香港科技大學
THE HONG KONG UNIVERSITY OF SCIENCE AND TECHNOLOGY

epoxsea

NARWHAL

Explorer Class
2018 MATE ROV Competition
Technical Report

HONG KONG

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I. ABSTRACT

Epoxsea Inc. ("Epoxsea") consists of sixteen multicultural students who are passionate about underwater robotics. The company has developed an innovative solution to the Applied Physics Laboratory (APL) at the University of Washington's (UW) request for a remotely operated vehicle (ROV) to assist in locating the wreckage of an airplane and returning its engine, installing or recovering seismometer and installing a tidal turbine and instrumentation to monitor the environment.

This year's ROV, Narwhal, is built upon successes and failures of Epoxsea's past ROVs. The mechanical division pushed for in-house development of manipulators, including rapid prototyping through 3D printing, for cost reduction.

With the introduction of new Electronic Speed Controller (ESC), Wi-Fi modules and acoustic sensors, extensive collaboration between the software and hardware divisions was crucial to tackling these challenges. The two divisions continued to develop on top of architectures inherited from previous years. The hardware division continues to waterproof electronic components using epoxy rather than with an electronic tube, while the software division continues to utilize Robot Operating System (ROS) for modularity.

With the combined efforts of Epoxsea's members over numerous man-hours of planning, development and testing, the team is confident that Narwhal is the most suitable ROV to fulfill the APL of UW's request for the proposal.

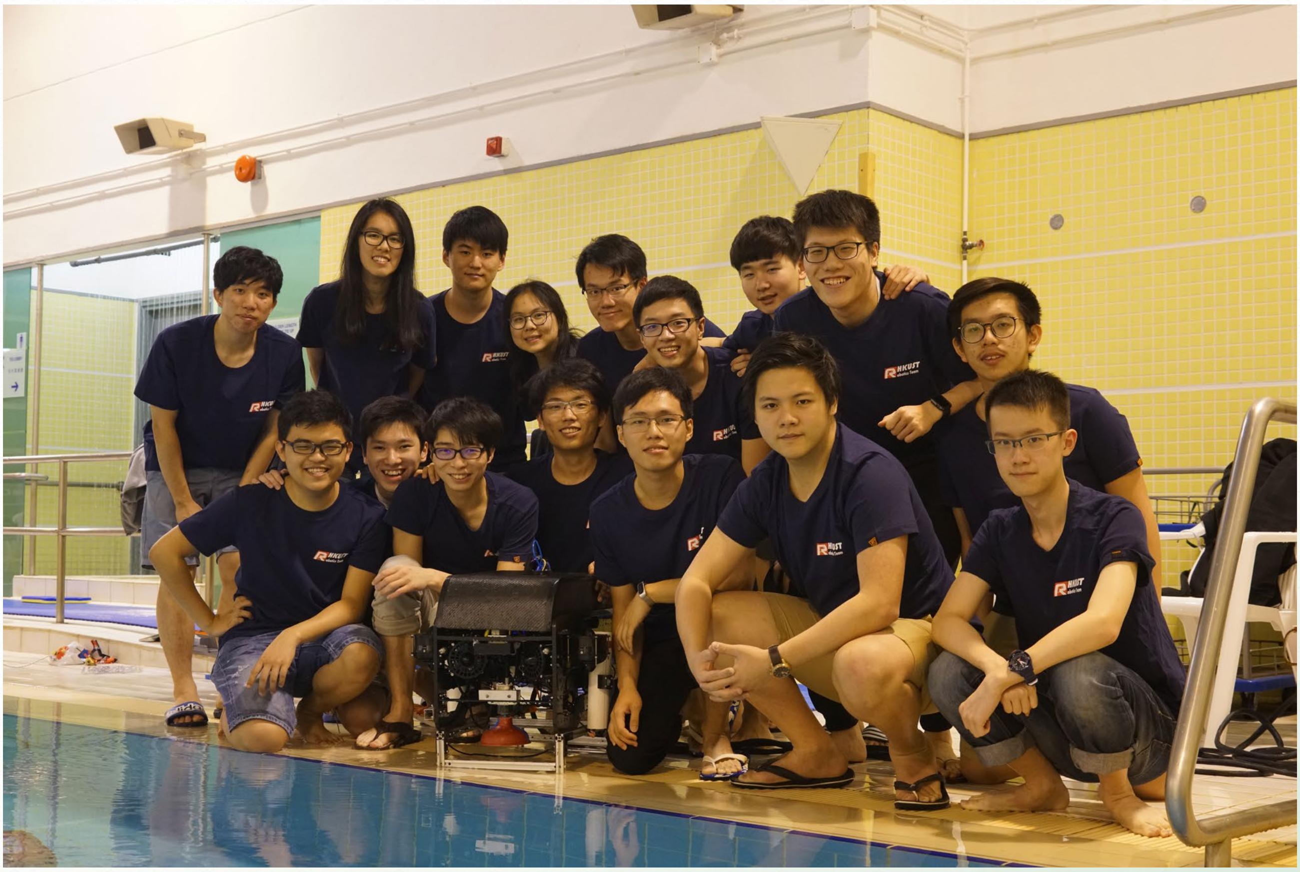

Figure 1 *Narwhal's Team Members*
Top row (left to right): Sanghyun Jeon, Ka Yan Yiu, Jaewook Lee, Mengdi Zhang, Tsz Ho Wong, Kuang Yu Hsueh, Jeongseok Hyun, Chee Hau Cheng, Riwandy

Bottom row (left to right): David Sun, Anthonie Tjendana, Kin Ip Mong, Minsoo Khang, Yat Wing Cheung, Adrian Prawira Susanto, Kevin Pratama

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II. DESIGN RATIONALE

A. Design Evolution

Epoxsea Inc. always strives to develop a ROV with improved functionality and higher performance from year to year. Narwhal's maneuverability has improved from last year's, Beluga's, design with an additional vertical thruster. Narwhal is able to achieve six degrees of freedom with improved agility without compensating its speed. To facilitate the design and development process, Narwhal's frame was customized with mounting holes of standardized distance (20 mm) and size (M4). This allowed the manipulators, cameras and electronic components to be positioned in an organized and modular manner. For example, all aluminum bars in lower-half of ROV have been designed with the above standards, greatly improving the versatility in its positioning. Additionally, new buoyancy foam R-3312 was used in place of previous year's in-house buoyancy foam. In comparison, buoyancy foam R-3312 can be shaped easily and is resistant to deformation under high pressure, saving a significant amount of time for the team[1].

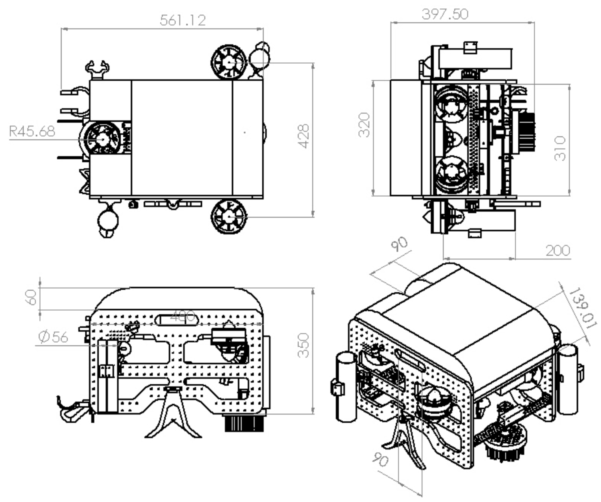


Figure 2 *Narwhal engineering drawing*

Epoxy was utilized to waterproof our Printed Circuit Boards (PCBs) and cables, after they were housed in a 3D printed container. This design has been proven to be both reliable and easily reproducible from previous year's experience. This year Dual Lock fasteners SJ3551 from 3M are used to secure the electrical housing instead of bolts. This method not only makes the housings more adjustable but also reduces the difficulties in their maintenance. 3D printed housings were designed with different depth to accommodate various sizes of PCBs and headers, allowing them to be organized neatly into the designated slots of the frame.

The software team focused on improving image processing and computer vision software, to address the requirements of this year's missions. For instance, previous year's algorithms had difficulty in processing images which are taken from non-perpendicular angle above the ground. With the implementation of improved algorithms, the team strives to mitigate this limitation for Narwhal. Additionally, the software team also developed a new image recognition software utilizing OpenCV libraries to tackle specific mission tasks this year.

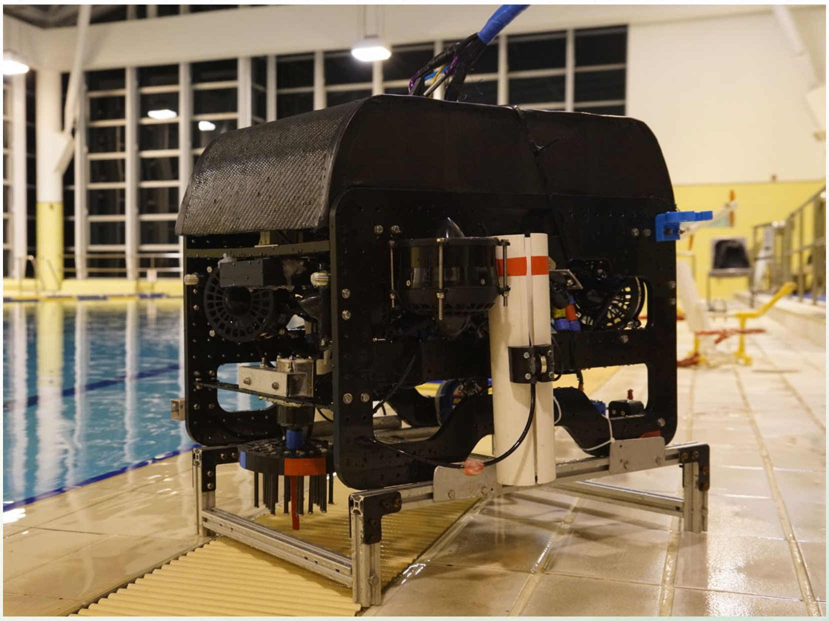


Figure 3 *Narwhal on the pool deck*

[1] Blue Robotics. (2018). *Subsea Buoyancy Foam: R-3312 - Blue Robotics*. [online] Available at: https://www.bluerobotics.com/store/parts/float-r1/.

B. System Interconnection Diagrams

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

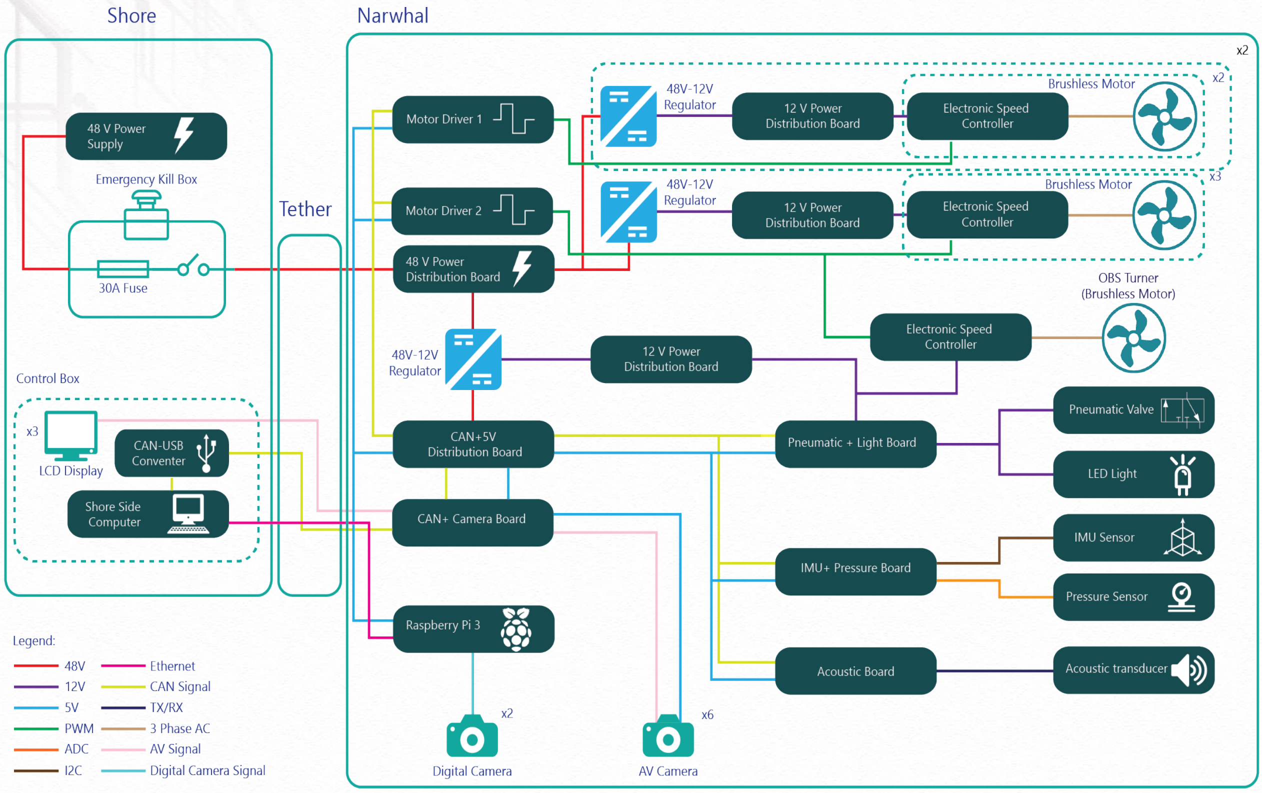


__Figure 4__ Electronics system interconnection diagram

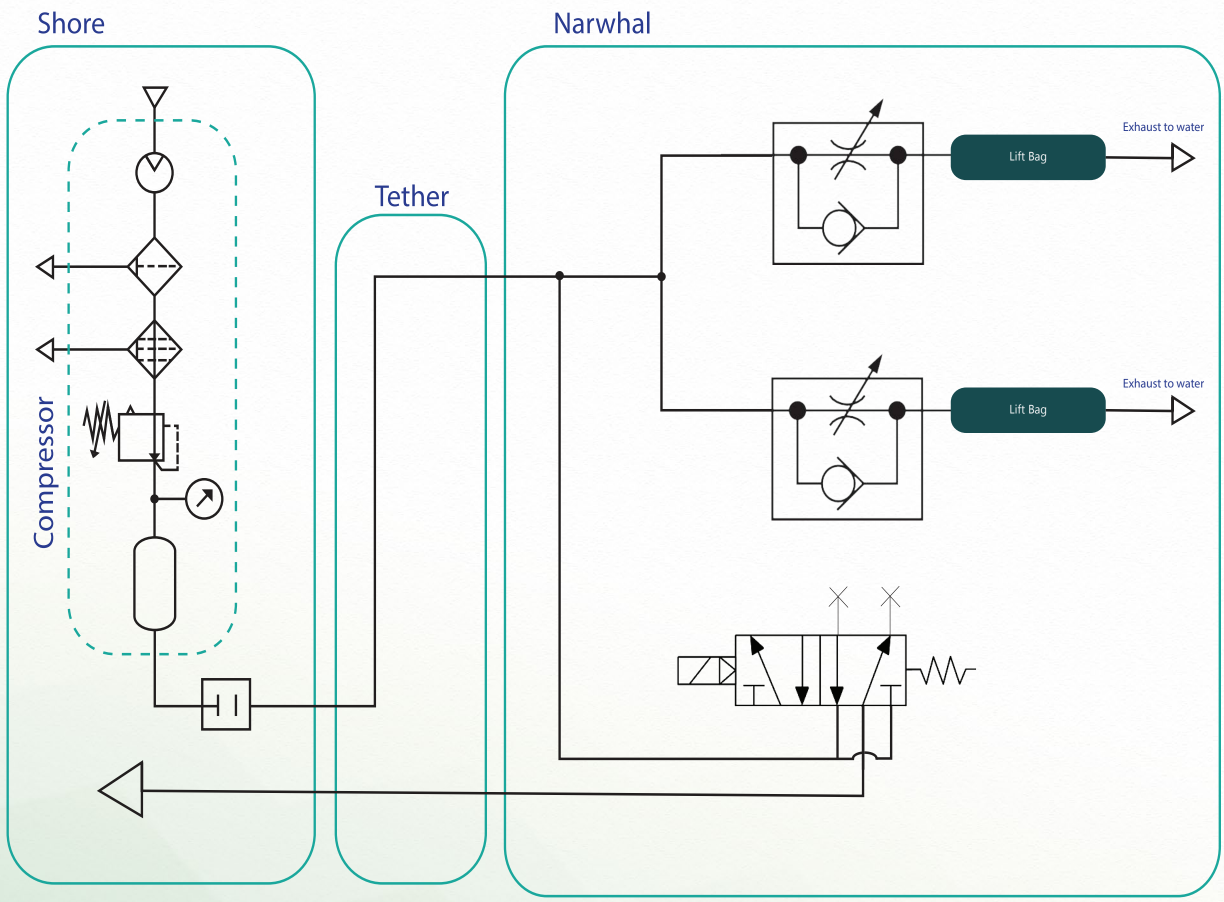


__Figure 5__ Pneumatics system interconnection diagram

C. Vehicle Core System

1) Mechanical

Frame

Narwhal's frame was designed in a two-tier architecture model, which has been proven to be reliable whilst offering high maintainability from Epoxsea's past experiences in Orca[2] and Beluga[3]. The top-layer has designated slots for all hardware parts, which allows for ease of installation and management of cables. Meanwhile, the bottom-layer constitutes of six aluminum bars for cameras and various manipulators for mission tasks.

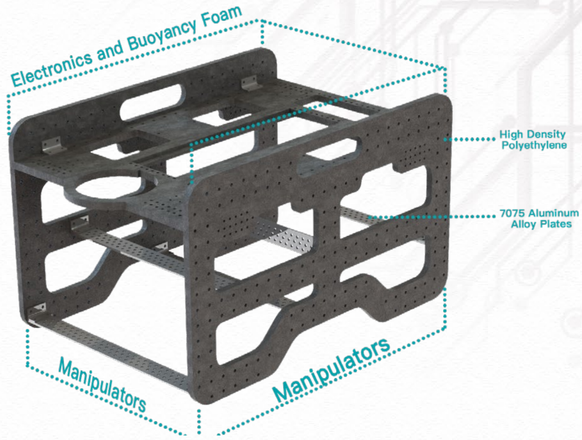


Figure 6 *Rendering of Narwhal's Frame*

Narwhal's top and side frames are built with High Density Polyethylene (HDPE). While being relatively cost efficient compared to its plastic counterparts (e.g. Polypropylene), HDPE's resistance to moisture and impact motivates the team to use this material for the main skeleton of the frame. The side frames are also designed with standardized measurements, as specified in design evolution, to facilitate the design process of different mounting mechanisms.

The bottom-layer of the frame was constructed using anodized 7075 aluminum alloy bars with perforated M4 sized holes to house manipulators and cameras needed for the competition. Anodized aluminum is chosen over other contemporary metals, such as 316 stainless steel, for its resistance to rust, remarkable tensile strength, and yet being relatively lightweight. Compared to HDPE, aluminum alloy is more malleable and has higher tensile strength[4]. These features allow the alloy to support heavy manipulators and other parts of the frame effectively.

Buoyancy

Epoxsea utilized Subsea Buoyancy Foam: R-3312 in place of previous year's expanded polystyrene for Narwhal's buoyancy foam (rationale discussed in design evolution). The team customized these foams to be hydrodynamic and be able to support the ROV in maintaining neutral buoyancy throughout the missions. Its hydrodynamic shape enables Narwhal to move with minimum resistance, while the neutral buoyancy provides high stability for Narwhal's execution of tasks.

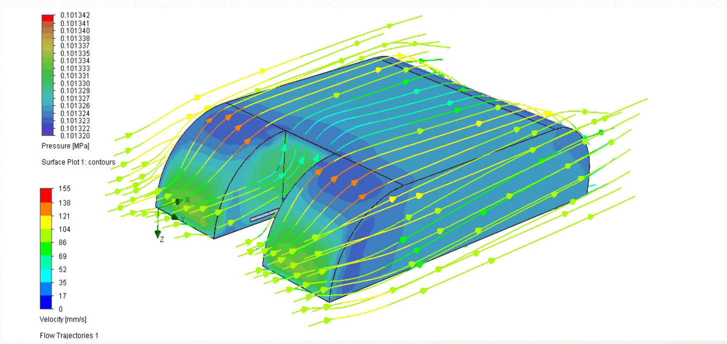


Figure 7 *Flow simulation of Narwhal's buoyancy foam*

Twelve blocks of buoyancy foams were integrated in Narwhal's design, with three in each corner. Such layout evenly distributes the buoyancy force across the frame, empowering the ROV to attain greater stability underwater.

[2] HKUST Epoxsea. (2016). *Orca Technical Report*. [online] Available at: https://www.marinetech.org/files/marine/files/ROV%20Competition/2016%20competition/2016%20TECH%20REPORTS/EXPLORER/HKUST_TECH_REPORT.pdf.
[3] HKUST Epoxsea. (2017). *Beluga Technical Report*. [online] Available at: https://www.marinetech.org/files/marine/files/ROV%20Competition/2017%20competition/2017%20Technical%20Documentation/EXPLORER%20class/HKUST_EPOXSEA_TechReport_2017.pdf.
[4] *Makeitfrom.com*. (2018). *7075 Aluminum vs HDPE*. [online] Available at: https://www.makeitfrom.com/compare/7075-AlZn5.5MgCu-3.4365-2L95-A97075-Aluminum/High-Density-Polyethylene-HDPE.

Shell

Narwhal's shell provides protection to the buoyancy foams and all of its electronic components. Constructed largely of foam-core board, the shell is glazed in three layers of epoxy, two layers of carbon-fibre reinforced polymer and a layer of fiberglass. The rigidity of the shell enables the ROV to withstand high hydrostatic pressure throughout its performance.

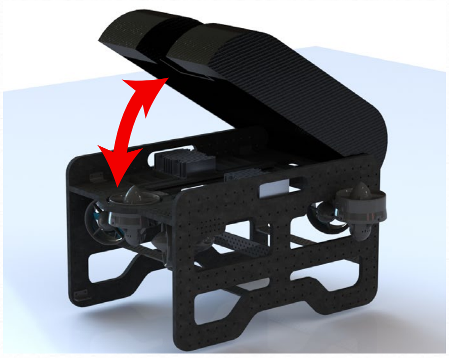


Figure 8 *Narwhal's shell mechanism*

The shell is mounted onto the top frame with two hinges at the back and a lock at the front of Narwhal. Such mechanism facilitates easy access for members to repair and maintain the system whenever necessary.

Propulsion

Narwhal's mobility is powered by T-200 brushless thrusters from Blue Robotics. This model was reused from previous years for its high reliability, durability and maintainability. Narwhal is equipped with seven thrusters to achieve six degrees of freedom, including pitch movement to meet the requirements of this year's missions. Four horizontal thrusters are mounted on the top layer and the rotational axis is tilted 30 degrees from the longitudinal axis. Such placement offers both stability and speed, as the torque created by each thruster is nullified by its complements, resulting in higher velocity.

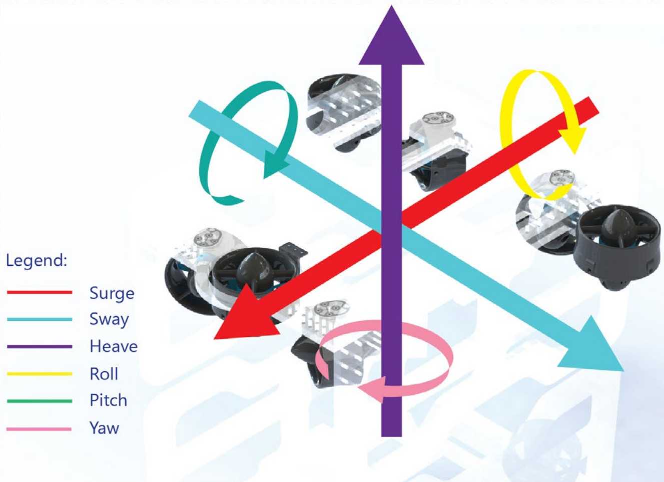


Figure 9 *Narwhal's six degrees of freedom*

The three vertical thrusters are arranged in an equilateral triangular formation with its centroid positioned at the intersection point of the diagonal of the top frame. This allows the center of thrusts to align with the center of the frame, offering Narwhal with additional stability during heave motions.

2) Electronics

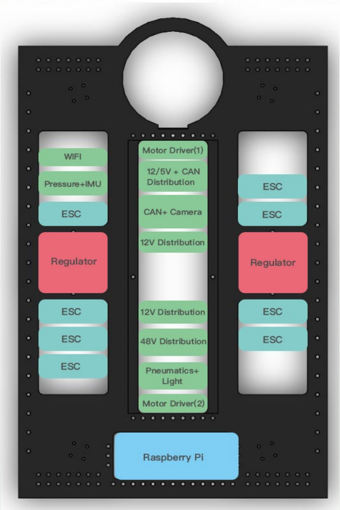


Figure 10 *Electronics board layout*

Narwhal's electronic subsystem follows Epoxsea's tradition of using the STM32 microcontroller units with CAN communication. The system consists of 10 PCBs, a Raspberry Pi and a pneumatic switch. The STM32F103 Microcontroller Unit was chosen over other microcontrollers for its robustness, sufficient peripherals and whilst being relatively affordable.

Our electronic architecture demonstrates Epoxsea's emphasis on modularity. As shown in Figure 10, Narwhal's electronic components are placed in designated areas to minimize the length of its connections to respective modules. This design allows us to maintain and debug the electronic boards efficiently.

Power Distribution

Each board on Narwhal receives 5V power and CAN communication signal simultaneously from one connection header. These boards have a self-recovery fuse after receiving 5V from “5V+CAN” cable as a safety precaution. This protects the whole system against excessive current and is able to reset automatically at any time during the mission. Three 12V outputs are derived from each 12V Splitter board, supplying 12V power to eight Electronic Speed Controllers (ESCs) and Pneumatic board.

Compared to Beluga, Narwhal’s boards demonstrate 20% reduction in size, allowing for economical usage of space to accommodate larger regulators and additional boards. Effective positioning of boards results in shorter wires and improved wire management. For instance, the 12V distribution board is placed close to ESCs and the clear view of the system assists Narwhal crew members in troubleshooting during mission run.

Controller Area Network (CAN)

CAN protocol is used for communication between the ROV and control box due to its high baud rate (up to 1.25Mbps) which enables rapid exchange of messages between its components. A centralized CAN/Camera board is connected to every board on Narwhal, and high-speed CAN transceiver (TJA1050) is installed on each of these boards, facilitating the communication. The pilot’s input to the controller initiates the transmission of CAN signals to corresponding MCUs, which are programmed to perform respective tasks. For instance, rotating thrusters at various speeds, switching camera channels, and controlling the pneumatic system. Additionally, maintaining differential impedance at each end of the CAN bus with low-value resistors reduced signal noise for accurate communication.

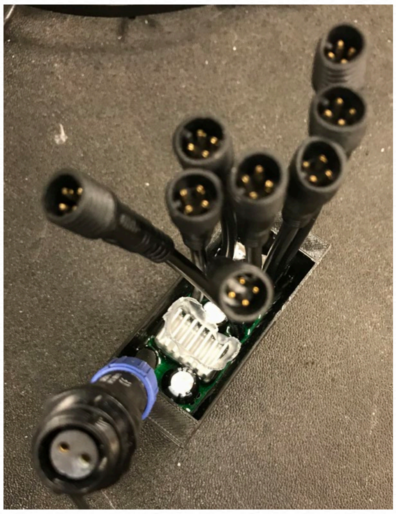


Figure 11 *CAN + 5V Board*

Electronic Enclosure

Instead of using a cast acrylic electronic tube, Narwhal continued the tradition of using epoxy for waterproofing our electronics system. As mentioned above, Narwhal has the advantage of using less epoxy owing to smaller boards and container dimensions as compared to previous year’s designs. This method of waterproofing eliminates the possibility of water leakages, whilst maintaining high modularity and simplifying the process of debugging.

Tether

Narwhal’s tether consists of six cables: two Category 6 Ethernet (CAT6) cables, two pneumatic pipes, and two power cables. These cables are shielded by a single layer of flexible Teflon casing, protecting the tether from wear and tear.

One of the Ethernet cables is used for CAN communication and AV

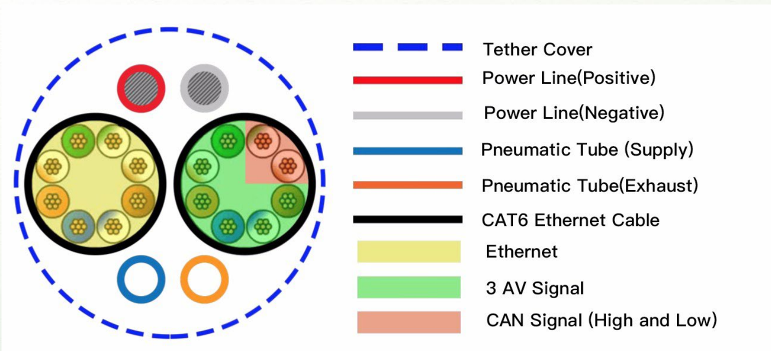
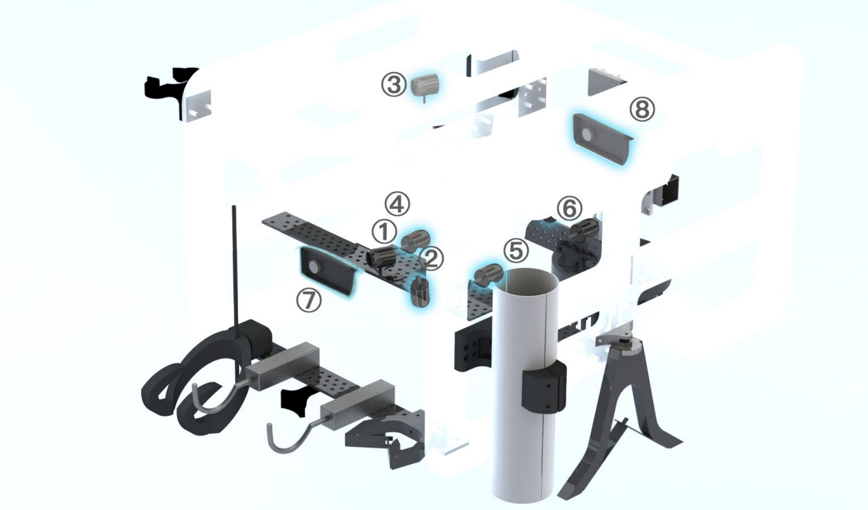


Figure 12 *Cross section of Narwhal’s tether*

camera video stream, while the other is used to establish connection to the Raspberry Pi and transmit digital images obtained from the digital cameras. The two pneumatic pipes are used for supplying and exhausting pressurized air. Two power cables, 48V and Ground, are specifically chosen to stabilize Narwhal's power supply.

Camera

Narwhal has six analog video (AV) cameras and two digital cameras installed. With one ethernet cable to control six AV cameras, Narwhal uses interchangeable AV camera channels. In order to achieve interchangeability in displaying the video feeds, the hardware members decided to utilize an ethernet cable to control these AV cameras. This allows for efficient space usage in installing screens, which will also prevent confusion as too many screens might be confusing to the pilot. On the other hand, the digital cameras are controlled by a Raspberry Pi, which provides the pilot with better viewing angles and higher quality images. The images taken by these digital cameras can also be utilized by Narwhal's software programs in tasks related to computer vision, such as color recognition or text recognition for the flight tail task.



The following cameras are used for:

1. Turbine Holder; Debris Hook
2. General Purpose
3. Multipurpose Hook; Acoustic Doppler Velocimeter; General Purpose
4. OBS Turner
5. Multipurpose Hook; General Purpose
6. Engine Hook
7. Aircraft Identification; Mooring Installation; General Purpose
8. Aircraft Identification; Mooring Installation; General Purpose

***Figure 13** Camera placements on Narwhal (side view)*

3) Software

The software team aims to improve the high-level modularity that was initially implemented in Beluga last year. As such, Epoxsea developed a bi-layer software architecture with a master-slave approach. The master layer is written in C++ with the ROS framework, while the slave is partitioned into two components: the ROV side system written in C using independent STM32 microcontrollers, and module specific system for Ocean Bottom Seismometer (OBS) leveling implemented in C++ using Arduino boards.

The master layer, which is run by the shore side computer is responsible for running the central ROS system, displaying camera outputs, and performing calculations. As for the vehicle control, a subset of the slave layer, a two-way communication protocol is set up, allowing commands, encoded into CAN frames, to be sent from the computer to their respective microcontrollers. Similarly, Narwhal's electronic boards send messages by the same protocol. The other subset of slave layer, which is implemented in Arduino, addresses certain tasks of the mission, such as Wi-Fi connection for OBS leveling and lift bag release. This layer does not go through CAN protocol and instead communicates directly to an independent computer.

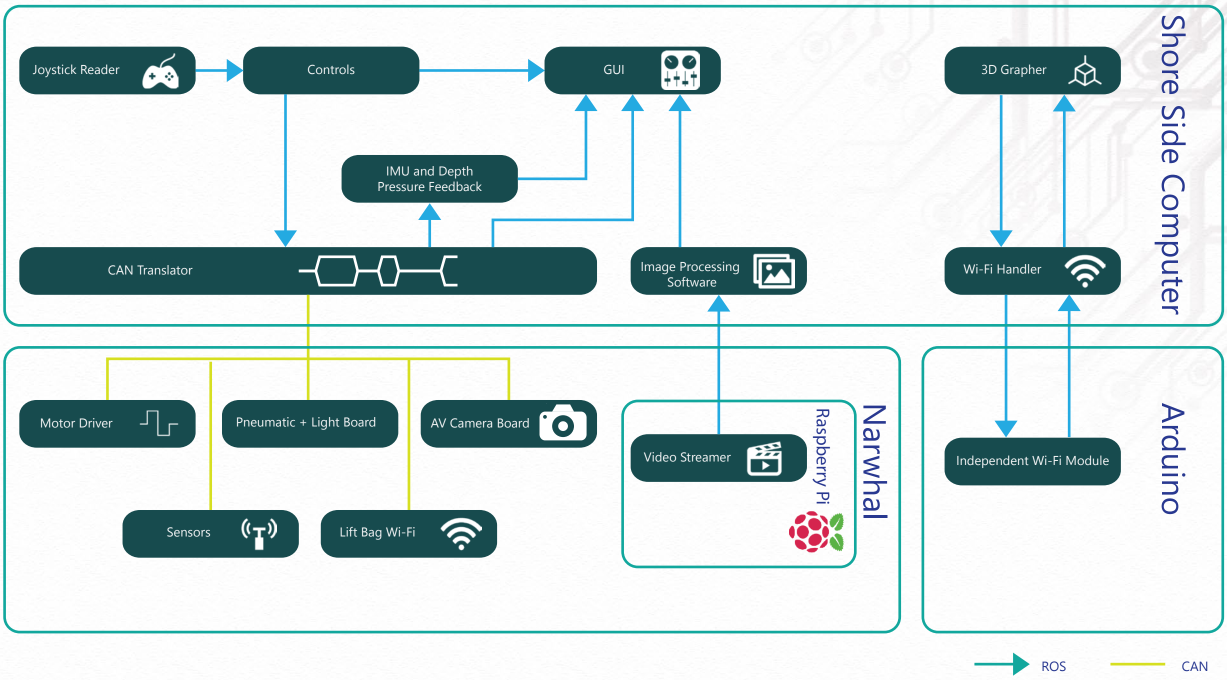


Figure 14 *Narwhal software architecture*

Robot Operating System (ROS)

The ROS framework is chosen for its high-level modularity and flexibility, alongside with its well-integrated libraries. In ROS, processes are executed as individual nodes, which are able to communicate with each other through a two-way communication publisher-subscriber model. Its development in C++ language also enables abstraction of the software system through object-oriented implementation, so as to reduce the complexity in code reading and feature implementation.

Moreover, the strong integration of ROS with third party libraries allows for incorporation of open source libraries. This includes OpenCV and Tesseract in Narwhal's image processing software. In addition, the modularity of ROS allows the system to run continuously regardless of individual nodes. These factors were the rationale for reusing ROS for Narwhal.

Graphical User Interface (GUI)

The software division has also developed a Graphical User Interface (GUI) written in HTML, CSS, and Javascript to communicate with the ROS system. One of the essential functions of the GUI is to provide the status of Narwhal motors and peripherals, as well as the video feeds provided by both AV and digital cameras. Other features include a newly integrated terminal interface to provide efficiency in performing additional operations like adjusting the parameters for emergency cases.

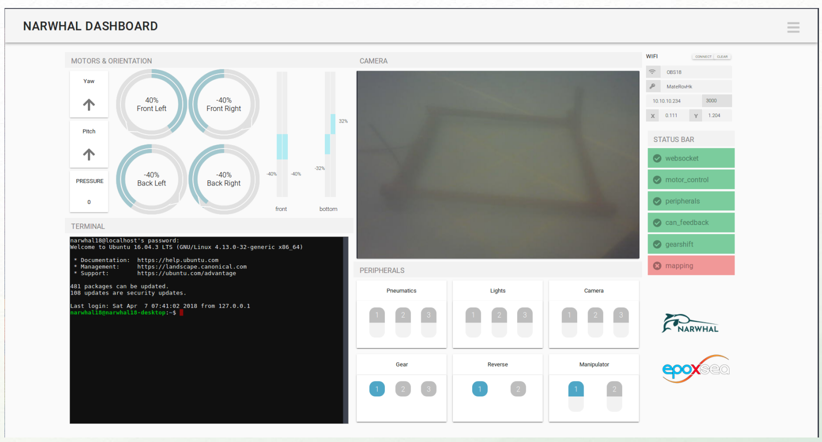


Figure 15 *Narwhal's Graphical User Interface dashboard*

The architecture of the GUI is based on a webpage that is connected with the ROS system. Vue Javascript framework is utilized alongside with Vuetify layout framework to provide user-friendly interface design. Rosbridge library enables seamless and direct communication between the page and the central ROS system. With this feature, users can view the Narwhal status and carry out operations such as connecting to Wi-Fi, image recognition, and others with convenience from intuitive control.

Inertial Measurement Unit

In order to enhance the movement of Narwhal, Epoxsea used Inertial Measurement Unit (IMU) to gain relevant data about Narwhal's orientation. The MPU-6050 module is used to obtain relevant data which are then processed by Madgwick's IMU and AHRS algorithm[5] to produce Narwhal's yaw and pitch orientations for auto stabilization.

Raspberry Pi

Raspberry Pi is integrated into the vehicle core system by utilizing the strong modularity of ROS framework. Ubuntu Classic 16.04 operating system is installed on the Raspberry Pi to align with the central ROS system in the shore side computer. Similar to Beluga, the Raspberry Pi is utilized as a video streamer. The Raspberry Pi will transfer digital image data to the image processing software which carried out on the shore side computer for better efficiency.

D. Mission Specific Feature

To tackle this year's Jet City set challenges effectively, the mechanical division has decided to construct passive manipulators that function optimally with Narwhal's design. All Narwhal's manipulators are visualized in CAD drawings and tested using in-house manufactured prototypes. With constant improvements through feedback from the pilot and divers, the passive tools designs are refined until they fullfill the requirements of the task and provide robustness of the design.

1. Debris Hook
2. Engine Hook
3. Liftbag Holder
4. Ocean Bottom Seismometer Turner
5. Acoustic Doppler Velocimeter
6. Multipurpose Hook
7. Turbine Holder

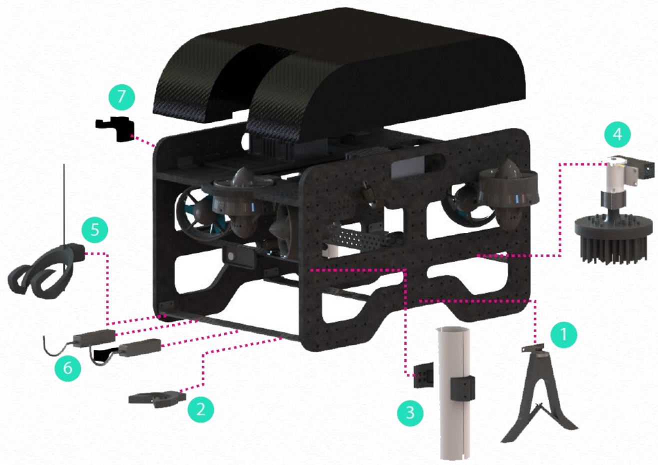


Figure 16 *Narwhal Manipulators*

1) Aircraft

Liftbag Attachment

By using a one-way hook design, the pilot is able to hook the lift bag onto the debris and the engine with minimal control. Additionally, both the lift bag and the pneumatic tube are connected by magnets to facilitate both inflation of the lift bag and detach. This not only reduces the amount of effort required from the pilot but also allows the pilot to finish the task in short time.

Figure 17 *Debris Liftbag Hook*

[4] Madgwick, S. (2010). *An Efficient Orientation Filter for Inertial and Inertial/Magnetic Sensor Arrays.* [online] Available at: http://x-io.co.uk/res/doc/madgwick_internal_report.pdf.

Aircraft Identification

The team has developed a software to identify the aircraft when the pilot positions the ROV to face the tail of the aircraft. The software is able to extract the desired features from the tail, such as the shape and its color. Using three different masks, each corresponding to the possible color, the software ecognizes the correct color of the aircraft tail. Subsequently, polygon approximation is utilized to match the shape of the aircraft tail. From these information, the aircraft type is then identified.

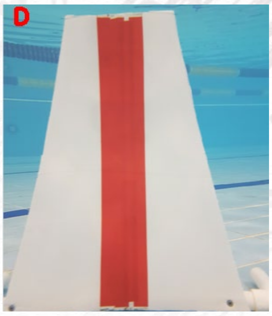


Figure 18 *Aircraft identification*

Acoustic Liftbag Release

When the pilot sends a signal to release the lift bag from debris, the applied voltage across the electromagnet will generate a magnetic force which will result in the releasing the debris from the solenoid. When the debris is no longer in contact with the hook, the lift bag will be detached from the debris and float to surface.

The acoustic release mechanism on the lift bag rely on the STM32 microcontroller unit and a modified HY-SRF05 ultrasonic module. Additional ports are incorporated for electromagnetic activation of the release mechanism. Upon receiving an acoustic wave with certain frequency, the MCU is programmed to send a high voltage to the MOSFET, hence releasing the lift bag by activating the electromagnet switch. Premature release is avoided by neglecting all acoustic waves sent from a source beyond certain range. Among all the underwater communication methods, acoustic is the most robust and has a long range due to its low attenuation underwater. Therefore, acoustic release mechanism was chosen for its reliability and speed.

2) Earthquakes

Ocean Bottom Seismometer Turner

The OBS turner consists of thirty-two short carbon fiber cylinders attached to a circular base of 10 cm radius operated by a motor. As Narwhal lowers its OBS turner to the OBS handle, cylinders in line with the handle will be pushed up while the remaining cylinders remain in place, horizontally locking the handle to the turner. This enables the ROV to turn the OBS handle with ease.

As the OBS turner does not require the OBS handle to be in any fixed alignment, the driver is not restricted to fix the turner into a particular orientation. Such versatile design enables the pilot to level the OBS in a short period of time.

Figure 19 *OBS turner in action*

Independent Wi-Fi Module

For effective transmission of the webpage from the onboard Wi-Fi module of OBS to the ROV, the independent sensor (Wi-Fi module) approach is adopted. The module is powered from shore and connected to an Arduino Uno, programmed to parse the data received from Wi-Fi module to a shore-side computer. Its compact size and increased portability enable Narwhal to establish a stable connection while leveling the Ocean Bottom Seismometer.

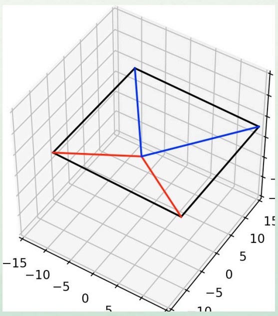


Figure 20 *Real-time 3D plot*

3) Energy

Mooring Installation

To determine the specified point for mooring installation, Narwhal's software members have developed a software which is able to locate this position. This software initiates after the pilot has successfully positioned the ROV such that the entire prop is visible in the image. By setting polygon approximation of the prop as the origin and a straight bounding rectangle around it as the target, the software corrects the perspective of the image to be perpendicular to the ground. The prop is then used as an indicator of length, for the software to determine the specified point for mooring placement.

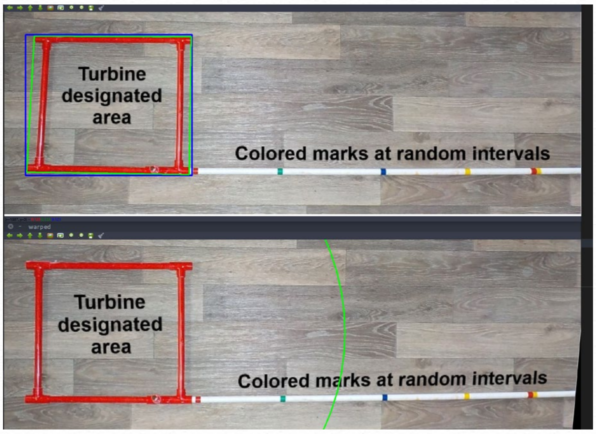


Figure 21 *Perspective correction of the designated area (from blue rectangle to green rectangle)*

Acoustic Doppler Velocimeter

The ADV attachment mechanism was constructed using Polylactic Acid (PLA) and takes on a horseshoe-like shape as shown in the figure. Its working principle relies on the ease of rotation of the U-bolt. As the horseshoe goes up the mooring-chain, the ADV will trace the curvature of the ADV attachment mechanism and slide towards the lowest point of the horseshoe. Once the U-bolt had reached the lowest point of the horseshoe, either one of the hooks will be automatically latched on the U-bolt. This mechanism was selected over other designs largely due to its advantages in not limiting the driver to approach the U-bolt in any specific direction. Such liberty allows the driver to put more attention in aiming the mooring line into the horseshoe and raising it.

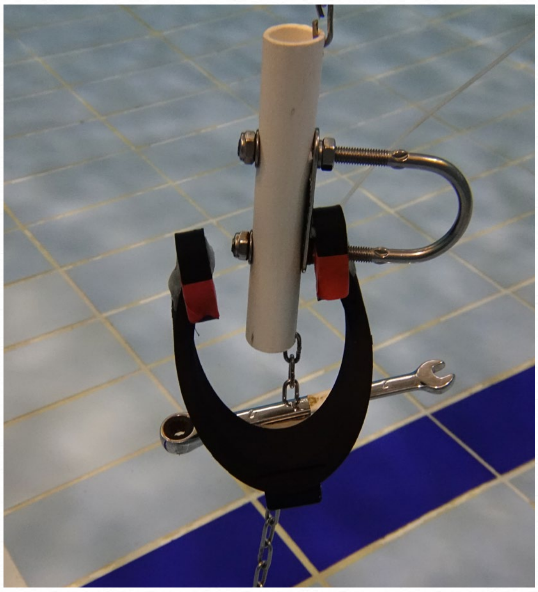


Figure 22 *ADV suspended on the mooring*

Suspension of ADV

The software team has incorporated hydrostatic pressure sensor to determine the vertical metric measurement of Narwhal underwater. The readings obtained from the sensor are first processed with hydrostatic equation to obtain the theoretical depth value, before calibrating it to the current pool's environment. The calibrated value assists the pilot in suspending the ADV at the specified depth.

Multipurpose Hook

A multipurpose hook was designed to be able to meet the needs of various mission tasks, such as transporting Intelligent Adaptable Monitoring Package (I-AMP) and picking up items underwater when needed. Similar to Beluga, the multiple hook was reused this year for its versatility and easy maintainability. However, for Narwhal's design, the hook was made of stainless steel to prevent corrosion and be able to provide high compressive strength.
The multipurpose hook was mounted on aluminum bars, with the mounting structure made from delrin which is able to withstand high shearing forces produced from lifting the turbine

base and I-AMP. Instead of using an active gripper, the passive multipurpose hook can perform all the transportation task and retrieve items underwater. Without involving any powered device, the hook is robust and effecive as same as the active manupliators.

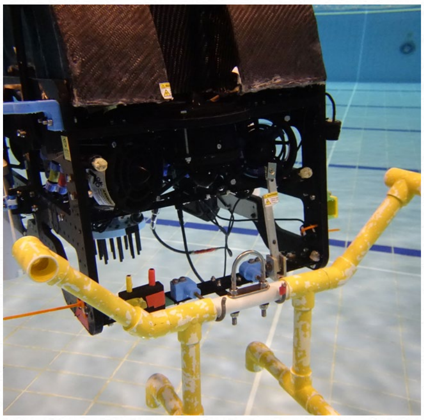


Figure 23 Multipurpose Hook holding the IAMP

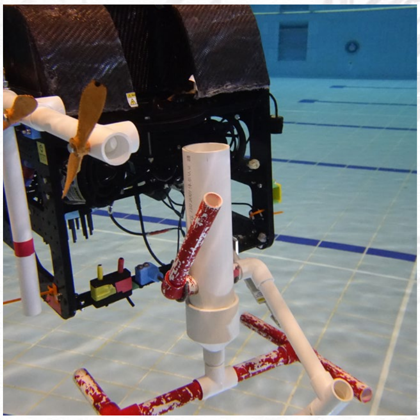


Figure 24 Multipurpose Hook holding the turbine base

Turbine Holder

The turbine holder is 3D printed with PLA and designed to lock the T-junction of the turbine array. This design was adopted to ensure that the turbine is kept in a stable position throughout its transportation to the turbine base. Keeping the turbine in a fixed position is of utmost importance as unpredictable swaying of the turbine makes it extremely difficult for the pilot to aim it in the turbine base. Also, it can minimize the time required as the turbine and the base can transport together.

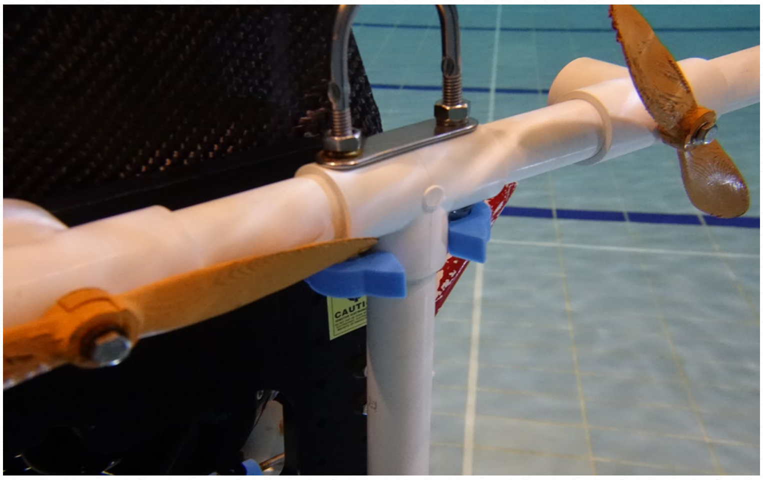


Figure 25 Turbine being carried by the holder

III. SAFETY

A. Safety Philosophy

Safety is Epoxsea Inc.'s utmost priority and it is not compromised under any circumstances. Epoxsea Inc. holds a strong belief that all accidents can be prevented through implementation of strict safety measures. With experience from previous years, numerous safety practices and protocols were developed and enforced to provide a safe and suitable environment for our engineers.

B. Vehicle Safety Features

Safety is ubiquitous in Narwhal's design and our engineers worked conscientiously to realize these features throughout its development. Mechanical engineers ensured the absence of sharp edges on Narwhal through filing and deburring. All moving parts in Narwhal, such as thrusters, were marked with visible warning labels to remind all crew members of the potential safety hazards. Handles were also integrated at the side of the frame to assist crew members in safely transporting Narwhal. In addition to these features, all thrusters were shrouded, equipped with thruster guards to prevent any foreign particles from entering them.

Figure 26 Narwhal's thruster with the guard

Electronic engineers installed a kill-box between the 48V power supply and the tether, which has an inline fuse within 21 cm of Anderson Powerpole connectors and an emergency stop button to cut off power immediately when needed. Additionally, all boards are equipped with an LED indicator to assist the deck crew during the dry run test onshore.

Software engineers programmed each motor driver with a watchdog timer that periodically checks inbound commands. This allows motor drivers to halt all operations when no valid commands has been received over a period of time. Additionally, a ramping algorithm has also been implemented on the motor drivers to prevent current spikes, which could potentially damage the electronics system.

C. Testing Protocol

Epoxsea strictly abides by a self-established testing protocol to ensure operational safety. Prior to underwater testing, crew members must perform a systematic dry run on shore. This allows the crew members to resolve any unforeseen problems in air before submerging the ROV. Alongside the protocol, the company has also developed a safety checklist which is enforced to all crew members. For example, crew members are only allowed to touch Narwhal if he or she has shouted "contact" and has been acknowledged by the driver. This is to avoid any possible injury which could result from accidental activation of manipulators and thrusters. In the event of an emergency, any crew member in proximity of the power supply must cut off power immediately to avoid or minimize casualty to both the crew and the ROV.

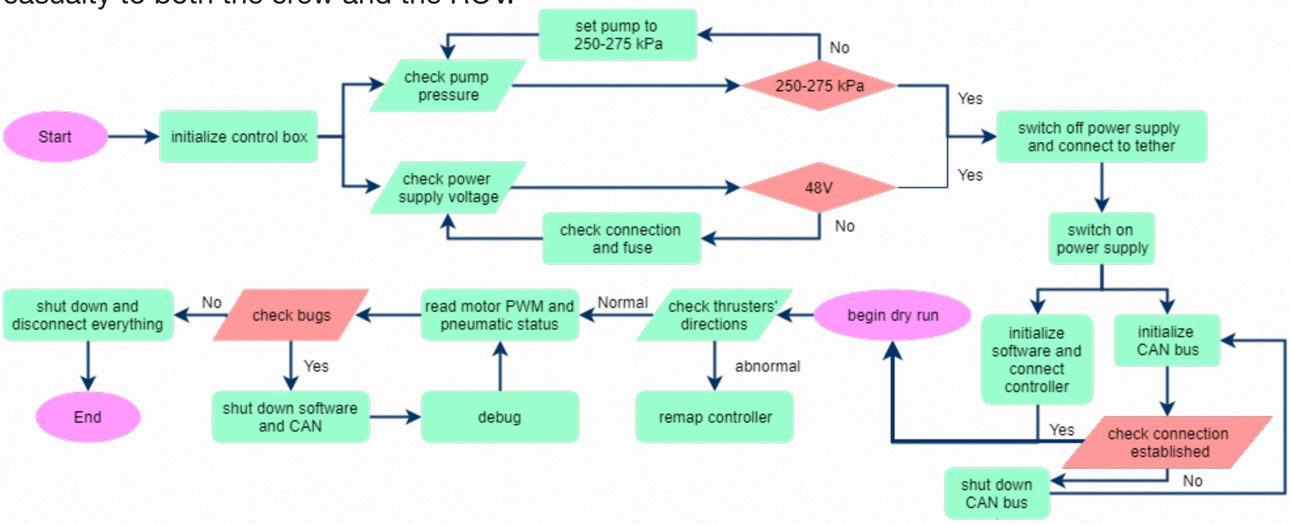


Figure 27 Flowchart of the testing protocol

D. Testing and Troubleshooting Technique

Epoxsea regularly tests Narwhal in water to assess its performance and stability. The ROV underwent its first water test in late January 2018. 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 the three-hour pool tests to evaluate Narwhal's performance in meeting mission objectives. Any unforeseen shortcomings in the design discovered will be addressed by the team after every pool tests.

For instance, the OBS handle turner was unreliable during the initial testing phase. It was discovered that the 3D printed turner was not able to clamp onto the handle securely. To address this, the team redesigned the turner utilizing Carbon Fiber Tubes.

Epoxsea's approach to troubleshooting is a step-by-step process which involves reproducing, isolating and diagnosing the problem. After problems were identified in the pool test, engineers will first attempt to reproduce the problem in the laboratory to confirm its existence, and not a false observation by crew members. Each component is then removed one-by-one to narrow the source of problem down to a single module. This module is then 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 also subjected to this test, to determine their reliability and expose potential problems. This year, Narwhal was designed to utilize more passive tools than active tools, minimizing potential problems and simplifying the troubleshooting process.

E. Lab Safety Practice

All members of Epoxsea are required to strictly adhere to safety protocols while working in the laboratory. Personal protective equipment such as safety goggles and hearing protectors are available in laboratory while masks are issued to every member for individual use. Safety goggles and hearing protectors must be worn at all times while handling machinery and power tools. Any members whose work results in producing multiple particulates, such as working with epoxy or fibers, are required to wear masks and protective gloves throughout the task. Overhead ventilation system must be used when soldering electronic components and handling epoxy to remove any fumes generated. With regards to air pump, the pressure gauge is constantly monitored to limit the pump's pressure at 2.75 bar (275 kPa) for safety.

Figure 28 *Mong, member of the mechanics division grinding aluminum*

In Epoxsea, all new members undergo rigorous peer-to-peer training prior to any laboratory tasks, ensuring that all members are aware of the safety protocols. Every member is encouraged to remind and help one another upon witnessing a potential safety hazard, such as turning off unused tools and assisting with heavy lifting. All members are also encouraged to proactively update the safety protocol when deemed necessary, to minimize the occurrence of dangerous situations.

IV. PROJECT MANAGEMENT

A. Organization Structure, Planning, and Procedures

Company

In pursuit of a carefree, culturally harmonious working environment, Epoxsea encourages open discussions amongst team members during decision making processes whilst relying heavily on self-management for daily operations.

After the Epoxsea team 2018 is formed, the Gantt chart in Appendix B is discussed for the run-up to the Hong Kong regional competition to ensure that all members are informed of the upcoming schedule and expected work distribution over time.

Bi-weekly meetings are held to review progress of each division, set short-term goals and revise future plans according to the Gantt chart. These meetings are initiated by the Chief Executive Officer of Epoxsea Inc. to address tasks prioritised for that specific time frame according to the Gantt chart, followed by financial analysis and reporting by the Chief Financial Officer. The Chief Technical Officer of Epoxsea Inc. is in charge of time and task management, as well as keeping Epoxsea on schedule for the building and testing of

Narwhal. Weekly goals are also posted inside the laboratory to act as a reminder and to emphasize the importance of adhering to the work schedule.

Owing to the fact that the Narwhal team consists of mostly new members, a series of events are organised by the senior members to establish and strengthen team bonding. These include regular business dinner parties and participating in the Hong Kong University of Science and Technology Robotics Team War Game activity.

Figure 29 *Epoxsea bonding through a wargame outing*

Mechanical

Our mechanical division emphasizes on designing passive manipulators. Passive manipulators are reliable and light. This allows the ROV to accelerate faster and therefore performing the required task in a shorter time. They have high maintainability due to its simple structure and seldom come across any technical issues while testing. Each of our passive manipulators have been designed specifically to perform a desired task effectively and efficiently. Besides, as passive manipulators offer high stability and reliability, which is an essential factor to a high performance ROV. In a competition, this is a very important factor since every second spent can affect the outcome of the competition. Furthermore, passive manipulators are easier to manufacture as compared to its active counterparts.

Electronics

During the first meeting, the hardware division exercised division of labor based on the system interconnection diagram shown, for example the 48V Power distribution board, motor drivers, and the independent Wi-Fi board. Each member takes charge of designing and soldering the board they had chosen in the beginning, along with the maintenance of the associated sensors. In order to provide a reliable hardware architecture for other divisions to test their prototypes, bimonthly deadlines are put in place for examination and production of backup modules for emergency troubleshooting use. A chat group acts as the main communication channel between the hardware members where we discuss about work schedule, notify each other of faulty components and share further improvement on a daily basis. Depending on the members' speciality, some members focus on working on the ROV whilst some are devoted to research and development of using acoustic in the Aircraft mission.

Software

This year, the software team had decided to reuse the ROS framework from previous years due to its high modularity and adaptability. Following the first release of the ROV Explorer Class manual in December 2017, the software team had created a checklist of all necessary ROS "nodes" for respective functions such as: teleoperation, motor control, CAN communication, GUI, etc. Through the modular framework of ROS, software members were able to work on different tasks at their own pace concurrently. The use of tools like GitLab for version control, software documentation and bug tracking also proved to be of great assistance to the team especially when all members were new to the ROV competition.

Every member was encouraged to commit their assigned programming tasks to the GitLab promptly to allow other members to review, provide suggestions and most importantly update everyone on the overall progress of the software team. The team focused on developing the core software systems of the ROV (motor control, teleoperation, CAN communication and GUI) in January before progressing on to developing mission-specific programs from February to April.

B. Budget and Cost Projection

The majority of the budget was spent on electronic and mechanical parts, of which a large sum is invested in the electronic materials due to more demand for electronic components to tackle the missions. These include ESP8266 Wi-Fi modules, Arduino UNO, Raspberry Pi, USB cameras and acoustic sensors. In response to the increase in hardware expenses, expenditure in other areas had to be balanced. Most of the budget allocated to the mechanical division was used to manufacture the frame of the ROV and for maintenance of the 3D-printer. Passive manipulators were used where possible to save costs and enhance stability. Narwhal's mechanical division strives to use existing materials in the workshop to avoid unnecessary waste of PLA material, reducing the overall cost for manipulator prototyping. The budget and cost projection of Narwhal are attached in Appendix D and E respectively.

V. CHALLENGES

A. Technical Challenge

Optical Character Recognition

Flight tail recognition is one of the crucial tasks in the Aircraft mission. Apart from the algorithm to recognize flight tail's shape and color, the team has developed a backup program, Optical Character Recognition algorithm (OCR), to accomplish this task. This program aims to recognize flight tails by analyzing the characters displayed on them. However, in order for the OCR software to output an accurate result, certain conditions have to be met, such as: the tail's orientation, luminance of the tail, and its distance from the ROV. Additionally, different combinations of texts would require modifications of the algorithm for an accurate result. Aside from the algorithm, distinct random noises are always present in an OCR reading which could affect the output of our program to a large extent. As such, software members are constantly challenged in removal of these noises.

Figure 30 *Noisy image of aircraft tail*

Due to the unavailability of accurate open-source OCR and the exorbitant prices of commercial softwares, software members are incessantly trying to develop an OCR which could produce accurate results regardless of the surrounding conditions. While these problems can never be fully mitigated, the team has been optimizing the OCR algorithm by incorporating various libraries. The team's current solution is to deskew the image captured and minimize noises with Gaussian filter. Software members will continue to explore various means to minimize these limitations and optimize the OCR algorithm.

B. Non-Technical Challenge

Changes in personnel

Team Epoxsea 2018 is dominated by newcomers in working with remotely operated vehicles. With only one continuing member from last year's Epoxsea team, most of the team members had to learn their respective roles and cooperate towards the evolution of Narwhal within a short period of time. Nevertheless, the members overcame this challenge by conquering a steep learning curve at the beginning of the development process and have all successfully contributed towards Narwhal's progress. Members from last year provided technical training to the newcomers. In addition to this, peer-learning happened often during the process, which accelerated the development further. Specifically for software development, common programming techniques such as pair-programming and code review were also utilized to improve the quality of the software and coordination in between team members.

Moreover, our team is comprised of people from different backgrounds and cultures, such as Korea, Indonesia, Belgium, and many others. Due to this, each of us may have a different approaches due to varying mindsets that emerge when problems need to be solved. Although difficult uncomfortable adjustments had to be made at the beginning, all of the members of Narwhal have adapted well to each other, establishing a supportive and conducive working environment in the workshop.

VII. FUTURE IMPROVEMENT

Flashing programs into STM32 microcontrollers

For the past three years, Epoxsea Inc. has been utilizing epoxy in waterproofing all of the ROV's hardware components. While this method has been proven to be effective keeping the components waterproof, its major limitation is that the STM32 boards can no longer be flashed with a new program. After numerous months of brainstorming, the team has narrowed down to two possible improvements to this limitation. One possible improvement is to connect flashing pins of STM32 to waterproof headers such that the boards can still be flashed after it is epoxied. Alternatively, the ESP8266 Wi-Fi module could be linked to the pins of STM32 to reflash new programs by external WiFi connection. While these suggestions could not be fully realized in Narwhal's design due to time limitations, Epoxsea engineers will continue to improve and develop on this limitation in future designs.

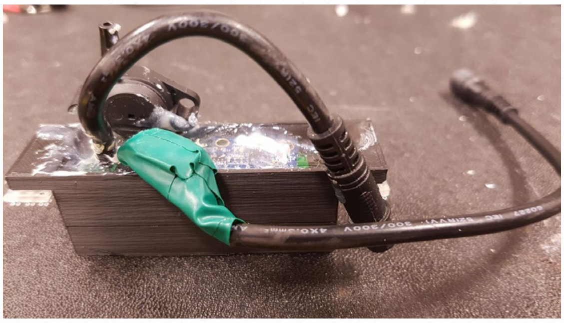


Figure 31 *Epoxied IMU board that has an imperfect program*

VI. LESSON LEARNED

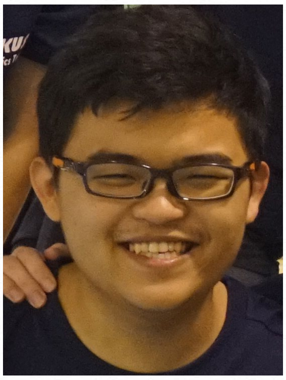
ESP8266-01 Wi-Fi module

The OBS task of this year's mission required the team to try out a new Wi-Fi module (ESP82366-01). Unlike bluetooth modules, utilizing Wi-Fi module was a new technical challenge for the team due to the lack of experience in handling the module. Both the hardware and software teams encountered great challenge in implementing the module as the team's research showed that much implementation of the module was done on Arduino and not on STM32 boards. Additionally, as all STM32 boards on the ROV communicated by CAN protocol, and integrating the ESP8266-01 module into this communication network proved to be a great challenge for the team. After multiple weeks of research and trial and error, the team was able to transmit and receive short string messages between two Wi-Fi modules. While the team ultimately relies on independent Wi-Fi sensors with Arduino boards for the OBS task, the hardware and software skills developed were transferred and applied in the lift bag release mechanism.

Critical Path Method

Since most of the team members are new to ROV, emphasis is put on effective resource management in order to optimize the development of Narwhal. It has been realized using an industrial engineering concept, the critical path method, to analyze and tailor our progression towards meeting the expectation set by the Gantt chart. For example, the scheduling of prototypes depends heavily on the arrival of materials purchased outside Hong Kong. By implementing this concept, bottleneck activities are identified from the tasks checklist, updated after biweekly pool tests. Each bottleneck that may hinder the overall progress was identified and addressed individually. With this system in place, prototyping and development of Narwhal could be achieved as efficiently as possible.

VIII. REFLECTIONS



"At the beginning of my time as a junior software member in Epoxsea, I thought that most of my work would be developing parts I was in charge of. But my experience had proven that developing Narwhal was a very collaborative process. I would find myself discussing not only with fellow software members, but also with hardware and mechanical members in figuring out the best solutions to complete the tasks. As Narwhal members came from vastly different backgrounds, I have also come to appreciate the challenges and advantages that come from it. Overall, it has been a very meaningful experience."

Figure 32 *David Sun (Indonesia)*

"Joining Epoxsea as a junior hardware member, I do have a lot to learn on both technical skills and communication with teammates. It was really rewarding for me to witness our very own working ROV for the first time after weeks of developments and hard work. I am also grateful to have supportive and warm teammates. They helped me out in acquiring the essential skills and created a great team atmosphere. Working with them has helped me to familiarize myself in communicating ideas with English. Overall, it has been an extraordinary experience working in Epoxsea and I am looking forward for the new possibilities within the team."

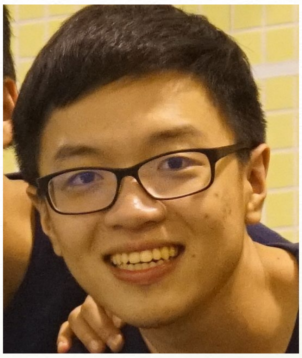
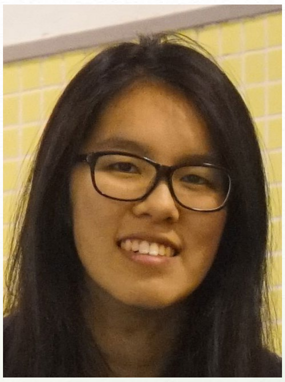


Figure 33 *Kuang Yu Hsueh (Taiwan)*



"Serving in EPOXSEA as a senior hardware member and one of the two female members of the team, my responsibilities were no different from the guys. Each of us fully immerse ourselves into the technological development of the ROV as well as logistics preparation. Within the team of 16, an open and understanding environment encourages us to treat one another as equals and our contributions not to be bounded by stigma. All in all, it has been a rewarding learning experience and it was a privilege to work with such talented and passionate members. "

Figure 34 *Ka Yan Yiu (Hong Kong)*

IX. CORPORATE SOCIAL RESPONSIBILITY

Whilst continuing its tradition of providing technical support to the annual community engagement project, the Underwater Robot Competition for Youth organised by the Center for Global & Community Engagement (GCE), Epoxsea is also becoming more conscious of its impact on the environment and we started this transformation by focusing on our carbon footprint.

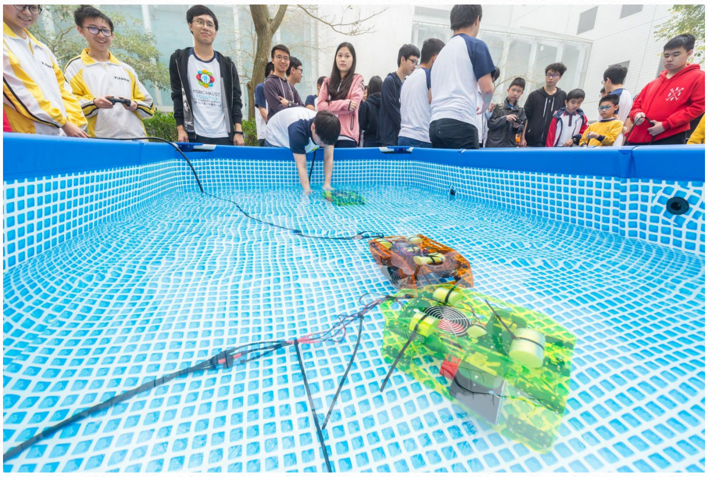


Figure 35 Narwhal members helping with GCE Underwater Robotics Competition for Youth

Epoxsea reuses its resources whenever possible. Separate reusable syringes for each of the epoxy solutions are kept and used throughout the entire process, and accurate calculation of epoxy required for each mechanical and electronic component, allows us to reduce waste created. We keep in mind that every 1 kg epoxy saves reduces our carbon footprint by 5.7 kg of CO_2[6]. We also rely heavily on 3D printing technology for our manipulators' prototypes and electric housings. Our primary printing material is biodegradable polylactic acid (PLA). 90% of our control box is reused from previous years. By eliminating the need to replace and recreate key components of our control system, it greatly reduces our hardware waste.

Figure 36 Reused syringes for each epoxy solvent A and B

An alternative method for Epoxsea to control its carbon footprint is by upholding a careful design process. Every year, we only have one frame design manufactured from HDPE. And this became a tradition for each generation of Epoxsea's ROVs. Since the environmental impact of HDPE mainly originates from the manufacturing process and its absence of biodegradability at its end of life, we limit our carbon footprint by keeping the optimized frame design and modifying its components as we develop our vehicle for the competition[7].

[6] *"Alternative Sites Assessment and Route Selection Report (Phase 2)"*, Greater Dublin Drainage, Dublin, 2012. [Online]. Available: http://www.greaterdublindrainage.com/wp-content/uploads/2012/05/Appendix-16_Carbon-Footprint-Assessment.pdf.

[7] K. Sangwan and V. Bhakar, *"Life cycle analysis of HDPE Pipe Manufacturing – A Case Study from an Indian Industry"*, Procedia CIRP, vol. 61, no. 24, pp. 738-743, 2017.

X. ACKNOWLEDGEMENTS

Epoxsea would like to express our greatest gratitude to the following supporters for their assistance in the development of Narwhal:

HKUST School of Engineering — for their continued support, sponsorship and providing laboratories for Epoxsea's use.

Center for Global & Community Engagement (GCE) — for supporting Epoxsea

HKUST Design and Manufacturing Services Facility (DMSF) — for providing technical guidance and advice to the company.

HKUST Student Affairs Office (SAO) — for granting us permission to test Narwhal at the swimming pool.

Dr. Kam Tim Woo — our supervisor for his continued guidance and advice that helped point us to the right direction.

Chun Yin Leung and Sau Lak Law — our mentors for their recommendations and help during robot design process.

2016-2017 EPOXSEA ROV Team Members — our senior members for providing technical training and mentorship during robot design process.

Mr. Andreas Widy Purnomo — alumnus and Chief Executive Officer (CEO) of Navatics Technology Ltd. for giving Epoxsea assistance on the acoustic release task.

MATE Center — for organizing the international underwater ROV competition, providing a platform for the community to learn about marine technology, and promoting STEM education around the world by solving real world problems.

The Institution of Engineering and Technology, Hong Kong (IET HK) — for organizing the Hong Kong/Asia Regional of the MATE International ROV Competition 2018 and educating the Hong Kong public on marine technology.

RS Components Ltd. — for sponsoring electronic components for Epoxsea.

Electronic Data Information Source EDIS — for providing a hosting server for the company website

XI. REFERENCES

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XII. APPENDICES

Appendix A: Operational Checklist

General:
- o Communication is loud and clear
- o Only crew members are working on Narwhal
- o No running near the pool

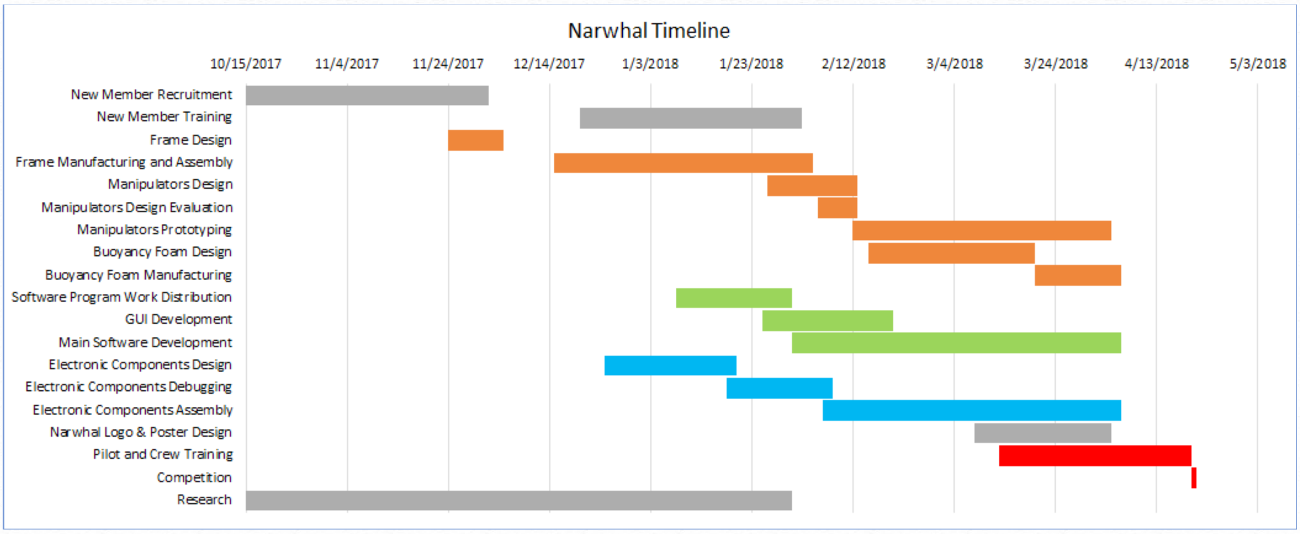
Before mission run:
- o All connections are secured and correctly connected
- o Cameras are not blocked
- o No wires are loose
- o Air pressure is below 275 kPa
- o Area between control box and Narwhal is neat and tidy
- o Electronic and pneumatic systems are working
- o No electronic components are exposed
- o Dry run is completed

During mission run:
- o No bubbles are coming out
- o "Contact" is called when anyone touch Narwhal
- o Status of Narwhal is monitored
- o Tether is not too loose or too tight

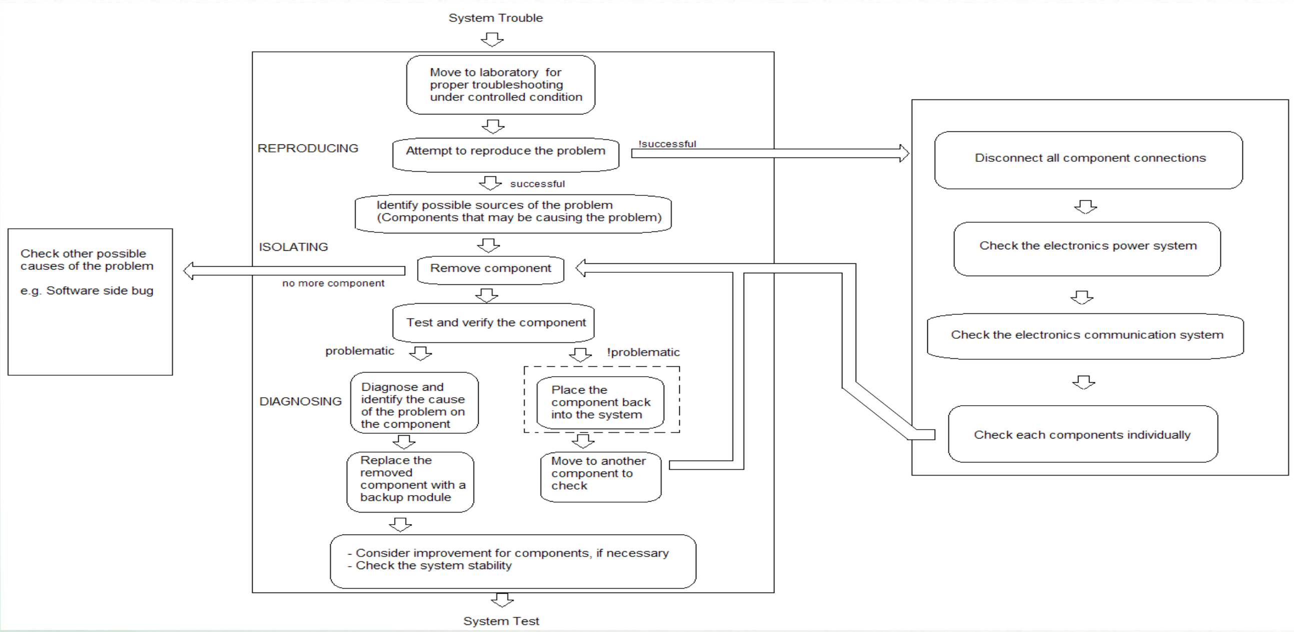
Protocol:
- o "Kill" when power need to be cut immediately
- o "Contact" when anyone is going to touch Narwhal
- o "Launch" when Narwhal is safe to operate under water
- o "Release" when ROV side want to open the gripper

After mission run:
- o Power supply and air pump are turned off when disconnecting tether
- o Electronic parts are remain dried during disconnecting
- o Controller is not in contact
- o Tether is kept neatly

Appendix B: Gantt Chart



Appendix C: Electronics Troubleshooting Checklist



Appendix D: Budget and Accounting

Proposed Budget

Category	Description	Price (USD)
Research and Development	Mechanical	$ 600.00
	Hardware	$ 700.00
	Software	$ 220.00
Tools		$ 380.00
Machine Development	More modular/flexible frames	$ 760.00
	Cameras	$ 150.00
	Vector thrusters	$ 1,270.00
	Sensors	$ 130.00
	New Version ESC	$ 510.00
	Remaining miscellaneous	$ 500.00
Non ROV Devices	Lift bag	$ 200.00
	OBS	$ 250.00
Shipment		$ 637.00
Props		$ 318.00
	Total	$ 6,625.00

Cost Breakdown

Category	Type	Description/Examples	Market Price (USD)
Hardware	Purchased	T200 Thrusters(7 pcs)	$ 1,183.00
Hardware	Purchased	48 to 12 V Regulators	$ 76.47
Hardware	Purchased	Printed Circuit Boards	$ 135.00
Hardware	Purchased	Anderson Plugs	$ 17.50
Hardware	Purchased	Analog Waterproof Cameras	$ 152.00
Hardware	Donation	Raspberry Pi 3	$ 35.00
Hardware	Purchased	USB Camera	$ 31.70
Hardware	Purchased	30A Electronic Speed Controllers (7 pics)	$ 225.00
Hardware	Purchased	Waterproof LED	$ 11.70
Hardware	Purchased	Waterproof Connectors	$ 259.03
Hardware	Purchased	Tether Wire	$ 76.40
Hardware	Purchased	Electronic components	$ 131.78
Hardware	Purchased	Acoustic sensors	$ 49.36
Hardware Components Sub-Total (1)			$ 2,383.94
Control Box Components	Re-used	LCD Display, from Orca/ Epoxsea 2016	$ 177.45
Control Box Components	Re-used	Keyboard, from Orca/ Epoxsea 2016	$ 29.64
Control Box Components	Re-used	AV Hub, from Orca/ Epoxsea 2016	$ 7.00
Control Box Components	Purchased	Xbox Controller	$ 14.80
Control Box Components	Re-used	Power Supply, from Beluga/ Epoxsea 2017	$ 45.37
Control Box Components	Re-used	Computer Components, from Stingray/ Epoxsea 2015	$ 300.00
Control Box Components	Re-used	Control Box Case, from Stingray/ Epoxsea 2015	$ 150.00
Control Box Components Sub-Total (2)			$ 724.26
Mechanical Components	Purchased	Narwhal HDPE Frame	$ 159.30
Mechanical Components	Purchased	SMC Valve Manifold	$ 27.00
Mechanical Components	Purchased	Carbon Fiber Cloth	$ 27.08
Mechanical Components	Purchased	CNC Service	$ 637.00
Mechanical Components	Purchased	Buoyancy foam	$ 144.00
Mechanical Components	Purchased	Mechanical components miscellaneous	$ 255.00
Mechanical Components	Purchased	Epoxy	$ 152.90
Mechanical Components Sub-Total (3)			$ 1,402.28
Narwhal Cost [(1) + (2) + (3)]			$ 4,510.48