rovotics
underwater solutions

Cuttlefish

Jesuit High School
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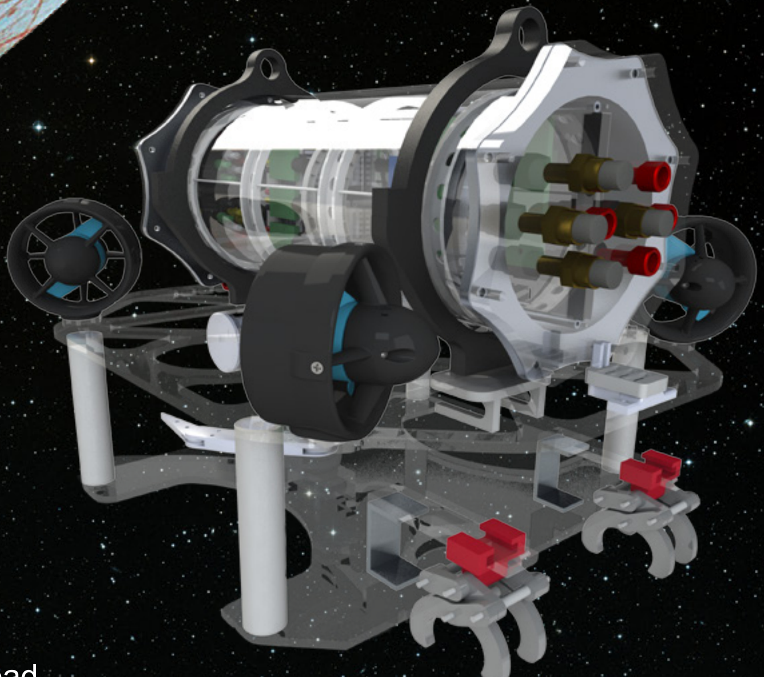

CAD rendering of *Cuttlefish.*

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I. Introduction

A. Abstract

Cuttlefish is Rovotics' first dual-purpose Remotely Operated Vehicle (ROV), and is designed to operate both in outer space under the frozen crust of Jupiter's moon, Europa, as well as in the deep waters of the Gulf of Mexico. *Cuttlefish* is designed for outer-space transport, and comes fully equipped with tools for lunar exploration, scientific study, equipment and oil sample recovery, deepwater coral studies, and wellhead manipulation.

Rovotics, a nineteen-person company (Figure 1), has the capability to deliver state-of-the-art ROVs like *Cuttlefish*, custom designed to meet mission requirements. Efficiently organized into departments by specialty, including design, manufacturing, electronics, and software, Rovotics utilizes program management methods, along with document and source code management systems, to manage the product development cycle. Designs are produced completely in-house, using a Computer Numerical Control (CNC) mill, custom-printed circuit boards, composites, 3D printers, and other specialized equipment.

Cuttlefish is the result of months of planning, research and analysis, manufacturing, and testing under strict safety protocols. Unlike its predecessors, *Cuttlefish* has been optimized for size, weight, and the requirements of space travel. Its light weight and compact design allows for increased speed, maneuverability, and power efficiency. These features, along with a new custom-designed gripper and improved electronics, make it Rovotics' most advanced vehicle yet.

This technical document describes the development process and design details that make *Cuttlefish* the best ROV to fully meet the requirements specified in the NASA and Oceaneering International Request for Proposals (RFP).

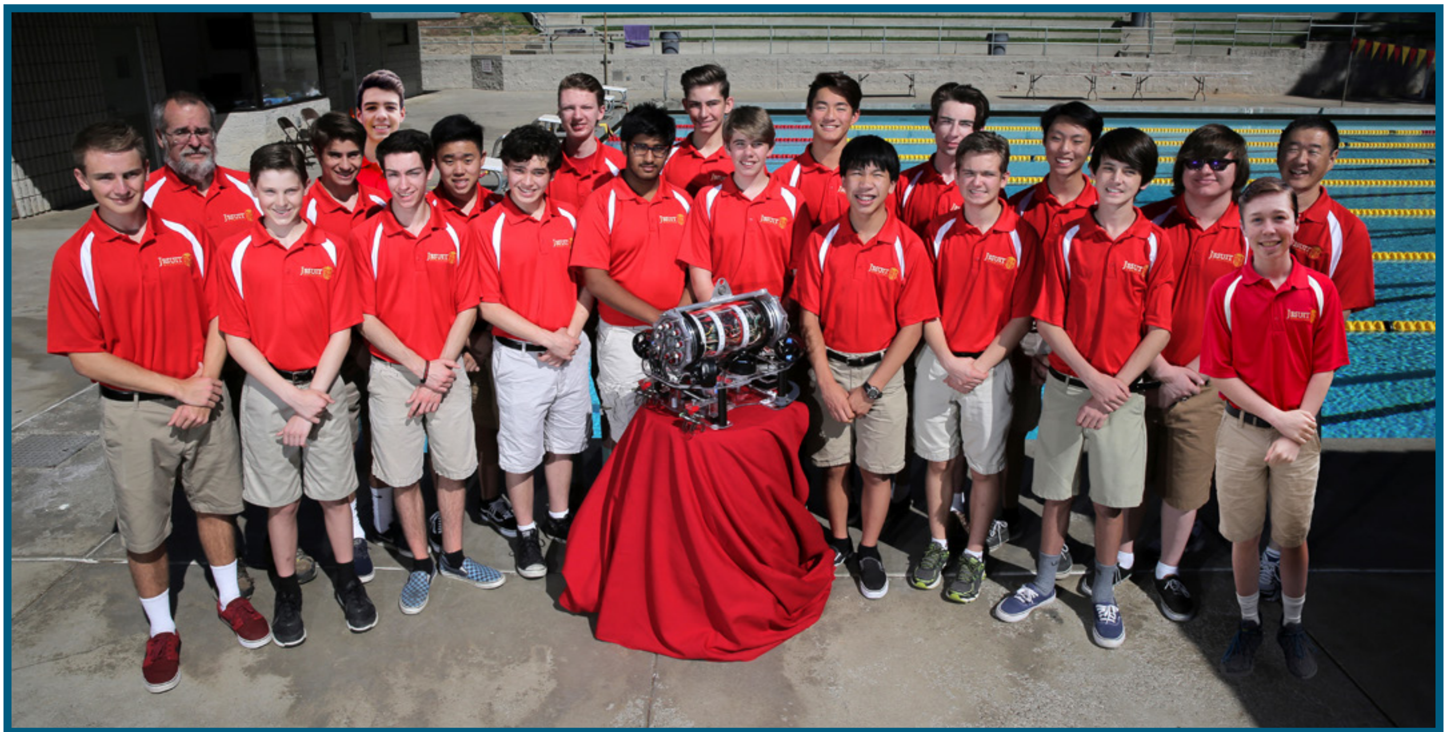

Figure 1. Rovotics 2016 company photo with their newest ROV, Cuttlefish.

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II. Design Rationale

A. Mechanical Design Process

To streamline the design process, Rovotics used a multi-step approach to allow the team to envision the end result early, reducing the number of miscalculations, omissions, and revisions. The process began with a brainstorming session where many creative ideas and designs were sketched on the whiteboard and alternatives were explored (Figure 2). The company selected the best designs by weighing factors such as size, weight, effectiveness, cost, complexity, ease of manufacturing, safety, and serviceability. Proof of concept designs were mocked up with PVC parts and wood cutouts to create physical models as shown in Figure 3. At this stage, different ideas were quickly shared, debated, and changed until a favored concept emerged. Two of the major design constraints for this year's ROV were size and weight. Careful planning and design addressed the size restriction. Meeting the weight requirement proved to be much more difficult. In order to meet the target weight of 17 kg, it was necessary to reduce the weight of the core components used on Rovotics 2015 model, *Stingray*. Replacing these core components with lighter-weight alternatives reduced the weight of the core design to 8 kg, 47% of the target weight. (Figure 4).

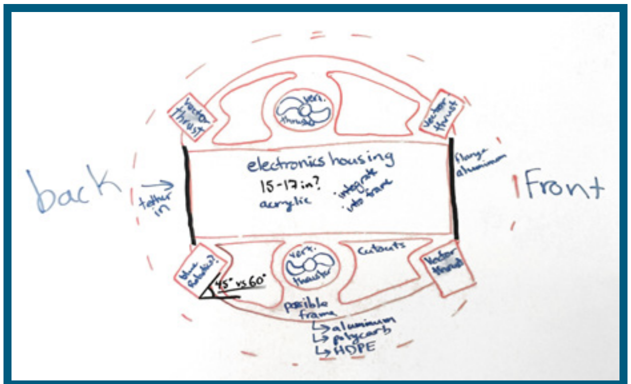


Figure 2. Conceptual whiteboard design of Cuttlefish.

Figure 3. Proof of concept design using PVC parts and wood cutouts.

Next, component designs were rendered digitally into Computer Aided Design (CAD) files using either SolidWorks or DraftSight (see cover page for full vehicle rendering). The CAD files were prepared for machining by converting them into Drawing Exchange Format (DXF) files for our CNC mill, .x3g files for our 3D printer, or detailed work orders for manual manufacturing.

Core Components		*2016 Cuttlefish*			*2015 Stingray*		
Name	Quantity	Model	Component Weight (g)	Total Weight (g)	Model	Component Weight (g)	Total Weight (g)
DC Converters	4	Murata DC-DC	150	600	Zahn DC-DC	315	1,260
Thrusters	6	BlueRobotics T100	294	1,764	Seabotix BT100	709	4,254
ESCs	6	BlueRobotics ESC	27	162	Sabertooth 2x25	90	540
Tether	1	*Cuttlefish*	4,200	4,200	*Stingray*	6,123	6,123
Pressure Housing	1	*Cuttlefish* (Acrylic)	1,338	1,338	*Stingray* (Aluminum)	10,325	10,325
		Total Weight		**8,064**			**22,502**
		Percentage of target ROV weight (17kg)		**47%**			**132%**

Figure 4. Weight comparison of core components on Cuttlefish vs. last year's Stingray.

For parts targeted for production on the CNC mill, the CAD models were converted into a Computer Aided Manufacturing (CAM) format, SheetCam. Using SheetCam, Rovotics engineers generated the "G-Code" toolpath files from the drawings, which were then loaded into the "Mach 3" machine control software. Mach 3 controls the CNC mill movements based on the G-Code, allowing the machinist to quickly and accurately produce parts.

For manual manufacturing, a new technique was employed in the production of the upper and lower frame components. 1:1 paper patterns of the components were printed out, adhered to polycarbonate sheets, and cut out with a bench scroll saw. Detail finishing was completed using an oscillating spindle sander. This method proved to be very accurate and cost effective, allowing the design and manufacturing departments to progress through three frame revisions as the design of the frames was optimized (Figure 5). Rovotics also considered waterjet cutting the frame components from aluminum stock, but ultimately decided against this due to the cost of waterjet cutting and the weight of the aluminum.

Figure 5. Rovotics' three-step manual frame manufacturing process: preparing a 1:1 paper platform pattern (left); cutting a polycarbonate platform based on the pattern with a bench scroll saw (center); and detail sanding the platform with an oscillating spindle sander (right).

B. Design Evolution

This year, the design philosophy at Rovotics required a fundamental change due to the weight restriction in this year's mission. Design was driven not only by function, cost, and manufacturability, but also by buoyancy. Although this added a layer of difficulty to the process, the result is a new systematic design methodology that will change future Rovotics products.

Cuttlefish is the next step in the evolution of Rovotics' product line. Designed from the ground up specifically for space exploration, *Cuttlefish* benefits from the company's experience in designing vehicles for subsea pipeline inspection and repair, offshore oilfield maintenance, scientific exploration in the Arctic, and operation in wave surges and powerful currents.

A vast majority of the components that make up *Cuttlefish* and its associated tools are original designs created by Rovotics' engineering staff and are manufactured in-house. Although *Cuttlefish* is not based on any previous design, some essential components, such as its custom switching video boards, are updated designs from previous company developments. Details on these proprietary components and other systems are described in the following sections.

Every manufacturer must consider "make/buy" decisions during the product development process. Components that can be efficiently produced in-house with available capabilities are generally more economical to make. Certain services and components requiring specialized manufacturing processes that exceed Rovotics' manufacturing capability are outsourced, such as the fabrication of printed circuit boards and large scale printing. Commercially-sourced major components are limited to thrusters, speed controllers, servos, cameras, and microcontrollers.

Similarly, efficiency may be gained by reusing certain proprietary components or designs that were developed on previous projects. With the exception of the Tether Control Unit (TCU), all components used on *Cuttlefish* are new this year. The TCU was originally built by Rovotics with the expectation that it would be reused each year as long as MATE power control requirements remain unchanged. By reusing the TCU, Rovotics stayed within budget and saved manufacturing time.

C. Frame

Designed to be lightweight and serviceable without sacrificing rigidity, *Cuttlefish's* frame consists of two clear polycarbonate platforms connected by four coated steel struts designed to function as ballast. The simple design of the frame allows repairs to be made quickly using common tools. Each platform serves as a flat working area and has cutouts that reduce drag while increasing serviceability. The top platform integrates the electronics housing and all six thrusters into one rigid piece, while the bottom platform holds all of *Cuttlefish's* tools (Figure 6). The platforms are connected by four screws and one SubConn electrical connector, making them easily separable. This allows for different departments to work on each frame simultaneously without interfering with each other, reducing servicing time.

Figure 6. Cuttlefish's frame, fully assembled, with its electronics and thrusters on the top platform and tools on the bottom.

D. Thrusters

Cuttlefish uses six Blue Robotics T100 thrusters. Rovotics' previous ROV designs have used SeaBotix thrusters, but a design change was made due to the new size and weight requirements. Figure 7 provides a comparison of the SeaBotix BT150[9] and the Blue Robotics T100[1] thrusters. For comparable thrust profiles, the Blue Robotics T100 thruster is 41% of the weight of the SeaBotix BT150. Each T100 thruster on *Cuttlefish* was continuously stress tested for an average of two hours, well in excess of expected mission times, to ensure proper thrust capabilities as well as compatibility with our voltage converters. Additional testing was conducted to ensure that *Cuttlefish* could manage the larger power requirement of the new T100 thrusters.

	Dry Weight	Wet Weight	Power	Forward	Reverse
Blue Robotics T110 Thruster	295 g	120 g	135 W	2.36 kgf	1.85 kgf
Seabotix BT150 Thruster	709 g	340 g	80 W	1.9 kgf	1.75 kgf

Figure 7. A comparison of the specifications for Blue Robotics and SeaBotix thrusters.

For horizontal control, four of the six T100 thrusters are mounted at 45° angles in the corners to provide stable vector control, allowing all thrusters to contribute to the total propulsion in the cardinal directions, minimizing flow interference with accessories in the center of the vehicle. For example, comparing four 45° thrusters with two parallel thrusters in each direction shows that the 45° mounting results in greater thrust [4 * COS(45) = 2.8x thrust vs. 2x thrust]. The remaining two thrusters are used for vertical control.

Each T100 thruster weighs 295 g in air and produces a maximum forward and reverse thrust of 2.36 kgf and 1.85 kgf, respectively. The T100 thrusters have an operating voltage of 12 V and a maximum operating current of 12.5 A, well within *Cuttlefish's* power budget.

Figure 8 is a chart detailing the extensive testing of *Cuttlefish's* thruster voltage converters. As shown in blue, the voltage converters never reach the manufacturer's maximum operational temperature, even with two T100 thrusters running at full speed on one voltage converter for a period of 18 minutes, shown in green.

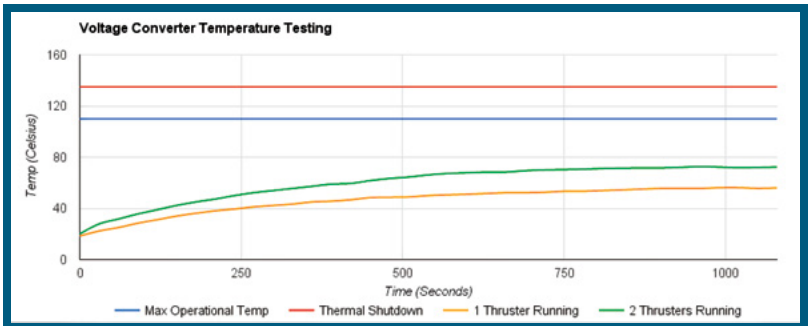


Figure 8. Rovotics' test data showing the voltage converters operating below thermal shutdown with two thrusters at full thrust.

E. Buoyancy

By applying Archimedes' Principle[6], the design team determined that *Cuttlefish* could have a maximum displacement of 17,000 cm³. Given this displacement and the density of water at 1 g/cm³, our maximum weight would be 17 kg for a neutrally buoyant ROV. At over 7,000 cm³, the watertight acrylic electronics housing is *Cuttlefish's* single largest displacement component, and serves as the buoyancy device. This dual-purpose design allows *Cuttlefish* to meet size restrictions by eliminating the need for a separate styrofoam buoyancy device. Because the housing creates more buoyancy than *Cuttlefish* requires, steel was selected as the material for the four struts that connect the top and bottom platforms to provide ballast, and their size was adjusted to achieve nearly neutral buoyancy.

Cuttlefish's tether achieves neutral buoyancy by means of aluminum air chambers attached at evenly-spaced increments along its length. These chambers, which have been used successfully on previous generations of Rovotics' products, are proven to be incompressible at depths exceeding 13 m.

F. Electronics Housing

Cuttlefish's main electronics are housed in a 16.51 cm x 38.10 cm (6.5 in OD x 15 in) outside diameter acrylic tube sealed with a custom welded aluminum flange at each end. The flanges are fixed in place by two bayonet seals, and the polycarbonate endcap plates create o-ring face seals with the outside of each flange. Acrylic and polycarbonate were chosen over aluminum because of their high-strength, light-weight, and nearly-neutrally-buoyant properties. The housing's cylindrical shape has a low drag coefficient, which allows *Cuttlefish* to efficiently move through water. Additionally, acrylic is transparent, allowing for visual inspection of components and status lights within the housing as part of the pre-launch safety checklist and post-mission structural inspection.

The polycarbonate endcap plates have Blue Robotics and SubConn connector penetrations, which allow for communication, power, thrusters, and accessories to connect to the internal electronics. One of the plates has connector penetrations coming from the tether and is permanently attached to the electronics platform so that when the plate is removed, the electronics come with it. The other plate is fitted with a vacuum test plug for pre-mission seal testing to verify hull integrity. This plate is fixed and has connector penetrations that lead to the rest of the ROV and are integrated to male pin connectors that connect to female banana jacks on the removable electronics platform (Figure 9). As the internal electronics assembly is inserted and removed, it aligns to connect and disconnect with these removable connectors with the assistance of a large alignment pin. The endcap design can be disassembled, allowing full access to the electronics system by removing four nuts on each end of the acrylic tube. In addition, the housing is lined with RGB LED lights which can be used to indicate operational status.

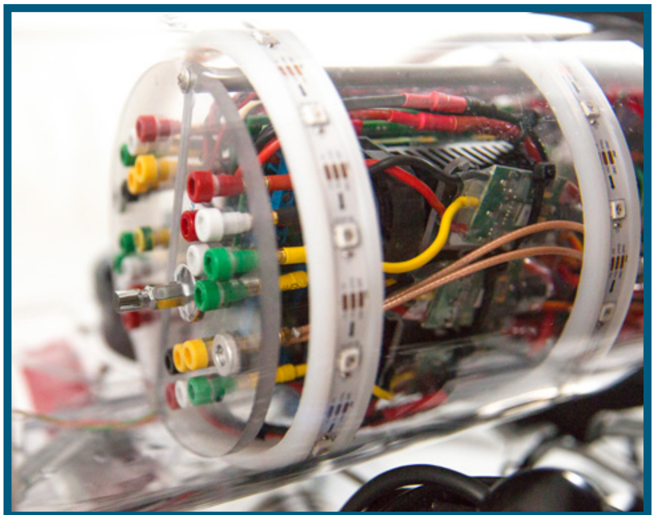


Figure 9. Electronics housing showing female banana connectors on the bulkhead.

While its main purpose is to keep the electronics dry, safe, and serviceable, the entire housing assembly is an integral component of *Cuttlefish's* frame as well as *Cuttlefish's* source of buoyancy, as described in the buoyancy section above.

G. Electrical Systems

Tether Control Unit (TCU)

The TCU is a hub for power, communications, and video distribution for *Cuttlefish*, and is a critical safety subsystem. The copilot can monitor vehicle status via the TCU's sensor and monitor display, as well as shut down ROV power in case of an emergency. For cost efficiency, the majority of *Cuttlefish's* TCU was reused from last year's ROV design, but has been modified to accommodate a mounted 12 V monitor for displaying live video feeds from the ROV (Figure 10). This TCU design has proven to be durable, easy to ship, and allows the team to quickly mobilize and demobilize during product demonstration.

Figure 10. Cuttlefish's TCU and incorporated electronics.

As illustrated in the Systems Interconnect Diagram (SID) (Figure 11), MATE-supplied power for the ROV system (48 VDC) enters the TCU through a 40 A fuse calculated to 150% of the max ROV current draw as described in the competition manual (for ROV system protection), a 30 A switchable circuit breaker (which doubles as a redundant power switch for added safety), and the primary power switch. Analog voltage and current meters on the TCU control panel allow the copilot

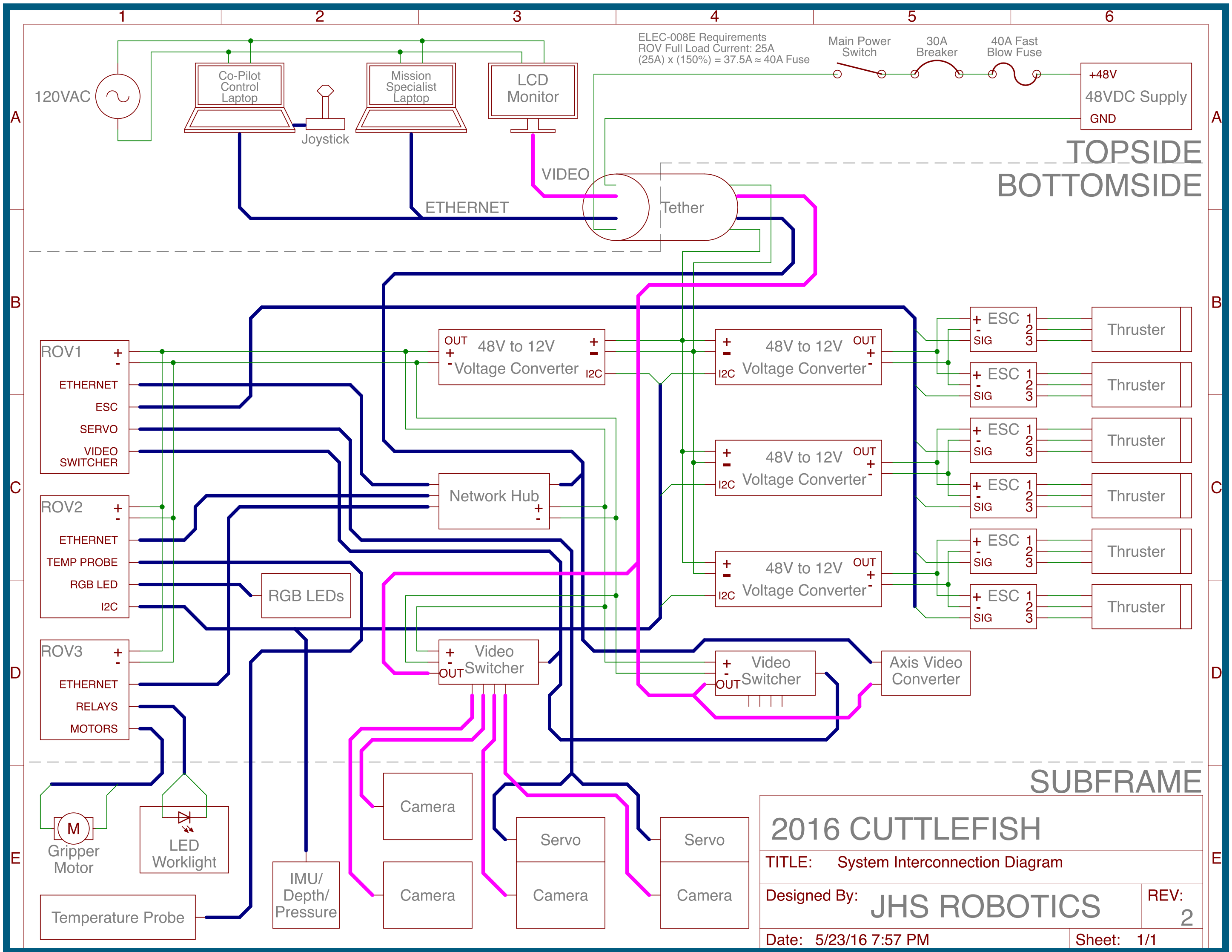


Figure 11. Rovotics Systems Interconnect Diagram (SID).

to monitor power consumption to ensure that *Cuttlefish* is operating properly and under safe conditions. In the event of a critical system failure, the meters provide vital information on the nature and source of the problem, allowing for faster troubleshooting.

The TCU video system receives two video lines from the ROV: one goes to an Axis Internet Protocol (IP) video converter, and the other to an integrated monitor. The Axis video converter can stream video to any IP-enabled device, such as an iPhone, Android, or tablet, allowing multiple users to view current operations, and enables the operations manager to assess coral condition. The integrated monitor allows the copilot to monitor the accessory video feed from the TCU control panel.

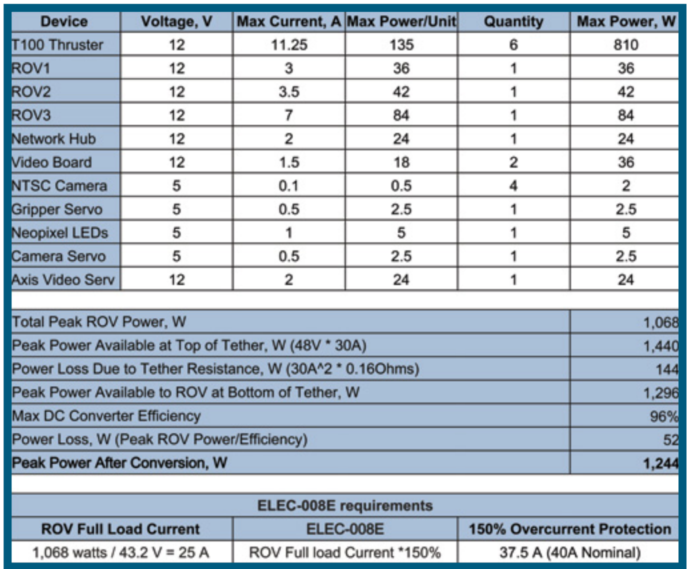
Tether

Cuttlefish's newly-developed tether uses a method of construction proven reliable on previous Rovotics products. The tether shelters multiple communication cables within a single flexible sheathing to prevent tangles and keep the cables organized and protected.

The tether contains one Category 5 Ethernet (Cat5e) cable, a 2/12 American Wire Gauge (AWG) high-performance silicone-insulated DC power line, and two 735A coaxial video cables. The Cat5e carries data via the Ethernet protocol from the ROV to the TCU. Cat5e was chosen over alternatives such as coaxial, Cat4, or Cat6a cables based on its ability to resist interference, cost, and flexibility. The Ethernet cable is split into two four-pin terminations which can each plug into the TCU. Both terminations use the T568B standard for Cat5e cables. One termination is dedicated to general communication with *Cuttlefish's* microcontrollers. The other termination is used for receiving data from an Axis video converter, which requires a large amount of bandwidth. The 735A coaxial video cables were chosen for resistance to interference, small diameter, and 75 ohm impedance for camera compatibility. The power lines are a sufficient gauge to minimize voltage drop over the 23 m tether while maintaining flexibility. The power cable is sized for the maximum fuse-limited current draw of 30 A. The power cable has a calculated resistance of 0.16 ohms with a maximum voltage drop of 30 A * 0.16 ohms = 4.8 V. This gives *Cuttlefish* a minimum operating voltage at the ROV of approximately 43.2 V, which is above the 40 V minimum cut-off voltage of the DC-DC voltage converters. The 2/12 AWG power lines were upgraded this year to high-performance, silicone-insulated, stranded-core wire, providing increased flexibility and a 50% mass reduction to *Cuttlefish's* main power conductor. 12 gauge silicone wire measures 42.3 grams per meter while standard 12 gauge copper wire measures 80 grams per meter. Previously, the tether weighed 6.6 kg, but with a reduction in the mass of the power conductor, the tether now weighs 4.2 kg, creating a 37% total weight reduction for the same length of tether.

Electronics

Cuttlefish's electronics are organized into two sections. At the forward section of the ROV are the microcontrollers, video switching boards and low voltage components. Located in the aft section of the ROV are the DC-DC voltage converters and Electronic Speed Controllers (ESC)s. This separation helps provide electronic noise isolation for the video switching boards.



Device	Voltage, V	Max Current, A	Max Power/Unit	Quantity	Max Power, W
T100 Thruster	12	11.25	135	6	810
ROV1	12	3	36	1	36
ROV2	12	3.5	42	1	42
ROV3	12	7	84	1	84
Network Hub	12	2	24	1	24
Video Board	12	1.5	18	2	36
NTSC Camera	5	0.1	0.5	4	2
Gripper Servo	5	0.5	2.5	1	2.5
Neopixel LEDs	5	1	5	1	5
Camera Servo	5	0.5	2.5	1	2.5
Axis Video Serv	12	2	24	1	24

Total Peak ROV Power, W	1,068
Peak Power Available at Top of Tether, W (48V * 30A)	1,440
Power Loss Due to Tether Resistance, W (30A^2 * 0.16Ohms)	144
Peak Power Available to ROV at Bottom of Tether, W	1,296
Max DC Converter Efficiency	96%
Power Loss, W (Peak ROV Power/Efficiency)	52
Peak Power After Conversion, W	**1,244**

ELEC-008E requirements		
ROV Full Load Current	**ELEC-008E**	**150% Overcurrent Protection**
1,068 watts / 43.2 V = 25 A	ROV Full load Current *150%	37.5 A (40A Nominal)

Figure 12. Cuttlefish's maximum power budget.

The power budget was developed by looking at the maximum current draw of all the components. The maximum load was determined by referring to the voltage converter's absolute maximum ratings. Based on the power budget developed (Figure 12), *Cuttlefish's* power delivery system is robust and capable of meeting the sustained needs of the ROV, even under the most demanding conditions. *Cuttlefish* is equipped with four 600 W Murata DC-DC voltage converters[5] mounted on custom Rovotics circuit boards, which lower the 48 V input from the tether to 12 V for system use. It does so at high efficiencies, which exceed 95% under normal operating conditions. Each board has a maximum output of 50 A and features active cooling with the use of fans. Three of the power conversion boards are allocated to powering the six thrusters, and the fourth board is allocated to powering the microcontrollers, ethernet hub, Axis video encoder, and cameras. The Axis video encoder allows certain camera feeds to be accessed easily through multiple topside computers, which allows the mission specialist to analyze the images coming from the cameras.

Cuttlefish's control and communications electronics consist of three custom microcontroller systems, two custom video switching boards[4], four National Television System Committee (NTSC) video cameras (with the capacity for up to eight), an ethernet hub, and an Axis IP video converter. Each microcontroller (ROV1, ROV2, and ROV3) consists of an Arduino Ethernet Microcontroller with a custom-designed shield suited for the specific tasks the controller is responsible for. All three microcontroller systems have ethernet capabilities and are linked to an ethernet hub so that all communications between the microcontrollers and topside are consolidated into one ethernet cable.

ROV1 is dedicated to navigation and video control, and communicates with the ESCs, camera servos, and video switchers. It sends pulse width modulated signals to the ESCs to control the speed and direction of *Cuttlefish's* six thrusters. It also sends binary signals to the video switcher boards to select their input feeds. Each video switcher board can choose from one of four different inputs, which allows the pilot to switch between NTSC camera feeds.

ROV2 is dedicated to telemetry feedback and sensory measurements. It takes readings from an internal temperature and humidity sensor, an external temperature sensor, and an inertial measurement unit (IMU). It also receives data feedback from the four DC-DC voltage converter boards. Using the data from the voltage converters, the copilot can monitor the status of the converters by reading electric characteristics such as output voltage, input voltage, output current, and temperature. For safety, in the event of a critical electrical failure, such as a short circuit or power surge, the voltage converters automatically shut down to prevent further damage to the system. ROV2 also provides power and data output to *Cuttlefish's* individually addressable RGB LEDs.

ROV3 is dedicated to accessories, and is equipped with six 12 V solid state relays and two 12 V bi-directional motor drivers. External devices such as LED lights and extra motors can be driven directly from the board, which allows for the attachment of extra grippers and other accessories.

Internal and external telemetry is provided from a wide array of sensors, supplying *Cuttlefish* with mission-critical data in real time. The internal temperature and humidity sensor allows the pilot to monitor the environmental conditions inside the electronics housing, alerting the pilot to overtemperature conditions and water leakage. The external temperature probe allows the pilot to take temperature measurements of the surrounding environment. The OpenROV IMU/Compass/Depth[18] module is a single device that integrates multiple sensors onto a single board with one communication interface. The purpose of the IMU is to provide inertial and positional feedback from *Cuttlefish*, which can be used for precision control of *Cuttlefish's* movements.

Submersible Connectors

Cuttlefish uses both Blue Robotics cable penetrators and SubConn wet-mateable electrical connectors to connect the main electronics housing to accessories and the tether. When deciding between the Blue Robotics cable penetrators and the SubConn connectors, the type of connection required was taken into account. The most notable difference between these connectors is that the SubConn connector is separable and the Blue Robotics connectors create a permanent cable penetration through the bulkhead. For serviceability, the tether connections and accessory connector on the ROV use SubConn connectors. Devices that are permanently attached to the ROV use the Blue Robotics cable penetrator.

H. Software

Overall

Cuttlefish's software consists of two parts: topside code and bottomside code. The topside code, CuttleCode, operates on the copilot's laptop. The bottomside code is the software on the microcontrollers within *Cuttlefish*. For software flowcharts, see Appendix A.

Topside

CuttleCode is the latest version of Rovotics' topside control software. Written in C++, using QT Creator as the Integrated Development Environment (IDE), CuttleCode features an intuitive Graphical User Interface (GUI) that allows the copilot to easily control important operations and emergency functions on the ROV, monitor communications, and display sensor data. CuttleCode provides vital telemetry and sensor data pertaining to the mission. It runs on a laptop with a Linux operating system and communicates with a Logitech joystick connected to the laptop's USB port. CuttleCode receives data from the joystick and interprets it using a vector control algorithm. The algorithm takes the joystick data and determines the necessary speed and direction of each of *Cuttlefish's* six thrusters. The algorithm features proportional control, which makes small, precise movements possible while simultaneously allowing for the large amounts of thrust required for traveling long distances. A user-adjustable dead zone prevents unintentional movements due to minute changes in the joystick's position. After the values for speed and direction are determined, they are sent down to *Cuttlefish's* bottomside. Hotkeys on the laptop's keyboard allow the copilot to easily control specific functions on the ROV.

CuttleCode, along with its developer tools can now be deployed instantly on a virtual machine, providing needed redundancy to the control laptop. This new approach saves huge time and effort for software engineers by avoiding the setup and troubleshooting of system environment issues during development.

Bottomside

Cuttlefish's three microcontrollers, ROV1, ROV2, and ROV3, each have their own independent code that allows them to complete their specific tasks. The microcontrollers use a User Datagram Protocol (UDP) connection over ethernet to CuttleCode. For safety, in the event of communication loss, *Cuttlefish's* controllers shut down and enter into safe mode until the connection is reestablished. In safe mode, thrusters, motors, and all other accessories are disabled. For troubleshooting, all packets that are received by the controllers are echoed back up to topside.

ROV1's software receives UDP packets that contain values to control *Cuttlefish's* thrusters, camera servos, and video switchers. These components perform real-time critical functions. To reduce latency, functions which are not real-time critical are the responsibilities of ROV2 and ROV3.

ROV2's software reads data from *Cuttlefish's* external temperature probe, internal temperature and humidity sensor, and the ROV2's software also receives packets from topside which contain values to control *Cuttlefish's* smart RGB LEDs. The software controls multiple lighting patterns which can be used for system diagnostics.

ROV3's software receives packets from topside which contain values to control up to six 12 V solid-state relays and two bi-directional motor drivers. The copilot can use CuttleCode's GUI to toggle lights and motors attached to ROV3.

I. Tools

Depth Sensor

Cuttlefish is equipped with a barometric depth sensor. Previous Rovotics' products have used depth sensors with a resolution up to 10 cm. To improve sensor accuracy, the company has selected the OpenROV IMU/Compass/Depth module[8] for *Cuttlefish*. The high-resolution pressure sensor will resolve pressure to 20 Pa, which translates to a depth resolution of 0.2 cm. This depth sensor module was chosen because it also includes an accelerometer, gyroscope, and geomagnetometer which communicate using an Inter-Integrated Circuit (I2C), only requiring a two wire bus for communicating to all four sensors. The depth sensor is calibrated by comparing it to a known barometric pressure when the ROV is out of the water. Rovotics designed a compact housing to provide protection for this critical sensor array. Due to the complex geometry of the housing, it is 3D printed with Acrylonitrile Butadiene Styrene (ABS) plastic, with vents leaving the gel sensor exposed to the environment, yet protected.

Cameras

Two tilting cameras with 170° wide-angle lenses assist with pilot navigation. Each camera is mounted on a 90° vertical servo motor and made waterproof with a bayonet-sealed cast acrylic tube (Figure 13). Each camera, along with the servo mount, gives the pilot 260° visibility. The camera pods are fifth-generation renditions of a successful Rovotics product that has been refined over the past four years. The newest version, found on *Cuttlefish*, is more compact than previous versions and is constructed from easily-interchangeable parts, all produced by Rovotics. In addition to the two tilting cameras, *Cuttlefish* has two stationary task-specific cameras mounted in custom-designed Rovotics' housings, which are used to view tool operations.

Figure 13. Cuttlefish navigation camera mounted on a servo motor and sealed in its housing.

LED Work Light

For operating in low light conditions, a commercially-available light was waterproofed with clear epoxy. The light is inexpensive, readily available, and can illuminate a large area around *Cuttlefish*, which is ideal when paired with our wide-angle camera system. A cool-white LED was selected for minimal color distortion in water.

RGB LEDs

Four circular rings of individually-addressable RGB LEDs in the electronics housing provide lighting to other areas around *Cuttlefish* not illuminated by the LED work light. In addition to illumination, the LEDs function as a visual indication of *Cuttlefish's* operational status. Pre-programmed light patterns and colors can be used in place of verbal communication between the deck crew and pilot.

Gripper

Cuttlefish is equipped with a custom under-articulated gripper designed to be multifunctional and adaptable to different-shaped objects. The gripper is machined from aluminum halves that form internal channels when put together. These channels act as pathways for four thin cables that drive the gripper open and closed. A waterproofed servo is attached to a winch that drives the cables.The cables utilize a double-joint system that allows the gripper to adapt to any object it closes on. The tips of the gripper are sheathed in custom-molded rubber to maximize the gripper's traction while cushioning objects it clamps on to.

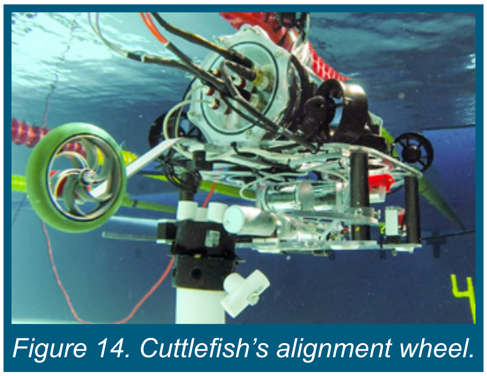


Figure 14. Cuttlefish's alignment wheel.

Alignment Wheel

During testing, it was difficult for pilots to achieve simultaneous vertical and horizontal alignment when inserting connectors to receptacles. A retractable alignment wheel (Figure 14) was added to the front of *Cuttlefish* to provide vertical stability when completing tasks. It is made up of a wheel attached to a retractable aluminum extension.

Bolt Stands

Two pre-aligned wellhead bolt stands on the front of *Cuttlefish* are oriented for horizontal bolt insertion (Figure 15). The stands provide very little resistance once the bolts have been inserted into the wellhead flange, aiding with this delicate operation. This is an advantage over using a gripper that only allows for one bolt to be picked up at a time.

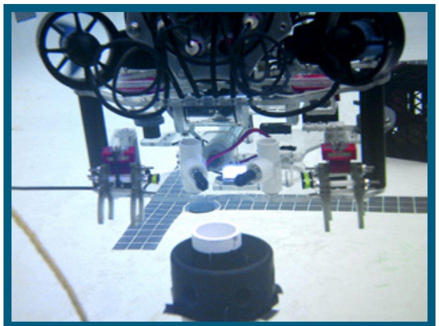


Figure 15. Bolts stands holding two bolts as Cuttlefish approaches the flange.

Multi-Purpose Hooks

Rovotics custom designed adjustable multi-purpose hooks for *Cuttlefish*. The hooks are made out of PVC Type 2, which is lightweight, corrosion resistant, and readily available. The height and angle of the hooks can be manually adjusted by the deck crew. The simplicity of the design allows them to be used in multiple tasks.

Temperature Probe

An external remote temperature probe is housed in a cone, providing a captive space for venting fluids. Capturing fluids in this confined space achieves stable readings for temperature ranges between -55°C to +125°C with a ±0.5°C accuracy[2]. Rovotics has had great success using this type of temperature probe on previous ROVs.

Figure 16. A Rovotics-designed vertical lifting clamp.

Vertical Lifting Clamps

Cuttlefish is equipped with two vertical lifting clamps (Figure 16). Each clamp is fully-mechanical, using a rubber band tightly wound around two pins. Rubber bands were chosen because they are inexpensive, highly elastic, and easily replaceable. The clamp is open just enough to snap over and secure the oil sample. When the clamp is lifted, its gripping tongs apply pressure against each other - the heavier the object, the greater the clamping pressure. This tool is an improvement upon a design from last year's ROV, where it was used to pickup a segment of pipeline.

Magnetic Retriever

A cluster of five powerful neodymium magnets provide 10 kg of pickup force for ferrous objects like the wellhead bolts. This is an adaptation of a previous design that was successful in retrieving magnetic objects.

J. Product Demonstration

Task 1 - Outer Space: Mission to Europa

To determine the thickness of the ice and the depth of the ocean, the pilot aligns a visual reference point on *Cuttlefish* to the depth markers denoting the bottom of the ice sheet and seafloor (Figure 17). At each marker, the copilot takes note of the depth sensor's measurement and then calculates the thickness of the ice and the depth of the ocean.

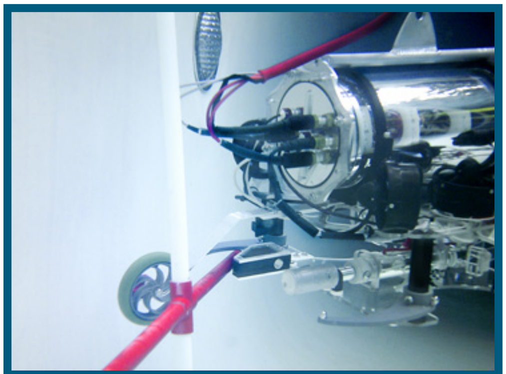


Figure 17. Cuttlefish aligning with a depth marker.

Cuttlefish uses a temperature probe housed in a cone to provide a captive space for the venting fluid. To measure the temperature of venting fluid, the pilot positions the cone over the venting fluid while the mission specialist records the temperature. *Cuttlefish* can actively log temperature and depth together, developing a thermal profile as it descends into the depths.

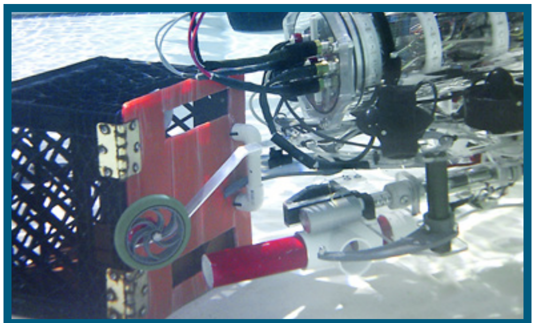


Figure 18. Cuttlefish opening the door to the port on the power and communications hub.

Four steps are required to connect the Environmental Sample Processor (ESP) to the power and communications hub: retrieving the ESP's cable connector from the elevator, laying the ESP cable through three waypoints, opening the door to the port on the power and communications hub (Figure 18), and inserting the cable connector into the port. To accomplish these steps, the pilot first retrieves the ESP's cable connector using the gripper, then lays the cable through three waypoints by dragging it along the seafloor behind the ROV. Multiple camera feeds confirm that the cable has been successfully laid through each waypoint. Next, the pilot uses the multi-purpose hook to open the door on the power and communications hub. Finally, the pilot drives forward to insert the ESP cable connector into the port. An alignment wheel keeps *Cuttlefish* aligned, making this operation quick and simple for the pilot.

Task 2 - Inner Space: Mission-Critical Equipment Recovery

To position the eight CubeSats so that the serial numbers are visible, the multi-purpose hook is used to flip them to the correct side. In order to flip a CubeSat, the pilot first positions the hook into an opening in the CubeSat, then maneuvers *Cuttlefish* to flip the CubeSat over (Figure 19). After the CubeSats with the correct serial numbers are identified, they are picked up with the hook and placed into the collection basket.

Figure 19. Cuttlefish flipping a CubeSat.

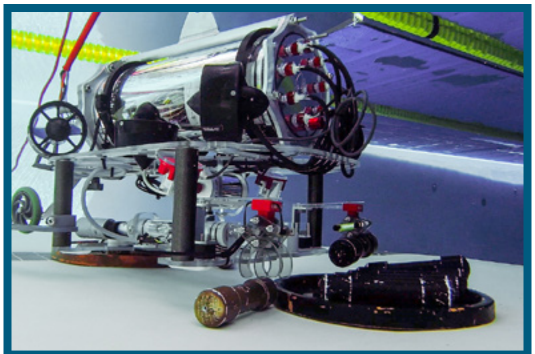


Figure 20. Cuttlefish retrieving an oil sample.

Task 3 - Inner Space: Forensic Fingerprinting

When ready to retrieve the oil samples from the seafloor, *Cuttlefish* lowers itself over a selected sample, attaching one of the vertical lifting clamps to the sample (Figure 20). The process is repeated with the second vertical lifting clamp and sample. Once samples from both oil mats are attached, *Cuttlefish* brings them to the surface to be analyzed by the deck crew. The vertical lifting clamps and samples are easily removed from the ROV with quick-release tabs. Once on deck, the mission specialist opens the oil samples and analyzes the gas chromatographs to determine the origin of each oil sample.

Task 4 - Inner Space: Deepwater Coral Study

Cuttlefish's LED work light provides cool-white illumination for accurate color representation when photographing coral colonies. Its cameras are attached to an onboard IP video streaming converter. Real-time video is available to any desktop browser running on *Cuttlefish's* network. A mission specialist on deck captures screenshots of two coral colonies from the video feed. While the pilot continues working, the mission specialist assesses the condition of the coral colonies relative to previous years, using the coral colony handbook.

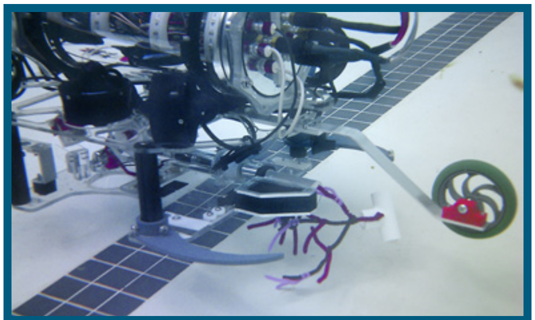


Figure 21. Cuttlefish retrieving a coral sample.

The coral samples are retrieved from the seafloor (Figure 21) and returned to the surface using the gripper. The pilot maneuvers the ROV to align the gripper with two coral samples. Once aligned, the electrically-powered gripper closes on both coral samples, and *Cuttlefish* returns them to the surface.

Task 5 - Inner Space: Rigs to Reefs

To install a flange to the top of the wellhead, the pilot maneuvers the ROV to the elevator and aligns the gripper to the flange. Once the flange is aligned, the gripper closes, capturing it. The pilot then moves to the wellhead and aligns the flange with the top of the wellhead. The flange is placed on the wellhead and released by the gripper.

To secure the flange to the wellhead, the pilot retrieves the wellhead bolts from the elevator using the magnetic retriever located beneath the lower ROV platform. The next time *Cuttlefish* surfaces, the deck crew removes the bolts from the magnetic retriever and places two of them into the bolt stands located on the front of the ROV. Later in the product demonstration, the pilot aligns the bolt stands on *Cuttlefish* to the holes in the flange and maneuvers the ROV to insert the bolts. Removing the bolts from the magnetic retriever and placing them in the bolt stands by hand reduces the complexity of the required tools and the weight of the ROV.

To install the wellhead cap over the flange, the pilot maneuvers the ROV to the elevator and aligns the gripper to the wellhead cap. Once the cap is aligned, the gripper closes, capturing it. The pilot then moves to the wellhead and aligns the wellhead cap with the top of the wellhead. The cap is placed on top of the flange and released by the gripper (Figure 22).

After installing the wellhead cap, the ROV returns to the elevator and aligns the gripper with another bolt. Once aligned, the gripper closes, capturing the bolt. The pilot then moves the ROV to the cap and inserts the bolt by lowering it into a port on the wellhead cap. The process is repeated for three more bolts to secure the wellhead cap to the flange.

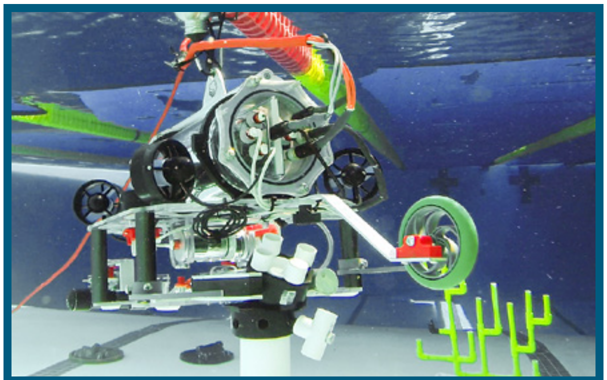


Figure 22. Cuttlefish installing the wellhead cap.

K. Troubleshooting and Testing Techniques

Rovotics began the troubleshooting process by identifying and isolating the problem through Root Cause Analysis (RCA)[3]. Small-scale component tests were run until the problem was located. Company employees then brainstormed various ways to remedy the problem before deciding on a course of action based on factors such as size, weight, simplicity, cost, and time required.

The entire vehicle was tested in a full-scale “dry run” in which the vehicle was powered and bench tested in a controlled environment to ensure safety. The vehicle was then placed into a practice tank for several rounds of integration testing to determine its center of buoyancy, adjust camera positions, and find the vehicle’s limits. The vehicle was also specifically tested under adverse environmental conditions to simulate the parameters of the product demonstration.

In order to meet the challenges of Mission to Europa, Rovotics chose several new components to meet the size and weight requirements. To expose potential problems, new components such as the thrusters, ESCs, and DC-DC voltage converters were subjected to hours of extensive testing to determine performance, behavior, and reliability.

Testing provided valuable data about the new components, allowing Rovotics to improve *Cuttlefish’s* performance. Through testing, it was discovered that running a thruster at full power for 15 minutes and simultaneously reversing the direction of the motor caused the motor bearing to misalign and the motor to seize. As a result, the control system was programmed to limit the motors to 75% of their maximum power to avoid producing excessive heat.

Components were tested in simulated deep water environments. *Cuttlefish* was placed in a pool at a depth of 4 m with negative pressure inside of the electronics housing to create a simulated pressure of 12 m. Cameras were tested in a chamber pressurized with water from a garden hose. This simulated the placement of cameras at a depth of 12 m. A mathematical simulation was also performed using Under Pressure Design Software[10], which resulted in a failure depth of 75 m.

III. Safety

A. Company Safety Philosophy

Employee safety is a Rovotics core value and our company's highest priority. We believe that all employees have the right to a safe work environment and that all accidents are preventable. Our rigorous training, safety procedures, and safety protocols allow us to avoid accidents preemptively.

B. Lab Protocols

Since safety is Rovotics' core value, specific safety protocols are implemented while working in the lab (Figure 23). Rovotics uses Job Safety Analysis (JSA) forms for employees to create and review before performing risky operations. New forms are created whenever a new manufacturing process is introduced. The company's handbook is used to train everyone on safety practices such as back safety, electrical safety, hazardous materials handling, housekeeping, and tool safety. Readily accessible Material Safety Data Sheets (MSDS) are available for every product used in Rovotics production.

Figure 23. Engineers using personal protection equipment while operating machinery.

Rovotics' lab facility features a chemical vent hood so that the soldering of electronics can be completed without fume exposure. The work area maintains a negative pressure relative to the room and the fumes are carried up ducting to a roof-mounted vent.

C. Training

A peer-to-peer system is used for the safety training of new employees. Newly-hired employees observe veteran employees operating tools and machinery. Veteran employees then closely supervise and mentor new employees as they begin to use the equipment. After new employees demonstrate safe and proper operating practices, they can work independently. All employees police each other at all times to make sure that everyone follows established safety protocols.

D. Vehicle Safety Features

Cuttlefish contains numerous safety features designed to keep the crew, ROV, and work environment safe during operation. Handles on the ROV top platform and struts are clearly labeled for the deck crew to safely use during launch and retrieval of the ROV, preventing injuries to the crew. Various waterproofing techniques ensure all electronics remain dry, protecting both personnel and equipment from short circuits. In the event of leakage, a leak detector monitored by one of the microcontrollers detects moisture and humidity in the electronics housing and alerts the pilot to shut down and return to the surface. The clear acrylic housing allows for visual inspection of the electronics by the deck crew. RGB LEDs on the ROV indicate the current ROV operating status. Yellow lights are an indication that the thrusters have been disabled. The TCU is the main power and control hub for *Cuttlefish*. It has easily-readable analog gauges, allowing the deck crew to quickly determine if power delivery to the ROV is outside safe operating values. If the values are outside of the safe operating range, the TCU has a large power switch to quickly cut power to all bottomside systems.

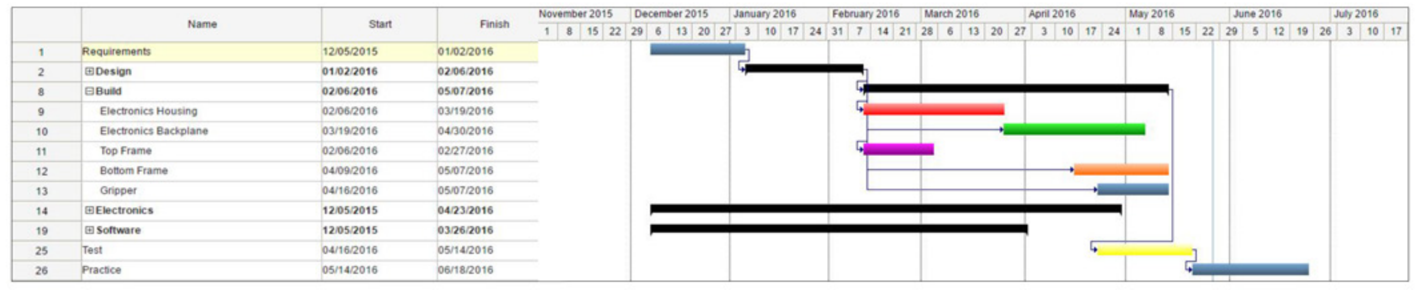
E. Operational and Safety Checklists

Operational safety protocols are dictated by Rovotics' Operational and Safety Checklists (Appendix B) and are closely followed before and after deployment of *Cuttlefish*. The company also follows operational JSAs for ROV launch, recovery, and waterside safety.

IV. Logistics

A. Scheduled Project Management

To complete *Cuttlefish* on time, Rovotics leadership used a Gantt chart to guide their decisions about scheduling and resources. The company CEO delegated responsibility to the heads of each department, who in turn led all department employees in the development of components and deliverables required by MATE. Resources such as the CNC mill and 3D printer were managed with production schedules arranged by component priority. Figure 24 shows one of the Gantt charts used for scheduling.



	Name	Start	Finish
1	Requirements	12/05/2015	01/02/2016
2	⊞**Design**	**01/02/2016**	**02/06/2016**
8	⊟**Build**	**02/06/2016**	**05/07/2016**
9	Electronics Housing	02/06/2016	03/19/2016
10	Electronics Backplane	03/19/2016	04/30/2016
11	Top Frame	02/06/2016	02/27/2016
12	Bottom Frame	04/09/2016	05/07/2016
13	Gripper	04/16/2016	05/07/2016
14	⊞**Electronics**	**12/05/2015**	**04/23/2016**
19	⊞**Software**	**12/05/2015**	**03/26/2016**
25	Test	04/16/2016	05/14/2016
26	Practice	05/14/2016	06/18/2016

Figure 24. Rovotics' Gantt chart for core components.

Each workday started with a kickoff meeting, where the Gantt chart was reviewed and the CEO assigned specific production goals to each employee. At each workday's closing meeting, the daily goals and accomplishments were reviewed again, and the Gantt chart was updated to reflect current production progress. Production goals not met were worked on individually by employees between workdays. Employees that completed their work on time in a skillful and enthusiastic manner were rewarded with more interesting and complex assignments designed to keep them motivated and further develop their skills.

B. Team Organization and Assignments

Rovotics is organized into key functional departments including Design, Manufacturing, Electronics, and Software to produce the final ROV. Reporting directly to the CEO, the functional leads are responsible for implementing their assigned deliverables according to the project schedule. Several key deliverables produced by these departments include the integrated buoyancy designed by Collin Meissner, the lightweight polycarbonate platforms for the frame built by James Whitcomb-Weston, the proportional thruster control software implemented by Cassidy Nguyen, and the custom Arduino shields developed by Andrew Chang.

Throughout the development effort, senior members of each team are also tasked with training junior members. Additionally, Rovotics encourages cross-functional development, giving team members the opportunity and incentive to broaden their skills in other disciplines during down times or when their assigned tasks are complete. By developing their knowledge of fields outside of their primary discipline, team members gain big-picture perspective and are able to provide greater value to the company.

C. Collaborative Workspace

Rovotics used a low-cost cloud storage system, Google Drive, to manage documents and files. Google Drive allowed Rovotics employees to access shared company files, streamlining work both at and away from the lab. Through the use of Google's Apps for Work, employees were able to collaboratively edit documents by allowing multiple employees to edit a file simultaneously. Any newly created or edited files were automatically updated, ensuring uninterrupted access to the most current version of a document.

D. Source Code Management

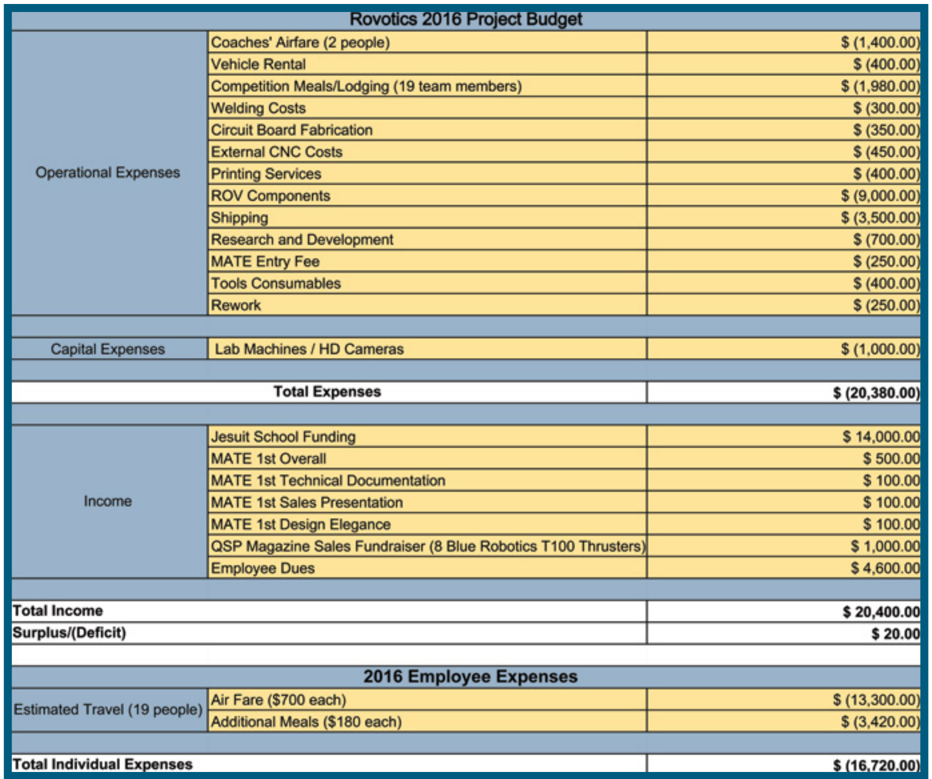
To better manage parallel software development by multiple programmers, Git was used as a Version Control System (VCS). By using a VCS, Rovotics kept track of overall changes to software and managed multiple versions. Git was selected because it is a well-supported and highly-adopted Distributed VCS (DVCS) that provides each individual programmer with a remote and local copy of the full repository instead of a central shared repository. In addition, Git enables critical software branching and merging which is important when multiple people are working on the same file or interdependent files. Should problems arise, Git allows a restoration of previous versions.

For accountability and efficiency, the software lead was responsible for the management of source code files. Any software issues or questions were directed to the software lead and resolved quickly. This required programmers to include detailed commit messages during development.

E. Budget and Project Costing

At the beginning of the season, a budget is prepared by Rovotics with estimated expenses based on the prior year's actual expenses. Employee airfare expense is estimated but listed separately since Rovotics employees pay for their own air travel. Each year, the company also plans for at least one large capital expense to improve lab tools and resources. This year, the company budgeted for the purchase of an oscillating spindle sander, scroll saw, and a high-definition vision system. Due to this year's mission requirements, planned funding for a high-definition vision system was reallocated to the purchase of new light-weight components required for outer-space transport.

Income was estimated from Jesuit High School, fundraisers, employee dues, and donations and added to the budget. See Figure 25 for our complete budget. As a high-school-based company, Rovotics' income is limited and the company must adhere to the budgeted expenditures. On a monthly basis, purchase receipts are entered into a Project Costing sheet and tracked against the budget. The 2016 Project Costing sheet is shown in Figure 26 on the following page.



Rovotics 2016 Project Budget		
Operational Expenses	Coaches' Airfare (2 people)	$ (1,400.00)
	Vehicle Rental	$ (400.00)
	Competition Meals/Lodging (19 team members)	$ (1,980.00)
	Welding Costs	$ (300.00)
	Circuit Board Fabrication	$ (350.00)
	External CNC Costs	$ (450.00)
	Printing Services	$ (400.00)
	ROV Components	$ (9,000.00)
	Shipping	$ (3,500.00)
	Research and Development	$ (700.00)
	MATE Entry Fee	$ (250.00)
	Tools Consumables	$ (400.00)
	Rework	$ (250.00)
Capital Expenses	Lab Machines / HD Cameras	$ (1,000.00)
Total Expenses		**$ (20,380.00)**
Income	Jesuit School Funding	$ 14,000.00
	MATE 1st Overall	$ 500.00
	MATE 1st Technical Documentation	$ 100.00
	MATE 1st Sales Presentation	$ 100.00
	MATE 1st Design Elegance	$ 100.00
	QSP Magazine Sales Fundraiser (8 Blue Robotics T100 Thrusters)	$ 1,000.00
	Employee Dues	$ 4,600.00
Total Income		**$ 20,400.00**
Surplus/(Deficit)		**$ 20.00**
2016 Employee Expenses		
Estimated Travel (19 people)	Air Fare ($700 each)	$ (13,300.00)
	Additional Meals ($180 each)	$ (3,420.00)
Total Individual Expenses		**$ (16,720.00)**

Figure 25. Rovotics 2016 Project Budget.

Rovotics 2016 Project Costing

	Item	Description/Notes	Type	Qty.	Amount	RE-USED	Total
Cuttlefish Core Vehicle Expenses	Arduino Ethernet		Purchased	3	$ 65.00		$ 195.00
	NTSC Cameras	Front and Back ROV cameras	Purchased	5	$ 25.00		$ 125.00
	Inertial Measurement Unit (IMU)	OpenROV IMU/Compass/Pressure	Purchased	1	$ 130.00		$ 130.00
	T100 Blue Robotics Thrusters	New thrusters that help with weight	Purchased	6	$ 110.00		$ 660.00
	Blue Robotics ESCs		Purchased	6	$ 25.00		$ 150.00
	Blue Robotics Cable Penetrators		Purchased	12	$ 4.00		$ 48.00
	IP Video Converter	Axis 7001 NTSC to IP video converter	Purchased	1	$ 156.00		$ 156.00
	Networking Hub	5 port 10/100 Ethernet Hub	Purchased	1	$ 25.00		$ 25.00
	Video Switching Board	Custom PCBs from SunStone	Purchased	2	$ 35.00		$ 70.00
	ROV1 custom shield	Custom PCBs from SunStone	Purchased	1	$ 55.00		$ 55.00
	ROV2 custom shield	Custom PCBs from SunStone	Purchased	1	$ 65.00		$ 65.00
	ROV3 custom shield	Custom PCBs from SunStone	Purchased	1	$ 57.00		$ 57.00
	DC-DC converter board	Custom PCBs from SunStone	Purchased	1	$ 57.00		$ 57.00
	NeoPixel RGB LEDs	2 meters	Purchased	2	$ 16.95		$ 33.90
	Video Board Discrete Components	MAXIUM Video Chip, resistors, connectors, capacitors Digike	Purchased	2	$ 35.00		$ 70.00
	ROV1 Board Discrete Components	resistors, connectors, capacitors Digikey	Purchased	1	$ 30.00		$ 30.00
	ROV2 Board Discrete Components	resistors, connectors, capacitors Digikey	Purchased	1	$ 25.00		$ 25.00
	ROV3 Board Discrete Components	resistors, connectors, capacitors Digikey	Purchased	1	$ 26.00		$ 26.00
	Subconn Connectors		Purchased	4	$ 150.00		$ 600.00
	3mm banana jacks pairs	Banana jack connector for bulkhead	Purchased	25	$ 1.95		$ 48.75
	Tether Cabling	60m 12 AWG Silicon Wire	Purchased	1	$ 120.00		$ 120.00
	Tether Cabling	30m Cat5e Data	Purchased	1	$ 35.00		$ 35.00
	Tether Cabling	Beldin 735 Coax Video	Purchased	2	$ 40.00		$ 80.00
	Tether Cabling	Polyester Sheathing	Purchased	1	$ 28.00		$ 28.00
	Tether Cabling	Strain Relief	Purchased	2	$ 25.00		$ 50.00
	Leak Detectors		Purchased	2	$ 2.90		$ 5.80
	DC to DC converters	600W Murata DC-DC converters	Purchased	4	$ 90.00		$ 360.00
Cuttlefish Subframe Expenses	Camera POD Servos	HiTech HS-53 Micro servos	Purchased	2	$ 22.00		$ 44.00
	Gripper Servo	HiTech Standard servos	Purchased	2	$ 27.00		$ 54.00
	External Temperature Sensor	Waterproof DS18B20 Digital Temperature Sensor	Purchased	2	$ 9.95		$ 19.90
	Depth Sensor	OpenROV IMU/Compass/Depth Module	Purchased	1	$ 120.00		$ 120.00
	NTSC Cameras	600TVL 1/4 1.8mm CMOS FPV 170 Degree Wide Angle Lens	Purchased	6	$ 15.00		$ 90.00
	Silicon Molding Compound	Liquid Silicon for Molds	Purchased	1	$ 45.00		$ 45.00
Stock Expenses	Acrylic Stock	TAP Plastics	Parts Donated	1	$ 125.00	$ 125.00	$ 125.00
	16cm I.D Acrylic Tube	Electronics housing	Purchased	1	$ 120.00		$ 120.00
	Aluminum Stock	Tubing, Channel, Plate - Online Metals	Purchased	1	$ 199.99		$ 199.99
	HDPE Stock	TAP Plastics	Purchased	1	$ 123.00		$ 123.00
	Polycarbonate Stock	TAP Plastics	Purchased	1	$ 210.00		$ 210.00
	Type II PVC Stock	TAP Plastics	Purchased	1	$ 122.11		$ 122.11
	Nuts, Bolts, Screws	Stainless Steel - Emigh Hardware	Purchased	1	$ 392.18		$ 392.18
	Shop Consumables	Drill Bits, Sand Paper, Epoxy, Solder, Saw Blades	Purchased	1	$ 565.69		$ 565.69
	3D Filament	ABS Printing Filament	Purchased	3	$ 22.45		$ 67.35
Consumables	CNC bits	CNC bit from McMaster Carr	Purchased	5	$ 19.00		$ 95.00
	Bandsaw Blades	Fine tooth blades for metal	Purchased	1	$ 89.00		$ 89.00
	Glues and Marine Epoxies	Marine Epoxy for potting	Purchased	3	$ 9.00		$ 27.00
	Shop Supplies	Towels/Sandpaper/Small Tools	Purchased	1	$ 500.00		$ 500.00
Fabrication	Welding	Electronics Housing Flanges and Tether Hard Point	Purchased	1	$ 325.78		$ 325.78
	Custom machining	2 end cap flanges from eMachineShop	Purchased	2	$ 146.00		$ 292.00
Rework	Rework Costs	Replacement Parts Arduino Ethernet -Damaged while testing	Purchased	1	$ 67.00		$ 67.00
	Rework Costs	Replacement Parts, Blue Robotics T100 thruster	Purchased	1	$ 136.00		$ 136.00
	Rework Costs	Version 2 of video board	Purchased	1	$ 57.00		$ 57.00
	Rework Costs	Version 2 of DC-DC power converter board	Purchased	1	$ 125.00		$ 125.00
Total Invested in ROV Cuttlefish (Purchased plus Re-used, and Donated)						$ 125.00	$ 7,317.45
Tether Control Unit Expenses	TCU Case	DeWalt Modular Toolbox, from 2014	Re-used	1	$ 75.00	$ 75.00	$ 75.00
	Netgear Router	Re-used from 2014	Re-used	1	$ 65.00	$ 65.00	$ 65.00
	Netgear Switch	Re-used from 2014	Re-used	1	$ 25.00	$ 25.00	$ 25.00
	Axis IP Video Server	Re-used from 2014	Re-used	1	$ 125.00	$ 125.00	$ 125.00
	DC-DC Power Converter	56V-12V, re-used from 2014	Re-used	1	$ 16.00	$ 16.00	$ 16.00
	Ethernet Connectors	Nutric Panel Mount Mod 8 Pass Through, from 2014	Re-used	8	$ 7.00	$ 56.00	$ 56.00
	BNC Video Connectors	Re-used from 2014	Re-used	4	$ 6.00	$ 24.00	$ 24.00
	LED Panel Lights	Re-used from 2014	Re-used	5	$ 5.00	$ 25.00	$ 25.00
	Main Power Switch	Re-used from 2014	Re-used	1	$ 28.00	$ 28.00	$ 28.00
	Amp Meter	Re-used from 2014	Re-used	1	$ 12.00	$ 12.00	$ 12.00
	Air Button	Re-used from 2014 (installed but not in use)	Re-used	1	$ 4.00	$ 4.00	$ 4.00
	Pneumatic Relay	Re-used from 2014 (installed but not in use)	Re-used	1	$ 12.00	$ 12.00	$ 12.00
	Laptop LCD Display	Laptop LCD and Video Converter Board, from 2014	Re-used	1	$ 130.00	$ 130.00	$ 130.00
Mission Control Center	Mission Monitor	Re-used from 2014	Re-used	1	$ 295.00	$ 295.00	$ 295.00
	Mission Laptop	Re-used from 2014	Re-used	1	$ 1,195.00	$ 1,195.	$ 1,195.00
	Mission Joystick	Re-used from 2014	Re-used	1	$ 39.00	$ 39.00	$ 39.00
Total Invested in ROV Control System (Purchased plus Re-used and Donated)						$ 2,126.	$ 2,126.00
Printing Expenses	Printing Expenses	Marketing Displays, pamphlets, decals, etc.	Purchased	1	521.19		$ 521.19
Shipping Expenses	Shipping ROV	Estimated round trip	Purchased	1	$ 4,000.00		$ 4,000.00
	Shipping Crate	Wood and fasteners	Purchased	1	$ 220.00		$ 220.00
Travel Expenses	Transportation Expenses	Air Fare for coaches	Purchased	2	$ 860.97		$ 1,721.94
	Lodging	Competition Lodging for employees 11 rooms x 5 nights	Purchased	55	$ 120.00		$ 6,600.00
	Meals	Breakfast included with lodging, lunch included from MATE	Purchased	1	$ 500.00		$ 500.00
Registration Expenses	MATE Fees	MATE Competition Registration	Purchased	1	$ 260.00		$ 260.00
Capital Expenses	Mission Prop Materials	PVC pipe, concrete and rope	Purchased	1	$ 235.00		$ 235.00
	Shop Tools	Ryobi 16" Scroll Saw	Purchased	1	$ 100.00		$ 100.00
	Shop Tools	Oscillating Spindle Sander	Purchased	1	$ 140.00		$ 140.00
	Shop Tools	New Dell Laptop	Purchased	1	$ 975.00		$ 975.00
	Software	DocsFlow	Purchased	1	$ 200.00		$ 200.00
Meal Expenses	Food and Snack	Food and snacks in the lab	Purchased	1	$ 2,500.00		$ 2,500.00
Total Miscellaneous Expenses							$ 17,973.13
Total Expenses							$ 27,416.58
Total Donated/Reused						$ 2,251.	$2,251.00

Figure 26. 2016 Rovotics project costing sheet.

V. Conclusion

A. Challenges

Configuring buoyancy proved to be one of the most difficult technical challenges this year. The electronics housing provided 7 kg of buoyancy, which was expected to be counteracted by the weight of tools, cameras, and electronics. However, these components displaced more water than expected, adding to the buoyancy provided by the electronics housing. Ballast was added in the form of steel struts, but this put *Cuttlefish* over the weight limit for the first weight range. By choosing smaller electronics components, Rovotics was able to reduce the volume of the electronics housing. This reduced the buoyant force, resulting in less ballast and lowering the weight of *Cuttlefish*.

Figure 27. Configuration diagram detailing thruster order and direction.

In addition, the software department experienced challenges with the vector drive. It is critical that the manufacturing, electronics, and software departments reach a consensus with each other regarding which side of the ROV will be considered the bow and what the thruster numbering order will be. Not doing so early in the season resulted in the electronics and software departments numbering the thrusters differently, which caused setbacks in the schedule. Having to reorder the speed controller to match the control program delayed the company's ability to perform the initial power-up testing. To establish a guideline for all departments to follow, a configuration diagram was developed that detailed the thruster numbering order (Figure 27). As a result, Rovotics has developed procedures to prevent similar confusions from occurring in the future.

The main non-technical challenge this season was the change in coaching. Rovotics' previous head coach, Rolf Konstad, retired after the 2014-2015 season. Coach Konstad was an integral part of the team due to his unique skillset which allowed him to offer both technical and administrative assistance. Oversight of these areas was taken on this year by various team members, coaching staff, and mentors, and an operational handbook was created to ensure continuity through the change. To avoid conflicts and ensure consistency in team communications, defining and assigning tasks to the individuals assuming the roles previously filled by Coach Konstad was critical. Communication between these individuals was enhanced by the use of collaborative workspace, weekly progress updates, and Gantt chart updates.

B. Lessons Learned and Skills Gained

Every year, Rovotics employees learn a host of new skills and capabilities. This year, employees in the mechanical department were trained to use the new scroll saw and oscillating spindle sander. By using this equipment, employees were able to save hundreds of dollars which would have otherwise been spent on more expensive manufacturing processes, such as waterjet cutting. In the electronics department, employees became more proficient in CAD software and more knowledgeable in electronics theory, enabling them to design new circuits such as switching power supplies, bi-directional motor drivers, and solid state relays, and implement those designs onto custom-printed circuit boards. The electronics department also learned the advantages of testing designs by integrating them into a complete system. Finished designs, such as the DC-DC voltage converters, would pass unit testing, but would fail when they were installed into the ROV. By doing integrated system tests on components, employees learned how to save time and money by finding and fixing problems more quickly. Employees in the software department learned the advantages of committing code to GitHub regularly. By doing so, team members could collaboratively review and integrate changes. This sped up troubleshooting, saving time. All employees gained interpersonal skills and became better at communicating with one another about manufacturing instructions, design ideas, and problem solving. We all became friends. Shy employees learned how to be more comfortable around other employees in a work environment and were able to become more productive.

C. Future Improvements

One of the main goals this year was the integration of a depth sensor into *Cuttlefish's* control system. With this added sensor, Rovotics has been able to add the feature of depth hold. Plans for next year's vehicle include the integration of the IMU depth sensor and compass into the Heads Up Display (HUD). Once fully integrated into the control system, the IMU and compass will add the capability of basic auto-navigation features.

Additionally, the company is investing in high-definition cameras for improved visibility. *Cuttlefish* uses standard NTSC cameras that have a limited resolution and by today's standards are becoming obsolete. With the industry's focus on telepresence, Rovotics feels it will be necessary to research and implement higher definition camera systems. This focus on telepresence is evident in the current live streaming event of the Okeanos Explorer in the Mariana Trench[7]. Geologists and marine biologists are conducting research from facilities around the globe with only the ROV operating crew local to the ship in the western Pacific off the coast of Australia.

D. Senior Reflections

Reflections were written by this year's retiring Seniors (Figure 28).

Collin Meissner
2015 CEO, Mechanical Design and Manufacturing Lead

I would like to thank MATE for planning and organizing the annual underwater ROV competition, and allowing Jesuit Robotics to participate in such a valuable and rewarding learning experience. The MATE competition and the four years I have spent on the Jesuit Robotics team have helped me to develop technical and leadership abilities far beyond anything I could have learned in the classroom. I have gained skills and experience in mechanical design, CAD software, manufacturing, project management, and presentations to the media, government officials, and local businesses. I have never worked so hard or had so much fun in my life. I will be leaving Jesuit Robotics this year to study mechanical engineering at Johns Hopkins University, but I know I will be applying the knowledge and skills I've gained from MATE and Jesuit Robotics for the rest of my life, giving me a head start in my college and career.

Killian Randle
CAD Lead

I would like to thank MATE and Jesuit High School for providing me with this opportunity for educational and social growth during my high school career. The experiences of operating a CNC mill and designing complex parts in CAD have been critical to my development, as they have improved my confidence and given me valuable experience in the field. My participation in robotics has provided lessons of leadership and cooperation, as well as technical knowledge and skills, which will assist me in my career no matter which field I choose. I have no doubt that in the future, I will look back on this time not only as useful in my everyday life, but also as a fond memory, and I deeply thank all those who have supported me throughout this worthwhile endeavor.

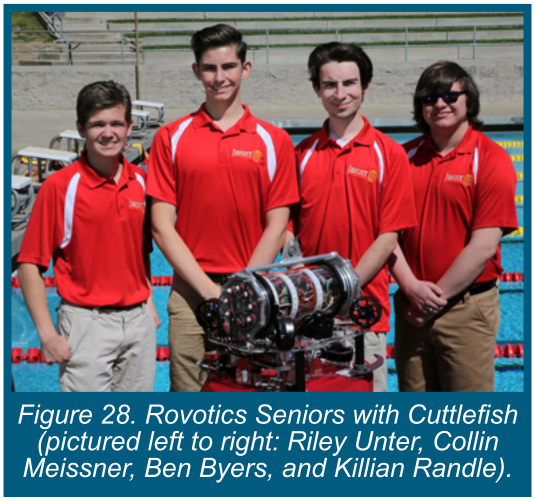


Figure 28. Rovotics Seniors with Cuttlefish (pictured left to right: Riley Unter, Collin Meissner, Ben Byers, and Killian Randle).

Riley Unter
Engineer

Before I joined the Jesuit Robotics team, I barely knew how to operate a computer. Now I know how to operate a computer, 3D printer, lathe, and several other machines that I didn't even know existed before. I would like to thank MATE for making the competition possible each year and for allowing Jesuit Robotics to participate. I cannot imagine what my high school years would have been like without this team. I would like to thank the coaches, the parent volunteers, and my fellow teammates for not only making this team possible, but for also introducing me to something that I love doing every Saturday. As a result of my experience at robotics over the last four years, I have grown into the person I am today. I can now say with confidence that I want to be a mechanical engineer, and I will be studying mechanical engineering at The University of Portland next year.

Ben Byers
2015 Electronics Lead, Programmer, Pilot

I would like to thank all the students, parents, coaches, and especially MATE and Jesuit High School for making the robotics program at Jesuit possible. As a fourth year member, I've been given the opportunity and motivation to further my ability to solve problems into something that will remain a lifelong passion. During my time on the team, my skills in software development and the field of engineering in general grew considerably, and by my junior year I was the electronics lead, where I spent a majority of my time teaching underclassmen the very same things I had learned in my early years on the team. There is nothing I loved more than the Saturday workdays, spending the whole day at the lab building amazing friendships and gaining invaluable experience. None of this would have been possible without the environment provided by the Jesuit Robotics team and MATE.

E. Acknowledgements

Rovotics would like to thank the following benefactors:

- **MATE Center and Marine Technology Society** - Sponsoring this year's competition
- **National Science Foundation** - Their funding of the MATE competition
- **NASA Johnson Space Center Neutral Buoyancy Lab** - Hosting this year's competition
- **Oceaneering International** - Their support of the MATE competition
- **Jesuit High School** - Generous donation of funding and pool time
- **Jay Isaacs, Head Coach** - His time, creativity, knowledge, and guidance for the last eleven years
- **Steve Kiyama, Assistant Coach** - His time, experience, and guidance of the team
- **Cheryl Kiyama, Operations Manager** - Her time, experience, and management of the team
- **Jim Claybrook of Weldmasters** - Welding our aluminum flanges and tether hard point
- **MacArtney Connectors** - Providing connectors at a reduced rate
- **GitHub** - Providing complimentary private code repositories
- **Travis CI** - Providing continuous integration for private GitHub repositories
- **TAP Plastics** - Donation of stock plastic
- **SolidWorks** - Donation of SolidWorks 3D software
- **FMC/Schilling Robotics** - Facility tour
- **Mentors** - Marc Aprea, Craig Law, Jayanth Pingili, Dawn Remme, Pedar Remme, David Weston, Kelly Whitcomb-Weston
- **Our Families** - Their continued support and encouragement

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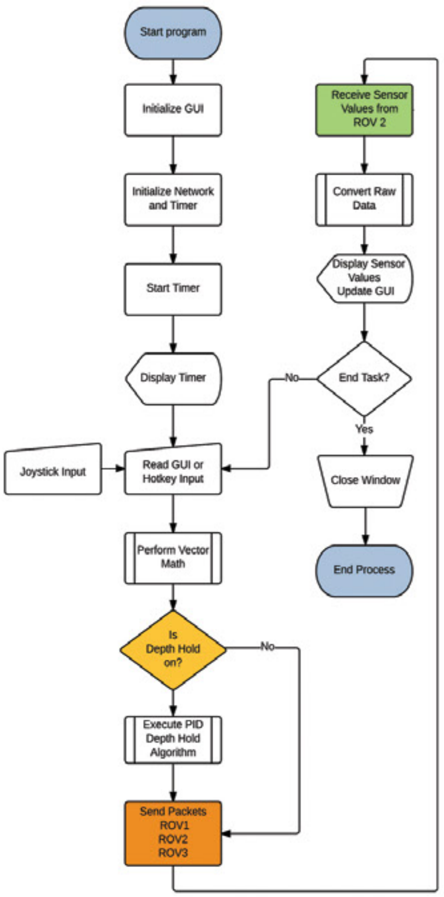
VI. Appendices

A. Software Flowcharts

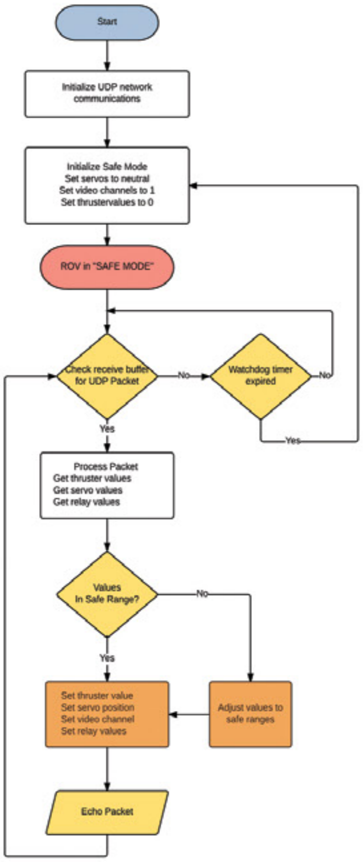
Topside: CuttleCode



Packet Structure

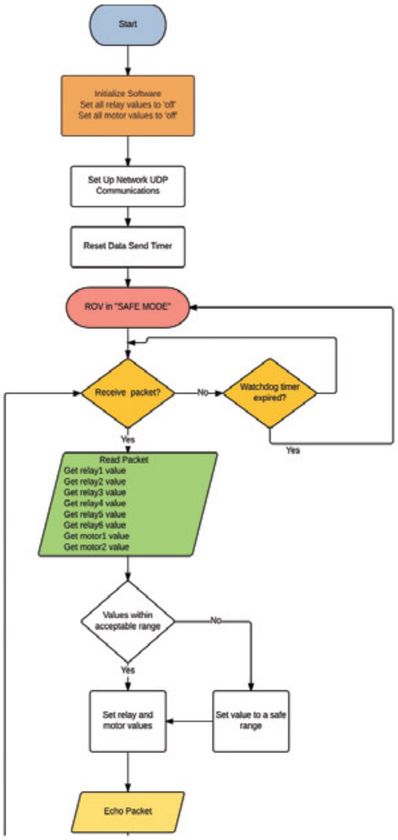
ROV 1 UDP Packet Structure	UDP Header, Thruster1, Thruster2, Thruster3, Thruster4, Thruster5, Thruster6, Servo1, Servo2, Video Switch 1, Video Switch 2
ROV 2 UDP Packet Structure	UDP Header, External Pressure, External Temp1, Internal Temp2, Internal Humidity, IMU, NeoPixel Lights
ROV 3 UDP Packet Structure	UDP Header, Relay 1. Relay2, Relay3, Relay4, Relay5, Relay6, Motor1, Motor2

Bottomside: ROV1



Bottomside: ROV2

Bottomside: ROV3



B. Operational and Safety Checklists

Pre-Power

- ☐ Area clear/safe (no tripping hazards, items in the way)
- ☐ Verify power switches and circuit breakers on TCU are off
- ☐ Tether flaked out on deck
- ☐ Tether connected to TCU and secured
- ☐ Tether connected and secured to ROV
- ☐ Tether strain relief connected to ROV
- ☐ Electronics housing sealed
- ☐ Visual inspection of electronics for damaged wires, loose connection
- ☐ Nuts tight on electronics housing
- ☐ Thrusters free from obstructions
- ☐ Power source connected to TCU
- ☐ Vacuum test electronics housing (see vacuum test procedure)
- ☐ Check vacuum port is securely capped

Vacuum Test Procedure

- ☐ Connect vacuum hand pump to ROV electronics housing
- ☐ Pump electronics housing to -50 kpa vacuum
- ☐ Verify electronics chamber holds -50 kpa vacuum for 5 minutes
- ☐ Remove vacuum pump and securely cap vacuum port

Power-Up

- ☐ TCU receiving 48 Volts nominal
- ☐ Control computers up and running
- ☐ Ensure team members are attentive
- ☐ Call out, “powering on!”
- ☐ Power on TCU
- ☐ Call out, “performing thruster test”
- ☐ Perform thruster test/verify thrusters are working properly (joystick movements correspond with thruster activity)
- ☐ Verify video feeds
- ☐ ROV lights indicate “Safe Mode” (green)
- ☐ Test accessories

Launch

- ☐ Call out, “prepare to launch”
- ☐ Deck crew members handling ROV call out “ready”
- ☐ Call “launch”
- ☐ Launch ROV, maintain hand hold
- ☐ Wait for release order

In Water

- ☐ Check for bubbles
- ☐ Visually inspect for water leaks
- ☐ If there are large bubbles, pull to surface immediately
- ☐ Wait 5 minutes, then check leak detector
- ☐ Engage thrusters and begin mission

ROV Retrieval

- ☐ Pilot calls “ROV surfacing”
- ☐ Deck crew calls “ROV on surface”
- ☐ “ROV captured”, kill thrusters
- ☐ ROV lights indicate “Safe Mode” (green)
- ☐ Operation Technician (OT) powers down TCU
- ☐ OT calls out “safe to remove ROV”
- ☐ After securing the ROV on deck, deck crew calls out “ROV secured on deck”

Leak Detection Protocol

- ☐ Surface immediately
- ☐ Power down TCU
- ☐ Inspect (may require removal of electronics)

Loss of Communication

- ☐ Cycle power on TCU to reboot ROV
- ☐ If no communication, power down ROV, retrieve via tether
- ☐ If communication restored, confirm there are no leaks, resume mission

Pit Maintenance

- ☐ Verify thrusters are free of foreign objects and spin freely
- ☐ Visual inspection for any damage
- ☐ All cables are neatly secured
- ☐ Verify tether is free of kinks
- ☐ Visual inspection for leaks
- ☐ Test onboard tools
- ☐ Replace elastic tensioners on pipe clamp tools
- ☐ Verify camera positions
- ☐ Washdown thrusters with deionized water