



# BELUGA Technical Report

MATE ROV Competition 2017

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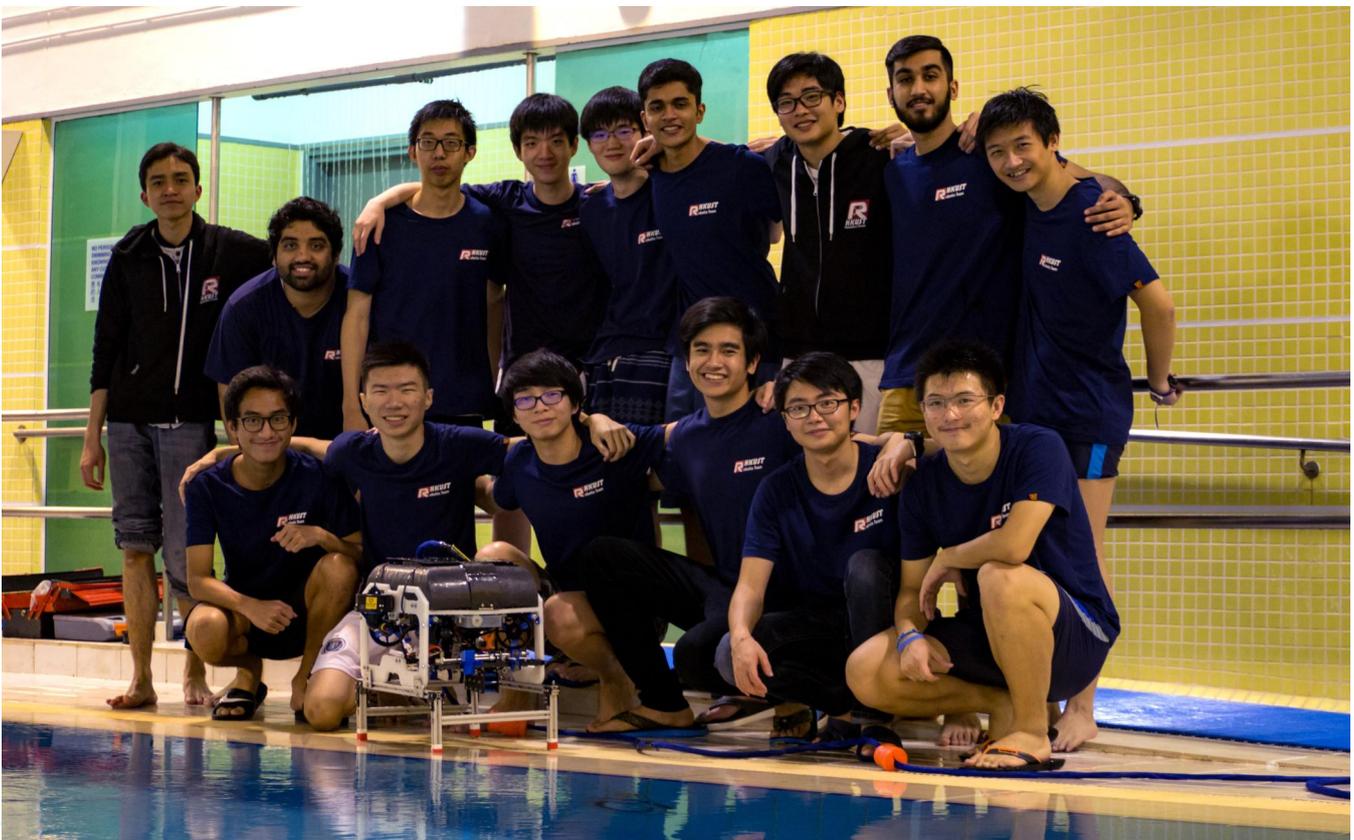


## I. ABSTRACT

Epoxsea Inc. (“Epoxsea”) consists of fifteen multicultural students who are passionate about underwater robotics. The company has developed an innovative solution to the Port of Long Beach’s request for a remotely operated vehicle (“ROV”) to assist in Hyperloop construction, water and light show maintenance, environmental cleanup, and risk mitigation at the Long Beach waterfront.

This year’s ROV, Beluga, is built upon successes and failures of Epoxsea’s past ROVs. Epoxsea continues waterproofing electronic components using epoxy rather than with an electronics tube for modularity. The team also pushes for in-house development of components, including rapid prototyping through 3D printing, for cost reduction. Extensive collaboration between mechanical and electronic division has yielded a compact and elegant ROV with a high degree of serviceability and functionality. The software division also experimented with ROV simulation and sensor filtering for research and development, as well as developed an online scoring system for the Hong Kong Regional competition for the Ranger class.

With the combined efforts of Epoxsea’s members over thousands of man-hours of planning, development, and testing, the team is confident that Beluga is the most suitable ROV to fulfill the Port of Long Beach’s request for proposal.



**Figure 1** Top row (left to right): Randitya Setyawan Mohamad, Gaurav Vijai Jeandani, Dennis Chen, Richard Lawrence, Hongseo Yoon, Aadhithya Vignesh Jeyakumar, Heng Su, Akshay Kapur, Daniel Cheung

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## II. DESIGN RATIONALE

### A. Design Evolution

Beluga’s design process began with considering the physical dimensions and thruster configurations. A customized frame was designed with the intent of making the electronics system easy to install and manipulators easy to service. Improvements made to Beluga’s form factor and design has allowed for a roughly 15% decrease in weight at 10.7kg. The team addressed thruster performance issues faced last year and improved Beluga’s maneuverability by featuring six thrusters, as compared to last years’ four. The vectored propulsion, enabling five degrees of freedoms, allows for a more intuitive control for the pilot and a more powerful forward and backwards movement.

Last year, Epoxsea opted for a different approach when it came to waterproofing electronic components, which was done by placing each component in their own 3D printed housing sealed with epoxy. While the waterproofing technique has remained the same this year, the execution has become more methodical. Beluga’s top plate features large rectangular cutouts in the middle and sides to allow standardized electronic components to fit snugly within the frame. This allows for electronics components to be placed interchangeably.

The software team focused on writing reusable system code, and experimented with computer vision for the Risk Mitigation mission. Extensive efforts into research and development allowed us to fulfill improvement goals set last year, specifically an improved IMU filter and the creation of a simulation platform (see Orca Technical Report\*).

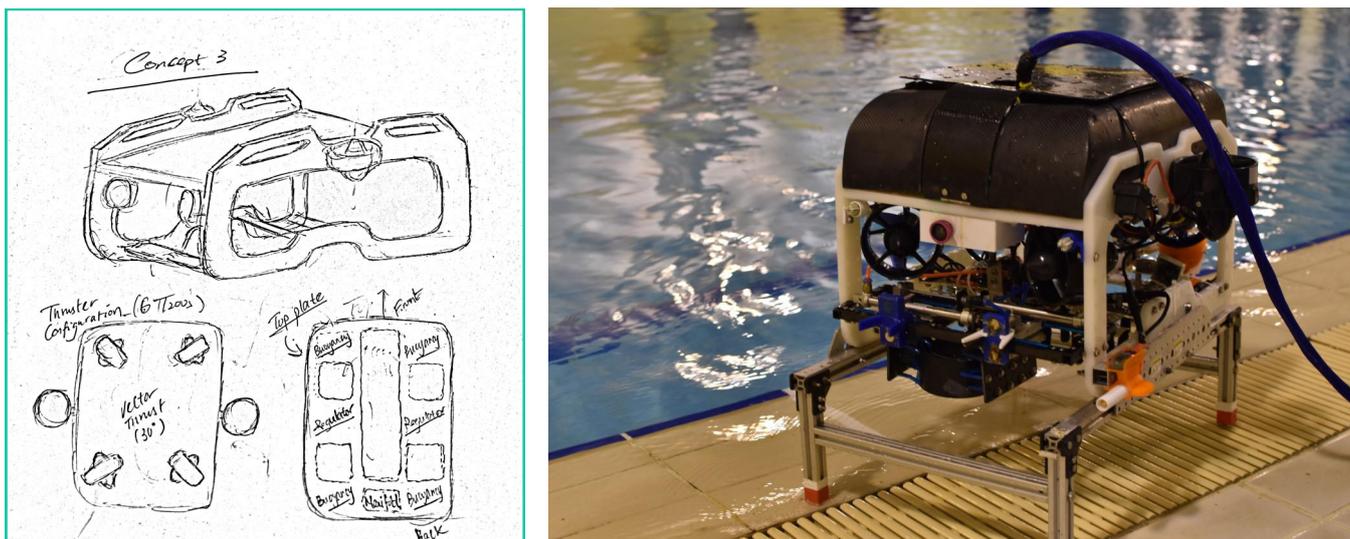


Figure 2 Early conceptual designs of Beluga (left) and Beluga on the pool deck

\*[https://www.marinetech.org/files/marine/files/ROV%20Competition/2016%20competition/2016%20TECH%20REPORTS/EXPLORER/HKUST\\_TECH\\_REPORT.pdf](https://www.marinetech.org/files/marine/files/ROV%20Competition/2016%20competition/2016%20TECH%20REPORTS/EXPLORER/HKUST_TECH_REPORT.pdf)



## B. System Interconnection Diagrams

The following are system interconnection diagrams of the pneumatics and electronic systems used in Beluga.

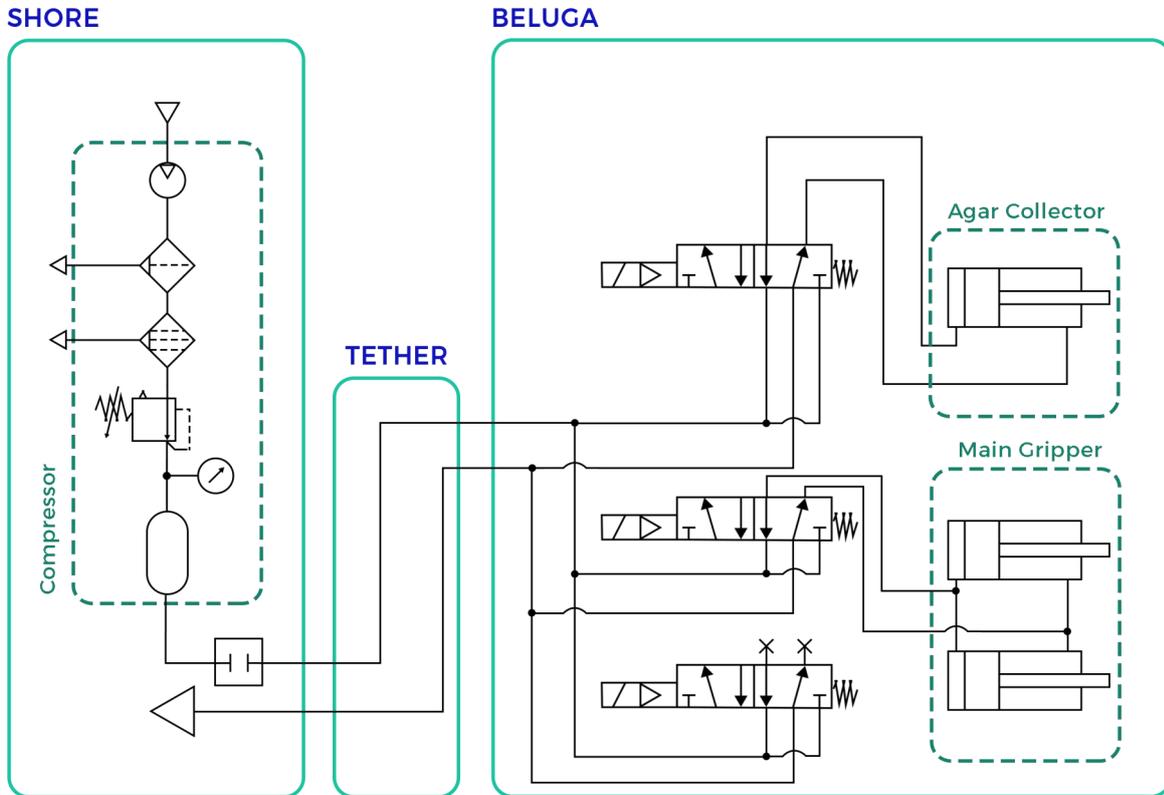


Figure 3 Pneumatics system interconnection diagram

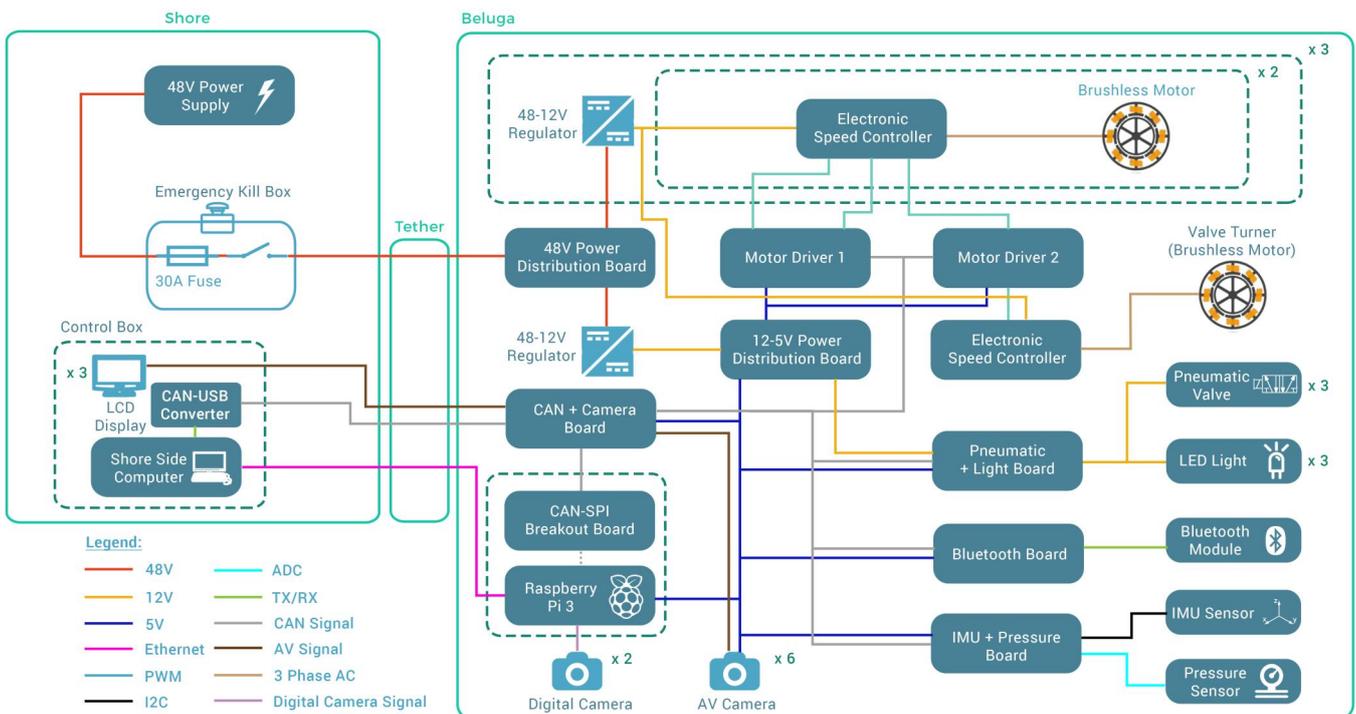


Figure 4 Electronics system interconnection diagram

## C. Vehicle Core System

### 1) Mechanical

#### Frame

Beluga's frame adopts a two-tier design, as shown in Figure 5, which eases repairs and maintenance works needed. Handles are also integrated on each side of the frame, making it easier to retrieve and launch Beluga from any direction. The side frame's bottom indentation makes transporting Beluga by hand easier and gives clearance for larger manipulators. The top and side plates are constructed from High Density Polyethylene (HDPE) while the supports at the bottom are made from 7075 aluminum alloy plates.

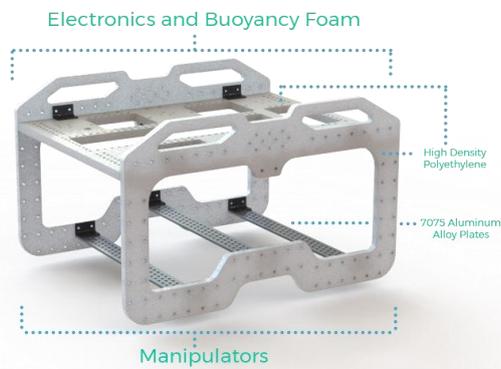


Figure 5 Rendering of Beluga's frame

HDPE was selected over other polymers such as Delrin due to the lower price while offering the rigidity that the frame requires. HDPE is also more fatigue resistant compared to other polymers such as polycarbonate. The bottom plates are manufactured from aluminum to increase structural integrity and were designed in thin strips instead of a whole plate to save cost, material, and weight. This design improves serviceability as payloads can be mounted and repaired easily. Regularly spaced M4 holes are also present all over the frame to give ample options for component placements and weight distribution adjustments.

The frame components of Beluga, designed by Epoxsea, was fabricated using Computerized Numerical Control (CNC) machining by an outside manufacturing-service. This was done to maximize design phase of the frame, mission-specific manipulators, and overall ROV system (see Appendix B for Gantt chart). On top of this, higher control of the frame's accuracy can be realized, such as straightness and distance of consecutive holes.

#### Buoyancy

To compensate for the weight of frame, manipulators, and electronic components, a buoyancy foam was fabricated in-house, and mounted on top of the Beluga, such that neutral buoyancy can be achieved. The foam was designed around three main factors: net buoyancy force generated (calculated by Archimedes' Principle), manufacturability, and potential obstruction to the electronics.

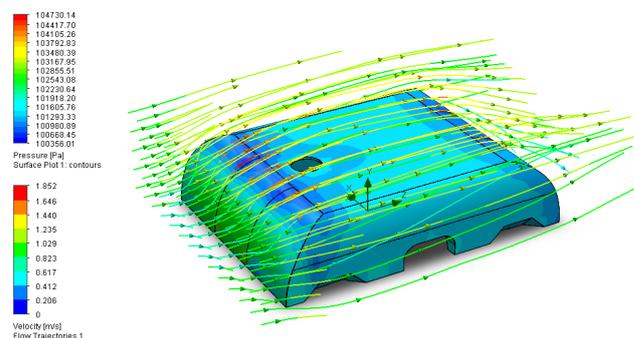


Figure 6 Flow simulation of Beluga's buoyancy foam

As seen in the Figure 2 and 6, there are two main components to the buoyancy system: the foam and the lid. This utilization of lid allows for quick access to electronics under it for repair or maintenance when needed. The buoyancy foams are made out of expanded polystyrene (EPS), which is more accessible, cheaper, and lighter than other foams (such as polyurethane).



EPS' low compressive strength is compensated by layers of carbon-fiber composite on the foam's surface. These two layers of carbon-fiber reinforced polymer also prevents water from accumulating in the foam, and retains shape of foam under hydrostatic pressure. On the other hand, the lid is made out of carbon-fiber, fiberglass, and epoxy layered on top of each other to make it rigid yet light. The foams and lids are then surface finished for aesthetics.

**Propulsion**

Beluga is powered by six T200 brushless thrusters from Blue Robotics. This particular model was chosen again this year due to its excellent reliability, durability, and maintainability from last years' experience. Four horizontal motors are positioned at an angle of 30 degrees relative to the longitudinal axis. The resulting vector thrust not only allows for greater speeds, but allows Beluga to strafe in any direction. Two thrusters fixed in the vertical axis allow for heave/roll movements. This configuration equips Beluga with 5 degrees of freedom, as shown in Figure 7.

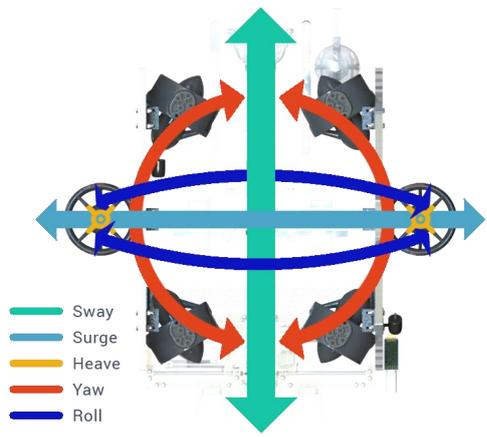


Figure 7 Beluga's five degrees of freedom

**2) Electronics**

Beluga's electronics subsystem provides power and communication among all sensors and actuators. The system includes nine PCBs that utilize the STM32F103 microcontroller and a Raspberry Pi. This microcontroller was chosen for its robustness, lower price point, and large variety of peripherals. The configuration of the electronic components in Figure 8 was chosen after careful consideration of board dimension and point to point connections between boards. Figure 9 shows the actual implementation of this design. In contrast with a centralized architecture, our architecture allows for easier maintenance and hot-swappable parts, in accordance with the company's emphasis on modularity.

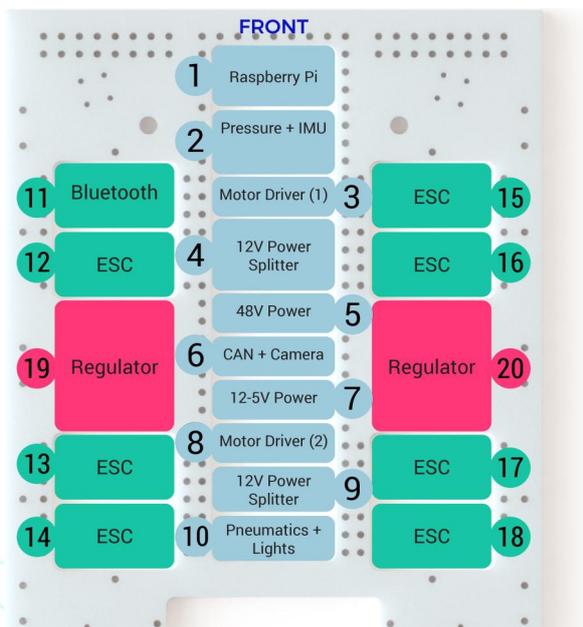


Figure 8 Electronic boards layout plan (Top view)

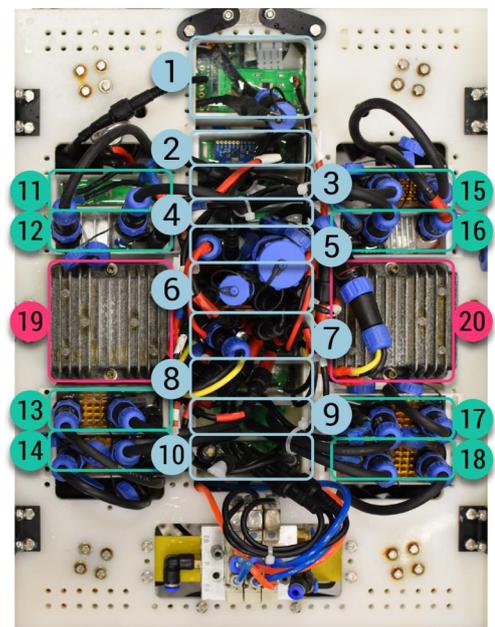


Figure 9 Photo of electronic boards layout (Top view)

The motor driver is responsible for controlling up to 4 motors simultaneously, and the pneumatic board is responsible for issuing control signals to the pneumatic solenoid valves and powering the lighting system. The pressure + IMU board utilizes the on-board analog-to-digital converter (ADC) of the STM microcontroller to poll measurements from the MPX4250 pressure sensor. It also interfaces with the MPU9250 sensor, providing 3-axis accelerometer, gyroscope, and magnetometer data.

### **Power Distribution**

Beluga's primary source of power is regulated by four 48V-12V DC-DC regulators. The 12V output from one of the regulators supplies power to an in-house 12V-5V converter, which transmits the necessary 5V to each board. This dedicated converter removes large unnecessary components and minimizes the sizes of each board. Designing the converter in-house minimized cost, since only required components were included on the Beluga.



**Figure 10** 12V-5V Regulator and Distribution Board

The three other 12V regulators' outputs are supplied to a custom splitter board, which provides more 12V outputs to power the seven electronic speed controllers (ESCs). This splitter board was specifically made to address cable management issues witnessed on last year's Orca. As an extra safety measure, self-recovery fuses are implemented on each board. By distributing the point of connections for supplying power, there was considerable improvement in troubleshooting, cable management, and board size reduction.

### **Controller Area Network (CAN)**

Beluga uses CAN protocol as the communication protocol between ROV and shore-side computer due to its simplicity and success in previous Epoxsea ROVs. Each board represents an individual node, which is connected over a shared bus integrated with the centralized CAN/Camera board. Messages exchanged between boards and computer are processed by an embedded STM microcontroller and high-speed CAN transceiver (TJA1050) on individual boards to execute their specific functions. Moreover, maintaining differential impedance at each end of the bus using low-value resistors helps eliminate noise.

The high-baud rate offered by CAN architecture (up to 1.25Mbps) allows messages to be exchanged rapidly, and sensors and actuators to respond with minimal delay. Moreover, the implementation of CAN bus architecture provides a significant advantage over other serial protocols in terms of multiplexing electrical wiring on the ROV; only one point of connection to the ROV using the Ethernet cable in the tether is needed. Each board is then connected to the dedicated CAN port on the camera board in order to connect to the shared bus.

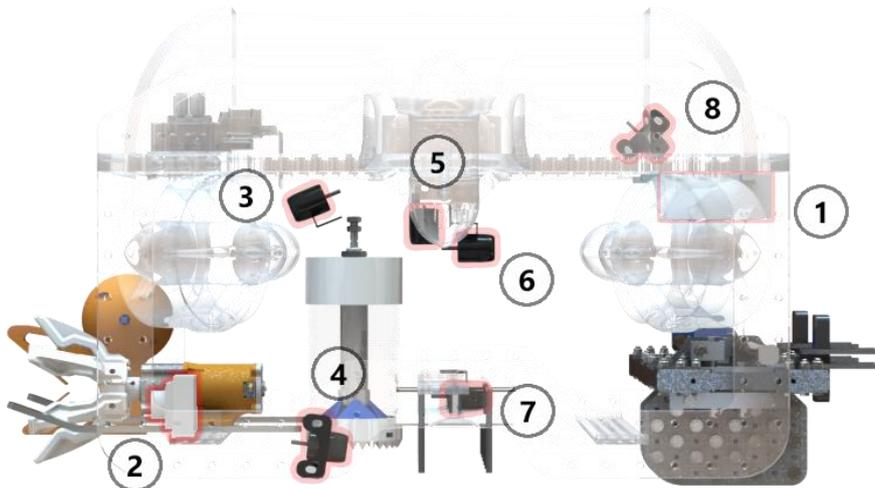
### **Cameras**

Given the number of manipulators used on Beluga, this year's challenge was to optimize the number of cameras as well as their mounting positions, in order to give the pilot the best viewing angles for manipulators and surroundings. The optimization significantly reduces





the number of cameras used: from fifteen to six analog video (AV) cameras and two digital cameras, seen in Figure 11 below. The amount of cameras on last year's ROV was decidedly redundant and ineffective. Therefore, reducing it drastically saved cost and weight due to the use of fewer cables. Moreover, having only two interchangeable AV cameras per feed creates a more intuitive operating experience through faster access to the desired camera.



The following cameras are used for:

1. Incident Site Mapping; General Purpose
2. Incident Site Mapping; General Purpose
3. Valve Turner, Buoy
4. Beacon Retriever
5. Agar Collector
6. Main Gripper; Rebar Retriever; General Purpose
7. Main Gripper

Figure 11 Camera placements on Beluga (side view)

### Electronics Enclosure

The design of Beluga's electronics system was planned along the mechanical frame design. Each board is 65mm wide and epoxied in board-specific 3D printed casings for waterproofing. They are then inserted into designated slots on the frame.

Waterproofing the boards by epoxying was inherited from Orca (2016) as it eliminates possibility of water leakage, which is an immediate risk for an underwater vehicle. Alternative solutions like electronic tubes require heavy and more frequent maintenance.

As previously shown in Figure 9, this year's electronic component layout is much more organized compared to last year's, where boards were placed in any free space. This improvement reduced clutter and aided cable management and troubleshooting. Most importantly, this implementation resonates with the intention of maintaining high modularity, such as quickly substituting a defective board with a new one.

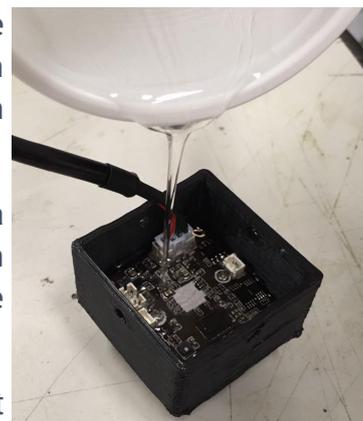


Figure 12 A digital camera being epoxied in its 3D-printed casing.

### Tether

Beluga's tether shields multiple cables in one single flexible protective casing. This allows for ease of storage and use, and protects the cables from wear and tear. The tether consists of two Category 6 Ethernet (CAT6) cables, two pneumatic pipes, and two 13 AWG power cables. The four 48-12V DC-DC

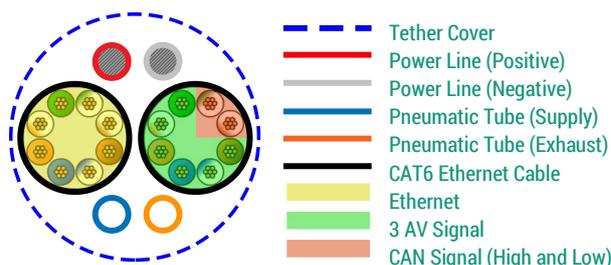


Figure 13 Cross section of Beluga's tether

regulators on Beluga have operating input range of 35V to 60V. To establish a safety margin, a 5% to 10% voltage drop was considered acceptable for the power system. With the tether length being 20m, a 5% drop corresponds to resistance per length value of 4 mΩ/meter and 10% drop corresponds to 8 mΩ/meter. These matches AWG value of around 11 to 14 respectively; thus, a 13 gauge cable which satisfies these bounds was chosen. One of the CAT6 cables is used for video streams and CAN communication protocol, while the other is used to establish an Ethernet connection between the onboard Raspberry Pi and a router inside the shore side computer. Furthermore, two pipes are used to supply and exhaust the pressurized air to and from the pneumatic system onboard the ROV. Despite the amount of components inside, the tether still weighs 3.5 kg.

### 3) Software

Epoxsea developed a dual-layer software architecture, with upper layer written in C++ and implemented using the ROS framework, and lower layer written in C and deployed on independent STM32 Microcontrollers, each programmed for specific piece of hardware. As shown in Figure 14, shore operations are managed through a single computer responsible for controlling Beluga, viewing cameras, performing calculations, and displaying system information. The control box dispatches commands that are encoded as CAN messages to the microcontrollers connected to the CAN bus; furthermore, feedback messages and sensor data are relayed through the same network back to shore.

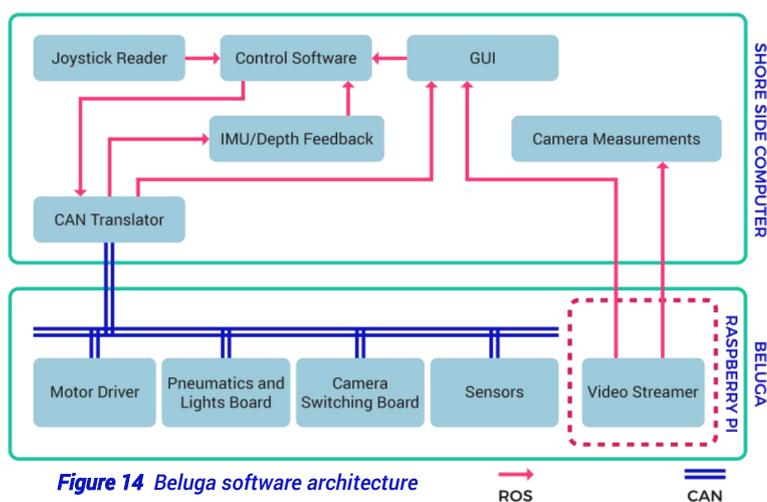


Figure 14 Beluga software architecture

The goal of this year’s software system was to retain the same high-level of software modularity in previous years by using independent microcontrollers and the ROS framework, but develop high quality and reusable software based on the improvement goals set last year, specifically a more sophisticated IMU filter and a simulation platform.

#### ROS Framework

The ROS framework was chosen because it allows for parallel peer-to-peer communication among different independent processes called nodes, where data can be asynchronously communicated using a publisher/subscriber model. The framework is inherently object oriented, abstracting away low-level details that one would usually need to implement. This reduced the complexity of understanding the system from a macro level, making programming more time-efficient and code more readable. Each node is also encapsulated, reducing the complexity of maintaining each node since they only interface with other nodes via a message topic and unnecessary information is hidden.

A decentralized system with a standardized protocol grants a lot of flexibility, subsystems can be swapped quickly for testing without needing to reconfigure other processes, for



example, switching between two IMU filter designs. Another advantage is that ROS is well integrated with other libraries, such as OpenCV, which is utilized for distance measurement task in the Risk Mitigation Mission, as well as Gazebo, for internal simulation practice. Because of this multitude of benefits, ROS became the ideal framework for our software division.

### Inertial Measurement Unit

To get meaningful and usable information out of our IMU sensor, an Extended Kalman Filter<sup>7</sup> is implemented in our system. The filter estimates the vehicle's orientation from gyros, accelerometers, and magnetometers readings. This approach produces more accurate estimates than last year's complementary filter. Vehicle orientation in both quaternion and Euler representations and depth readings are regularly published to the vehicle state topic. The control software node subscribes to this topic and uses the vehicle state information to actively maintain Beluga's roll, yaw, and depth using PID control.

### Graphical User Interface

The software division developed a user-friendly GUI written in JavaScript. Its primary purpose is to present telemetry data and video feed. Additional features include customizing camera profiles, remapping Xbox controls, tuning PID values, and enabling PID control. Compared to the RQT framework utilized last year, the new GUI offered greater functionalities with no visible decline in performance speed, which was a concern. This was done by using the Rosbridge library to allow JSON APIs to communicate with ROS, enabling the GUI to function as a node and exchange information with other nodes. As it is written with web technology, the GUI can also be viewed on other devices such as smartphones or tablets.

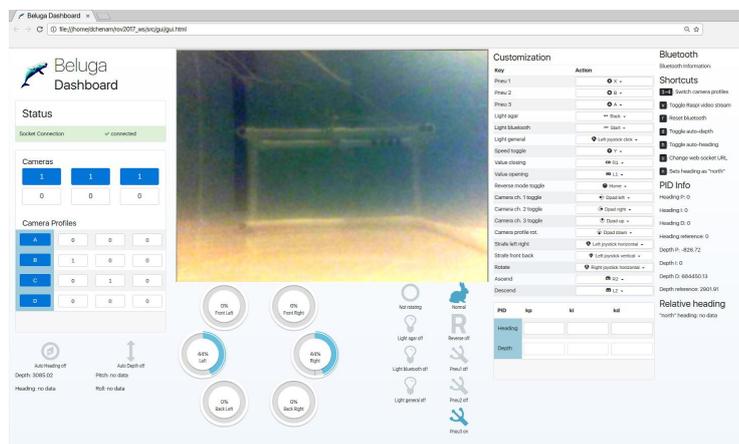


Figure 15 Screenshot of the GUI Dashboard

### ROV Simulator

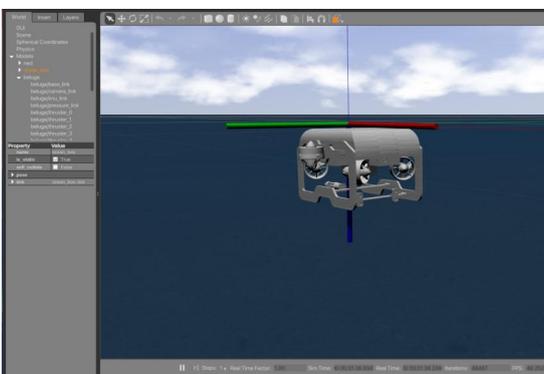


Figure 16 Screenshot of Gazebo Simulation

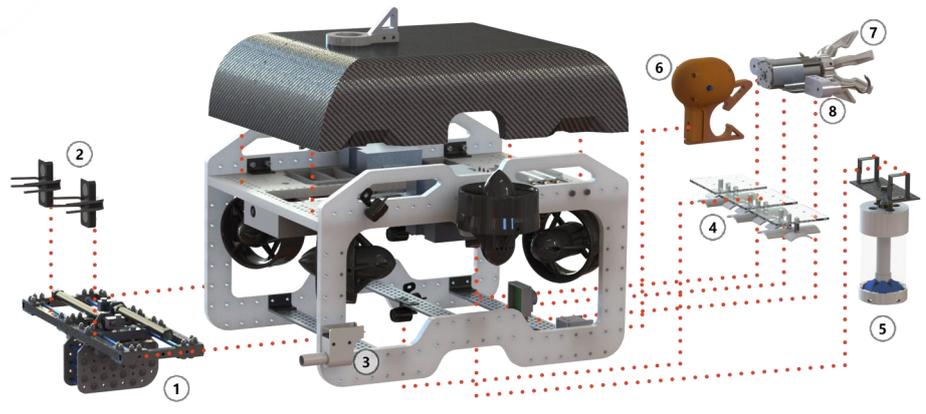
An internal simulator was developed to help train pilots and test the control software. Beluga's motion was modeled using Fossen's equations of motion<sup>2</sup> to express external forces acting upon a mass, which simplifies the ROV as a rigid body. Gazebo was utilized to simulate actuators and underwater sensors, and create better renditions of an underwater environment. Possible improvements in the future can include the implementation of cameras and props to simulate mission runs.

<sup>7</sup>Marins, João Luís, Xiaoping Yun, Eric R. Bachmann, Robert B. McGhee, and Michael J. Zyda. "An extended Kalman filter for quaternion-based orientation estimation using MARG sensors." In *Intelligent Robots and Systems, 2001. Proceedings. 2001 IEEE/RSJ International Conference on*, vol. 4, pp. 2003-2011. IEEE, 2001.

<sup>2</sup>Thor I. Fossen, *Handbook of Marine Craft Hydrodynamics and Motion Control* (Chichester, West Sussex: Wiley, 2011), 51-56.

## D. Mission Specific Features

1. Main Gripper
2. Rebar Collector
3. Bluetooth Module
4. Beacon Retriever
5. Agar Collector
6. Buoy
7. Valve Turner
8. Multipurpose Hooks



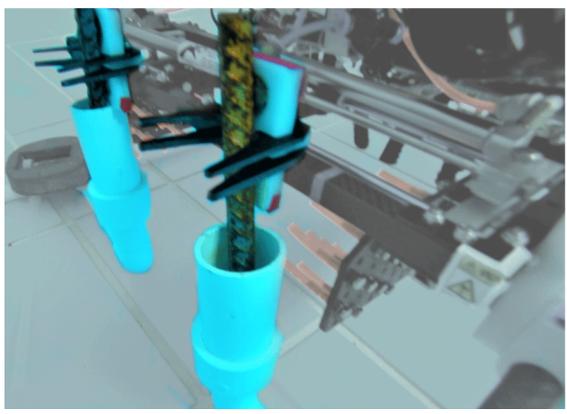
**Figure 17** Beluga Manipulators

Beluga’s mission-specific manipulators were prototyped and mainly manufactured in-house. All manipulators undergo a design-realization phase where general working principle is thoroughly worked out with whiteboard and CAD drawings. Prototypes are then produced with resources available to Epoxsea for testing, and improved upon pilot’s feedback.

### 1) Hyperloop construction

#### Rebar Retriever

The rebar manipulator has two neodymium magnets to pick up the rebar reinforcement rods. Small guidance arms are installed to assist pilot during rebar insertion process. Magnets are encased in a Delrin shell, while guidance arms are constructed from a glass fiber plates for durability and impact resistance. Both parts were fabricated in-house to save cost given the simplistic design and assembly process. Two identical rebar manipulators are placed on the front side of Beluga to allow the retrieval of two rebar simultaneously.



**Figure 18** Rebar insertion into base plate

#### Beacon Retriever



**Figure 19** Beacon Retriever

The beacon manipulator is a passive manipulator that enables Beluga to retrieve and store multiple positioning beacons easily. It consists of four equally spaced 4mm pneumatic pipes and PVC pipe segments on top, both of which are covered with Velcro loops. A clear acrylic plate on top provides clear view for the pilot. Compared to the original idea of using an HDPE slab covered with Velcro loops, the current retriever allows secure retrieval that can be done from any orientation as shown in Figure 19.



The design is economical as its materials are readily available in the laboratory. For quicker retrieval of three beacons, three of this manipulator are installed on Beluga.

### Multipurpose Hook

A pair of multipurpose hooks are installed on the rear end of Beluga, which can be used to carry out tasks such as disconnecting the power connector, transporting the hose adapter and removing the pin during the Hyperloop Construction. They are made from inexpensive materials such as a small Delrin block and a screw hook, making it easy and affordable to manufacture in house. The small footprint and simplicity of the design makes it a versatile tool for underwater deployment.

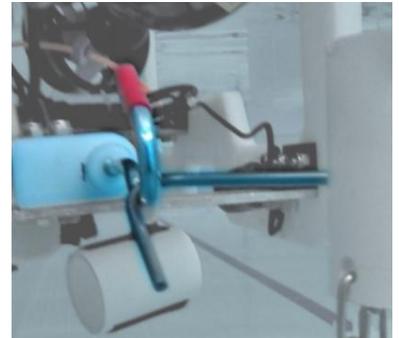


Figure 20 Multipurpose hook removing pin

## 2) Light and Water Show Maintenance

### Main Gripper

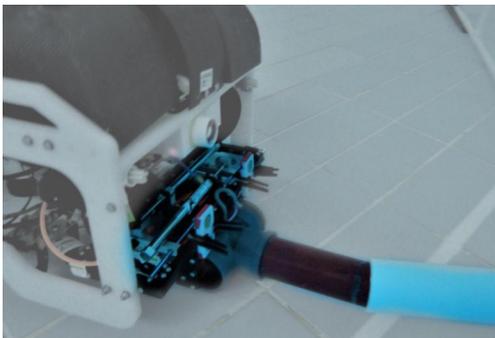


Figure 21 Main gripper inserting power connector

Beluga is equipped with a gripper mechanism designed and developed in-house. It is oriented to accomplish several sets of tasks, namely inserting the connector into the power port, installing the new fountain as well as retrieving the old fountain and clam specimens. The main gripper adopts a clamping mechanism where two linear pneumatic actuators extend in opposite directions to provide an opening of up to 170 mm, abundant space for the pilot to pick up large objects easily.

Each cylinder is connected to a plate that consists of an array of screws with pneumatic piping, providing flexible tips and multiple contact points for a strong, tight grip around any object even under high accelerations. The clamping hand is fabricated out of a 3mm carbon fiber board while the frame of the main gripper is constructed out of carbon fiber tubes to reduce the overall weight concentrated towards the front.

### Valve Turner

The valve turner consists of a set of fingers coupled with a commercial waterproof brushless motor. The fingers narrow down from large to an exact size to make it suitable for turning the valve (see Figure 22). This manipulator can also be used passively. Motor's rotor output is transmitted through a planetary gearbox, giving the valve turner a larger output torque. This manipulator was created using materials readily available in Epoxsea, such as a repurposed gearbox from an old motor set, and in-house 3D printed fingers. The design is proven to be cost effective while having a small form factor.



Figure 22 Valve turner used to turn the gate valve

### 3) Environmental Cleanup

#### Agar Collector

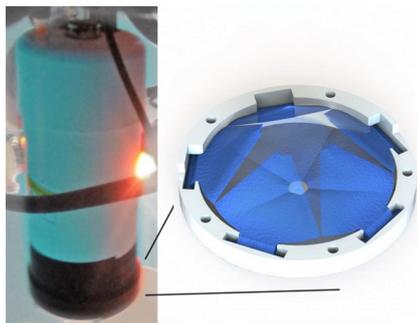


Figure 23 Extended agar collector

The agar collector collects sediment samples from a contaminated area. It consists of PVC tube with a one-way valve mechanism mounted on the bottom. Initially, a suction mechanism was considered, but the valve has proven its reliability in collecting the sample after testing. The valve, shown in Figure 23, has 3D printed flaps that only opens into the tube. When pneumatic cylinder extends, sediment sample pushes the flaps up and is forced into the PVC tube. The flaps then close and secure the sample when the tube is retracted.

### 4) Risk Mitigation

#### Bluetooth Module

To obtain a 7-digit serial number from containers, the mechanical division designed a 3D printed housing, shown in Figure 24, for a Bluetooth module (top) and a white LED (bottom). The Bluetooth module is waterproofed with slow-curing epoxy, while the LED is protected with a cylindrical tube underneath. The tube also acts as a guidance for inserting the LED into the light port – this approach would help Beluga stay stationary while the Bluetooth is pairing.

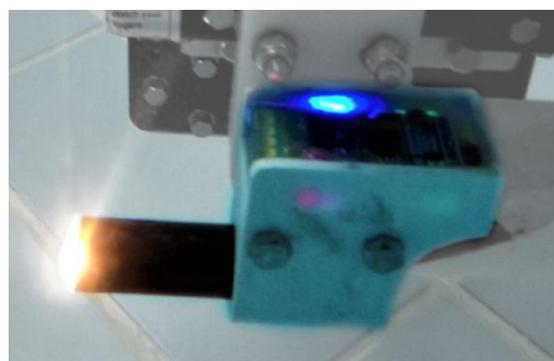


Figure 24 Bluetooth and LED housing

#### Buoy

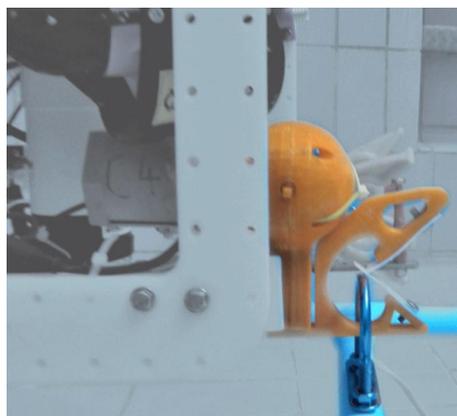


Figure 25 Buoy being attached onto a container

Beluga is equipped with a detachable buoy, shown in Figure 25, to mark location of the high-risk container. The buoy consists of float, string reel, and hook. The bulb-like float is 3D printed with 20% infill density to generate positive buoyancy. Inside the buoy lies a reel that stores 5 meters of string, which ties the float and hook together. Having the string stored in the float reduces risk of it tangling with other objects. The hook has a large opening for guidance and locks onto the bolt by two flexible plastic plates that serve as one-way locking mechanism. This simple design helps pilot attach the hook onto the U-bolt easily and securely.

#### Incident Site Mapping

The software division developed a simple software approach that uses monocular camera system to measure distance between high-risk container and the other three containers. Beluga's pilot just has to position camera at the same level as the U-Bolt of the high-risk container and take one picture of each low-risk container.

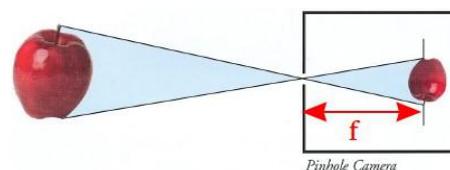
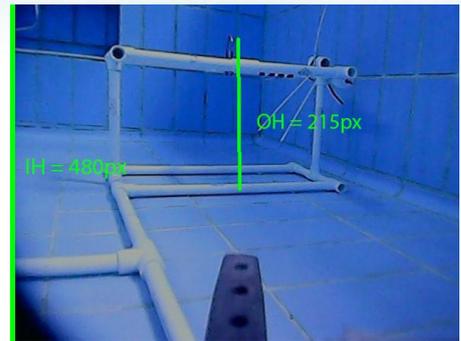


Figure 26 Diagram of pinhole camera



Since Beluga directly faces each container to take their picture, its heading is used to find the required angle measurements. By using the dimensions in Figures 26 and 27, the actual distance can be computed through the pinhole camera mathematical model, which finds the ratio of the product of the focal length ( $f$ ), container height (27cm), and image pixel height (OH), to the product of the object pixel height (IH) and camera's height. Since these parameters are known, the real distance between two containers can be determined. Figure 27 demonstrates this model by finding the actual distance from the high-risk container to the shown container through the pixel measurements.



**Figure 27** Screenshot captured from camera, with IH and OH measured in pixels

### III. SAFETY

#### A. Safety Philosophy

Epoxsea prioritizes safety above all else, and believes that all accidents are preventable by implementing strict safety measures. Therefore, numerous safety practices and protocols are enforced to ensure that all members are working under a suitable and safe environment.

#### B. Vehicle Safety Features

Safety is inherent to vehicle design and considered throughout Beluga's development. Mechanical engineers ensured the absence of sharp edges on Beluga through filing and deburring. Moving parts such as thrusters are also marked with visible warning labels. The side of the frame has handles integrated for crew members to safely transport the ROV, as detailed in Design Rationale. The electronics division installed a kill-box between the 48V power supply and the tether, which has an inline fuse and an emergency stop button to cut off power immediately when needed. In addition, each board features an LED indicator for the deck crew to quickly inspect operational status of Beluga. The software division programmed the motor driver with a watchdog timer that periodically checks inbound commands, such that motor driver will stop turning the thrusters if no valid command is received. The software division also implemented ramping algorithm on the motor driver to prevent current spikes that could damage the electronics system.



**Figure 28** Beluga's T200 thruster with safety sticker

#### C. Testing Protocol

Epoxsea has established a testing protocol to ensure operational safety. Before testing Beluga underwater, members must perform a systematic dry run as unforeseen problems are easier to resolve in air than underwater (see Figure 29). The company has established a

safety checklist, included in Appendix A, which must be followed by all members. For example, crew members are allowed to touch Beluga if and only if Beluga is idle, as injury may result from accidental activation of manipulators and thrusters. In the event of an emergency, any crew member closest to the power supply must immediately cut off power to avoid injury to the crew and damage to the ROV.

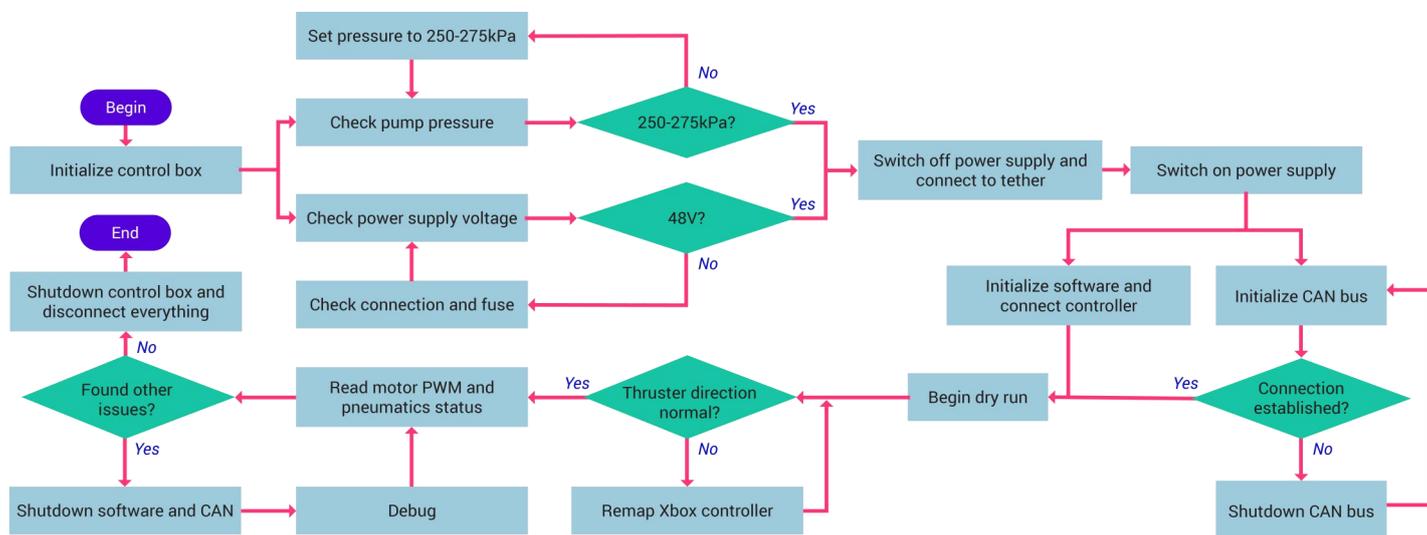


Figure 29 Flowchart of the testing protocol

## D. Testing and Troubleshooting Techniques

Epoxsea regularly tests Beluga in water to assess its performance and stability. The vehicle underwent its first water test in late January 2017. Initially, tests were performed in a large bucket to verify the core functionalities of the vehicle: movement, cameras, and buoyancy. After the core functionalities were established, the team proceeded to three-hour pool tests to evaluate Beluga’s performance in completing missions. Any unforeseen shortcomings in the design phase is discovered and ideas are brainstormed to address the issue. For instance, the valve-turner was unreliable in the first week of testing. It was discovered that our 3D printed prototype could not bear the torque that was induced by the motor and planetary gear-set. To address this, the valve-turner was rebuilt from aluminum alloy.

Epoxsea’s approach to troubleshooting is a step-by-step process which involves reproducing, isolating, and diagnosing the problem. Problems are usually discovered after a water test. The engineers will first attempt to reproduce the problem in the laboratory to ensure that it is not a false observation by crew members. Each component is then removed one-by-one to pinpoint the source of problem down to a single module (see Appendix C). Hereafter, the problematic module is thoroughly tested to diagnose and rectify the problem.

Individual components are tested inside a tank pressurized by an air compressor to simulate deep water environments. New prototypes or waterproofing methods are subjected to this test to determine reliability and expose potential problems. This year, improvements to solenoid valve waterproofing were made using 12-hour epoxy. The valve is tested under 20m of simulated depth. Upon verifying there is no exterior damage and the valve is functional, the decision to adopt this waterproofing method to Beluga was made.





## E. Vehicle Safety Features

All members of Epoxsea are required to follow safety protocols while working in the lab. Personal protective equipment such as safety goggles and hearing protections are available in the laboratory while masks are issued to every member for individual use. Safety goggles and hearing protectors in the lab must be worn while handling machinery and power tools. Masks must be worn by individuals while machining or working with epoxy or fibers to prevent the inhalation of



**Figure 30** Hans, member of the electronics division, soldering a PCB

dangerous chemicals or particulates. The overhead ventilation system must be used when soldering electronic components and handling epoxy to remove any fumes generated. When using the air pump, the pressure gauge is monitored to keep the pump's pressure at 2.75 bar (275 kPa). New members follow a rigorous peer-to-peer training at the beginning of team formation to ensure proper use of tools. At Epoxsea, every member is encouraged to remind and help each other when witnessing potential hazards, such as turning off unused tools and assisting with heavy lifting. All members are also encouraged to proactively update safety protocol whenever a dangerous situation arises, to ensure that the same situation does not occur in the future.

## IV. PROJECT MANAGEMENT

### A. Organization Structure, Planning, and Procedures

#### *Company*

Epoxsea promotes experimentation and free flow of ideas as culture. This is done through a flat organizational structure, where day-to-day operations are self-managed while decisions are made collectively. The Gantt chart in Appendix B is used to keep track of upcoming objectives so that the core system was established before other features are developed on top of it. Bi-weekly meetings are also held to set weekly goals in addition to discussing and trying to resolve any obstacles together to ensure smooth progress.

For the first month, new members of Epoxsea were guided by senior members in integrating to their respective divisions, so they could begin designing and testing early on. This fostered teamwork and allowed new members to rapidly and thoroughly understand the design and development process of an ROV. Once the members were ready, they were given more freedom towards approaching problems, and the Gantt chart served more as a tool to understand current priorities that needed to be addressed.

### Mechanical

In the mechanical division, manipulator designs are thoroughly evaluated by considering alternatives before moving to development phase. Important decisions are made in this planning phase, such as material selection and rationale in choosing passive or active manipulators – for instance, active manipulators are more versatile than passive manipulators in completing tasks but more susceptible to mechanical failure. Senior members would share experience and offer feedback to correct conceptual and design flaws to avoid operational issues. During development phase, prototypes are fabricated using readily available resources to test performance and reliability, which further improved upon pilot’s and team’s feedback.



Figure 31 Manipulator Realization Process

### Electronics

The electronics division promoted an open environment, in which all team members are encouraged to suggest their own ideas. Each member is responsible for a particular board design, but are encouraged to learn the overall electronics system to create a free-flow of ideas to seek continual improvement. Development began with identifying issues that occurred in previous years’ ROVs and proposing refinements that can be made to our system. The integrated design of the electronics within the Beluga frame itself was a collaborative effort between the electronic and mechanical division. In order to achieve this seamlessly, the divisions had extensive meetings, formalizing the concepts.

### Software

This year, the software division established a streamlined organizational workflow. Design began not on the computer, but on the whiteboard, where core functions were determined. A software system was designed such that each ROS “node” served a specific function, but was adaptable to support multiple features and extensible to integrate new ones. The team also used tools like GitLab for version control, software documentation, and bug tracking. The use of a phase-release developmental process further enabled the engineers to develop and test the Beluga’s software systems concurrently. Developing iteratively, the team is able to have a working full system with partial functionalities to debug and test while waiting for additional sensors and electronic boards to arrive. A phase-release process holds numerous advantages including: reduction of risks, promotion of system modularity, appropriate expertise delegation, and early training and feedback for the new engineers.

## B. Budget and Cost Projection

A large part of the budget for developing Beluga was allocated towards electronic components because there is more need for mission-critical electronic components, such as the Raspberry Pi and USB cameras. On the other hand, the budget for mechanical components was more conservative, reducing overall costs of developing Beluga. This also encourages better quality manipulators to be produced with less material footprint. The budget and cost projection of Beluga are attached in Appendix D and E, respectively.



## V. CHALLENGES

### A. Non-Technical Challenge

This year, Epoxsea set up a 3D printer and an in-house developed vacuum-former for more convenient prototyping in the laboratory. However, the company was then faced with disorganization and limited work space. In order to resolve safety concerns associated with these issues, Epoxsea reevaluated its space management methodology, and organized team cleaning and lab layout remodeling sessions, to rectify space issue and fortify team bond. The challenge would be to continue this spirit and maintain a productive working environment.

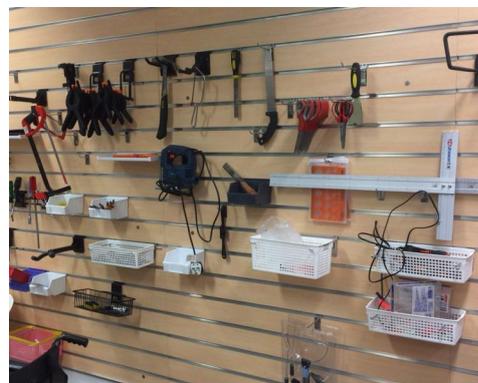


Figure 32 Mechanical tool rack after reorganizing

### B. Technical Challenge

One challenge that Epoxsea faced was processing magnetometer data obtained from the MPU9250 IMU for calculating the vehicle's heading. The raw measurements are passed to the Kalman filter where the heading is estimated. Passing the measurements unprocessed resulted in outputs that are unreliable due to hard-iron and soft-iron distortions. Hard-iron distortions are induced by ferromagnetic materials present in the same reference frame as the sensors, such as mounting screws and permanent magnets on the thrusters. Soft-iron distortions are deflections on the already existing magnetic field. Due to the presence of these distortions, a calibration method had to be devised.

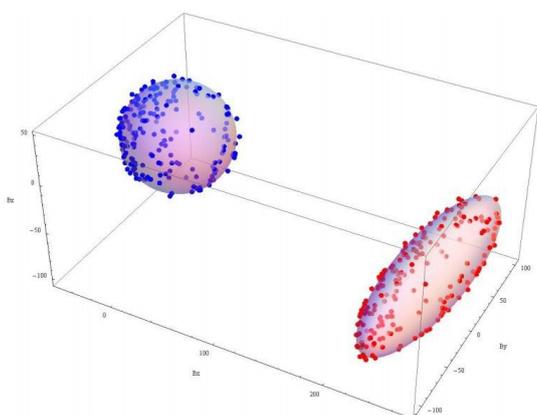


Figure 33 Plotted magnetometer data; calibrated (blue) and distorted (red)<sup>3</sup>

To compensate for errors, hard-iron and soft-iron distortions are modeled to an ellipsoid surface with an offset from the origin<sup>3</sup>. The calibration process consists of fitting ellipsoid surface to a large number of sample measurements. After the ellipsoid parameters and origin offset are obtained, the raw measurements are transformed from ellipsoid surface to a sphere centered at the origin. This transformation removes hard- and soft-iron distortions. Before mission runs, the magnetometer is calibrated by rotating the ROV in a figure-eight pattern, similar to that of a smartphone compass calibration.

After testing, it was found that the heading information obtained from the calibrated measurement is more reliable, with error as small as 10 degrees. Overall, the solution is not perfect, since some errors still persist and there is an added procedure before mission runs. In the future, the company will explore the possibility of calibrating the magnetometer biases in real time.

<sup>3</sup>Ozyagcilar, Talat. "Calibrating an ecompass in the presence of hard and soft-iron interference." Freescale Semiconductor Ltd (2012).

## VI. LESSONS LEARNED

### Mentoring

This year, there is stronger emphasis on peer-to-peer training as many members are expected to retire by the end of current competition season. December to January was spent improving new members' technical skills and safety awareness. Mechanical engineers were adapted with laboratory tools and mechanical designs. Learning how to use tools properly ensures safety of members and lifespan of tools, while better mechanical design understanding reduces waste material and eases assembly. Electronic engineers learned electronics theory to get accustomed with analog sensors. Software engineers were familiarized with ROS so their software could be reviewed and tested early on. The team spent considerable amount of time together, where new members became more confident at voicing out their ideas and senior members become better communicators.



**Figure 34** Daniel (bottom left) and Dennis (second from right) from software introducing Linux to electronics and mechanical divisions

### Additive Layer Manufacturing

The introduction of a Delta 3D printer in Epoxsea deepened the company's knowledge on additive layer manufacturing. It is now possible to prototype a design that would be difficult if not impossible to fabricate via conventional methods (such as milling, drilling, and sawing), while also allocate more time for improving designs. Learning how to operate the 3D printer was quick as it only requires users to convert SOLIDWORKS file to an STL file, which is then translated into G-code using a slicer software (CURA) for the printer to read.

More frequent use of additive layer manufacturing this year also increased the mechanical division's experience in choosing material and means of manufacturing. For instance, during development of valve turner's mount/motor housing, the mechanical division tried to use 3D printed Polylactic Acid (PLA), 3D printed fiber-reinforced nylon, and CNC milled 6061 aluminum alloy. Through evaluation, it figures each has its own suitable usage in Beluga.

Material	Tensile Strength (MPa)	Ductility (%el)	Density (g cm <sup>-3</sup> )	Evaluation
(3D Printed) Polylactic Acid <sup>4</sup>	22	1.6	1.3	Lightweight, suitable for non-structural or low-load bearing purposes—used for the <u>detachable buoy</u>
(3D Printed) Fiber-reinforced nylon composite <sup>5</sup>	160	5	1.4	Lightweight, suitable for moderate loads and low impacts— used for one-way mechanism in <u>agar collector</u>
(Milled) 6061 Aluminum <sup>6</sup>	310	12	2.7	Suitable for structural and high-load bearing purposes— used for <u>valve turner</u> motor housing/mount

**Table 1** Evaluation of material and their means of manufacturing

<sup>4</sup>"PLA Copolymer." 2017. MatBase. <https://www.matbase.com/material-categories/natural-and-synthetic-polymers/thermoplastics/agro-based-polymers/material-properties-of-polyactic-acid-copolymer-pla-c.html#properties>

<sup>5</sup>"Polyamide - Nylon 6,6 - 30% Glass Fiber Reinforced (PA 6,6 30% GFR) Material Information." 2017. GoodFellow. <http://www.goodfellow.com/A/Polyamide-Nylon-6-6-30-Glass-Fiber-Reinforced-Polymer.html>

<sup>6</sup>"Aluminium 6061-T6; 6061-T651." ASM Aerospace Specification Metals Inc. <http://asm.matweb.com/search/SpecificMaterial.asp?bassnum=ma6061t6>



## VII. FUTURE IMPROVEMENTS

### *Electronic Speed Controller (ESC)*

For the past two years, Epoxsea has been using commercial Electronic Speed Controllers (ESC) to drive the ROV's brushless motors. The ESC used for Orca's thrusters in 2016 exhibited a major limitation of producing different maximum forward and backward speeds, inhibiting agile and precise movement. As such, since November 2016, Epoxsea has delved into research and development for the creation of an in-house ESC that utilizes Field Oriented Control (FOC), such that it is able to precisely control the torque and

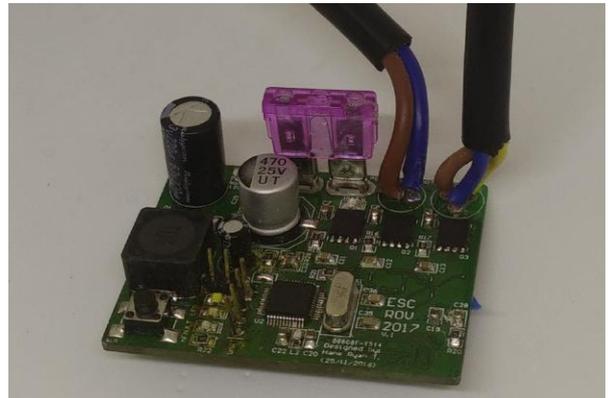


Figure 35 In-house ESC

rotational speed. FOC requires additional components to measure voltage and current in each phase, and the resulting hardware is far more complex than off-the-shelf ESCs. However, due to the shortcomings in design, Epoxsea's electronics engineers were not able to integrate the ESC into Beluga in time. Despite this, Epoxsea engineers still strive to improve the present design from previous developments.

### *Time management*

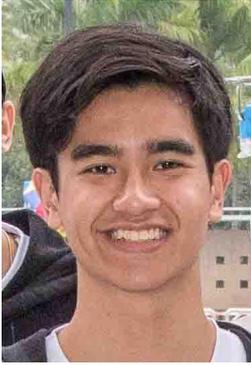
Epoxsea would benefit from better time management in the next competition season. Members often need to postpone their deadlines as they are eager to work on many tasks at once, resulting in lowered overall productivity. In the future, delegating one task to less members, and each member to less tasks could significantly increase productivity by increasing incentive and sense of responsibility in each member.

## VIII. REFLECTIONS



"As a new electronics member of the HKUST ROV team, I think that joining this great team has been a truly memorable experience. After hours of work to create continual developments to the robot it feels satisfying to see it come to fruition. I believe that I have went through a steep learning curve that has taught me numerous things ranging from the technical electronics skills to the interpersonal skills required to communicate with the rest of my team. I am really pleased that as an electronics engineer, there is much cooperation with the mechanical and software side of the team. This in turn allowed me to learn all these other aspects of underwater robot development. This journey has not been without its challenges, and every time my team and I solve these problems, it makes joining this team feel even more worth it."

*- Mohammad Hanif Dean Nadhif (Indonesia)*



“This is my second year in the HKUST ROV Team, but that does not imply that I stopped learning. Building upon last year’s experience, I have been able to assist in the development of more sophisticated technologies. Apart from continuing my role as a software engineer, I am also this year’s chief executive officer, and holding this position is another learning experience itself. It takes a team effort to develop a high-performance ROV, and having to keep everyone on track and motivated can be difficult, but possible. No matter what the results of this year would be, I could still say that working with a different team to design a ROV remains to be a novel and exciting experience.” - **Gian Miguel Sero Del Mundo (Philippines)**



“What’s my experience in robotics? Well. “Fun”, “Thrilling”, “Mind blowing”, “Exhausting”, “Fruitful”. The list goes on. Joining HKUST ROV team has been one of the best experiences I had in my university life. Apart from the confidence gained from learning all the technical knowledge and practical skills, I enjoyed the time spent with students who shared the same interest in robotics, the thrill that I had when things didn’t turn out to be what was expected, and the satisfaction that I had when we successfully solved all the problems and built a functional robot from scratch. I am eager to come back next year.” - **Tan Tun Jian (Malaysia)**

## IX. CORPORATE SOCIAL RESPONSIBILITY

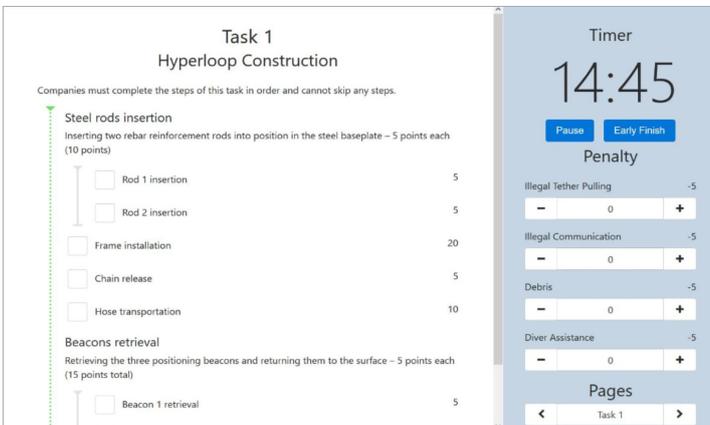


Figure 36 “Mission Helper” developed for Hong Kong regional competition

Epoxsea helped IET Hong Kong, organizer of MATE ROV regional competition in Hong Kong, coordinate the competition for Ranger Class. The software division developed an electronic scoring system for the organizers to save paper and promote sustainable use of resources. This also gave judges access to a platform to quickly input and cross check scores of 24 Ranger teams that joined the competition.

Raising awareness of STEM field in Hong Kong is a tradition in Epoxsea, especially in areas of engineering and underwater-related technologies. On April 2017, Epoxsea helped coordinate the annual Underwater Robot Competition under the “Center for Global and Community Engagement” program. This community engagement project targeted primary and secondary school students to help them understand the fun of Inclusion, Science, Technology, Engineering, Art, and Mathematics (iSTEAM). Epoxsea’s former member, Abby Yao, was invited to China Hardware Innovation Camp on July 2016 to share her experience in building an ROV and participating in ROV MATE competition.



## X. ACKNOWLEDGEMENTS

Epoxsea would like to extend their most sincere gratitude to the following benefactors for their support in the development of Beluga:

**HKUST School of Engineering** – for providing sponsorship and labs for Epoxsea to use.

**HKUST Center for Global & Community Engagement (GCE)** – for coordinating the ROV inclusion competition.

**HKUST Design and Manufacturing Services Facility (DMSF)** – for providing technical support and suggestions to Epoxsea.

**HKUST Student Affairs Office (SAO)** – for allowing us to use the swimming pool for testing Beluga.

**Dr. Kam Tim Woo** – our supervisor, whose guidance and advice helped us improve both our technical and non-technical skills.

**Chun Yin Leung and Sau Lak Law** – our mentors, whose guidance proved to be invaluable.

**MATE Center** – for organizing the international competition, providing a platform for the growth of the entire community, and promoting STEM education around the world.

**The Institution of Engineering and Technology, Hong Kong (IET HK)** – for organizing the Hong Kong/Asia Regional of the MATE International ROV Competition 2017.

**RS Components Ltd.** – for sponsoring electronic equipment for Epoxsea.

**Dassault Systems** – for providing SOLIDWORKS Student Edition CAD software for Epoxsea.

**EDIS** – for providing a hosted server for our website and internal use.

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## XII. APPENDICES

### Appendix A: Operational Checklist

#### Before mission run:

- Ensure no loose wiring or any physical damage
- Ensure all submersible connectors are sealed
- Set compressor output to 275 kPa.
- Check nominal power supply output is 48V
- Test all thrusters, pneumatic actuators, and cameras
- Shore side calls "Ready to launch"

#### Launching:

- Control side calls "Launch"
- Mount detachable manipulators
- Handle ROV into water
- Shore side calls "Go"

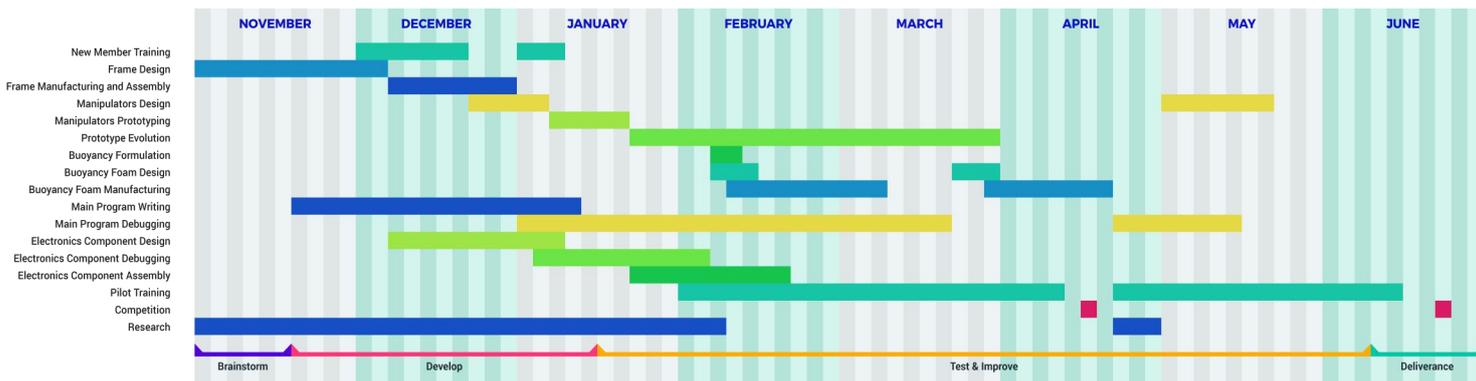
#### Item retrieval:

- Control side calls "Retrieve"
- Shore side calls "Contact"
- Check items in gripper, beacon retriever, and agar collector
- Bring items to control side
- Launch ROV

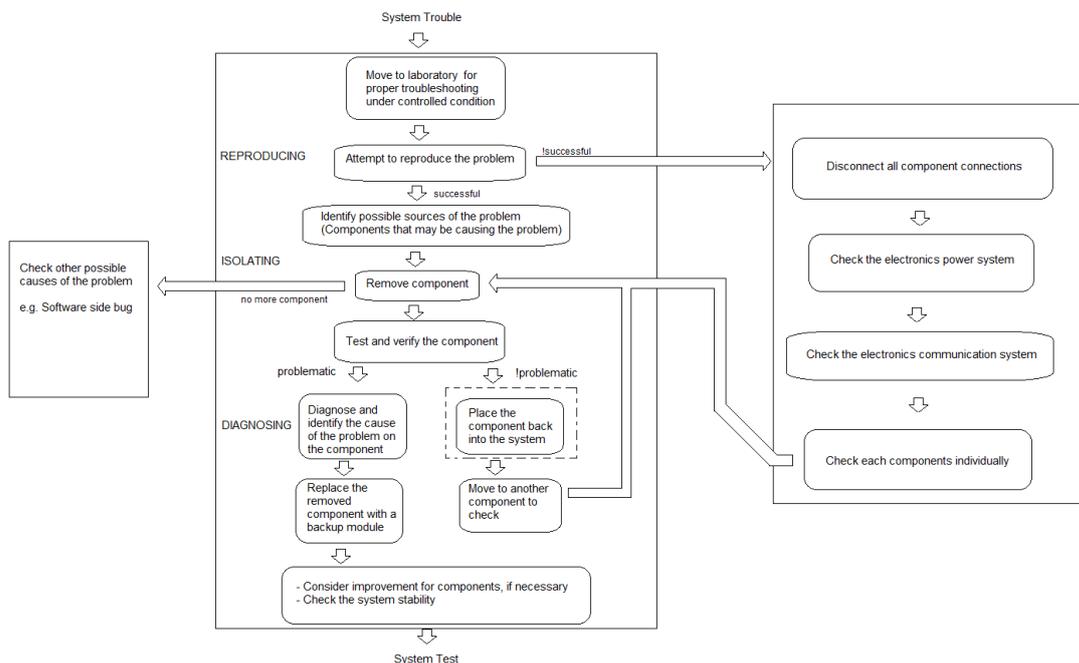
#### End of mission:

- Control side calls "Bring up"
- Bring up ROV
- Shore side calls "Kill!"
- Power down ROV, control box and air compressor
- Stow tether securely

### Appendix B: Gantt Chart



### Appendix C: Electronics Troubleshooting Flowchart







## Appendix D: Budget

<b>Travel Expenses (USD)</b>		<b>Beluga/Machine Development (USD)</b>		<b>Sponsorships</b>	
Airfare (15 members, 2 mentors)	\$10,000	Mechanical Components	\$1,950	Airfare (from University)	\$4,095
Hotel (5 nights, 6 rooms)	\$8,740	Electronic Components	\$3,900		
Rental Van	\$65				
<i>Travel Sub-Total</i>	\$18,805	<i>Operations Sub-total</i>	\$5,850	<b>BUDGET NET TOTAL</b>	\$20,560

## Appendix E: Cost Projection

<b>Type</b>	<b>Item</b>	<b>Market Price (USD)</b>
<b>Electronic Components</b>		
<u><i>Beluga</i></u>		
Purchased	Brushless Motor	\$121.80
Re-used	T200 Thrusters (2 pcs), from Orca/Epoxxsea 2016	\$338.00
Parts Donated	T200 Thrusters(4 pcs), from BlueRobotics (Guts&Glory Award 2016)	\$676.00
Purchased	48 to 12 V Regulators (4 pcs)	\$91.00
Purchased	Printed Circuit Boards	\$42.00
Purchased	Anderson Plugs	\$11.33
Purchased	Analog Waterproof Cameras	\$62.40
Purchased	Uninterruptible Power Supply	\$38.50
Purchased	Raspberry Pi Cameras	\$60.48
Purchased	Raspberry Pi 3	\$35.00
Purchased	30A Electronic Speed Controllers (7 pcs)	\$276.00
Purchased	Waterproof LED	\$11.70
Purchased	Connectors	\$329.81
Purchased	Wire	\$52.00
<u><i>Control Box</i></u>		
Re-used	LCD Display, from Orca/Epoxxsea 2016	\$177.45
Re-used	Keyboard, from Orca/Epoxxsea 2016	\$29.64
Re-used	Xbox 360 Controller, from Stingray/Epoxxsea 2015	\$14.80
Re-used	AV Hub, from Orca/Epoxxsea 2016	\$7.00
Purchased	Power Supply	\$45.37
Re-used	Computer Components, from Stingray/Epoxxsea 2015	\$300.00
Re-used	Control Box Case, from Stingray/Epoxxsea 2015	\$150.00
<b>Electronics Sub-Total</b>		<b>\$2,870.28</b>
<b>Mechanical Components</b>		
Purchased	Beluga HDPE Frame	\$210.00
Re-used	SMC Double Acting Cylinders (3 pcs), from HKUST Robotics Team	\$99.60
Re-used	SMC Valve Manifold, from Stingray/Epoxxsea 2015	\$39.00
Purchased	SMC 5/2 Solenoid Valve	\$176.68
Re-used	High Density Polyethylene Stock, from Orca/Epoxxsea 2016	\$65.00
Re-used	Polystyrene Stock, from Orca/Epoxxsea 2016	\$20.80
Re-used	Carbon Fiber Cloth, from Orca/Epoxxsea 2016	\$84.00
Purchased	3D Print Service	\$73.84
Purchased	CNC Service	\$94.34
Purchased	Epoxy	\$187.59
<b>Mechanical Components Sub-Total</b>		<b>\$1,050.85</b>
<b>Beluga Cost</b>		<b>\$3,921.13</b>