod*, the company's previous ROV, the central axis of the vertical thrusters are mounted in line with the plane of the frame's side plates, which reduced outer dimensions while ensuring enough internal space.

The company considered various materials for the frame in order to reduce overall weight including plastics such as high-density polyethylene (HDPE) and polycarbonate and metals such as 6061-T6 aluminum and 7075-T6 aluminum. Calculations demonstrated that aluminum offered a higher strength-to-weight ratio, even when considering the need for additional buoyant material. While 7075-T6 would allow for even lower mass for the same strength, the company chose 6061-T6 to reduce cost since it received a donation of material from an industry sponsor.

To further reduce weight, material was removed from the aluminum plates, keeping only the sections required for structural integrity. Overall, 84.72% of material was removed. Finite element analysis (FEA) was used to validate the structural integrity of the ROV. The final design was waterjet cut by the company and anodized for a professional and anti-corrosive finish. The resulting frame has a mass of 1.78 kg. This lightweight frame helps minimize the amount of foam needed to keep the ROV neutrally buoyant, which results in a smaller overall mass.

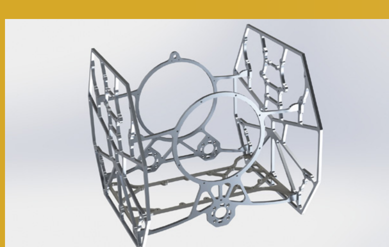


*Fig. 5 - Complete frame rendering*

*Fig. 6 - One of the two vertical plates*

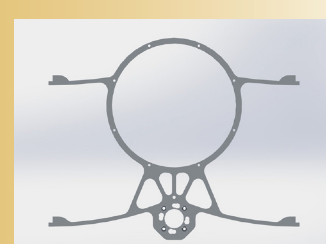


*Fig. 7 - One of the two horizontal plates*

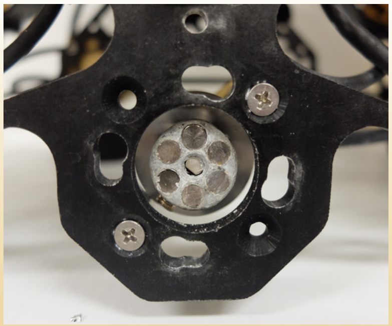


*Fig. 8 - Quick-release mount*

This year's frame includes a quick-release mount. It consists of four keyhole slots in a circular pattern cut into the frame. Button-head bolts with standoffs fit into these slots, locking into place with an eighth-turn and a quick-release pin. This mount allows for tools to be quickly and easily replaced if necessary, such as if a tool is damaged or tools need to be switched during vehicle operation.

## C. Integrated Electronics Tube

In previous years, in order to reduce the effects of electromagnetic noise and to ensure sufficient cooling, Proven Robotics has used two separate electronics enclosures: a polycarbonate tube for the control electronics and a box made principally of aluminum for the power system. This year, the enclosures were combined into the Integrated Electronics Tube (IET), with the control electronics sealed in a forward dome, the power system in an aft tube, and an octagonal Tunnel Coupling to divide them. This coupling, like the separate housings, blocks noise, dissipates heat, and has independent seals to limit the consequences of a leak – all with a significantly reduced weight. Five bundles of sealed wires pass through the coupling to electrically connect the Electronics Dome and Power Tube, while fifteen 16-mm Binder electrical connectors protrude from the sides of the Tunnel Coupling connect the IET to the rest of the ROV. The Electronics Dome holds the Raspberry Pi, the Backplane Shield Board, and the ROV's primary camera while the Power Tube holds the ESC Board, Power Bricks Boards, and Power Distribution Board.

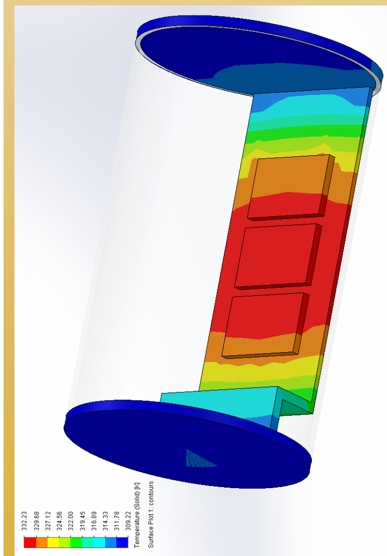


*Fig. 9 - SolidWorks thermal Simulation*

The Tunnel Coupling was machined out of a 20.32-cm diameter 6061 aluminum round stock using a combination of a computer numerical control (CNC) active-tooling lathe, which allowed the easy milling and drilling of the octagon, and a 3-axis CNC mill. A flange was waterjet-cut out of an aluminum plate to reduce material waste and machining time. This was then welded to the coupling.

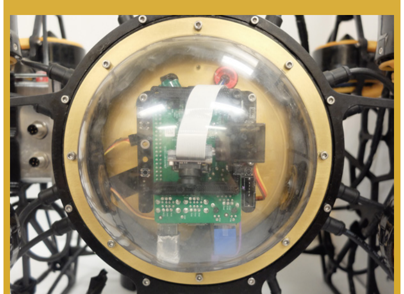


*Fig. 10 - Electronics Dome*

The polycarbonate Electronics Dome is sealed to the coupling using a neoprene rubber gasket, eight evenly spaced screws, and an aluminum ring. The ring prevents the dome from cracking and distributes load to ensure the gasket forms an even seal. On the rear of the coupling, an aluminum sealing flange, epoxied to the polycarbonate Power Tube, seals in a very similar way. Gasket face seals were selected over O-rings because gasket seals are easier and more reliable to assemble, simpler to machine, and require less accurate tolerances.

*Fig. 11 - Power Tube*

Inside the Power Tube, a waterjet-cut 6061 aluminum mounting plate, called the Power Sled, was designed to serve as a support structure for the power electronics and to dissipate heat from the Power Brick Boards to prevent overheating. The geometry of the sled was designed to preserve space for connectors through the center end cap, while maximizing the space for the electronics. A SolidWorks flow simulation, as well as a MATLAB script, was used to model the thermal environment of the Power Tube, ensuring that a sufficient amount of heat would be dissipated to prevent damage to the electronics.

## D. Cameras

ROV *Cetacean* has a total of five cameras to provide the pilot with visual feedback during operation. The primary camera is mounted on a servo motor inside the Electronics Dome, allowing the pilot to adjust camera angle as desired. The four secondary cameras are strategically placed around the ROV to provide the pilot with a better view of tools that cannot be seen from the primary camera. For flexibility, the secondary camera enclosures were designed to be resealable, allowing the cameras inside to be replaced if necessary. The aluminum end caps, machined in-house with a CNC lathe, have grooves for X-profile O-rings that form watertight gland seals against the polycarbonate tubes. Scratch-resistant acrylic sheets, through which the cameras look, are sealed onto the same polycarbonate tubes with marine epoxy and 3D-printed rings. When the vehicle is not in operation, 3D-printed, snap-on camera covers are used to prevent oils and fingerprints from obscuring the cameras' views.

Secondary cameras are mounted to the frame using the Universal Mounting System, designed to be attached anywhere on the ROV's frame and adjusted to accommodate nearly any desired camera orientation. To accomplish this, two brackets clamp onto a member of the frame plates. A ball joint, secured to one of these brackets and in conjunction with a similar clamp mounted to the camera housing, is used to adjust the camera direction. The balls were machined in-house from a 6061 aluminum rod using a CNC lathe and the brackets were cut from sheet 6061 aluminum using a waterjet.

## E. Buoyancy and Ballast

To ensure vehicle stability and ease of control, a foam buoyancy system and ballast were added to move both the center of mass (COM) and the center of buoyancy (COB) of the vehicle to the center of its thruster configuration, with the COB directly above the COM. The existing total mass, total displacement, COM, and COB of the ROV were estimated using SolidWorks and validated with various measurements. With these metrics, the necessary volume and COB of foam itself was calculated. The company designed and milled HCP 30 foam forms to these parameters. This foam was chosen because it retains its shape and buoyancy under high pressure.

## F. Basestation

The Basestation is Proven Robotics' surface control station. Last year's Basestation was modified to make internal components stronger and mountings more precise. Steel rods replaced the previous aluminum ones for increased structural integrity, and the monitor mounting plates were remade. When closed, the case is splash-resistant which protects the components inside. A master power switch in the Basestation provides additional safety for the surface electronics. The tether attaches directly to the ROV, with paracord acting as strain relief by being attached to the ROV and a surface mount while being shorter than the other cables. The paracord, Category 6 cable, two marine-grade power cables, and pneumatics line are all fed through a snakeskin wrap.

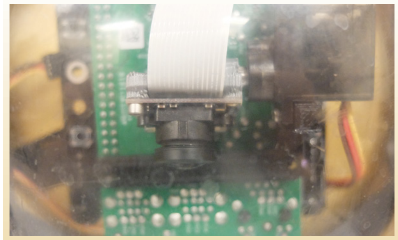


*Fig. 12 - Primary camera within the Electronics Dome*

*Fig. 13 - Secondary camera housing and lens cover*

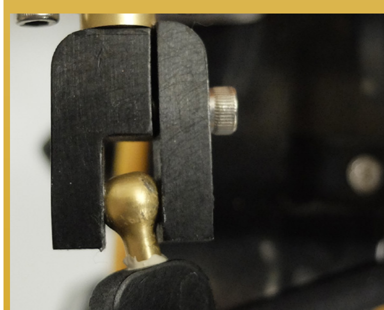


*Fig. 14 - Universal Mounting System*

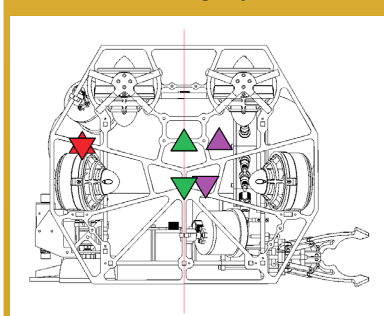


*Fig. 15*
*Purple: Original COM & COB*
*Red: Foam COM & COB*
*Green: Final COM & COB*

*COB: Center of Buoyancy (up arrow)*
*COM: Center of Mass (down arrow)*

# IV. Mission Tools Rationale

## A. Primary Manipulator

The Primary Manipulator (PM) is designed to be simple, reliable, and multipurpose, capable of completing a variety of mission tasks to reduce the total number of required tools. The PM, with its four end effectors, is able to manipulate a wide variety of objects in various orientations, but is optimized to grasp ½-inch and 2-inch PVC pipes and #310 U-Bolts, which are common components among the mission props. To make the design stronger and more compact than the previous year's "quad-pincer" design, 3D-printed parts were substituted with machined aluminum parts. The end effectors were waterjet-cut out of sheet 6061 aluminum while other structural components were CNC-milled out of the same material. The linkages that drive the end effectors were laser-cut out of HDPE and, as they are the simplest to produce and replace, act as intentional breakpoints in the case high-energy impact to protect the rest of the PM.

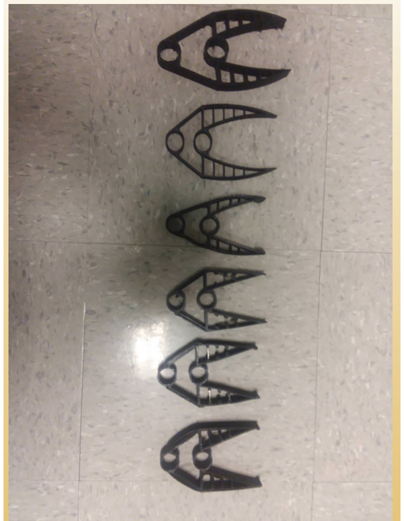


*Fig. 16 - Iterations of early PM designs*

The PM also makes use of a magnetic slip coupling and improved quick-release system. The magnetic slip coupling is composed of two complementary 3D-printed segments that each retain six magnets. This allows for mechanical power transmission between a Blue Robotics M200 waterproof motor and the PM's 6.35-mm Acme threaded rod, in order to drive the linkages. The magnets make the slip coupling both self-engaging and torque limiting; the magnetic alignment slips if subjected to too much torque, preventing jamming or damage to the PM assembly when fully extended or retracted. This slip functionality was validated by extensive, repetitive test actuation and dramatically reduced the jamming experienced in past designs. The coupling is used in conjunction with the previously discussed quick-release mount to allow tools to be removed from the ROV without removing the motor, which is useful for compact storage and maintenance. This functionality can be utilized for future tool development by allowing tools with a common mating fixture to be interchanged during vehicle operation.

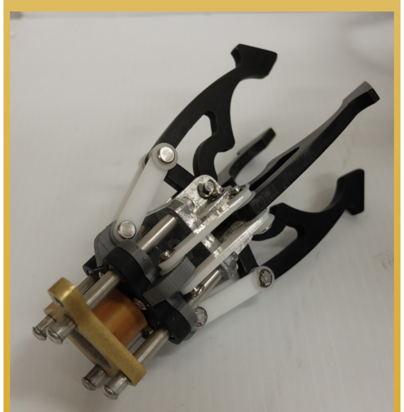


*Fig. 17 - Final Primary Manipulator*

## B. Ocean Bottom Seismograph Leveler

The Ocean Bottom Seismograph (OBS) Leveler's function is to turn the ½-inch PVC tees located in the four corners of the OBS frame, leveling it. A self-aligning end effector was designed and 3D-printed to fit over a ½-inch PVC tee in two separate, parallel orientations. Multiple versions of the end effector were prototyped in search for a low-profile, self-aligning design that would securely interface with the tees. The final design included cutouts to allow the pilot to visually verify that the tool is docked and PVC tees are spinning. A shaft collar attaches this end effector to a Blue Robotics M200 waterproof motor. The bidirectional motor allows the OBS frame legs to be both raised and lowered as needed. The motor was vertically mounted to the frame with the end effector facing downward to meet the upward facing PVC tees.

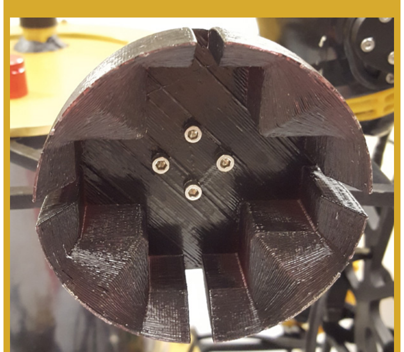


*Fig. 18 - OBS leveler*

## C. Lift Bag Attachment

The Lift Bag Attachment tool combines a commercial lift bag and an acoustically activated solenoid in order to complete the Aircraft task. It is able to attach to and lift the debris, deposit the debris, and then attach to and lift the engine to the surface. Research and testing conducted by Proven Robotics determined that commercial lift bags were readily available and more reliable than any of the evaluated in-house options. Therefore, an open-bottom lift bag from Carter Lift Bag, Inc. was chosen. The selected CB-25 lift bag supplies a lift of 111.21 N when fully inflated and has dimensions of 38.1 cm x 50.8 cm. The lift bag must be able to be stored on the ROV, so this relatively small size was desirable. The body of the lift bag attachment tool consists of a one-way mechanism, gated by a spring-loaded solenoid. The top and bottom of the opening geometry are 3D-printed due to their complex shapes and to reduce weight. The opening is designed to be self-aligning such that the U-bolts on the debris and engine can be pushed through the opening, but cannot be released without the actuation of the solenoid. The rear of the tool consists of a waterproof compartment housing the batteries and electronics required to actuate the solenoid. This enclosure is milled out of HDPE and is sealed with a gasket and polycarbonate sheet. An umbrella valve was added to the polycarbonate sheet to release air if pressure inside of the enclosure begins to exceed hydrostatic pressure. As a backup to the acoustic actuation of the solenoid, a ring is affixed to the top of the solenoid; the ROV is able to mechanically actuate the tool and release the load by pulling the ring with the primary manipulator.

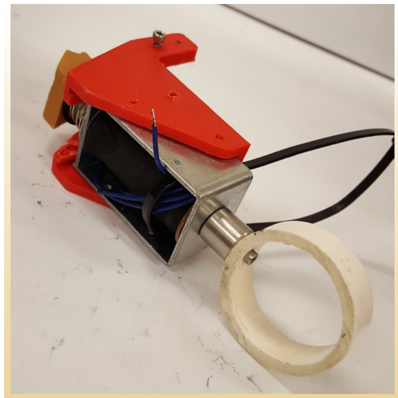


*Fig. 19 - Lift bag solenoid*

*Fig. 20 - Lift bag*

## D. Power Puck

The Power Puck is Proven Robotics' inductive power transmitter, which is used to supply 5 W at 5 V and 1 A to the OBS in the Earthquakes task. The design of the this tool was an interesting challenge for Proven Robotics, as it was the first time the company had worked with an internally powered device that was separate from the ROV. The inner electronics of the Power Puck, which include 4 AAA batteries in series, a 3-A fuse, and the 5-V, 1.5-A inductive charger, are secured in a 3D-printed scaffolding. AAA batteries were chosen for the design in order to fit all batteries within the small profile of the wireless charging module. The internal scaffolding can be removed in one piece, allowing for rapid maintenance and contributing structural rigidity to the electronics while in use. To ensure waterproofness, this scaffolding is enclosed in a 6.35-cm diameter polycarbonate tube. One end of the tube is sealed with a turned aluminum end cap and a gasket, while the other end is epoxied to a disk of waterjet cut aluminum. An umbrella valve was placed through one of the ends cap to equalize pressure in case of battery failure.

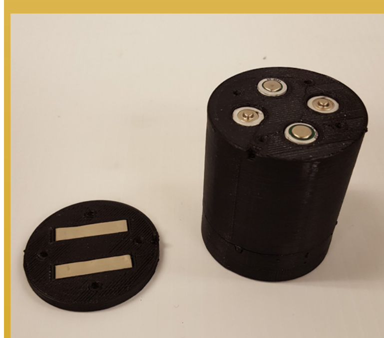


*Fig. 21 - Power Puck batteries (unsealed)*

*Fig. 22 - Power Puck inductive power coil*

## E. Acoustic Doppler Velocimeter

The Acoustic Doppler Velocimeter (ADV) must mount to a #310 U-Bolt on the mooring line as part of the Energy task. The ADV is made using ½-inch diameter PVC pipe, measuring approximately 24 cm in length, with a PVC tee on one end and a magnet epoxied to the other. In operation, the ROV grasps the PVC tee with the PM, approaches the mooring line, and magnetically connects the ADV to the U-Bolt.

# V. Electrical Design Rationale

## A. Electrical Overview

ROV *Cetacean* electronics are designed for reliability over the lifespan of the ROV. Control of the ROV begins with the surface electronics, which include a laptop computer, external monitor, and a 48-V power supply. Control data is sent directly from the laptop's Ethernet port to the ROV's Integrated Electronics Tube (IET) using a Category 6 cable, which provides noise immunity and the ability to handle a high data throughput. 48 V is also provided to the ROV using two 2.05-mm diameter marine-grade wires in line with a 25-A fuse. The IET is divided into two sections to provide noise immunity for the Raspberry Pi from the power electronics.

The tube portion of the IET houses the four Power Bricks Boards, the Electronic Speed Controller (ESC) Board, and the Power Distribution Board. These are placed in a vertical stack with the Power Bricks at the bottom and ESC Board at the top. The 48 V enters the tube portion of the IET and is converted to 12 V on the four Power Brick Boards. The 12-V power bus is then distributed by the Power Distribution Board to the ESC Board which in turn distributes 12 V to the eight thrusters and the motorized tools. The Power Distribution Board is also responsible for converting 12 V to 5 V using a buck regulator circuit and delivering this 5 V to the ESC Board and the Electronics Dome. The ESC Board also controls the thrusters and motorized tools.

The dome portion of the IET houses the Backplane Shield Board, the Raspberry Pi, and the Raspberry Pi Camera. The Backplane Shield Board contains connections for the 5-V and $I^2C$ buses to connect the Raspberry Pi to the rest of the electronics system, as well as other necessary integrated circuits (ICs) which are used to control different peripherals of the ROV *Cetacean*. The Raspberry Pi connects into the Backplane Shield Board through header pins and provides the processing capabilities for the ROV. The Raspberry Pi is also responsible for communicating with four USB cameras connected to the USB hub, and the Ethernet connection for the tether. All circuit boards on the ROV, with the exception of the Raspberry Pi and ESCs, were designed with EAGLE PCB Design and Schematic software and populated in-house.

## B. Power Bricks Board

There are four buck converter boards on the ROV located beneath the Power Distribution Board. Each board receives 48 V from the Distribution Board, converts it to 12 V using a 300-W buck converter circuit, and sends the 12 V back to the Power Distribution Board. The boards are mounted to the power sled to dissipate heat from the buck converters. The buck converter assemblies are also connected to the main $I^2C$ bus so that the performance of the buck converters can be monitored.

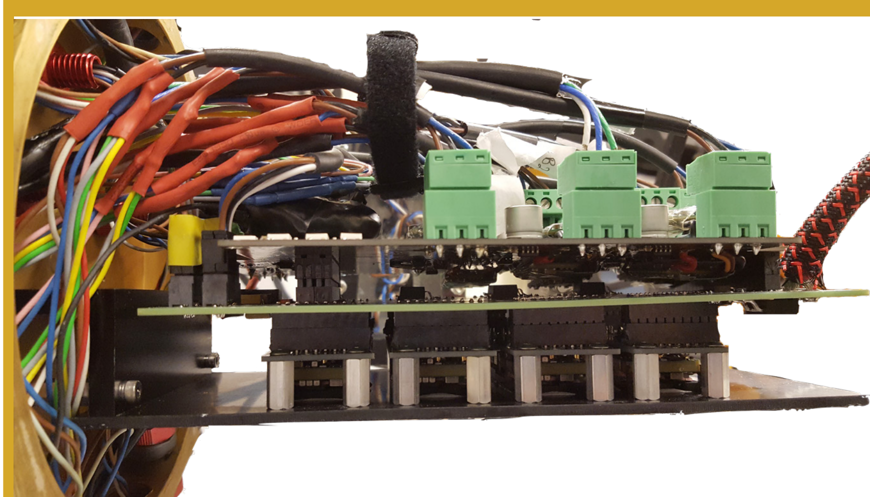


*Fig. 23 - Full power electronics stack*

## C. Power Distribution Board

The Power Distribution Board receives 48 V from the tether and I²C signal from the Raspberry Pi. The 48-V section is isolated from the rest of the board and has a reverse voltage protection circuit and a current measurement circuit to calculate the max power draw by the ROV. The 48-V rail is routed to four Power Bricks Boards, which connect to the bottom of the Power Distribution Board and convert 48 V to 12 V. The Power Distribution Board turns on the Power Bricks Boards once the voltage on the Power Distribution Board reaches 44 V to prevent damage to the paralleled buck converters. The 12-V bus from the buck converter boards is also connected to the Power Distribution Board. There is also a 12 V to 5 V buck converter that powers the Raspberry Pi and related digital components.

*Fig. 24 - Blue Robotics T200 thruster*

## D. Electronic Speed Controller Board

The ESC Board is used to power the 11 ESCs for the thrusters and tools. The AfroTech ESCs are directly soldered to the custom-built ESC Board to reduce the size and complexity of the electronics tube. The current draw of each ESC is monitored by a Hall-effect current sensor, and the temperature of the ESC is monitored by a thermistor. Analog samples are taken from the current sensors and communicated with an ATMEGA328P chip on the board over serial peripheral interface (SPI) using a series of 8-channel, 10-bit analog to digital converters (ADCs). A 12 V to 5 V linear regulator is used to provide power to the Hall-effect sensors, the ADCs and the ATMEGA microcontroller chip. The Raspberry Pi communicates with the ATMEGA's I²C peripheral. This chip reads the current sensors and temperature sensors and is capable of controlling the electromagnet and NeoPixels, although these features are not utilized. The speed and direction of the ESCs are controlled by a pulse width modulation (PWM) signal input provided by a 16-channel, 12-bit I²C-to-PWM converter controlled by the Raspberry Pi.

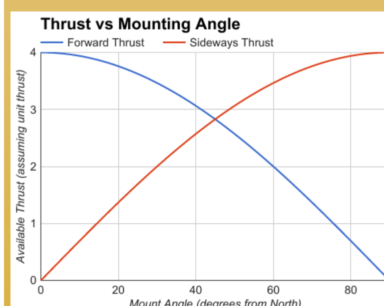



*Fig. 25 - MATLAB simulation of horizontal and vertical thrust vs. thruster mount angles*

## E. Blue Robotics T200 Thrusters

ROV *Cetacean* uses eight Blue Robotics T200 thrusters to control its movement. Four of the thrusters are oriented vertically with the other four mounted horizontally with offsets of 20° in from the side plates. From previous year's MATLAB models, it was determined that this orientation provided the best combination of horizontal speed and mobility as it provides full movement in all three translational and all three rotational axes. Having full movement was deemed necessary as it provides the ROV with better handling and easier navigation. Proven Robotics chose to use T200 thrusters again due to their high performance, good reliability, and low cost. Each thruster provides 34.81 N of thrust when powered at 12 V (Ref 11). These thrusters are more reliable than a thruster designed in-house, which justifies their purchase.

*Fig. 26 - Raspberry Pi 3 Model B*

## G. Raspberry Pi

A Raspberry Pi 3 Model B was chosen as the control component for the ROV due to its ability to host the main software processes while still providing low level control of the hardware. In addition, it permits a higher-level development environment. This allows the Software Department to focus on the overall concept with its members for cohesive development through shorter training periods for new employees, as well as quicker development cycles. The integrated debugging tools, as well as the vast community support for the used libraries and frameworks, allowed Proven Robotics to focus on functionality and system tests, while minimizing debugging periods.

## G. Backplane Shield

The Backplane Shield holds the Raspberry Pi and facilitates the connections between it and the controlled components on the ROV including the cameras, lights, and the ESCs. A camera is mounted on the board with a 3D-printed mount and sends video to the Raspberry Pi via a ribbon cable. The Raspberry Pi is powered with 5 V from the Power Distribution Board. An inertial measurement unit (IMU) and pressure sensor are also located on the board and are powered with 3.3 V from a linear regulator. The IMU is a small, commercially available board with easy-to-use on-chip software. Up to four other cameras send video to the Raspberry Pi's USB ports. $I^2C$ signal lines are sent to the Power Tube via multiple header pins. Several LEDs are used to indicate power and programmable functions for debugging indication.

## H. Acoustic Release

The acoustic release mechanism consists of two boards, a transmitter located on the ROV and receiver located on the Lift Bag Attachment tool. The Transmitter Board utilizes an ATTINY24-SSUR microcontroller to control an H-bridge and produce a piezoelectric signal. The drive signal can be easily tuned by reprogramming the microcontroller to modify the timing of the control code. Proven Robotics chose 16 kHz as the frequency of communication since that had the largest voltage output during lab testing. This signal was sent through the water by a piezo on the transmitter and then received by another piezo on the receiver board. This receiver board has an ATMEGA1284P-AU microcontroller running a fast fourier transform in order to detect spikes at 16 kHz. Upon detecting these spikes, the board powers a P-channel MOSFET, actuating a solenoid to release the Lift Bag Attachment tool.

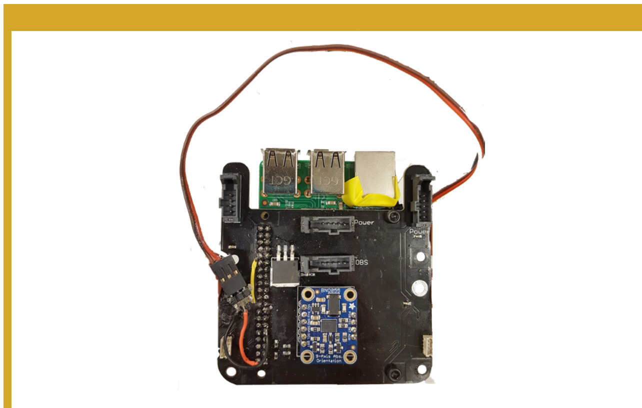


*Fig. 27 - Raspberry Pi on Backplane Shield*

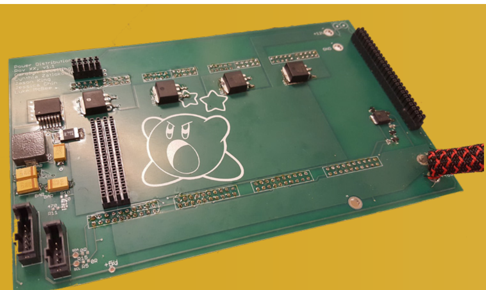


*Fig. 28 - Power Distribution Board*

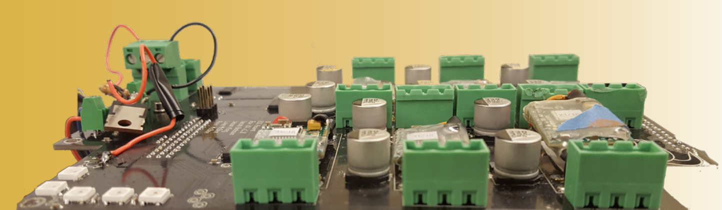


*Fig. 29 - ESC Board*

# VI. Software Design Rationale

## A. Software Philosophy & Overview

The software philosophy for ROV *Cetacean* is to make an architecture that leverages the power of current technology to facilitate quick development, easy debugging, and rigorous testing. GitHub was utilized to enable the entire Software Department to work simultaneously on the codebase while ensuring the software's stability and recoverability.

Proven Robotics built its software off the concept of a basic client-server architecture. This architecture allows the company to leverage many current web technologies that provide reliable data transfer with long-term support benefits. Building on this model, there is a custom-designed intermediary proxy called Pakfront. This separate piece of software runs on the client computer and connects to the ROV, managing data and video streams for the BattleStation to connect to as necessary, and logging that data for cause-of-failure investigations. The data stream passes control and state information between the Flask server on the ROV and the BattleStation. The video streams are sent separately from the Raspberry Pi, which is receiving images from the multiple USB cameras. Each component of software at each level in the hierarchy has its own testing suite to quickly identify problematic code components. Leveraging the multiple cores of the Raspberry Pi, ROV *Cetacean* runs all functions in near-real time.

## B. BattleStation

The BattleStation is Proven Robotics' mission control software, providing the pilot camera feeds and performance data, which allows them to control ROV *Cetacean*. This software translates the pilots' instructions from an Xbox-style controller into directions for the ROV. The driving display and communication with the ROV were achieved by implementing a web-based interface for the pilot, using HTML, CSS, and JavaScript, and running it on a flexible Electron framework. This allows for a fully functional, stand-alone desktop application; everything can run from one point of knowledge and requires very little prior knowledge.

This year Proven Robotics utilized ReactJS to make interchangeable and reusable components. The components are intended to assist in the completion of the pilot's tasks, as they provide critical information such as checking whether the controller is registering correctly or timing the mission. A major focus of the BattleStation is the camera display. The BattleStation was given the ability to switch between different camera feeds during drive time. It can also spawn computer vision processes, which consume the raw video stream from the Raspberry Pi and feed a modified stream to the driver's visual with a computer vision (CV) overlay. The BattleStation is also equipped with an extra wide screen to allow for a focus on multiple camera feeds. Any camera can be viewed from either the extra wide or laptop screen, without losing space for the informational displays for the pilot.

Additional components range from pure informational aids like control scaling, to more dynamic assistance to the pilot like the seismograph component. Once the data has been read in and relayed to the BattleStation, the component enables the pilot to generate a graph based off of the data that is displayed on the screen. This graph, combined with a flight path calculator, CV, and mission progress tracker, allows for the pilot to focus on the mission task and not worry about extraneous calculation or analysis and helps the pilot identify what is on the screen.

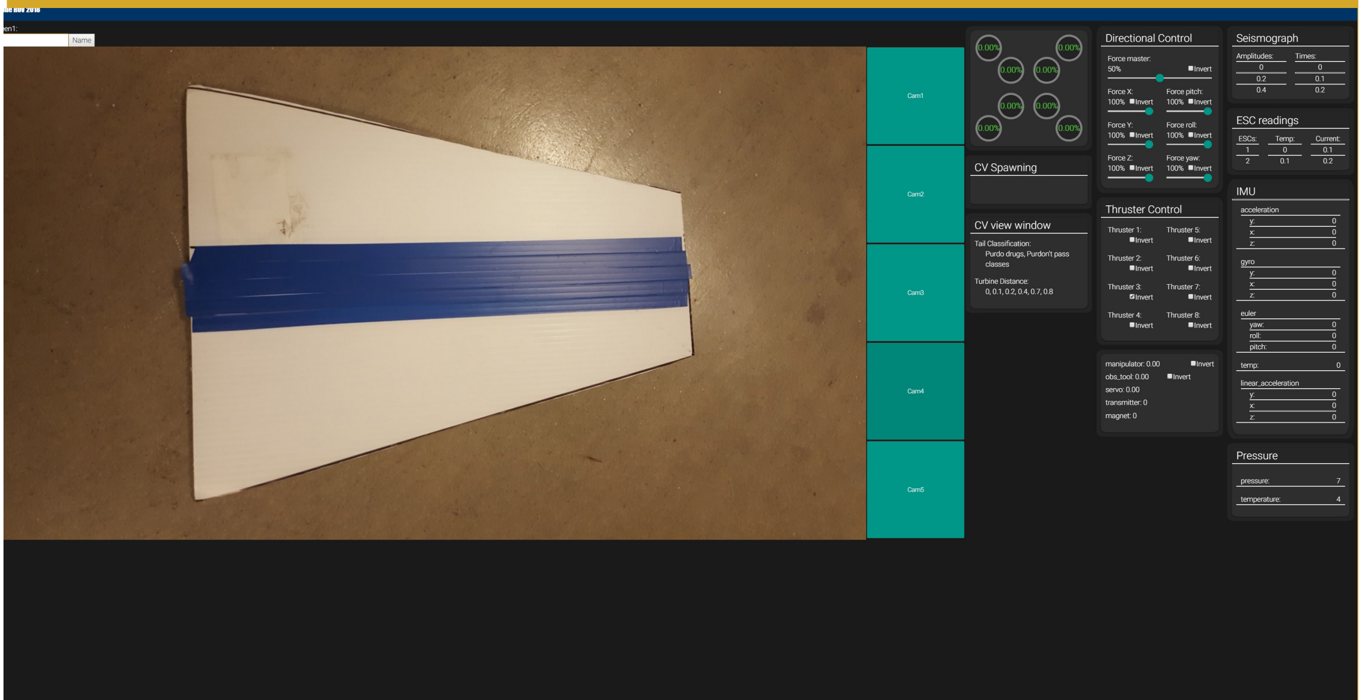



*Fig. 30 - BattleStation display*

## C. Tether Communications

Communication between the BattleStation and the ROV is intermediated by a program called Pakfront. When the BattleStation is run, it connects to ports on its own device configured to be used by the proxy. The proxy manages connecting to all external ROV software systems, such as the Flask server and the camera streams, and hooks them up to the internal ports. The proxy also has the ability to run integration tests and log communications for mission playback. All data stream communications are sent via the application level protocol Socket.io, formatted in JavaScript Object Notation (JSON), and sent over Transmission Control Protocol (TCP) and Ethernet between the ROV and the BattleStation. All video streams are encoded in MJPEG and sent over TCP and Ethernet to the BattleStation.

## D. Embedded Communication

The ROV is primarily controlled via a single Raspberry Pi, using I$^2$C, TCP, Ethernet, and USB connections to interface with the various onboard hardware and external connections. As mentioned in the Tether Communications section, the USB connections are used for reading the various camera streams, while the TCP and Ethernet connection relay both these streams and JSON packets between the ROV *Cetacean* and the BattleStation.

The Raspberry PI communicates with the ESCs, pressure sensor, and IMU through an I$^2$C to PWM controller. The I$^2$C lines from the Raspberry Pi are also connected to an ATMEL chip, which is in turn connected to IC's through SPI signals that read the electric current value for each thruster. The Raspberry Pi also uses I$^2$C to communicate with the depth sensor and the IMU. The IMU provides orientation, angular acceleration, and linear acceleration which are used for feedback in the automatic controls algorithms. The depth sensor measures pressure, which are translated to depth and then incorporated into the controls algorithms as well.

## E. Movement Control

The ROV is controllable in six degrees of freedom: forward and back, left and right, up and down, roll, pitch, and yaw. The placement and orientation of the thrusters was described in the "Blue Robotics T200 Thruster" section. The direction the ROV should move is given by the pilot in the aforementioned 6 directions and needs to be mapped to 8 thrusters. While this movement can be achieved with only six thrusters, using eight provides redundancy in case of mechanical or electrical failure. The input direction values range from -1 to 1, and the desired output array for the thrusters is an array of length 8 that should range from -1 to 1. The values of the input direction vector correspond to the speed desired, while the values of the thruster array correspond to the PWM output, and therefore power output. Movement control is modeled so that inputs are interpreted as a force vector, with the primary objective being to preserve the force direction. This process is achieved through a thruster mapping algorithm, which uses the center of mass, thruster position, and direction to calculate the appropriate thruster power values.

A thrust limiting section was also implemented in the thruster mapping algorithm. This ensures that each individual thruster will not exceed their individual maximum power value. The limiter calculates the power that is necessary for each thruster given a desired direction, and scales the thruster values down if any are over the threshold. When any PWM value is scaled down, the other thrusters are also scaled down proportionally to preserve the overall direction. Special care was put into ensuring that the force direction of the input would be preserved by using a thruster model algorithm to double check that the resultant direction of the ROV would be the same.

## F. Stabilization

The ROV is also capable of regulating certain input force directions (forward and backward, left and right, up and down, roll, pitch, yaw) to maintain a position or speed based on the inputs given from the sensors. Three different algorithms were created to achieve this using variations of proportional-integral-derivative (PID) control loops. Position stabilization can be performed on the most critical degrees of freedom, up and down, roll, pitch, and yaw. Speed stabilization can be performed on all six degrees of freedom, and depth control can modify the output of the horizontal and vertical directions to regulate the depth of the ROV.

## G. Computer Vision

The BattleStation approximates the shape and color of the tail in the camera stream by using color and shape approximating CV algorithms. This works by first identifying the color range of the airplane tail marks, and then identifying the shape of the tail mark through polygonal approximation. The software uses HSV (hue, saturation, value) spectral data to isolate the color and account for the sensitive lighting conditions by ignoring the value channel. Specific color range threshold values were hand-tuned to account for various underwater lighting conditions. Finally, a shape contouring algorithm is used to identify and eventually save the shape of the identified colors for the polygonal approximation to run on. The results of the largest connected component are returned to the pilot screen for display.

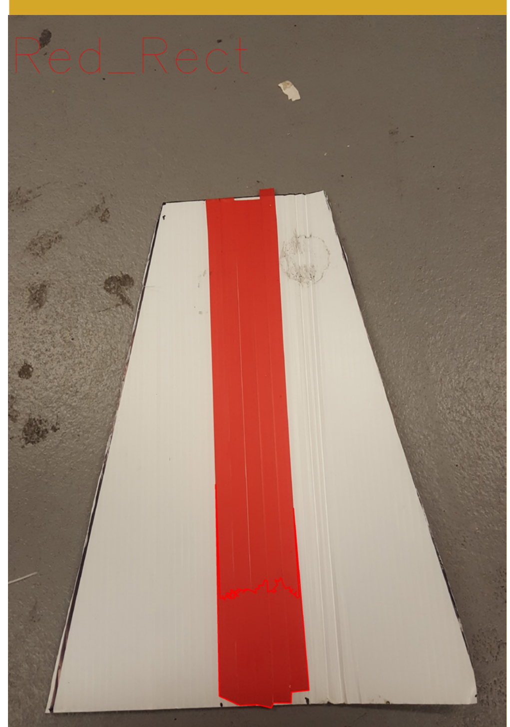



*Fig. 31 - Computer vision program identifying a red square*

# VII. Logistics

## A. Company Organization

Proven Robotics is divided into three technical departments: Mechanical, Electrical, and Software. Each department focuses on their technical area of the ROV and is led by a department head who reports directly to the CEO. Additionally there are five project groups, staffed with employees from the three technical departments, that each focus on a specific system of the ROV. These groups are led project heads who report to both the department heads and CEO. The structure of this year's project groups was modified from last year to address weaknesses in their layouts. Last year, the Structures and Connectors was reduced to only two people. This group was merged with the old Logic Boards and Embedded Programming group to form the new Logic Boards and Frame group. The other four project groups are Surface, Power, Sensors, and Tools. These groups facilitate cross-department communication and allow employees to focus on a specific system on the ROV. They also allow employees to get an understanding of how the entire ROV functions instead of focusing solely on the mechanical, electrical, or software systems of the ROV. Organizing the three technical departments and five project groups is the Administrative Department. The CEO is the head of this department, which also includes the Chief Operations Officer (COO), Chief Financial Officer, and sponsorship coordinators.

## B. Project Management

Proven Robotics' design cycle is divided into four stages: training, designing, manufacturing, and testing. During the training phase, new employees are recruited and trained in a combination of SolidWorks design, EAGLE design, Python, JavaScript, Web Development, and proper Github practices depending on the their department. Returning members may also take part in this training to improve or expand their knowledge of these programs.

Proven Robotics starts the design phase before mission specifications are released, and therefore only designs general components such as the frame, electronics enclosures, cameras, and the PM. These designs can all be modified after the mission specifications are released. After specifications are released, mission tools are designed and all components are finalized. A thorough design process is used to ensure that nothing is overlooked. First, the entire company brainstorms solutions to every mission task using the "Think, Pair, Share" method. This process involves individual members brainstorming solutions to a specific mission task, then discussing these solutions in a small group and combining similar ideas. The entire company discusses these ideas and is able to get a diverse set of solutions . Next, all parts are modeled in either SolidWorks or EAGLE to maximize each design's functionality and manufactuability. The company then holds a design review where company leadership, current employees, former employees, and other Purdue Students review every design. After all designs have been thoroughly vetted, the company moves to the manufacturing phase.

In the manufacturing phase, all components for the ROV are built. Employees work together to ensure that all tools and waterproof enclosures are machined, the frame is waterjet-cut, circuit boards are populated, and software is developed. Mission critical components are given priority, but all components have scheduled times to be manufactured. When a component is finished, it is thoroughly tested to ensure it can work as designed. If it fails testing, it is either fixed if the issue is small or redesigned and rebuilt if the issue is severe enough. Once all critical components have passed individual testing, the ROV is assembled and fully tested. Non-critical tools are added as they are finished.

## C. Project Costing and Budget

Proven Robotics creates its yearly budget based off of previous years' budgets and projected incomes and expenses. These expenses include the cost of producing ROV *Cetacean* and the costs of attending competition. Proven Robotics pays for flights and lodging for as many members to attend competition as the budget allows. The company receives income from various grants from Purdue University organizations along with sponsorships from companies and discounts on purchases. Each department has a strict budget, and must follow it throughout the year. This budget is revised after mission specifications are released to make sure all tasks can be completed. If any section of the budget overspends, Proven Robotics must either secure more funding or find new ways to reduce spending to ensure the company always operates in the black.

### Budget

| Proven Robotics' 2018 Budget (USD) | | | | | |
|---|---|---|---|---|---|
| Budget Category | Item and Description | Type | Amount | Total Amount | Budget Allocated |
| Electrical: Boards | PCB Printing (Power Boards, Camera Board, etc.) | Purchased | $219.91 | $219.91 | $500.00 |
| Electrical: Components | Buck Regulator Parts (Power Bricks and Discrete Components) | Purchased | $332.22 | | |
| | Components for Board Population | Purchased | $1,245.07 | | |
| | Tether Creation Material (Wires, Ethernet Cable, etc.) | Purchased | $29.00 | | |
| | Basic Electrical Supplies (Wires, banana plugs, fuses, etc.) | Purchased | $89.91 | | |
| | USB Cameras | Purchased | $83.63 | | |
| | Motors (for tools) | Purchased | $285.00 | $2,456.46 | $2,750.00 |
| Electrical: Equipment | Basic Equipment (Wire strippers, extension cords, etc.) | Purchased | $166.98 | | |
| | Power Supplies (for testing circuits) | Purchased | $119.68 | $286.66 | $750.00 |
| Electrical: Prototyping | Cameras | Purchased | $100.00 | | |
| | Test Boards and Parts | Purchased | $213.75 | $213.75 | $750.00 |
| Mechanical: Connectors | Connectors (Binder, Subconn, etc.) | Purchased | $564.95 | $564.94 | $500.00 |
| Mechanical: Equipment | Tap Sets and Tap Extractors | Purchased | $65.28 | | |
| | Experimental Equipment (Hand Pump, Toaster Oven) | Purchased | $41.26 | | |
| | Miscellaneous Equipment (Hex set, calipers, etc.) | Purchased | $231.49 | $357.29 | $1,000.00 |
| Mechanical: Machining | Miscellaneous (3D printing filament, band saw blade, etc.) | Purchased | $88.82 | $88.82 | $1,000.00 |
| Mechanical: Materials | Buoyant Foam (enough for next three years) | Purchased | 0 | | |
| | Stock materials (aluminum and polycarbonate) | Purchased | $461.65 | | |
| | Parts for tools (Screws, bolts, epoxy, etc.) | Purchased | $531.53 | | |
| | Basestation parts (Pelican case, snake skin, etc.) | Purchased | $219.58 | | |
| | Prop Parts (PVC, agar, corrugated plastic, etc.) | Purchased | $41.31 | $1,254.07 | $4,000.00 |
| Mechanical: Prototyping | Raw materials (Polycarbonate, HDPE, etc.) | Purchased | $105.85 | $105.95 | $500.00 |
| Mechanical: Thrusters | Blue Robotics T200 Thrusters and ESCs | Purchased | $1,225.80 | $1,225.80 | $2,000.00 |
| Total Expenses for ROV Construction | | | | $6,773.65 | $13,750.00 |
| Lodging & Travel | Hotels | Purchased | $4,367.16 | | |
| | Flights | Purchased | $7,700.00 | | |
| | Gas (for travel throughout the year) | Purchased | $72.79 | | |
| | Van Rental (for travel in Seattle) | Purchased | $1,164.80 | $13,304.75 | $15,500.00 |
| Team Apparel | T-Shirts and Polos | Purchased | $946.86 | $946.86 | $1,250.00 |
| Miscellaneous Costs | Poster Printing and Supplies | Purchased | $200.00 | | |
| | MATE Registration Fee and Fluids Power Quiz | Purchased | $315.00 | $515.00 | $2,500.00 |
| Total Expenses for Travel, Lodging, Team Apparel and Miscellaneous Costs | | | | $14,766.61 | $19,250.00 |
| Cash Income | Purdue Office of the Provost | Cash | $6,000.00 | | |
| | Boeing | Cash | $5,000.00 | | |
| | Indiana National Space Grant Consortium (INSGC) | Cash | $5,000.00 | | |
| | Purdue Engineering Student Council (PESC) | Cash | $4,000.00 | | |
| | Purdue School of Electrical and Computer Engineering | Cash | $3,000.00 | | |
| | Northrop Grumman | Cash | $1,000.00 | | |
| | Kleppinger Family & Northrop Match | Cash | $1,000.00 | | |
| | IEEE Central Indiana Section (CIS) | Cash | $500.00 | | |
| | Member Dues | Cash | $400.00 | | |
| | Carry-Over | Cash | $246.07 | $26,146.07 | $33,000.00 |
| Total Cash Income for 2017 Build Year | | | | $26,146.07 | $33,000.00 |
| Donations and Discounts | Blue Robotics | Discount | $173.12 | | |
| | Binder USA | Discount | $69.11 | | |
| | Dassault Systèmes | Donated | $5000.00 | | |
| | Digikey | Discount | $193.75 | | |
| | Advanced Circuits | Discount | $396.00 | $6,252.47 | N/A |
| Total Expenses | | | | ($21,540.26) | - |
| Total Cash Income | | | | $4,605.81 | - |
| Net Balance | | | | $4,605.81 | - |
| Next Year Investment | | | | $4,605.81 | - |

# VIII. Conclusion

## A. Testing and Troubleshooting

Full system testing of the ROV occurs after the design and building phases, and is critical in producing a functional vehicle. Tools are tested to make sure they function as designed, and all boards are checked for continuity and functionality. Initial functionality testing was performed out of water to ensure that the thrusters ran in the correct direction before any pool tests were performed. If anything doesn't perform as expected, Proven Robotics employees will use technical documentation and lab testing to determine the source of the issue. Once this is completed, the ROV is brought to a local pool for a full systems test and to practice mission runs. At the pool, a “dunk test” is performed to make sure all enclosures are still waterproof after transportation. These pool tests are planned such that more critical and important tests are conducted first to maximize benefits from the pool test. Before the ROV is put in the water, the Safety Checklist from Appendix A is used to make sure everyone present is safe.

## B. Challenges

Proven Robotics faced many challenges throughout the year, one of the largest being an adjustment to new leadership. The CEO, COO, Electrical Department Head, and three of the project group heads were in new roles this year, and these employees had to quickly learn their new roles as they were still expected to lead their respective groups while on a very limited timeline. Ultimately, every employee learned what they needed to do in their new roles and the company was able to function smoothly.

The biggest technical challenge the team faced this year was getting every system to reliably work at the same time. For several weeks towards the end of the year, when testing the ROV there would be a critical system that wasn’t working properly. After a few days of fixing the issue, a different system would go down. This process repeated until the company was able to get the ROV in a stable state and qualify. Proven Robotics was able to overcome these issues by working diligently to quickly fix any problems with the ROV so it could get back in the water and continue testing. If a solution couldn’t be found, a workaround was made that mitigated or removed the problem. One of the root causes of these issues was a lack of adequate testing time. The new design for the IET was more complex and time-consuming to manufacture than electronics enclosures in previous years, requiring an active tooling CNC lathe, CNC mill, and waterjet to fabricate all parts. However, the IET was necessary to fully test electronics, and so this added manufacturing time decreased the amount of time Proven Robotics had for the testing phase. While there was little that could be done to solve the problem during the year, this will be taken into consideration for next year.

## C. Lessons Learned and Skills Gained

All Proven Robotics employees learn technical skills relevant to their respective departments. All members of the Mechanical Department learn how to use SolidWorks for part design and how to plan for easily manufacturable parts. By making all parts in-house, employees have the opportunity to learn how to use CAM pathing, and how to operate a CNC Mill, CNC lathe, manual mill, manual lathe, waterjet, and a variety of hand tools. The Electrical Department learns how to make circuit board schematics, how to make layouts using EAGLE, and how to hand populate their boards. The Software Department learns how to develop their own code for a client-server architecture. Employees from all departments learn how to test their designs to make sure they work as intended.

In addition to technical knowledge, each employee learns they also learn about organization and time management. Every employee is on a strict deadline and must complete their projects on time.

Since every project is connected, any small delay can cascade through the entire company and cause major issues. These issues can be mitigated through clear and prompt communication between employees, and leadership assigning people to tasks that are tailored to their abilities. During weekly meetings, department heads and project heads talk with employees to see how their work is progressing. Weekly leadership meetings allow the department heads to get a better understanding of how each project group is progressing, and what needs to be done to keep overall deadlines moving forward. These discussions help the team meet their goals in a timely manner. They also learn how to work in multidisciplinary groups to accomplish a common goal.

## D. Future Improvements

Every year, Proven Robotics builds on what it has accomplished the previous year and tries to set itself up for even more growth in the future. One new technology that the company is researching is the technique of resin-stabilizing 3D-printed components. This process involves submerging a 3D-printed part in a resin bath, placing the part and bath inside a vacuum chamber, evacuating all the air from the part, and saturating the part with resin when pressure is reinstated. The part is then baked in an oven above the curing temperature of the resin but below the glass-transition temperature of the polymer for 15-20 minutes. This results in a part that is significantly stronger, water-tight, and machinable. Once fine-tuned, this process will allow Proven Robotics to rapidly produce structural components and electronics enclosures that are much lighter and more complex than can be achieved by current methods.

Another improvement to the ROV is the development of a smaller power conversion and distribution system. By using a divided board system with two different boards instead of one large board, as well as small, interchangeable custom-made ESC's, the company believes that the overall size requirement for converting and distributing power can be reduced by as much as 50%. This will allow the waterproof enclosure protecting the boards to be significantly smaller, drastically reducing the weight and total size of the ROV.

## E. Reflections

Purdue IEEE ROV has participated in the MATE Center competition for nine years now. Each year individuals share their experiences and pass on their knowledge.

> *My first year on the Purdue ROV team was an incredible experience. The team worked hard not only to build the ROV but also to build camaraderie. I joined the Electrical Department with no experience of soldering or board design. But team members were always patient to explain something or demonstrate a new process. Over the course of the year, I learned so many skills: designing a PCB, soldering components to a board, testing circuits, and soldering wire connections. When doing these, I rarely felt I was doing work. It was always an exciting new skill that I could use later. My experience deepened my interest in robotics and motivated me to continue exploring this new area of my life. Looking back on all the decisions and choices I made freshmen year, joining ROV was one of the best ones I made as it gave me long lasting skills and friendships.*
>
> - Grant Geyer (Electrical Department, New Member)

> *Deciding to spend the past 5 years as part of the Purdue ROV team has been the best decision of my college career. Throughout my time with the team, I've been able to be a part of tremendous growth, both personally and team wise. Not only have I been exposed to working with a real multidisciplinary team, I've learned a multitude of skills that I feel put me ahead of many others I've met throughout college. Though the technical work is what initially drew me to Purdue ROV, the people are what make the team special. It's a close knit community of really clever people working together to solve complex problems. I truly feel like I have made lifelong friends in ROV. I will continue to utilize the skills I've learned as a Design Engineer for Newell Brands.*
>
> -Joshua Berg (Mechanical Department Head, Graduating Senior)

# IX. Appendix

## A. Safety Checklist

**Pre-Power**
- ☐ Clear the area of any obstructions
- ☐ Verify power supply is "OFF"
- ☐ Connect tether to ROV
- ☐ Connect Anderson connectors of tether to power supply
- ☐ Check ROV
  - ☐ Check Integrated Electronics Tube seals
  - ☐ Check Manipulator and other mission tools

**Power Up**
- ☐ Pilot boots up laptop and starts BattleStation
- ☐ Pilot calls team to attention
- ☐ Co-pilot calls out, "Power on," and moves power supply switch to "ON"
- ☐ ROV deployment members verify ROV electronic status lights
- ☐ ROV enters water under control of deployment members
- ☐ Deployment members check for signs of leaks (e.g. bubbles)
  - ☐ If leaks occur, go to Failed Bubble Check
  - ☐ Otherwise, continue Power Up sequence
- ☐ Deployment members ensure that ROV remains stationary in water
- ☐ ROV is neutrally buoyant
- ☐ ROV is balanced in all directions
- ☐ ROV deployment members release any air pockets and shout "ROV ready"
- ☐ Pilot arms ROV and starts thruster test
- ☐ Deployment members adjust cameras to achieve desired viewing angles
- ☐ Continue to Launch procedures if no issues arise

**Failed Bubble Check**
- ☐ If many bubbles spotted during mission, the pilot quickly surfaces the vehicle
- ☐ Co-pilot turns power supply off and calls out, "Power off"
- ☐ Deployment members retrieve ROV
- ☐ Inspect ROV and troubleshoot
- ☐ If time remains after problems addressed, then return to Power Up sequence

**Launch**
- ☐ Pilot calls for launch of the ROV and starts timer
- ☐ ROV deployment members let go of ROV and shout, "ROV released"
- ☐ Mission tasks begin
- ☐ Go to Failed Bubble Check or Lost Communication if either problem occurs during the mission
- ☐ Continue to ROV Retrieval if mission completed

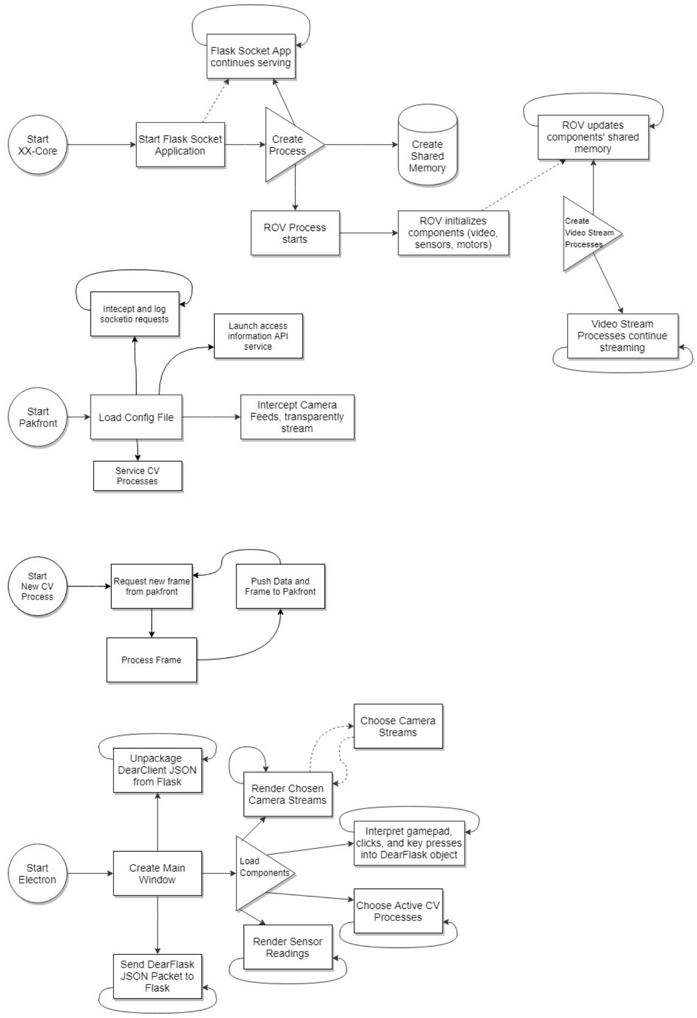
**Lost Communication**
- ☐ Steps attempted in order. Mission resumes when one succeeds.
- ☐ Co-pilot checks tether and laptop connections on the surface
- ☐ Pilot attempts to reset the BattleStation
- ☐ Co-pilot cycles the power supply
- ☐ If nothing succeeds, the mission stops
  - ☐ Co-pilot turns power supply off and calls out, "Power off"
  - ☐ Deployment team pulls ROV to surface

**ROV Retrieval**
- ☐ Pilot informs deployment members that ROV needs retrieval
- ☐ An ROV deployment member's arms enter the water up to the elbows
- ☐ The ROV deployment member pulls the ROV up from water after making contact
- ☐ Deployment team yells, "ROV retrieved"
- ☐ Pilot stops timer

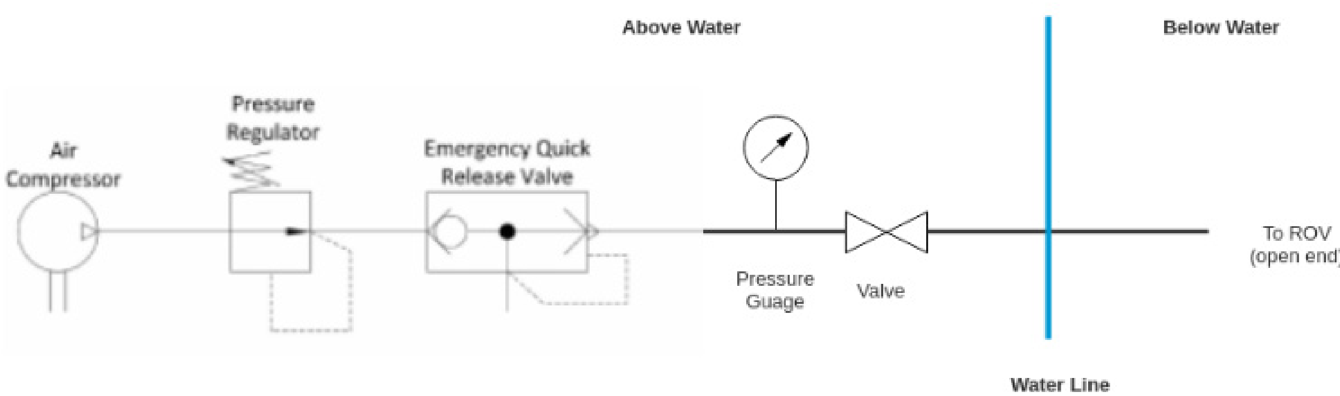
**Demobilization**
- ☐ Co-pilot turns power supply off and calls out, "Power off"
- ☐ Deployment members do a quick visual inspection for leaks or damage on ROV
- ☐ Pilot stops BattleStation and powers off laptop
- ☐ Anderson connectors of tether are removed from power supply
- ☐ Camera monitor and laptop are shut down and packed up
- ☐ Team vacates the area

# B. System Interconnect Diagrams

## Software Flowchart



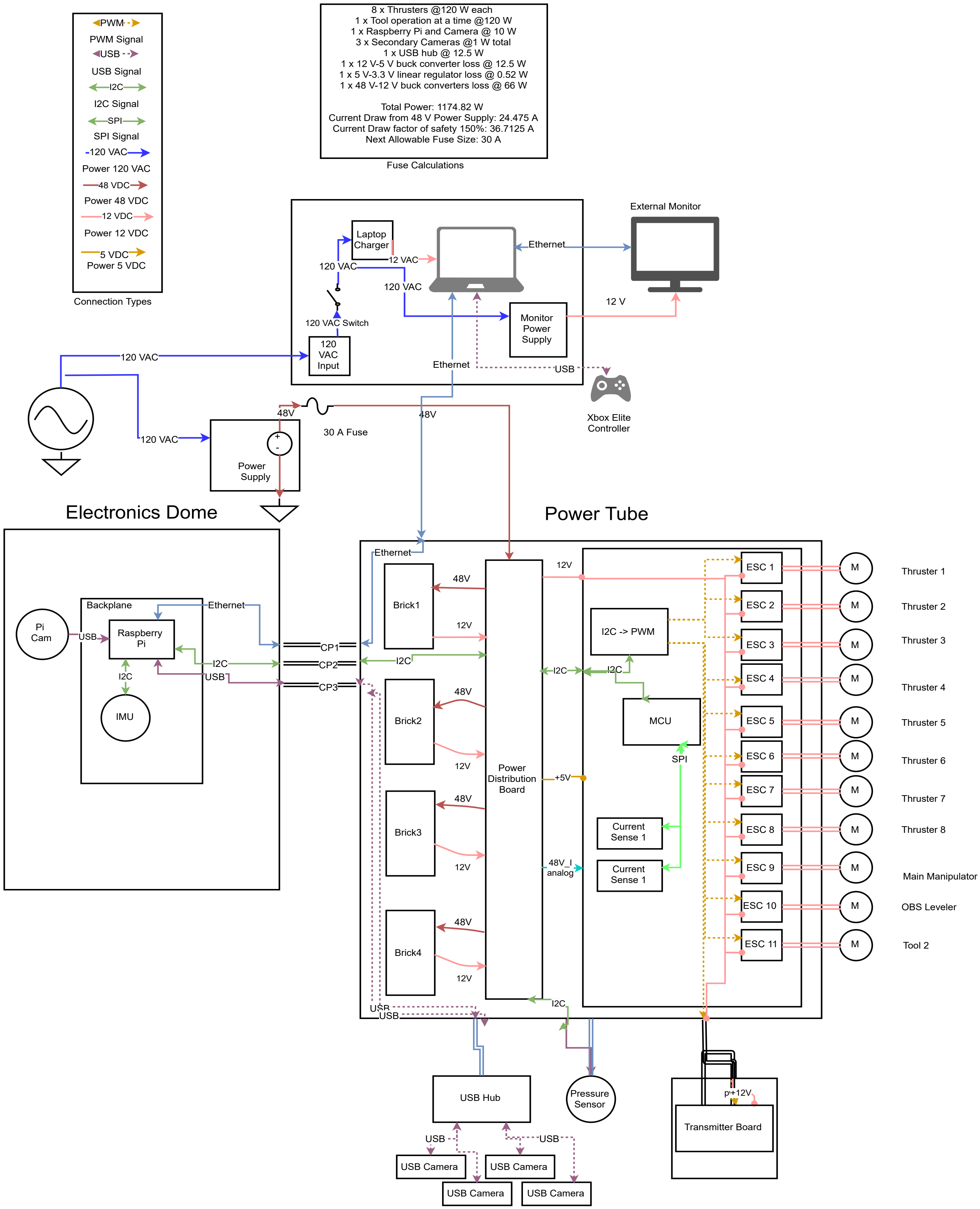

## Fluid Power System Interconnect Diagram



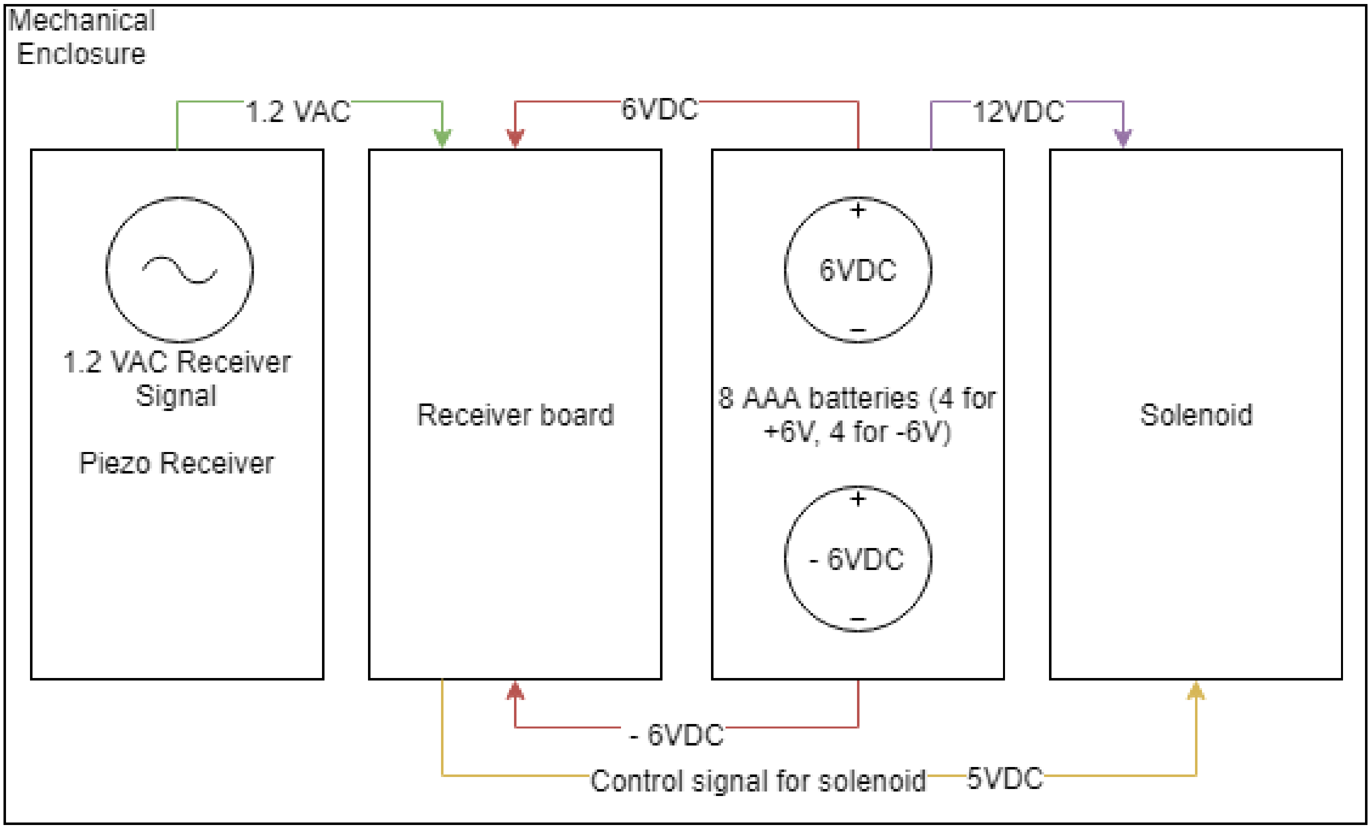
# Electrical Systems Interconnect Diagram

5/24/2018

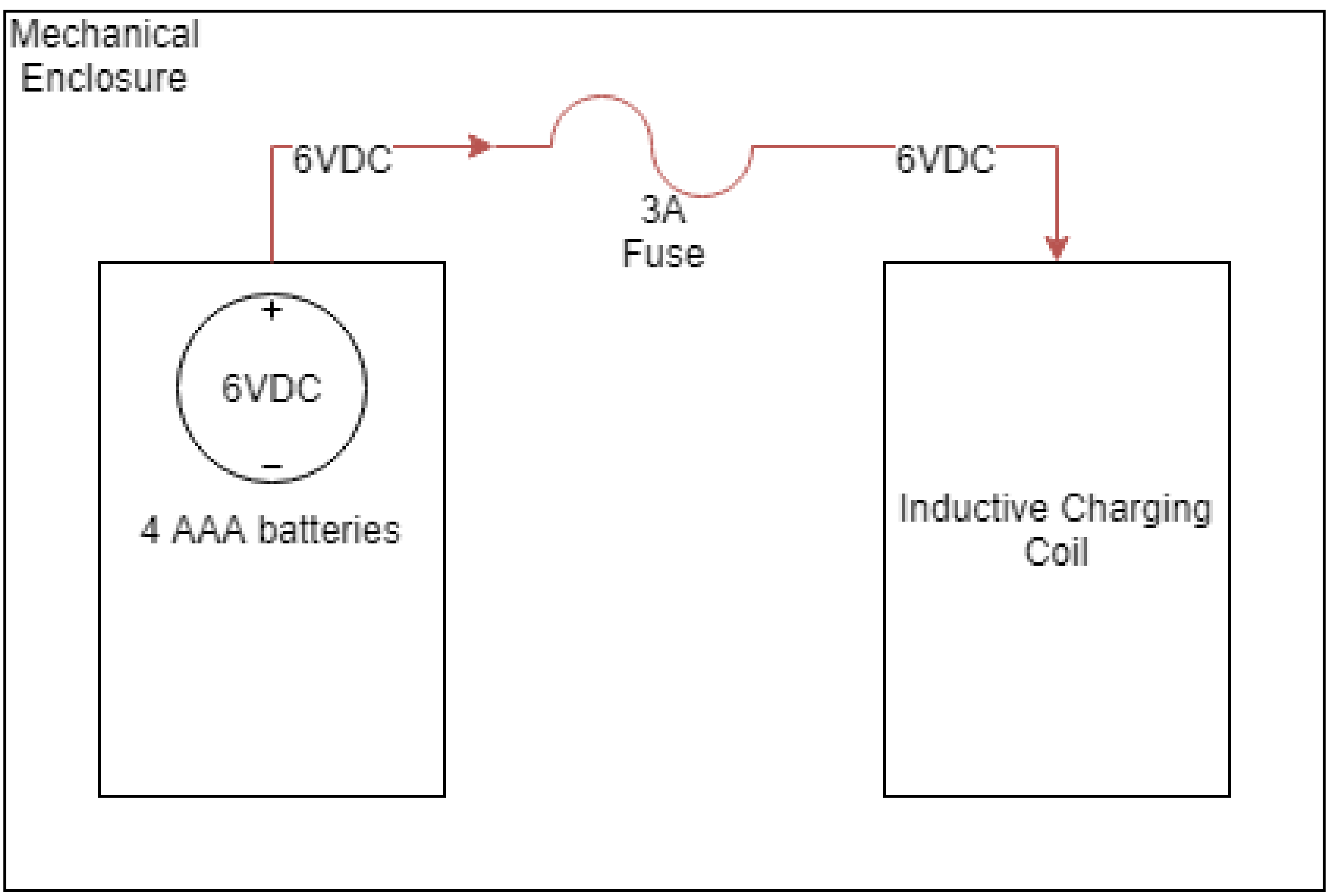
X10 SID



## Lift Bag Release Systems Interconnect Diagram




## Power Puck Systems Interconnect Diagram



## C. Acknowledgments

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