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

epoxsea

AXOLO

Technical Report

2021 MATE ROV Competition

HONG KONG

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CHRISTANTO, Nicholas Year 2 Double Degree Program

Chief Financial Officer
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Chief Technical Officer
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CHEN, Jung-chi Year 1 School of Engineering
LEUNG, Wai Man Year 1 School of Engineering

Electronic Engineers
SO, Yee Leuk Year 2 Electronic Engineering
LAM, Humi Year 3 Electronic Engineering
RUSLI, Filbert Year 2 Electronic Engineering
YU, Kuang Jung Year 1 School of Engineering

Software Engineers
DANG, Vu Minh Year 2 Information Systems
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LUI, Nok Year 2 Electronic Engineering
TSANG, Hong Ting Year 1 School of Engineering
WIDJAJA, Oscar Year 2 Double Degree Program

Supervised by
Dr. Kam Tim Woo, Chun Yin Leung, Sau Lak Law

Figure 1. Axolo's Team Member: (first row, from left to right) LIM Her Wei, LAW Ming Xian (former member) , YU Kuang Jung, TSANG Hong Ting, SO Yee Leuk, LEUNG Wai Man; (second row, from left to right) WIDJAJA Oscar, DANG Vu Minh, RUSLI Filbert, CHRISTANTO Nicholas, LO Hau Ching, CHEN Jung-chi'; (third row, from left to right) KWAN Cheuk Kit, CHAN Kei Chi , CHAN Kin Yan, LUI Nok, LAM Humi, CHAN Tsz Fung

I. Abstract

Epoxsea consists of seventeen multicultural students who are passionate about underwater remotely operated vehicles (ROV). With extensive collaboration between the hardware, mechanical, and software divisions, Epoxsea is proud to present our latest ROV, Axolo. It has been developed to aid in the health and balance of marine ecosystems, with focus on alleviating plastic pollution, reversing coral reef deterioration, and facilitating waterway maintenance in the Delaware River and Bay.

To accomplish such tasks, Axolo has been equipped with mission-specific manipulators to repair Seabins, remove plastic waste, nurse coral reef habitats, and monitor water quality. Axolo was constructed using hand tools, custom-made microelectronics, and advanced communication protocols under strict safety measures and careful project management. Months of quality control and prototyping had culminated in an advanced ROV capable of performing a wide range of tasks concerning global marine problems.

This technical document will outline the development process and constructional approaches that Epoxsea took to establish Axolo as the most suitable ROV to fulfil the request of proposal released by MATE ROV and the global community.

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II. Design Rationale

A. Design Evolution

Epoxsea Inc. has always placed high emphasis on improving functionality and performance. Built on the years of experience of Epoxsea, Axolo, our latest ROV has achieved a new height on both compactness and agility. We have successfully cut away 33% of the mass compared to Manta[1], making it a lightweight ROV that is easy to transport and deploy.

Epoxsea's engineers start the design process by analyzing the shortcomings of past ROVs and deciding on what we want to accomplish with the design of Axolo. After thorough discussions, we decided on three goals: push the concept of "buoyancy as frame", reduce the weight while ensuring compact form, and enhance the modularity of manipulators and cameras.

As a continuation of the "buoyancy as frame" design concept, Axolo uses buoyancy as the housing of electronics components. Distinguishing Axolo from past designs, the buoyancy does not have to be held in place by the frame. Instead, it is fixed in place by its own mounting holes and Dual Lock, allowing the weight of the Axolo to be more concentrated on its core, maximizing its agility, and reducing the overall weight.

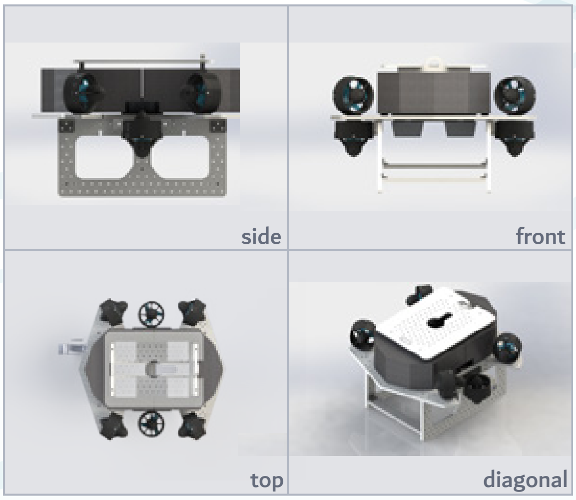


Figure 2. Axolo Solidworks Rendering

From Epoxsea's previous ROV, it is observed that aside from laying electronics in an orderly manner, spacing between them is also a key to maintainability. This year we had opted for a more spacious area for storing electronics components by reserving spaces between each row of electronics components. This allows the electronics components to be easily replaced without being obstructed by cables between them.

This year, Epoxsea has leaned towards utilizing off-the-shelf components over custom manufacturing. For example, we design the buoyancy to be attachable to the frame with off-the-shelf L-shaped connectors instead of a custom-made bracket which is more expensive. By doing so, Epoxsea could direct its budget towards value-added features as well as research and development to increase the performance in mission-specific features.

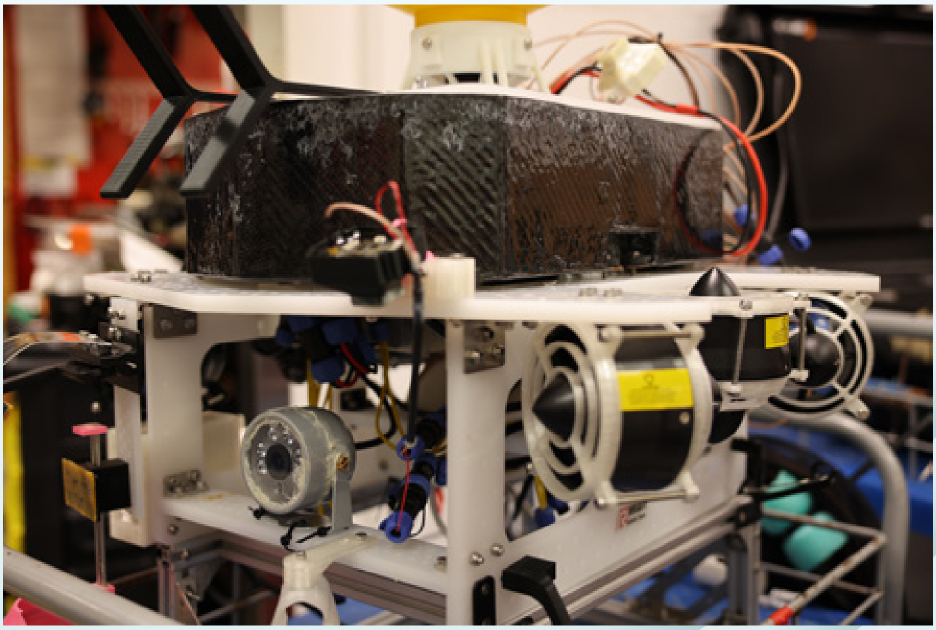


Figure 3. Axolo - Epoxsea's ROV

[1] HKUST Epoxsea. (2019). Manta Technical Report. [online] Available at: https://files.materovcompetition.org/TechReportArchives/2019/HKUST_EPOXSEA_Technical%20Documentation_2019.pdf

B. System Interconnection Diagram

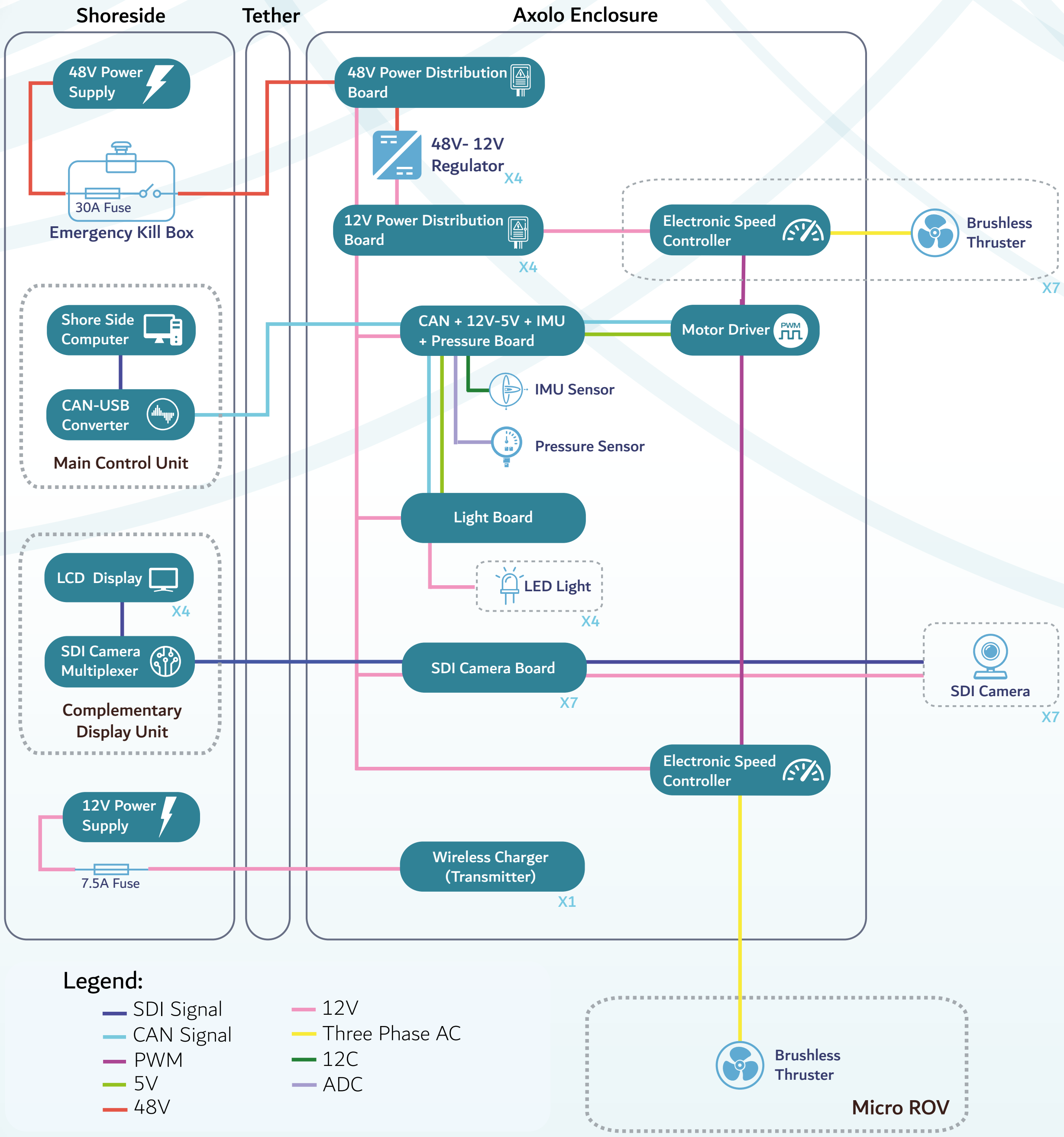


Figure 4. Electrical System Interconnection Diagram

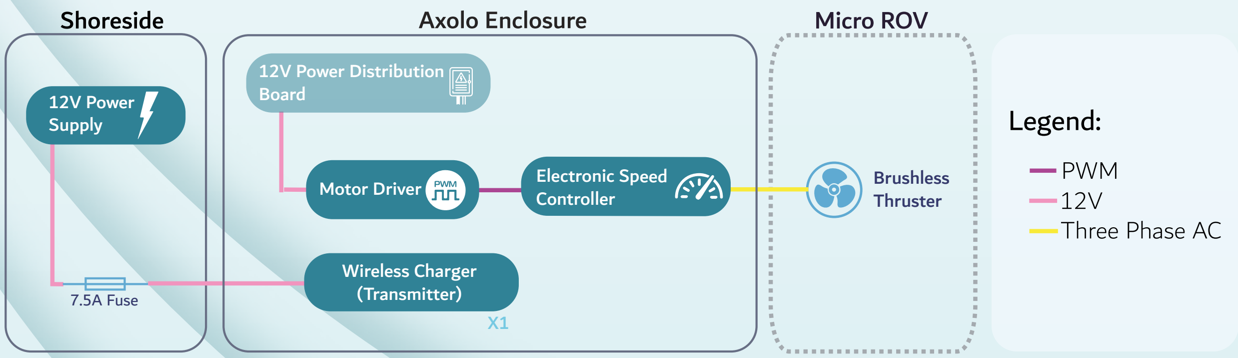


Figure 5. Non-ROV System Interconnection Diagram

C. Vehicle Core System

i. Mechanical

Frame

In order to remedy plastic waste problems from different depths of water, Axolo is equipped with mounting holes for mission-specific manipulators at its top, middle, and bottom, making the frame more versatile and allowing a greater degree of freedom (DOF) for the manipulators. Since Axolo is designed to floating debris and conduct maintenance for Seabin, this design is crucial to allow for manipulators that have access to the water surface.

For the material of the frame, Polypropylene (PP) is chosen due to its cost-effectiveness over Carbon Fiber Reinforced Polymer (CFRP), which was used in the previous design[1], while offering a high rigidity that Axolo needs. The use of PP was furthermore justified by its low density. Having a density of 0.90 - 0.91 g/cm^3, PP is almost neutrally buoyant in water. This reduces its weight, thus reducing the volume of buoyancy needed.

Another merit of choosing PP is that it is chemical resistant. Since this year's theme involves cleaning waste, Axolo is expected to operate in polluted parts of the ocean. A chemical resistant frame can ensure that the ROV stays uncorroded and safe no matter what pollutant it comes in contact with.

	Density		Compressive strength		Tensile strength		Chemical resistant		Cost		Total score
	Value (g/cm3)	Score (1-5)	Value (MPa)	Score (1-5)	Value (MPa)	Score (1-5)	Value (Yes/No)	Score (1-5)	Value (High/Low)	Score (1-5)	
PP	0.90 - 0.91	●●●●●	41 - 46	●●●●○	31 - 45	●●●●○	Yes	●●●●●	Low	●●●●●	23
CFRP	1.6	●○○○○	570	●●●●●	600	●●●●●	Yes	●●●●●	High	●○○○○	17
HDPE	0.95 - 0.96	●●●●○	4 - 23	●●●○○	23-29.5	●●●○○	Yes	●●●●●	Low	●●●●●	20

Figure 6. A study on material for frame

Buoyancy

Opposed to Manta's design, styrofoam was again chosen to be the material for buoyancy, a practice once done for Beluga[2]. The styrofoam was fabricated in-house by cutting styrofoam into specific shapes, then coating the buoyancy with 2 layers of epoxy and carbon fibre cloth. This practice enabled the buoyancy to withstand water pressure in Axolo's operational depth, while providing buoyancy force and cost effectiveness superior to PU in past design.

Furthermore, distinguishing Axolo from past design, its buoyancy is mounted to the frame directly. The buoyancy is embedded with off-the-shelf L-shaped connectors and Dual Lock. This allows the buoyancy to be connected to the frame without being held in place by any cage-like structure from the frame, simplifying the structure of the frame and eliminates extra from plates that serve a redundant purpose.

	Polystyrene	R-3318
Estimated cost (USD)	112.5	152.0
Density (g/cm^3)	0.170	0.288

Figure 7. Comparison between Polystyrene and R-3318

Figure 8. Buoyancy embedded with L-shaped connector and Dual Lock

[2] HKUST Epoxsea. (2017). Beluga Technical Report. [PDF]. Retrieved from https://www.marinetech.org/files/marine/files/ROV%20Competition/2017%20competition/2017%20Technical%20Documentation/EXPLORER%20class/HKUST_E.

Propulsion

Axolo's propulsion system consists of 6 Blue Robotic T200 thrusters, which are chosen for their durability, reliability and lightness. Inherited from Manta, 4 horizontal thrusters are placed at 30° on 4 corners to balance its ease of use, power consumption and cost. Observing past mission runs, we observed that it is most convenient for users to move towards targeted objects using forward motion, since it's aligned to the forward camera. As such, Epoxsea decided to choose this configuration to prioritize and maximize surge speed, while allowing Axolo to yaw and sway, which are also used but in a less frequent fashion in mission runs. Together with the 2 vertical thrusters mounted on the sides, these result in a total of 5 Degrees of Freedom (DOF).

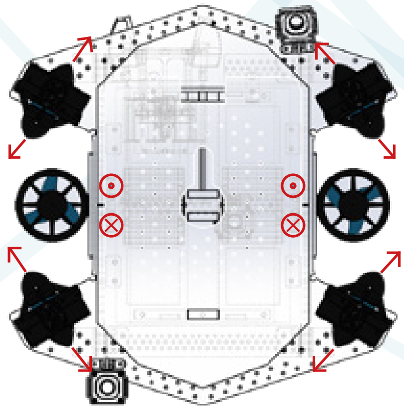


Figure 9. Blueprint of Axolo

ii. Electronics

Printed Circuit Boards (PCB)

Epoxsea has stayed with the tested STM32F103 microcontroller unit (MCU) due to its reliability and versatility. As our electronics system relies heavily on control signals for interfacing and manipulating electronics components, its reliability and versatility are highly useful for a wide array of functions to be implemented in a single board. Each board in Axolo operates a distinct function correspondingly, such as motor driver and light boards. They are connected to a centralized Controller Area Network (CAN) board that transmits the signal to and from the control box via a tether. LEDs on each of the boards help determine its status, which allow easy debugging as it allows us to distinguish and locate malfunctioning components. To decrease the overall size, PCBs are streamlined to perform their functions while taking up minimum space. To achieve this, boards sharing some similarities or close connections are combined into a single board. For instance, CAN, IMU, and Pressure parts are combined into one PCB.

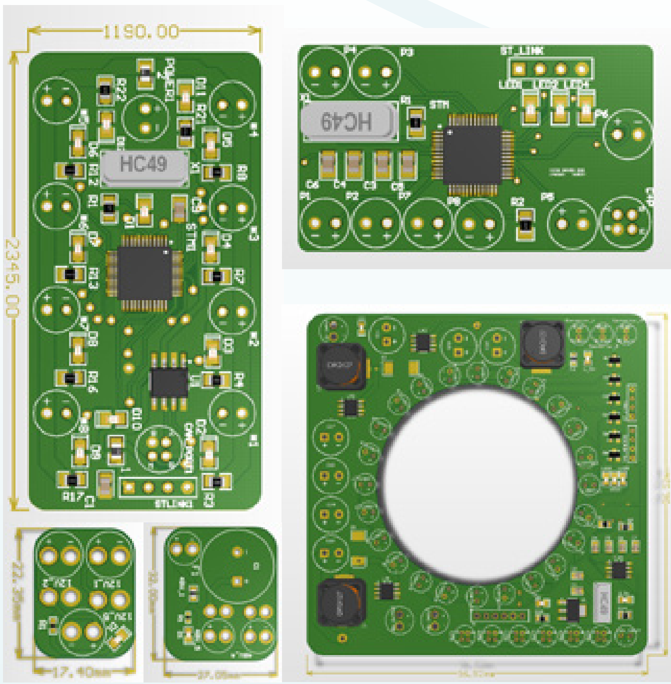


Figure 10. Printed Circuit Board layouts in Axolo

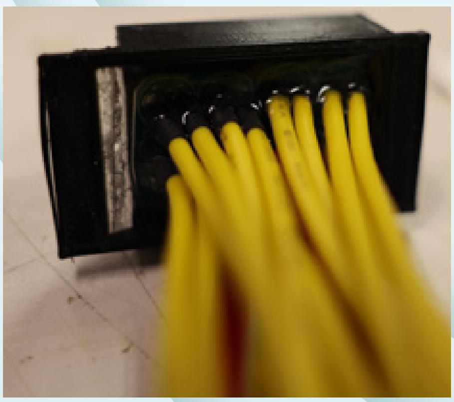


Figure 11. Power Distribution Board

Power Distribution

After passing through the tether, 48VDC goes directly to Axolo's 48V Power Distribution Board. The four regulators receive the high voltage in parallel and output 12VDC. Their aluminum casting supports good heat dissipation, and IP68 waterproof rating ensures water resistance for continuous work underwater. After conversion, 12V is distributed to 6 SDI Cameras, CAN+5V+IMU+Pressure Board, Light Board, 6 Electronic Speed Controllers, and Micro-ROV through the 12V Distribution Board. CAN+5V+IMU+Pressure Board then further converts 12V to 5V and provides it to the boards with MCU. Self-recovery fuses are included to keep the boards running under varying current without destroying the machine. For the Micro-ROV, 12V is provided through cables to serve the ESC.

Controller Area Network (CAN)

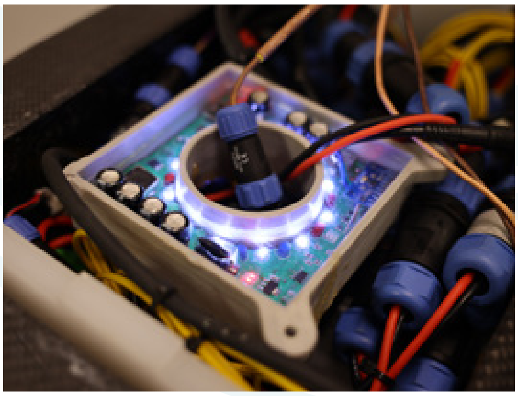


Figure 12. CAN board

Axolo uses the CAN protocol for the communication between the function boards in ROV and the control box. Thanks to the high baud rate (up to 1.25Mbps) enabled by the protocol, Axolo can rapidly exchange of messages between its components, ensuring the consistency of Axolo. The CAN communication in Axolo is facilitated by a centralized multi-purpose CAN/IMU/Pressure board, which serves as the main point of connection from the control box. The board distributes signals to other PCBs through high-speed CAN transceivers (TJA1050) mounted on every board, which were chosen for their speed, as well as protection against undesirable thermal conditions and electrical shorts.

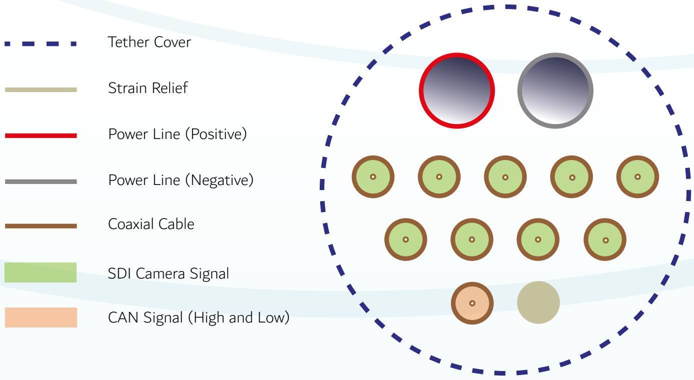


Figure 13. Tether cross section diagram

Tether

The main features for Axolo's tether is solidity and easy management. The tether consists of three parts: power, CAN signal and SDI signal to serve the function of the ROV. In total, twelve cables are included: two power cables insulated by PVC, one insulating CAN signal cable, and nine RG316 coaxial camera SDI signal cables. The tether is wrapped with a flexible PET braided cable sleeve alongside with a strain relief, ensuring the resistance of the cables by protecting it against damages caused by collisions and tensile strengths.

Camera

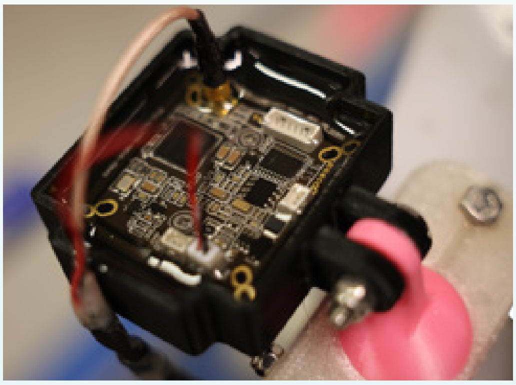


Figure 14. Camera on Axolo

Axolo is equipped with eight digital cameras to provide clear and wide vision for various mechanical and computer vision tasks. Each of the cameras is connected to a RG316 cable to transmit the digital signal back to the shoreside camera box. By following the Serial Digital Interface (SDI) standard, the video resolution can achieve 2048 x 1080 pixels in maximum with 10-bits RGB color quality. Together with the small video latency of 50 to 70 ms, the video can support ingenious movement for the driver, and accurate software tasks, for example, shape and colour recognition.

Electronic Enclosure

Figure 15. Epoxy between wires and headers

Epoxsea has kept the tradition of using epoxy for waterproofing our electronic components underwater. PCBs and their connected wires are immersed into epoxy to ensure they are isolated from moisture. The epoxy at the same time improves the strength of and rigidity of the boards. Also, our engineers found that the waterproof headers sometimes are not trustworthy in long-duration water tests. Water may leak inside the bulky header and short the wires. To secure our electrical system, we apply flexible epoxy on the connection part between wires and the ports of headers as double insulation. This also serves as a protection to the joint points from damages due to twisting and pulling.

iii. Software

The software development of Axolo seeks to continue the high-level modularity from previous Epoxsea's ROVs. Therefore, Axolo's software architecture follows a dual-layer approach, with an 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 a specific piece of hardware. In the upper layer, ROS allows developers to create modularized software packages using different languages such as Python or C++, which further accelerates development time and reduces unnecessary bugs as engineers can use their familiar languages during development. The lower layer of the architecture is implemented in STM32 MCUs programmed in C, using CAN protocol for communication.

Thanks to modularity and a streamlined process for developing software packages, Epoxsea's software engineers have a lot of freedom to explore different approaches to the missions. We were able to quickly test programs as soon as they are developed, and came up with effective solutions to computer vision tasks. The software packages used for the tasks were developed with the help of powerful functions from well-developed libraries like OpenCV, which further increases the reliability of our algorithms.

Graphical User Interface (GUI)

To accompany the upper layer functions of Axolo and allow for smooth interactions with the drivers, the software division developed an integrated Graphical User Interface (GUI) using HTML, CSS and Javascript along with Vue.js framework. The GUI allows the driver to monitor the status of Axolo's thrusters and identify issues during mission execution through data received directly from the ROS framework with the rosbridge suite. Thanks to the direct connection, there is virtually no delay between commands given by the driver to the software packages and response received from the programs. The driver can therefore quickly assess the success of the mission execution.

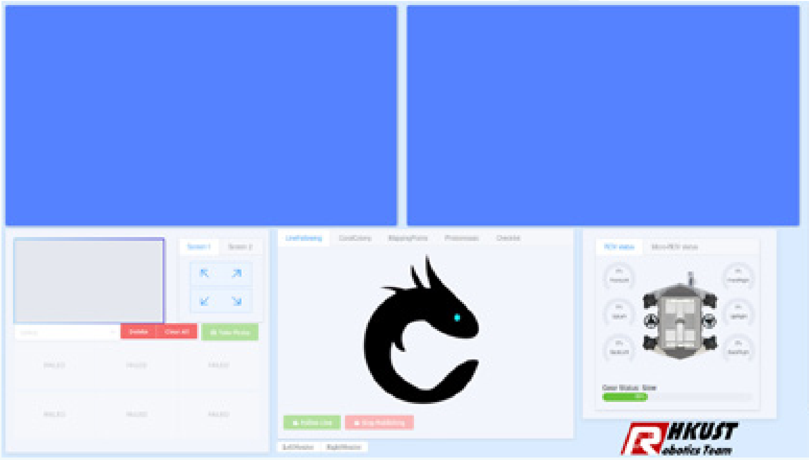


Figure 16. Graphical User Interface

Event-Drivent Architecture (EDA)

Event-Driven Architecture (EDA) is a commonly used paradigm in building complex systems with multiple interacting parts, such as the modularized system that Axolo implements. EDA is implemented by using an event bus for various packages to publish events that other packages can access. This feature allows decoupling of multiple parts of the program and multiple receiving packages to handle incoming events asynchronously, which, unlike the more commonly used request-response architecture.

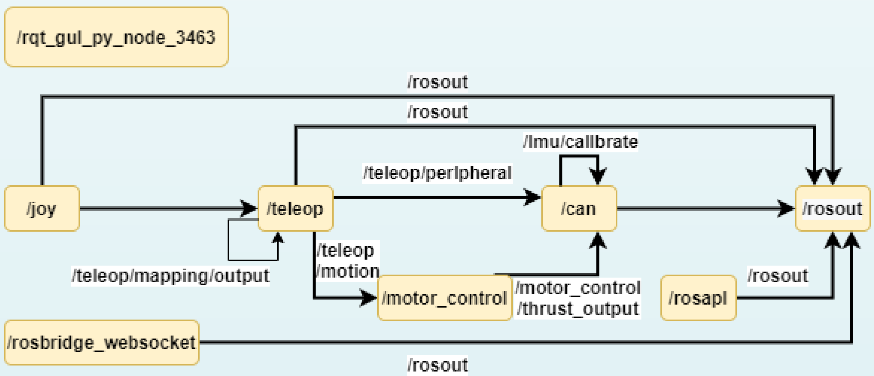


Figure 17. ROS Qt-based Framework (RQT) Graph

EDA provides modularity to Axolo's core software architecture. Its extensive use enables services to be modified and replaced easily resulting in a rapid and non-blocking development of Axolo's software.

D. Mission Specific Features

i. Task 1: The Ubiquitous Problem of Plastic Pollution

Seabin Maintenance

Since the seabin is not fixed in place and can be easily pushed around, Epoxsea's engineer foresaw that approaching it with an ROV would be a time-consuming task. Thus, we utilized one manipulator to achieve two sub-tasks: grabbing the old mesh bag and power port. The same principle applied to another manupulator for achieving the other two sub-tasks as well. Each of the manipulators has a U-shaped guide to aid Axolo in securing the seabin in front of it so that the pilot can approach it quickly with minimum effort.

Seabin Maintenance - Grabber

The grabber has a metal arm that would hook onto the mesh bag using its U-shaped tip. Since the pin can move vertically, Axolo can dive down to grab the power port before moving the mesh bag.

The lower part of the manipulator is a 2-in-1 device that combines the U-shaped guide and power port grabber. Small bumps on the grabber allow it to clip onto the power port securely.

Figure 18. Seabin Maintenance - Grabber

Seabin Maintenance - Releaser

This manipulator is designed to release the new mesh bag and power connector. The PVC tube cutted in half is used to hold the mesh bag and avoids rotation or wobble due to water flow. The rubber band helps fix the mesh bag and release it when slightly pressed onto the Seabin. To put the new power connector, the stand and two L-shape weights can stabilize the power connector and prevent any possibility of falling. Besides, the design of the lock can only be opened when the connector is put inside the power port.

Figure 19. Seabin Maintenance - Releaser

Figure 20. Releaser with mesh bag and power port

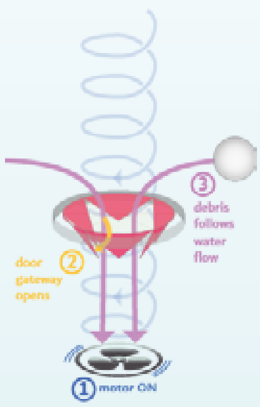


Figure 21. Floating plastic debris grabber mechanism

Figure 22. Grabber gateway

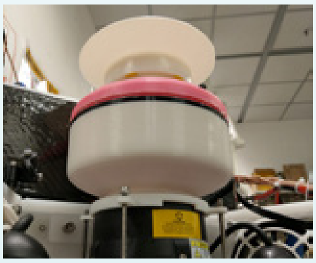


Figure 23. Floating plastic debris grabber

Floating Plastic Debris Grabber

The floating plastic debris is removed by water current. As the pair of vertical thrusters are switched on, a water current towards it would be generated. This allows the plastic to be carried into the containers that are mounted above the thrusters. The door gateway is opened along with the motion of the water flow, which allows the debris to pass through and slide to the side of the container. After all floating debris is collected, the motor is stopped and the top door gate closes automatically due to the buoyancy that is attached to the door.

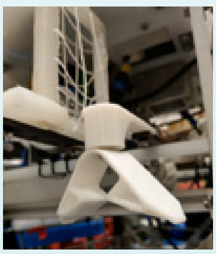


Figure 24. Sinking plastic debris remover

Sinking Plastic Debris Remover

Grabber for taking bottom debris consists of two components, an elastic pipe clamp, and a mount to the ROV, which the clamp can rotate freely under the mount. When approaching the PVC tube of the bottom debris, it allows the clamp to rotate to a suitable direction guided by the special inclined guide design at the bottom of the clamp. While moving down, bottom debris will be pressed into the clamp.

Ghost Pin and Ghost Net Capturer

These two manipulators will work in sequence in order to capture the ghost pin and ghost net. The ghost pin capturer consists of a small net. When Axolo pushes the pin with the pin capturer, the pin will be trapped inside the holes of the pin capturer. With the regular-shaped holes and softness of the string, the ghost pin can be easily captured and hung stably on the net. The driver can easily aim the pin and capture it with the aid of the guide. After removing the pin, the ghost net capturer is used to capture the free-floating ghost net. Axolo will insert the Y-shape rod into the holes of the ghost net and hold the net along its motion. The ghost net will be held stably with the designated angle of the Y-shaped rod of the manipulator.

Figure 25. Ghost net capturer

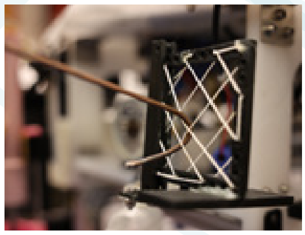


Figure 26. Ghost pin capturer

ii. Task 2: The Catastrophic Impact of Climate Change on Coral Reefs

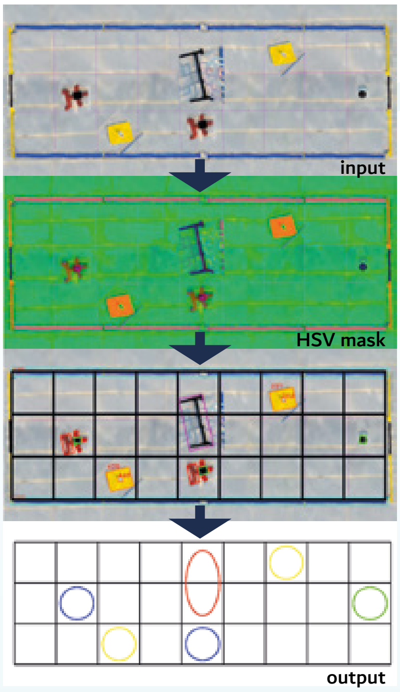


Figure 27. Process of coral colony mapping

Flying over Coral Reef

To fly autonomously over the Coral Reef, Axolo first identifies both of the blue painted PVC pipes within the video display. By performing multiple applications of object HSV masking, followed by the Hough Line algorithm, Axolo generates an accurate line contour of each of the blue PVC pipes with its respective angle of attack and linear coordinates on the video display. The coordinates and angle of Axolo are then compared with the default location of Axolo to determine the offset. The offset value is then fed into a proportional-integral-derivative (PID) controller. The PID controller calculates micro adjustments that provides feedback for Axolo in continuing its horizontal movement between the blue PVC pipes.

Coral Colony Mapping

To accurately identify different points of interest, Axolo finds the reddest (sea stars), yellowest (outplanting coral fragments), bluest (grid) and blackest (sponge and coral colony) HSV values from the coral reef image published from the GUI. These values are used as masks values of each colors. With coordinates of contours in the bluest mask, the program is able to obtain the size of the grid map and draw a 3x9 grid. With the help of aspect ratios and the specific masks, the program can find the shapes and colors of the masked objects. By comparing the coordinates to the inner blue lines of the map, the final coordinates can be identified and arranged in a 3x9 array. Finally, the program will use the array to draw the grid using basic OpenCV functions and publish the image to the GUI.

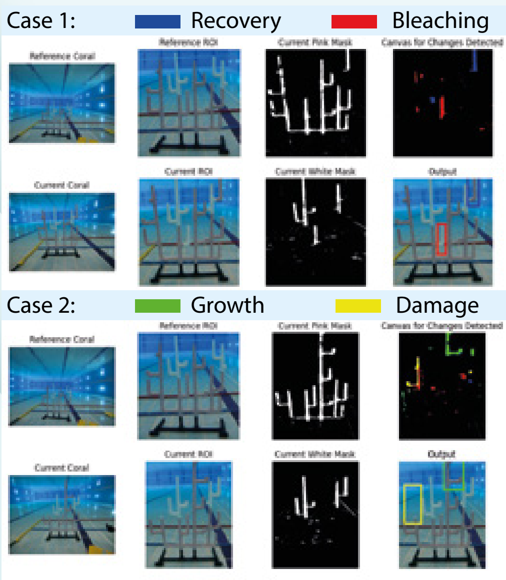


Figure 28. Mapping the changes in two coral images

Coral Colony Inspection

Axolo first identifies the coral using a custom-trained yolov5[3] model. By aligning the past and current coral according to the midpoint of their overall structure, this allows Axolo to obtain a region of interest for comparison. Next, Axolo produces pink and white masks of the coral structure using predetermined ranges in the HSV color space. Axolo can now determine areas of change between past and current coral by using pixel distance measurements implemented with the numpy library for fast array computations. Axolo is careful in finalizing such areas of change based on its contour area to filter out insignificant changes, which is inevitable due to noise. With all the significant areas of change now identified, Axolo draws the corresponding rectangles on the frames.

[3] G. Jocher, 2021. *YOLO (Version.5)* [Source code]. https://github.com/ultralytics/yolov5.

Coral Fragment Holder

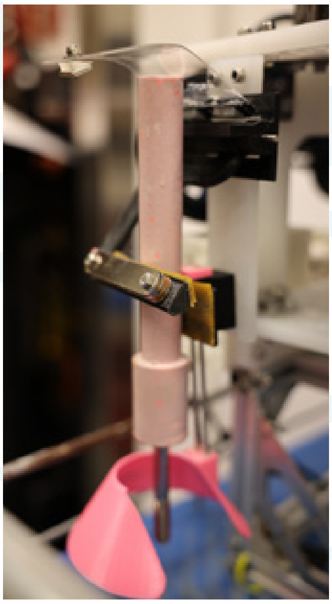


Figure 29. Coral fragment holder

The manipulator is designed as an S-shaped hook. There is an upper acrylic board connected via magnets. When Axolo goes downward, the coral will separate the upper board with the hook so that it can drop to hold the coral. The principle of the design is gravity and moment equilibrium. The attached rubber band increases the friction between the coral and the manipulator while the cone-shaped guide aids aiming at the coral reef, making the grip tight and secure. Afterwards, as Axolo touches the floor, the little board connected with the guide will support and lift the grabber so that the coral can outplant into the reef. This action also allows the manipulator to be reset and can be used multiple times.

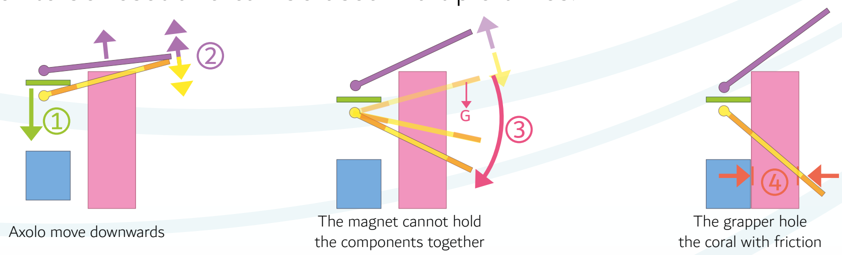


Figure 30. Coral fragment holder mechanism

Ox Bile Injector

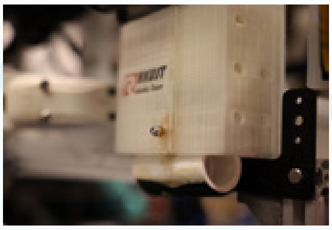


Figure 31. Ox bile injector

A container with magnets is designed to hold the modified injection device for sea stars with the right amount of magnetic force. As the injection device is attached to the sea star, it will be pulled by the sea star's weight. Thus falling off and securely placed on the sea star.

Sponge Grabber

The structural design of the sponge grabber relies on restoring force to achieve high speed. The grabber is loaded with a blocker to hold the grabber open, which keeps the rubber band expanded. The task will be completed in a vertical motion, in order to control the risk of knocking the lower part of the sponges. When Axolo goes downward, the top sponge will act as the trigger, which pushes up the blocker. That action releases the mechanism and grabs onto the sponge. The blocker is designed with rounded edges to limit the friction and lower the force required to remove it.

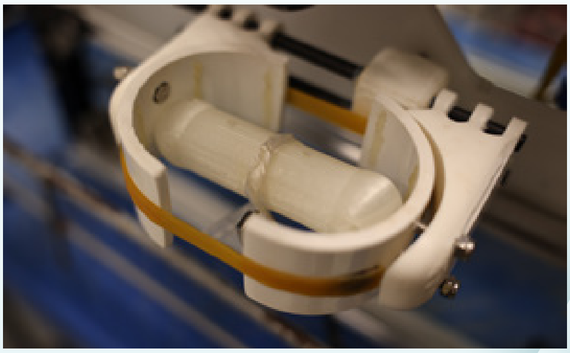


Figure 32. Sponge grabber

iii. Task 3: Maintaining Healthy Waterways II: Delaware River and Bay

Micro-ROV

Micro-ROV is designed to traverse the 3-meter pipe and retrieve the sediment sample. With a simplistic design, the Micro-ROV only consists of a thruster in a tailor-made frame manufactured with 3D printing. The task-oriented manipulator is capped at the front of the Micro-ROV. The sediment retriever is a bowl-shaped cap filled with a sponge covered with male velcro. The sediment sample would be taken by the front-end vertical on the manipulator.

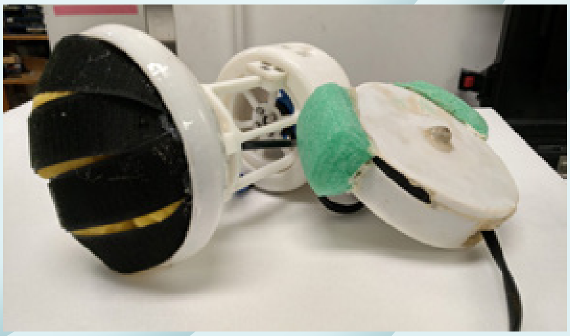


Figure 33. Micro-ROV with cable reel

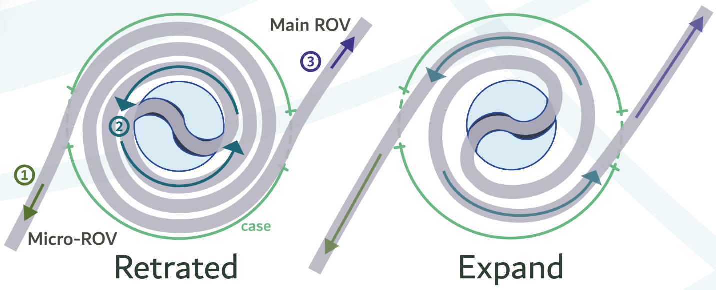


Figure 34. Cable Roller on Micro-ROV mechanism

Cable Reel

To avoid cable entanglement and ensure safety, Micro-ROV is equipped with a cable reel. This reel comprises a shaft with a constant force spring. Initially, a 3-meter cable is rolled around it. As the Micro-ROV moves forward, the cable is pulled out from the cable reel. The spring stores the potential energy of the rotation, and gains the ability to retract the cable as the Micro-ROV heads back to the main ROV while aligning it in a space-saving and untangled configuration.

Mussel Bed Inspection

For placing down the quadrat, a special lock consisting of a bended elastic rod is designed. The quadrat is hung on the horizontal plate and locked with the curved part of the bended rod. When approaching the floor, the bottom stand of the rod will touch the ground and be pushed by the downward motion of Axolo so that the curved part of the rod will leave the hook. Quadrat could thus be transported securely and deployed accurately onto the mussel bed.

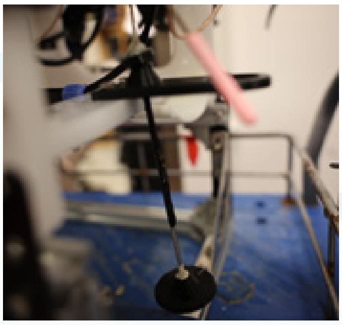


Figure 35. Lock with a bended elastic rod

Eel Trap Maintenance

For eel trap maintenance, the manipulator is a 3D-printed hook with a spring steel strip as a lid. Our manipulator would take the old eel trap by the U-Bolt.

The new eel trap would be secured by locking the U-Bolt under the spring steel during transportation. Upon hitting the ground, the new eel trap would be pushed out and released from the hook and be placed in the designated area.

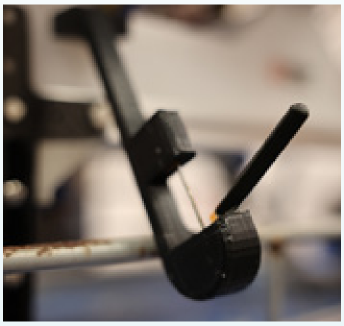


Figure 36. V-shaped hook picker

Figure 37. V-shaped hook with 8-shaped lock dropper

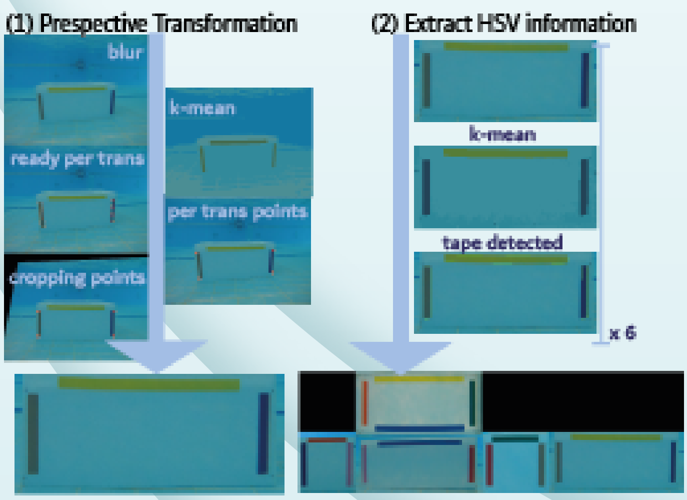


Figure 38. Process of photomosaic generator

Photomosaic Generator

Axolo first reads all the images from a folder that receives images taken by the camera. To obtain a top-down view of the 5 sides of the subway car, Axolo applies perspective transformation on each photo according to estimated outlines of the box. It enables Axolo to set the colored tapes as regions of interest (ROI) which are distinguished by their sharp contours from the white background. Axolo extracts the data of HSV color from the ROI and compares each of them to find the matching colors. Using this information, Axolo could stitch the corresponding images based on similar colors on their edges.

III. Safety

A. Philosophy

Safety is taken as the highest priority among the concerns in Epoxsea. To maintain a high standard of a safe working environment, Epoxsea implements strict safety regulations in different aspects of product development and provides sufficient laboratory safety trainings. This way, Epoxsea ensures that all employees obtain adequate knowledge of safety and prevent accidents when working.

B. Personal Protective Program

Newly hired employees at Epoxsea are obliged to undergo training before being allowed to use any machinery tools by themselves. Proper safety practices in handling common tools and equipment for different departments are demonstrated by related senior employees. Only after practicing under the supervision of senior employees, are they allowed to use the machines independently. To ensure every employee stays safe while working in the laboratory, they have to wear masks, ear protection, and safety goggles provided by the company. Employees are required to equip them appropriately and correctly.

Figure 39. Mechanical safety training in practice

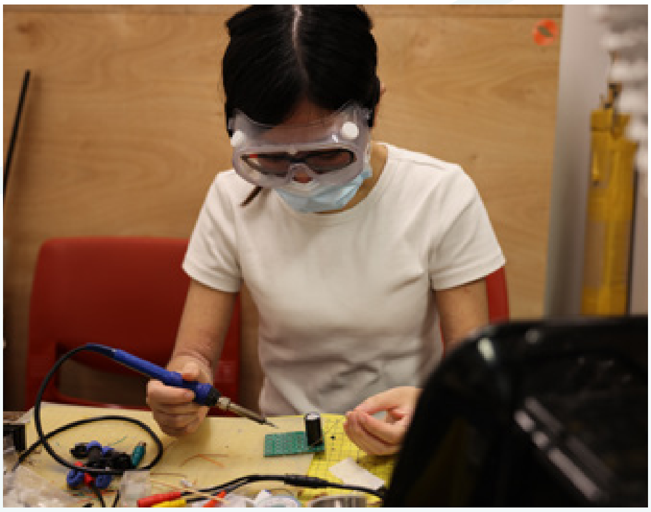


Figure 40. Safety practices by electronics team member

C. Equipment and Laboratory Safety Practices

After junior employees finish the safety training, they are expected to be able to use tools and equipments correctly. To reduce apprehensions of wear and tear, all employees are encouraged to report broken tools. A tutorial on broken tools will be provided if malfunction is caused by misuse. To maintain a good workplace and avoid accidental damage on tools or users, regular cleaning days are held and corresponding labels are pasted for storing. All the equipment, desks, and tools have to be cleaned after use. Epoxsea has prepared chemical vent hoods at the soldering stations to facilitate the soldering process without exposure to harmful fumes. Posters on the wall serve as a reminder to employees about the ramifications of ignoring the safety standards and policies set forth by the company.

Under the situation of COVID-19, some special policies of Exposea have been introduced. To maintain social distance and minimize overcrowding, part of the training session has been organized online instead of face to face. To ensure all staff have enough protection when they stay in the laboratory, it is mandatory to wear a mask and check temperature. If the body temperature of an employee is higher than 37.2 °C or the living area is experiencing the impacts of the pandemic, that employee will be recommended to work from home.

D. Vehicle Safety Features

With the safety concerns about Axolo, Epoxsea implements safety measures as an important element in the development of Axolo and makes sure that Axolo fulfills the standards given by MATE. Through the construction process of Axolo, different departments are assigned specific tasks in order to prevent the potential hazards in different aspects.

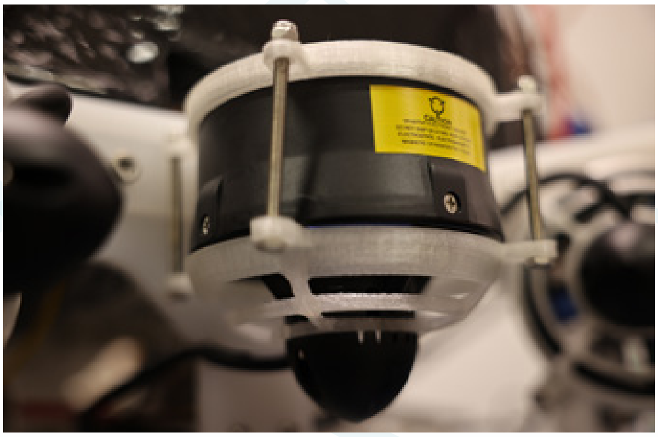


Figure 41. Shrouded thrusters with warning labels

For the mechanical division, the main task is to prevent the injuries caused by the structure and manipulators. Mechanical engineers ensured the absence of sharp edges on different parts of Axolo, by filling and deburring the corresponding edges. Thrusters are shrouded and installed with guards to prevent interference of thrusters with loose components and peripherals. All manipulators are installed stably with screws and mounts on Axolo. Warning labels are placed on the corresponding components as well such as “sharp edges” and “electrical hazard” as a clear reminder. To reduce safety hazards in mission runs, most of the manipulators are designed to function passively since they operate on weaker forces compared to active ones, thus would pose less danger to the user even in the case of malfunction. Besides, additional safety measures are also applied to the active components for performing the tasks. For example, the automatic tether rolling system is installed in Micro-ROV to ensure that the tether supply is sufficient and prevent the wire from being entangled or damaged.

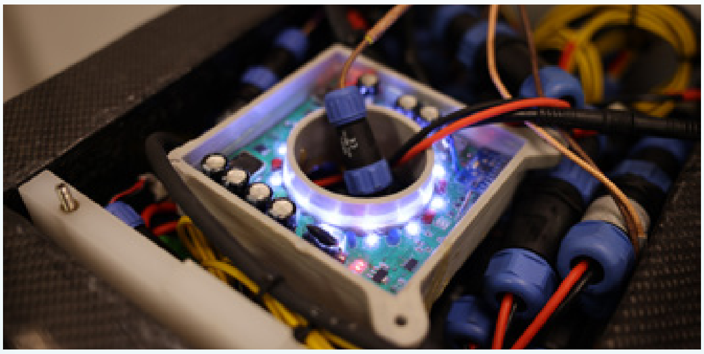


Figure 42. Wire management of Axolo

For the electronics department, to ensure that the power supply and circuits work properly, all boards are equipped with an LED indicator and color-coded cables to assist the deck crew debug error feedback and if the headers are connected properly. Zip ties, velcro and 3M Dual-Locks are used to prevent dangling and tangled wires. Additionally, a “kill-box” that includes a 30A fuse designated by MATE and an emergency stop button between the 48V power supply and the tether so that power can be cut off immediately when needed.

For the software department, to prevent current spikes and damage to the electronics system, a ramping algorithm has also been implemented on the motor drivers. Watchdog timers are programmed on each motor driver to periodically check the inbound commands for the suspension of the operations when no valid commands have been received after a specified period of time. Moreover, in order to discover critical errors in Axolo, candump and cansniffer, these two software commands are used to monitor CAN commands broadcasted throughout the system by outputting both the sent and received CAN messages onto the console.

E. Testing Protocols

To ensure operational safety, self-established testing protocol would need to be followed strictly by crew members. To resolve any unforeseeable problem in air, systematic dry tests must need to be performed on shore before testing underwater. Also, an operation checklist (Appendix A) was designed to avoid any possible injury by accidental activation of manipulators and thrusters. With communication protocols such as but not limited to shouting “contact” or “kill”, shoreside engineers could perform any operations without any risk of electrical shock and wounds caused by moving objects.

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 by both the crew and the electronics on the ROV.

IV. Testing and Troubleshooting

Axolo's modular architecture encourages employees to suggest innovative ideas on a regular basis in order to approach current problems from new perspectives. Axolo has gained a variety of strategic advantages as a result of this comparative calculation. Individual components are first tested using a comprehensive approach to evaluate their reliability and ensure that each sub-system in Axolo functions both independently and in conjunction with the rest of the architecture.

For the software department, any addition to the codebase must not only pass stringent test cases, but also comply with the continuous integration algorithm in place to ensure consistency. In terms of electronics testing, a digital multimeter is used to search for proper connection between the pins and wires on each PCB, as well as to ensure that there are no short circuits that could cause interference with other circuit boards and pose a safety risk. The initial manipulator prototypes are 3D-printed to prove their viability before going through a series of prototyping iterations to improve reliability, practicality, and ease of use. Besides, since parts are easily interchangeable, this development style contributed to Axolo's core concept of modularity.

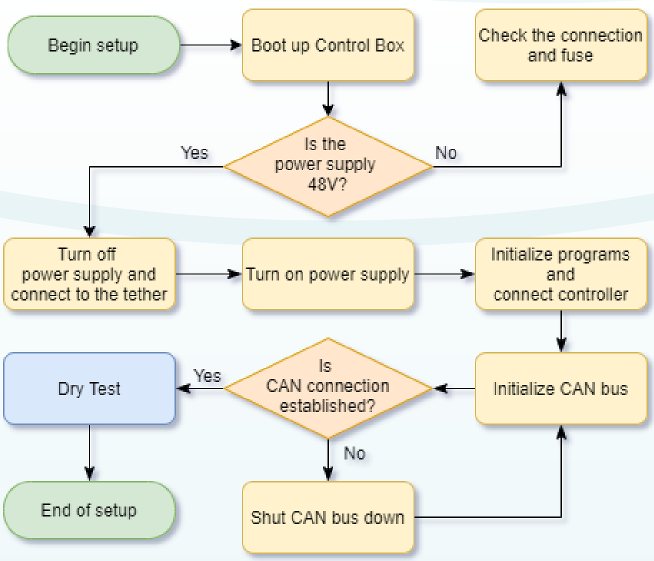


Figure 43. Testing and troubleshooting protocol

Prior to attempting mission runs, full vehicle testing consists of a two-step verification in accordance with our safety policy. The initial on-the-shore dry test involves powering the system in a controlled environment setup and testing each component's functionality as well as identifying possible safety hazards such as disconnected ports. Following the on-the-shore dry test, Axolo is put through a buoyancy test to ensure neutral buoyancy in the presence of variable manipulator weights, guaranteeing Axolo's stability and maneuverability. Axolo could only progress to mission-specific tasks after passing these evaluations, in which its performance and capabilities were further scrutinized. This cycle is repeated several times, totaling more than 40 hours of continuous quality inspection and assurance, allowing Epoxsea to produce the best product possible.

To define problems and possible solutions, Epoxsea has used both system-based and human-centric approaches. During water tests, problems often arise, and they are resolved during the debriefing that follows. Epoxsea's approach to troubleshooting is a step-by-step method that includes reproducing, isolating, and diagnosing the problem. To prevent operating on a false hypothesis, the engineers would first attempt to replicate the problem in the laboratory. The root cause of the problem is then narrowed down to a single module by isolating each part. Following that, the faulty module would be thoroughly tested and repaired. Epoxsea often employs a designated driver for each testing period, as this aids in the detection of situation anomalies that the system is unable to detect.

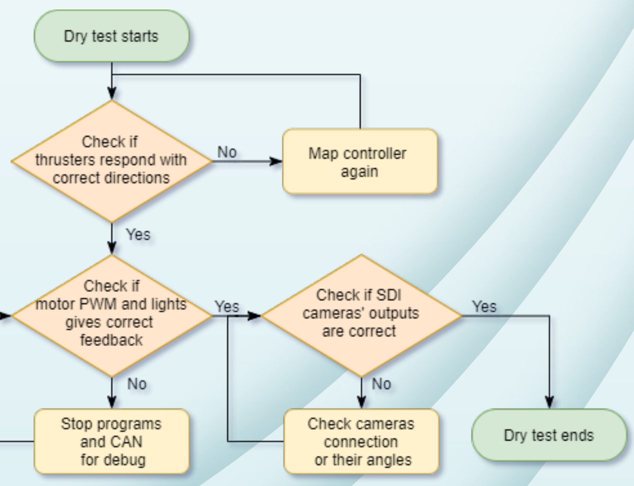


Figure 44. Dry test protocol

V. Project Management

A. Organization Structure, Planning, and Procedures

Epoxsea's core value proposition, as a multidisciplinary and multicultural company, was based on the quality and capability of its human resources. Axolo's versatility in coping with unexpected situations is increased by capitalizing on its employees' diversity. Culturally divergent viewpoints are embedded in the growth of Axolo, enhancing its robustness in dealing with unexpected situations. Every employee is a critical stakeholder whose feedback is highly respected, as demonstrated by meetings in which everyone was encouraged to speak up. Furthermore, since the company's organizational structure was horizontal, the majority notion was used to make final decisions. Team building events such as Laser Tag Day and nightly Company Dinners are held to cross cultural differences and forge strong bonds among employees. This inclusive community, combined with the horizontal organizational structure, provides a strong foundation for creating a friendly working atmosphere that boosts overall productivity.

i. Company

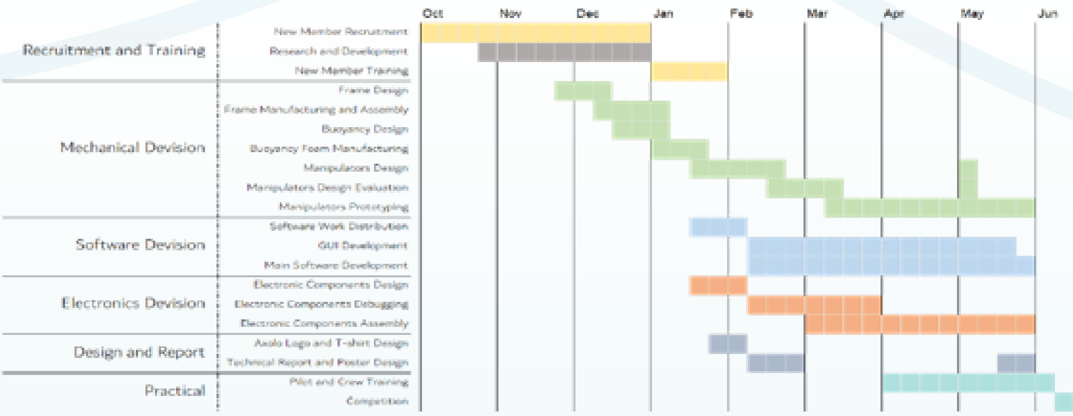


Figure 45. Gantt Chart of Axolo's development

Our company has used the Gantt Chart since the beginning of Axolo to keep employees informed about the project' macro view of the timeline. During the conception of the Gantt Chart, Epoxsea's senior employees from each division discussed the timeline of completion expectation. At the same time, senior employees also set focus on specific development such as deciding to only use passive manipulators after considering the tasks and modularity.

For communication and archives, our company utilizes Google cloud Platform as it enables real-time communication and document immutability. Following each water test, a meeting is held to get a more accurate picture of success, problems, and potential solutions, which are then refined by discussion with the rest of the company. Every meeting conclusion will be converted into specific, measurable, achievable, realistic, and time-based (SMART) targets, which will be allocated to specific employees and progress will be monitored in subsequent meetings.

ii. Mechanical

Axolo's mechanical division aspires to not only give reliable manipulators but also help its employees grow as a mechanical engineer and a team player. Rather than developing each manipulator individually, mechanical engineers are grouped in a manner similar to pair programming by means of the pair conducting research and discussing the alternative design solutions together before sharing their ideas to the division. Additionally, this year's cloud-based file storage system on Dropbox allows mechanical designs to be viewed and modified by anyone at any time, along with providing version control for aforementioned designs, promoting a more efficient co-working experience among mechanical employees. Besides fostering a harmonious team incentive, this approach facilitates identifying potential problems ahead of time and allows the mechanical division to take corrective measures during the early stages of development, which would save time and resources.

To a greater enhancement and guarantee of each manipulator, all of them are field-tested to ensure driver friendliness and operability. One example would be the design of a water sample collection mechanism, which has undergone several improvement stages throughout the development and testing stage. With the driver providing feedback on manipulator performance after each testing day, the engineer's responsibility would be to pinpoint the manipulator's inadequacies and improve its performance and reliability.

iii. Electronics

To improve work efficiency, tasks are splitted between different hardware members. Each member is responsible for designing and soldering their assigned board equipped in Axolo such as the motor driver and CAN. Internal deadlines are set for camera replacements and board debugging to ensure that the work progress meets expectations. Before water tests, each member also double checks the connections of Axolo and ensures no short circuit or open connection exists, ensuring the safety and smoothness of water tests.

iv. Software

Providing Basic controls and mission specific capabilities to Axolo has always been the goal of Axolo's software team. In order to allow software members to work simultaneously on multiple software packages with continual improvement. An agile development approach has been applied for Axolo. In this approach, software employees were able to work on different tasks at their own pace, with a high adaptiveness and constant response to changes. The use of GitLab server allows employees to push their code to have version control, software documentation and bug tracking by assistance from the team. Thus the quality of code can be maintained. As changes on one package affect other packages, hindering the development process, software employees were required to have continual modification and improvement on their code. For the flexible modification, server testing will be conducted followed by automatic retrieval and onsite testing, ensuring the usage of the latest version of software in water tests.

The whole software development life cycle is shown below:

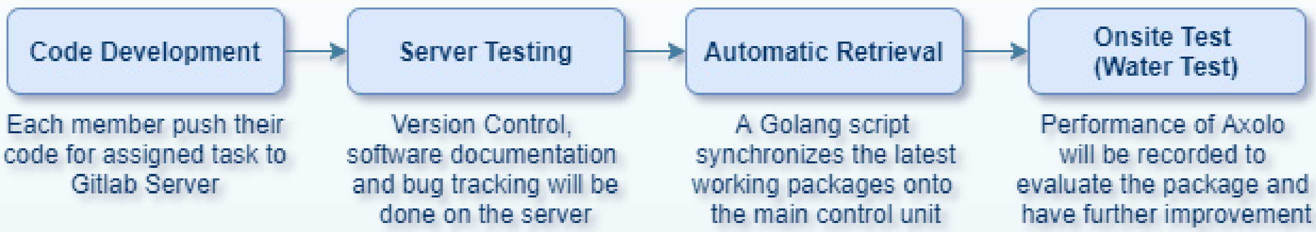


Figure 46. Software development pipeline

B. Budget and Cost Projection

The majority of Axolo's development budget is allocated to electronics and mechanical parts. For mechanical, a large portion is spent on the construction and manufacture of Axolo's frame, and the rest of the budget is allocated to the continuous development of task-oriented manipulators including purchase of various materials and tools. For hardware, to develop a stable and responsive hardware system, budget is allocated in the purchase and development of electronics to achieve stable signal and power transmission, high-quality video streaming using serial digital cameras, application of coaxial cables. Besides, this year, the control box is upgraded with additional monitors, new hardware system and new casing for more convenient control panel and sustainable usage. The budgeting is based on funding from HKUST and sponsorships. Moreover, due to the pandemic, the travelling budget was eliminated this year.

Aiming for efficient budgeting and sustainable use of materials, Epoxsea has devised detailed budget planning and conducted review on the past materials for reuse possibilities of tools and materials with proper maintenance and update. As a university-based company, Epoxsea searched for sponsorship from the school and companies including RS Components. With a limited budget, review of effective purchase and inventory of materials is done continuously to ensure efficient cost budgeting and working progress. After summarization for this fiscal year, USD 6143 was spent for the Axolo's development which is within the proposed budget of USD 6520. The budget projections and cost breakdown of Axolo are attached in Appendix C and Appendix D.

VI. Challenges

A. Technical

Due to the size limitation, buoyancy of Micro-ROV needed to be tailor made and the design of Micro-ROV was a great challenge to attain neutral buoyancy. Based on the experience, several types of material were examined. With limiting resources in tools, potential hazards might appear for manufacturing with Polyurethane (PU). Mounting challenges would occur again with an identical buoyancy manufacturing method with Polystyrene with carbon fiber coating as the main ROV. After intensive researching and experimenting with other materials, the special donut structure with sufficient inner support was designed and manufactured with 3D printing. Additive manufacturing's tailor-made structure eases the assembling process with freedom in connecting. Triangle inner support helped resisted underwater pressure.

Besides, cable management for Micro-ROV was also a great challenge. Should cable entanglement occur during deployment of Micro-ROV, it might lead to the safety hazard of shorted wire and damage the hardware system. Therefore, it is crucial to keep the wires in a safe place at all times. Ideally, the cables must be packed in a tight and orderly manner to minimize the space needed to store them. After numerous trial-and-error, Epoxsea successfully found the solution of using a constant force spring to roll the cable around it. The whole process does not require any power and can pack the cable tightly. Making it an environmentally friendly and space-saving solution.

B. Non-technical

An unexpected problem encountered this year was the outbreak of 2019-nCov. In the beginning, we scheduled to start the project in early February. Unfortunately, due to the outbreak of coronavirus, resulting in the closure of the campus, members can not work in the lab and complete tasks as scheduled. This slows down the development progression of Axolo, especially for mechanical and hardware division. Moreover, members from foreign countries could not arrive at the lab as scheduled, we needed to cooperate and work through the Zoom meeting, due to the difference in time zone, it became very hard for all members to compromise a time to have discussion, which further slowed down the development progression of our ROV.

Figure 47. First Axolo meeting, without full team due to COVID-19

Hence, our company prevents any possibilities of spreading by enforcing safety in the lab. Firstly, employees are obligated to measure their temperature before entering the lab. Employees with body temperature above 37.2 °C will not be prohibited to enter the lab. Furthermore, to limit the number of employees in the lab, our company arranges days where only some of the departments can work in the lab. This way, our company ensures safety and efficiency.

Besides the outbreak of the 2019-nCov, there is one expected challenge coming from being a multinational company. On the account of different cultures and mother languages that our members have, we may have encountered difficulties in communication. For the purpose of having all members in sync, we use English as our universal language, although it is sometimes hard to express some professional technical terms using English. Our company hopes that strictly using English can help employees get out of their comfort zones and develop their soft skills.

VII. Future Improvements

Employees at Epoxsea believe in a philosophy of continuous learning, which is why, at the end of each product life cycle, employees share positive feedback on future changes that can be implemented. Software testing is one major technological change that would be implemented, as errors are often found after implementing new components. While build testing has been implemented into the server to automate certain processes, extending this to the entire architecture will improve software quality. This can be achieved by identifying test cases with expected outputs in response to a particular input. All test cases must pass with any update made to the code to ensure that the changes do not break the existing base. However, much effort must be spent to ensure that the base is free of defects, and only then can test-driven production be proven to function. Otherwise, new modifications could be rejected due to a flaw in the foundational architecture, causing uncertainty and extending the debugging process.

VIII. Lessons Learned

Epoxsea learnt the importance of modular design for enhancing working efficiency through this year's experiment. Camera replacement has long been a troubling issue in previous generations of ROV in Epoxsea. In the past, we connected cameras to the shore by long SDI cables. Because cameras are vulnerable under water due to water leakage from the lens side and collisions, members have to reassemble the long tether frequently. This is a demanding process which needs at least three hardware members to work together for two hours or above. Missing cameras also cause inconvenience for testing manipulators and software computer vision tasks. After considering the pros and cons, we switch to the modular design. In Axolo, waterproof headers were soldered on the ROV side of SDI Camera cables and the cameras' signal output. Fast implementation of spare cameras is possible by only connecting the headers, making the replacement more flexible and efficient. Although the new method increases the soldering and epoxying time, allowing the team have a smooth testing process will be a priority concern.

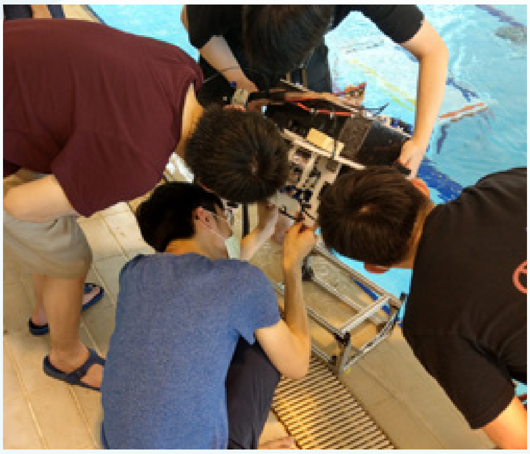


Figure 48. Hardware engineers switching camera onsite

Overall, adapting the more flexible modular design for lengthy cables to Axolo helps our company in the testing stage. This concept can also be applied on other parts of the coming ROVs. For example, we may separate the bulky CAN+5V+IMU+Pressure Board into two in the future for easy management inside a tidy frame.

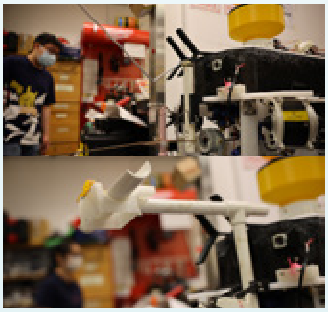


Figure 49. manipulators that switch between grapping and releasing step for seabin management

Epoxsea has also gained insight into problem-solving. In tackling the task of maintaining seabin, Epoxsea's engineers identified that seabin is a floating platform. It could be easily pushed around by the slightest water current. Even driving the ROV towards it could cause the seabin to drift away. The engineers anticipated that it would pose a great difficulty for Axolo's users to approach the seabin. Facing this problem, Epoxsea envisioned building a manipulator capable of performing all 4 steps of maintenance without moving Axolo itself. The solution would involve using a servo motor and building a manipulator of the size of a seabin. However, upon further developing it, it is discovered that not only does it add to the complexity of the hardware structure, installing a motor and a huge device in the front of Axolo also creates an imbalance of weight and induces drag, thus compromises its agility.

Upon weighing between convenience for the user and its effect on Axolo, Epoxsea decided to use a mechanical solution--breaking the device into 2 parts that are mounted on opposite sides of Axolo to minimize the imbalance in weight and employing plastic plates to hold the seabin in place. Furthermore, a lightweight manipulator also allows for greater modularity. Since its effect on the main movement is minimal, users can change the manipulators according to their preference without adapting to how the manipulator affects the movement.

IX. Reflections


Figure 50. Nicholas Christanto, chief executive officer

I am honored that Epoxsea has allowed me to lead the team as the Chief Executive Officer of 2021. My job scope mainly includes managing 17 talented individuals of different divisions, namely Hardware, Software, and Mechanical. My time as CEO has groomed my technical skills and helped me realize the importance of leadership skills, time management, and effective communication to increase overall productivity. I focused on managing the processes instead of people, aiming to create an encouraging environment where people are motivated to learn, grow and enjoy the journey. Besides, my experience as a software junior provided a deeper understanding of managing timelines and milestones efficiently. I hope that my employees have gained from my time as CEO as I did. I am eternally grateful for the once-in-a-lifetime opportunity given to me to sharpen my skills as a leader, as it has indeed been an unforgettable and rewarding journey.

I would like to thank all the ROV team for giving me such a unique experience. As a hardware member with no technological background, it was quite overwhelming at first when I have to learn everything from scratch. Fortunately, seniors and other teammates are very willing to help me with all kinds of problems. Finally, we successfully built an underwater robot together! The process was quite demanding, as we have to learn everything ranging from technical skills like designing the PCB to soft skills like communication and teamwork. As a result, I learned a lot during the process and made a lot of friends as well. It is the most worthy and valuable experience I had in my first year.


Figure 51. Kuang Jung Yu, junior electronic engineer


Figure 52. Her Wei Lim, junior software engineer

Coming into the first year of my university life, I had not expected to be part of such a hardworking and talented Robotics team; making me very grateful to be part of the group. We worked very efficiently among each other, often sharing ideas and collaborating with our respective sub-groups (Hardware, Mechanical, and Software). Being part of the Software division, I have learnt a lot of powerful tools in the fields of image processing (OpenCV) and robot software development (ROS). Although these are all relatively new to me, the process was made easier as I was able to discuss and work together with my peers. One especial benefit is that we understood our strengths and weaknesses and made sure that we used that to create something more powerful than if we had worked individually. Although we faced hardships during the frequent water tests that we perform to experiment with Axolo in underwater conditions, our team would hold a debriefing session each time in order to make sure that everyone understood the improvements that could be made. Overall, I am very thankful to be working with this team.

X. Acknowledgements

Epoxsea would like to express their most sincere gratitude to the following supporters for their assistance in the development of Axolo:

HKUST School of Engineering — for providing persisting support, sponsorship and laboratories for Epoxsea
HKUST Center for Global & Community Engagement (GCE) — for supporting Epoxsea
HKUST Design and Manufacturing Services Facility (DMSF) — for providing technical advice and guidance to Epoxsea on mechanical design
HKUST Student Affairs Office (SAO) — for granting us permission to test Axolo at the university's swimming pool
Dr. Kam Tim Woo — our supervisor, for his continuous consultation and advice that helped Epoxsea improve on both technical and non-technical aspects
Chun Yin Leung and Sau Lak Law — our mentors, for their guidance and technical help throughout the design process of Axolo
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 life problems
The Institution of Engineering and Technology, Hong Kong (IET HK) — for organizing the Hong Kong/Asia Regional of the MATE International ROV Competition 2021 and educating the Hong Kong public on marine technology
RS Components Ltd. — for providing electronic components for Epoxsea

XI. References

[1] HKUST Epoxsea, "Manta Technical Report", 2019. [online PDF]. Available: https://files.materovcompetition.org/TechReportArchives/2019/HKUST_EPOXSEA_Technical%20Documentation_2019.pdf

[2] HKUST Epoxsea, "Beluga Technical Report", 2017. [online PDF]. Available: https://www.marinetech.org/files/marine/files/ROV%20Competition/2017%20competition/2017%20Technical%20Documentation/EXPLORER%20class/HKUST_E.

[3] G. Jocher, 2021. *YOLO (Version.5)* [Source code]. https://github.com/ultralytics/yolov5.

[4] S. W. Moore, H. Bohm, and V. Jensen, *Underwater robotics : science, design & fabrication. Monterey,* Ca: Marine Advanced Technology Education (Mate) Center, 2010.

XII. Appendices

Appendix A: Construction and Operational Checklist

General
- ☐ Communication is loud and clear
- ☐ Only crew members are working on Axolo
- ☐ No running at the pool

Construction
- ☐ Ensure that the machinery/ tool is in good condition before using it
- ☐ Wear suitable personal protective equipment while working on cutting, drilling etc
- ☐ Wear protective gloves and avoid direct contact while handling chemicals
- ☐ Put back all the tools to their designated position after using them
- ☐ Perform soldering under a fume hood or in a well-ventilated area
- ☐ Turn off all the electronic appliances when they are not used

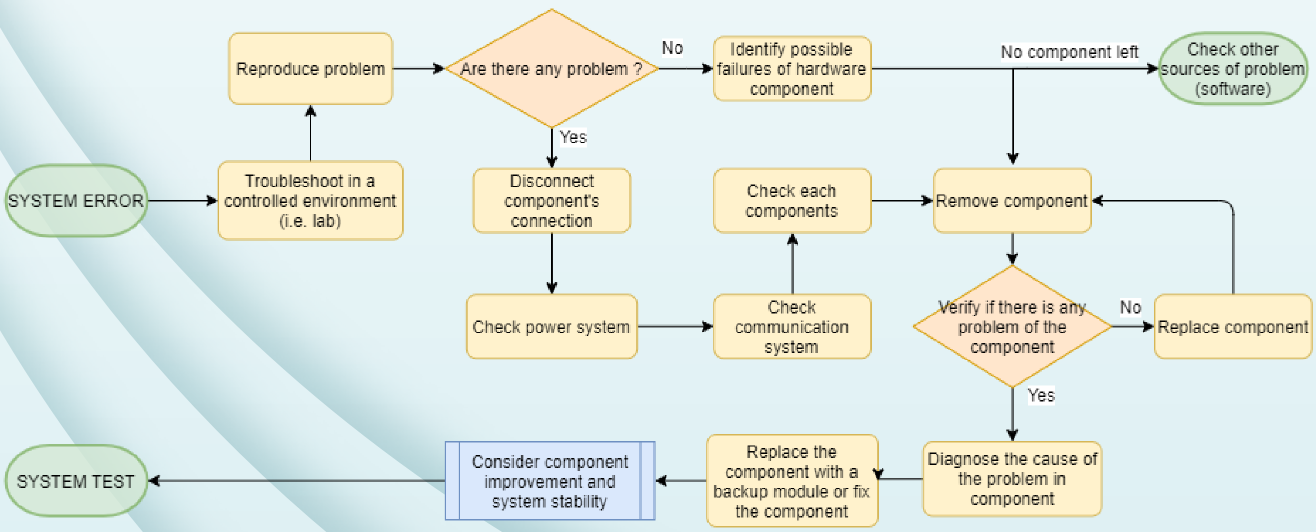
Before mission run
- ☐ All connections are secured and correctly connected
- ☐ Cameras are not blocked
- ☐ Cables and tether are properly tightened
- ☐ Tether area has no obstruction
- ☐ Electronic and pneumatic systems are working
- ☐ No electronic components are exposed
- ☐ Nuts on manipulators are properly fastened and bolted
- ☐ Dry test is completed

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

Protocol
- ☐ "Kill" when power needs to be cut immediately
- ☐ "Contact" when anyone is going to touch Axolo
- ☐ "Launch" when ROV is safe to operate underwater
- ☐ "Release" when shoreside crew open the gripper

After mission run
- ☐ Power supply is turned off when disconnecting the tether
- ☐ Electronic parts remain dry during disconnection
- ☐ Controller is not in contact
- ☐ Tether is kept tidily and neatly

Appendix B: Electronics Troubleshooting Checklist



Appendix C: Proposed Budget

Category	Description/Example	Budget (USD)
University Funding	The Hong Kong University of Science and Technology	6000.00
Sponsorship	RS Components	520.00
Total Income		6520.00
Research and Development	Mechanical	400.00
	Electronics	400.00
	Software	200.00
Tools		620.00
Machine Development	ROV Frame	500.00
	Buoyancy Foam	250.00
	ESC	350.00
	Thruster	1300.00
	Camera	400.00
	Sensor	200.00
	Remaining Miscellaneous	400.00
Micro-ROV	Frame	100.00
	ESC	30.00
	Thruster	50.00
	Remaining Miscellaneous	20.00
Control Box	Box	150.00
	Upgrade Electronics	400.00
	Remaining Miscellaneous	150.00
Shipment		350.00
Props		250.00
Total Expense		6520.00

Appendix D: Cost Projection

Category	Type	Description/Example	Budget (USD)
Electronic Components	Purchased	T200 Thruster (6 pcs)	1253.00
	Purchased	Brushless motor	35.00
	Purchased	Brushless motor (2 pcs)	86.00
	Purchased	30A Electronic Speed Controller (7 pcs)	189.00
	Purchased	48V to 12V Regulator (4 pcs)	62.00
	Purchased	Printed Circuit Board	225.00
	Purchased	Serial Digital Camera (8 pcs)	320.00
	Purchased	Waterproof Connector	375.00
	Purchased	Tether Wire	200.00
	Purchased	Electrical Components Miscellaneous	422.00
Hardware Components Sub-Total [1]			3167.00
Control Box Components	Purchased	Control Box Case	155.00
	Purchased	SDI Monitors (2 pcs)	310.00
	Re-used	Keyboard	15.00
	Re-used	Xbox Controller	15.00
	Re-used	Power Supply (Beluga, Epoxsea 2017)	45.00
	Purchased	CPU, Motherboard, SSD & Cooling Fan	425.00
	Re-used	RAM, Power Supply for Computer	223.00
	Re-used	Multiplexer	476.00
	Re-used	HDMI Capture Card	142.00
	Re-used	USB Hub	22.00
Control Box Components Sub-Total [2]			1828.00
Mechanical Components	Purchased	Polypropylene with CNC service	253.00
	Purchased	Buoyancy Foam	24.00
	Purchased	Carbon fibre cloth with epoxy	150.00
	Purchased	3D Printing Material and Related components	132.00
	Purchased	Mechanical Components Miscellaneous	269.00
	Purchased	Epoxy	320.00
Mechanical Components Sub-Total [3]			1148.00
Total Cost For Axolo [1] + [2] + [3]			**6143.00**

From above, total expenditure is within budget for this fiscal year.