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

epoxsea

MANTA
Technical Report
MATE ROV Competition 2019

Hong Kong

Chief Executive Officer
David Sun Year 2 Computer Science

Chief Financial Officer
Yat Wing Cheung Year 2 Dual Degree Program

Chief Technical Officer
Amanda Alodia Guito Year 1 Dual Degree Program

Software Engineers
Riwandy Year 2 Computer Science
Clyde Wesley Ang Year 2 Data Science
Pak Long Pang Year 1 Dual Degree Program
Kelvin Leonardo Year 1 School of Engineering

Mechanical Engineers
Tsz Ho Wong Year 2 Dual Degree Program
Jung Eun Ahn Year 2 Mechanical Engineering
Chi Shing Yeung Year 2 Mechanical Engineering
Bryan Suryaraso Gani Year 1 School of Engineering
Kai Ching Chong Year 1 School of Engineering
Chih-an Chou Year 1 School of Engineering

Electronics Engineers
Calvin Chee Hau Cheng Year 3 Computer Engineering
Yi-hsuan Ho Year 2 Dual Degree Program
Ting-kai Cheng Year 1 School of Science
Cheuk Chee Chan Year 1 School of Engineering
Joszef Maximillian Adiguna Year 1 School of Engineering

Supervised by Dr. Kam Tim Woo, Chun Yin Leung, Sau Lak Law, and Kin Ip Mong

Abstract

Manta, the latest innovation of Epoxsea, is a Remotely Operated Vehicle (ROV) developed to ace tasks relating to the Boon Lake, Boon Dam, and the South Fork of the Holston River. Besides entailing signature hydrodynamic features that ease the general operability, Manta is equipped with mission-specific components that are specially catered to inspect and repair dams, monitor water quality, determine habitat diversity, restore biodiversity, and preserve historical artifacts.

Through hours of research and development, Epoxsea, a workforce of eighteen, has gained the necessary skills to manufacture reliable and adaptable ROVs. Capitalizing on the expertise of its engineers, Manta was developed using heavy-duty machining, custom manufactured microelectronics, and advanced communication protocols under strict safety measures and efficient project management.

Months of fast-evolving prototyping and intensive testing culminated in the form of Epoxsea's most advanced machine yet, Manta, that embodies the principles of modularity, maneuverability, and maintainability. This technical document illustrates the product development process of Manta, making it the best available ROV, as a response to the request for proposal released by the MATE ROV and the Eastman Company.

Figure 1. Manta's Team Member. Top row (from left to right): Ting-kai Cheng, Bryan Suryaraso Gani, Yi-hsuan Ho, Calvin Chee Hau Cheng, Clyde Wesley Ang, Riwandy, Amanda Alodia Guito, Chi Shing Yeung, Kai Ching Chong, Pak Long Pang, Tsz Ho Wong. Bottom row (from left to right): Joszef Maximillian Adiguna, Chih-an Chou, Kelvin Leonardo, Cheuk Chee Chan, Jung Eun Ahn, David Sun, Yat Wing Cheung.

Table of Contents

Design Rationale

Design Evolution

Epoxsea has always been striving for excellence in the development of its ROVs, focusing on functionality and performance. Built on years of experience while exploring new technologies and materials, Manta, the latest addition to the company's line of ROVs, is customized for the needs of its customer, the Eastman Company.

During the research and development stage of the Manta, the engineers had inspected the company's previous ROVs and other ROVs on the market, from which several prevalent shortcomings were identified. Focusing especially on the vehicle's maintainability, modularity, and manufacturability, the engineers devised and evaluated different design approaches to Manta's core structure construction. Following the cost and benefit analysis, Epoxsea has formulated a highly revolutionary design philosophy: the "Buoyancy as Frame" concept. Through implementing this philosophy, Manta does not only address the apparent limitations, but also allow it to be a compact, durable, and flexible underwater exploration package.

Compared with Epoxsea's previous ROV, Manta is designed to be with high manufacturability, which phases out the need for employees to go through potentially harmful processes while minimizing the effects of inconsistencies from manual work with the use of precision tooling. The mechanical engineering team also utilized a large number of off-the-shelf components, such as hinges and buckles, which saves the company precious resources in terms of research, effort, and time.

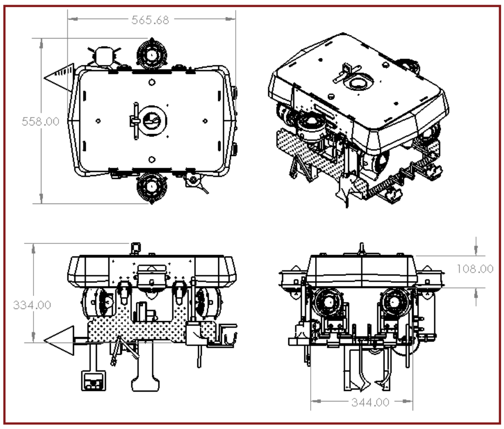


Figure 2. Manta's technical drawing

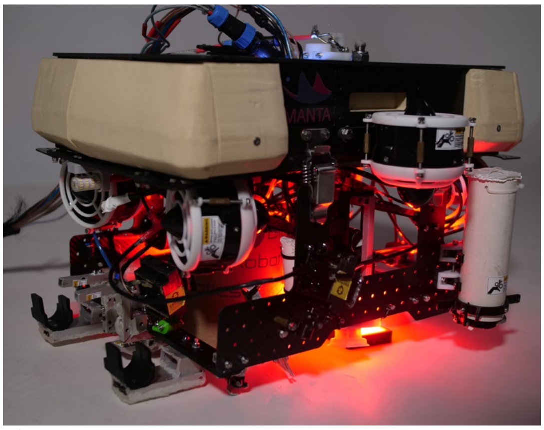


Figure 3. Epoxsea's ROV Manta

Through embedding all the core systems in the buoyancy integrated frame, Manta has overcome one of the biggest challenges that previous Epoxsea engineers faced, which is the maintainability of electronics and mechanical components. During the maintenance or set up period, the hardware bay and manipulators are designated to face upwards rather than being enclosed by a top buoyancy cover and placed at an upright position. This configuration then allows Manta's operators to have direct, unobstructed access to the components, facilitating the pre-deployment inspection, troubleshooting , and part replacement procedure.

Manta's camera subsystem comprises of serial digital cameras that are optimized for long-range video transmission, aiding underwater explorations at greater depths. This is a significant improvement from its predecessors' analog camera system, which was susceptible to signal noise encountered due to tether length. Apart from safety improvements, the choice of manufactured or off-the-shelf components saves the company precious resources in terms of research, effort, and time. Although Manta's design philosophy is radically different from Narwhal's, several components such as the tether casing and control unit monitor were re-used due to their reliability, enabling Epoxsea to invest in value-adding features with the budget.

System Interconnection Diagram

These are the system interconnection diagrams of pneumatics and electronics system used in Manta.

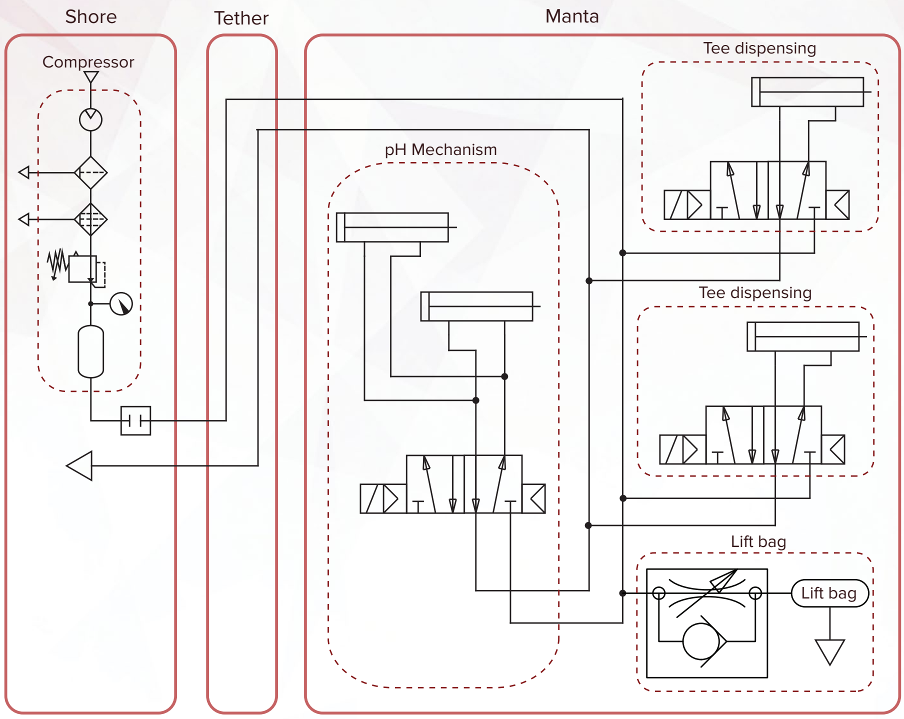


Figure 4. Fluid Power System Interconnection Diagram

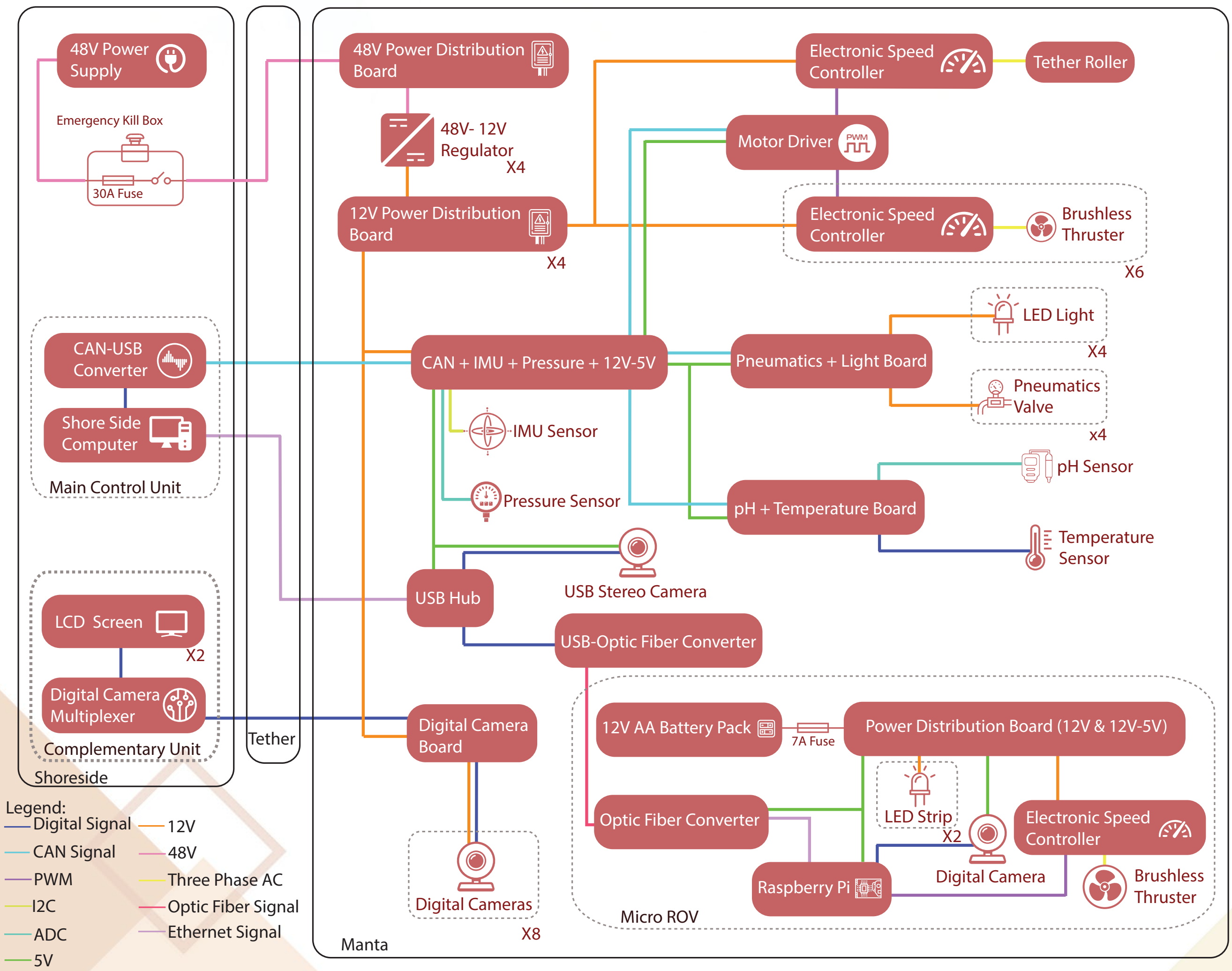


Figure 5. Electrical System Interconnection Diagram

Vehicle Core System

Mechanical

Frame

Manta's frame was constructed with the "Buoyancy as Frame" concept in mind. This architecture distinguishes Manta from its predecessors, as R-3318 buoyancy foam is incorporated into its frame to house the core system in a compact and slim model. As the frame is designed to be the hub of all components, it is engineered to withstand a considerable amount of extra load by fastening carbon fiber plates to the buoyancy foam. Additionally, Manta's inverted docking and custom-made stand facilitate ease of access to the hardware bay, leading to high maintainability during preparation and deployment.

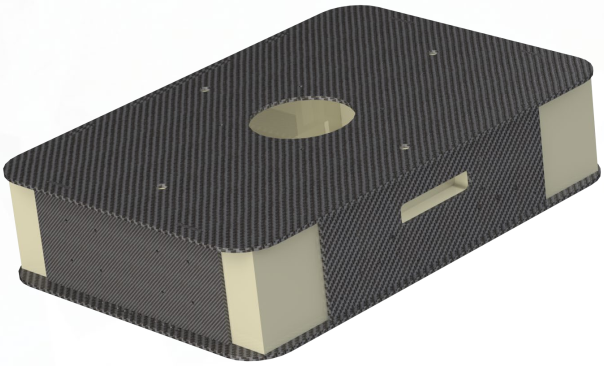


Figure 6. Manta's "Buoyancy as Frame" concept

Properties	Carbon Fiber Reinforced Polymer	Polyvinyl Chloride	High Density Polyethylene
Elastic Modulus (GPa)	70	3.4	0.8
Compressive Strength (MPa)	570	66	11.7
Density (kg/m^3)	1600	1300	970

Figure 7. Comparison of different frame materials

On top of its innovative design philosophy, Manta's frame was constructed with Carbon Fiber Reinforced Polymer (CFRP), a composite material made of carbon fiber bonded by polymer resin, providing lightweight rigidity as well as superior strength to weight ratio of 785 kN·m/kg. The use of CFRP is further justified by its high tensile strength and modulus of elasticity equipping the frame with considerable resistance towards impact and stress, besides being inherently water-resistant — all of which perfectly benefit Manta's performance as an exploratory underwater vehicle.

Interchangeable Manipulator Mount

Assembled with modularity in mind, Manta incorporates a separable manipulator mount, which is constructed with a horizontal carbon fiber plate attached to two anodized aluminum plates as the fixture, resulting in a space-efficient and user-friendly mount for the mission specific manipulators. The triangular-patterned M4 holes machined into the plate allow manipulators to be attached to either the plate or the aluminum bars fixed to the plate, providing flexibility in manipulator installation. The mount is then installed simply by using four buckles, which allows easier switching to a different mount with the corresponding mission specific manipulators installed for completion of another whole set of tasks.

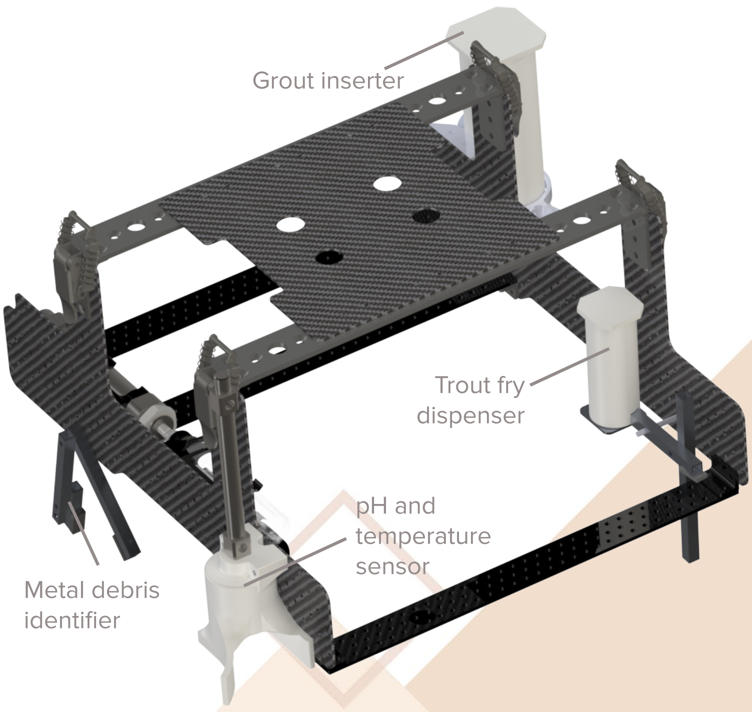


Figure 8. Interchangeable manipulator mount with some manipulators

Buoyancy

Manta is designed to have neutral buoyancy after taking the force exerted by the tether into account. This enables Manta to not be hindered by problems related to buoyancy during mission runs. Two blocks of polyurethane foam R-3318 have been machined to enclose the hardware bay inside the upper frame, ensuring the alignment of the center of mass and buoyancy. Unlike previous generations, buoyancy foam R-3318 is used instead of R-3312 due to its improved impact and hydrostatic pressure resistance, providing a more secure place for storing electronics components.

Attributes	R-3312	R-3318
Density (kg/m^3)	240	288
Compressive Strength (kPa)	2750	6600
Tensile Strength (kPa)	2950	5650
Shear Strength (kPa)	2600	4400
Flexural Strength (kPa)	4000	8400
Hydrostatic Performance (% wt. gain)	< 5% @ 135 psi	< 5% @300psi

Figure 9. Comparison of buoyancy foams

Hydrodynamic Feature

To enable high agility and mobility, it is important for Manta to be hydrodynamic and neutrally buoyant. Manta achieves this by equipping specially designed hollow hydrodynamic buoyancy blocks that reduce resistance and ensure performance stability under high speeds of movement. Air trapped inside the tailor-made 3D printed Polylactic Acid (PLA) blocks provide considerable buoyancy to balance the weight of the manipulators and electronics components.

Four of these blocks are mounted on Manta's externals to improve its maneuverability without needing software adjustments. The precisely engineered geometry of the hydrodynamic blocks creates a pressure difference between the top and bottom surfaces to counteract the effect of fluid resistance caused by the manipulators. More importantly, the hydrodynamic blocks are customized to allow for prompt adjustments when necessary.

Propulsion

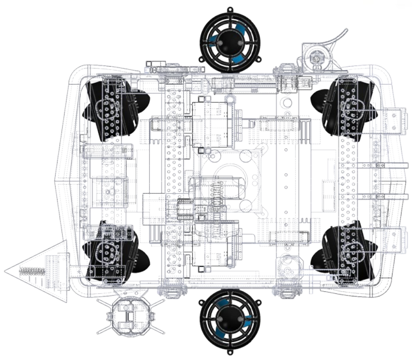


Figure 10. Manta's thruster configuration

Manta's propulsion system utilizes six Blue Robotics T200 thrusters, due to their durability and reliability. Compared to Narwhal's seven thrusters that incorporate six degrees of freedom, Manta uses six thrusters to satisfy the necessary five degrees of freedom, thus reducing the overall size of Manta compared to Narwhal. The horizontal thrusters are mounted at 30-degree angles to optimize maneuverability and efficiency, resulting in higher surge speed. Furthermore, the placement of the thrusters provides stability and speed, as unnecessary torque created by each thruster is counteracted by its complement.

Hardware Bay

The hardware bay is designed to maximize space available within Manta for enhanced component accessibility. The inner sides of the hardware bay have carved-in slots to better fit the waterproof regulators, creating designated slots for electronic components. This allows for a designated component placement system, enabling easy access if needed. Furthermore, the placement of the hardware bay eases debugging when it is upturned.

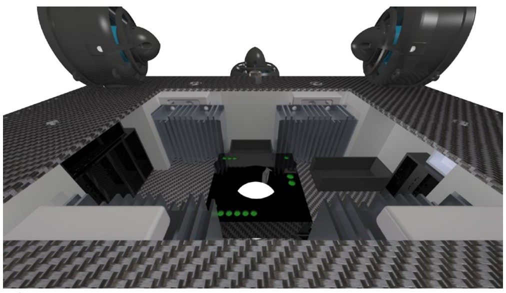


Figure 11. Manta's hardware's bay, inverted position

Modularity plays a key role in the placement of specific boards, as most boards have to be placed in optimal spots. As such, even though the hardware bay may be compactly filled, crew members are able to debug faster by referring to the approximate locations of each board, helping reduce the time needed to remove and replace malfunctioning components. Finally, the minimum spacing between the frame and the manipulator mount allows wiring to be as short as possible, increasing organization, reducing clutter and preventing overcrowding of the hardware bay.

Electronic Housing
For underwater vehicles, ensuring that all electronics are safe from contact with water is of utmost importance. Although there are simpler ways to implement waterproofing, Epoxsea has chosen circuit board potting due to its proven anti-leakage properties when compared to other methods. Specifically chosen amongst urethane and silicone due to its performance in electrical insulation and moisture resistance, epoxy is poured into 3D printed cases which are custom fitted for each board. These designated containers are meant to achieve compactness in electronics housing placements for space efficiency and modularity, both of which are vital in the smooth replacement process of defective components, troubleshooting efforts, and efficient cable management.

Electronics

Printed Circuit Boards
Multiple generations of ROVs have opted to operate with the STM32F103 microcontroller unit (MCU) because of its support and reliability. Its extensive feature set is justified by its prevalence in Printed Circuit Boards (PCB) that require control signals for interfacing with and manipulating different electronics components. Each board serves its own distinct function, and is connected to a centralized Controller Area Network (CAN) board that controls the distribution of signals. LEDs at the tether connection point near the CAN board indicate whether connected modules receive CAN signals for easy troubleshooting. Each respective board is equipped with a CAN transceiver that interprets commands to and from the shoreside computer. To decrease overall size, PCBs are designed to carry out a wide range of functions of similar needs without sacrificing modularity. For instance, the Light and Pneumatics components are combined into a single board as they both need 12V of power, whereas the pH and Temperature modules are integrated as they share a sensor which receives analog and digital signals.

Power Distribution
Manta receives 48V from shoreside supply through a custom power distribution PCB, which is converted into 12V outputs through four regulators, each providing up to 360W. The regulators are potted under a IP68-rated aluminum shell tested at full load, providing a sizeable current buffer to Manta's electronics with protection against excessive current draw, short circuits and overheating. The 12V outputs are then connected to three 12V splitter boards that distribute to 7 electronic speed controllers, a pneumatics board, serial digital cameras, and the CAN board. Other PCBs receive 5V power from the central board to power the MCU, and are also equipped with self-recovery fuses that prevent excessive current draw and allows the safe restarting of boards during mission runs.

CAN (*Controller Area Network*)
Manta maintains communication with shoreside operators using the CAN protocol that has proven to be reliable in long distances and prevent disruption from malfunctioning components. CAN also has a high baud rate of up to 1 Mbps, enabling rapid exchange of messages between its components and minimizing response delays from sensors and manipulators. Manta includes a centralized multi-purpose CAN / IMU / Pressure board that serves as the main point of connection for the tether and connects to other boards for effortless distribution of signals to other PCBs. Signals are then received on each board by high-speed CAN transceivers (TJA1050), which are selected for its speed, protection against undesirable thermal conditions and electrical shorts, that interpret the message complemented by LED indicators for troubleshooting.

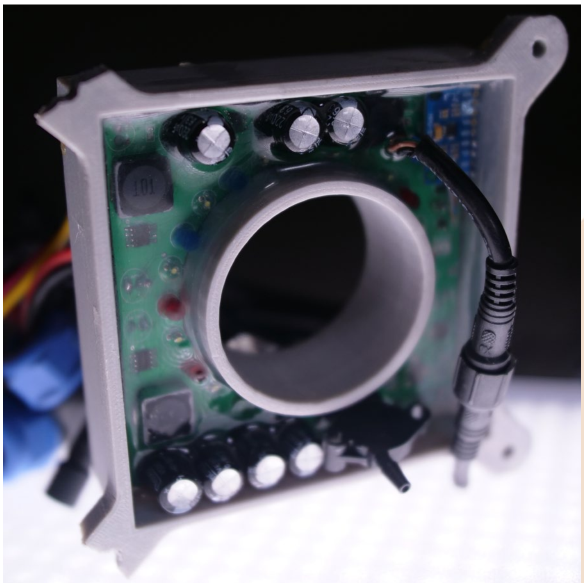


Figure 12. Design of the multi-purpose CAN / IMU / Pressure Board of Manta

Tether

Reliability, sturdiness, and ease of handling are the focus of Manta's tether. The manageable tether supports the required control signals, power, and pneumatics that Manta needs from shoreside control units. The tether houses a pair of 12 American Wire Gauge (AWG) DC power lines insulated with polyvinyl chloride (PVC), a pair of rubber-insulated CAN cables, eight individual RG316 coaxial video cables, an ROV-powered USB cable and a set of two polyurethane (PU) pneumatic tubes that are protected under a flexible and toughened Teflon casing that minimizes risk of injury when handling the tether.

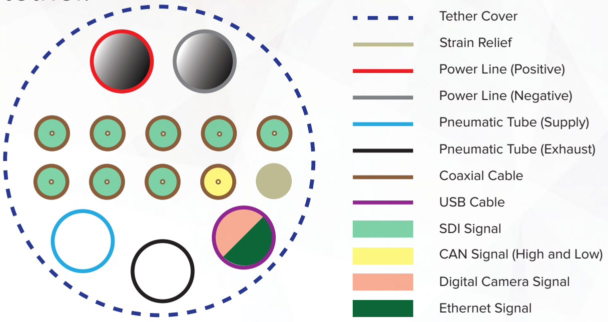


Figure 13. Tether cross section

The coaxial cables are flexible and exhibit a low 50Ω impedance, making it ideal for video transmission over long ranges. The DC power lines and pneumatic tubes are re-used from Narwhal to minimize cost while maintaining performance and safety standards. Connectors on either side also feature strain relief to reduce possible damages, which in itself is additional security towards electrical hazards.

Camera

Camera Technology	Analog (NTSC)	Universal Serial Bus	Serial Digital Interface
Maximum Resolution	720 x 470 px	4000 x 3012 px	2048 x 1080 px
Video Output Quality	Prone to Signal Noise	8-bit RGB Color	10-bit RGB Color
Compression	Yes	Yes	No
Transmission Signal	Analog	Digital	Digital
Video Latency	20 to 40 ms	120 ms	50 to 70 ms
Ready for Image Processing	No	Yes	Yes

Figure 14. Comparison between SDI, analog, and USB cameras

Manta's camera system provides a significant upgrade from previous implementations of an analog and dual digital Universal Serial Bus (USB) camera setup to a set of eight serial digital cameras. Although the analog and dual digital cameras provide a modular and interchangeable platform, Manta's serial digital cameras provide a video feed with superior quality allowing ease of ROV controls while exhibiting a similar video feed latency as our previous camera setup.

The camera system also allows for improved image processing on the shoreside control unit, with the high responsiveness of serial digital cameras allowing for faster completion of image processing.

Shoreside Control Unit

The main control unit has two compartments divided by a milled acrylic plate. The topside is mounted with a 22-inch computer monitor, whereas the bottomside contains the AMD motherboard with a Ryzen processor capable of running intensive processes necessary for Epoxsea's multithreaded software architecture. Four USB extension ports have been re-routed from the motherboard to the surface of the acrylic panel to simplify plugging of essential connections such as the CAN to USB interface. The wires underneath the acrylic panel are secured to the sides of the main control unit, complying with the safety requirements.

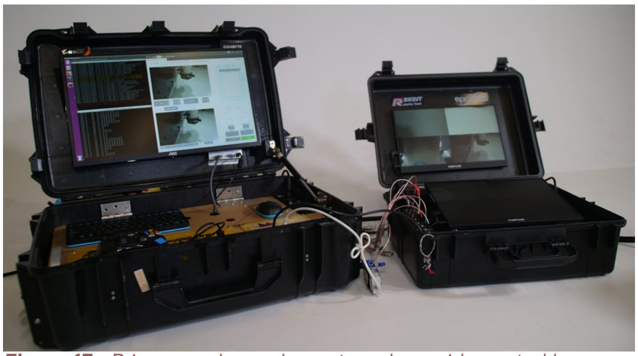


Figure 15. Primary and complementary shore side control box

A complementary control unit to house the renewed camera system in a compact container has been set up to feature two mounted 19-inch monitors that receive outputs from the video feed multiplexers to display 8 high-definition camera streams that are relayed back to the main control unit for processing. Besides enhancing the ability of the pilot to navigate by increasing the available camera views from three to eight, the crew members are able to simultaneously operate the computer on the main control unit to assist in mission runs.

Software

Manta's software architecture emphasizes modularity to accommodate the growing complexity of Epoxsea's codebase. Through extensive research on communication frameworks such as the Robot Operating System (ROS) and networking protocols including the CAN, Manta maintains simplicity and robustness with a master and slave configuration. In the master layer, ROS gives the freedom to create standalone software packages using multiple languages, encompassing Python and C++, which makes it possible for the software engineers to craft algorithms in their familiar language, consequently accelerating development time and reducing unnecessary bugs. Meanwhile, the slave layer is implemented in STM32 MCUs programmed in C, with CAN protocol for communication. This regulates commands sent from the master layer while allowing for modularity in code design.

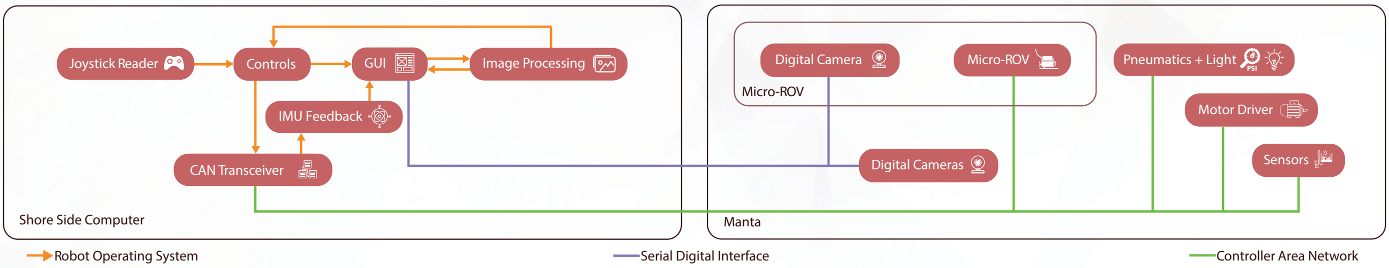


Figure 16. Software System Interconnection Diagram

Graphical User Interface

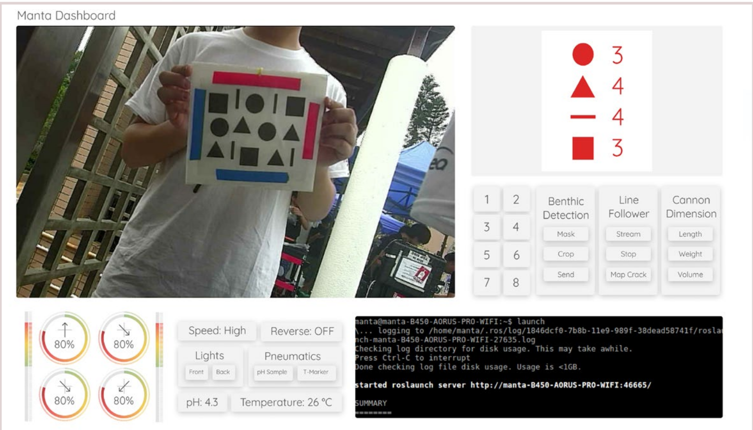


Figure 17. Manta's Graphical User Interface.

The Graphical User Interface (GUI) is an integrated platform used to monitor Manta's status by receiving data from ROS and communicating back with user-friendly browser elements. Developed as a web-based application using HTML, CSS, and Javascript along with Vue.js framework and Element.ui library, Manta's dashboard aims to maximize its pilot's ease of use through intuitive controls.

In line with its good design principles, the layout is compartmentalized into sections with specific purposes: the live video streaming allows interchangeability amongst the eight SDI cameras, the image processing canvas enables photo taken to be exported to the custom-made OpenCV backend, and the control status section summarizes information regarding the real-time data of the motors, lights, manipulators, and sensors.

Event-Driven Architecture

Event-Driven Architecture (EDA) is a commonly-used programming paradigm used in building complex systems with multiple interacting parts. 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, which unlike the commonly-used request-response architecture, allows multiple receiving packages to handle incoming events asynchronously.

Manta's core software architecture, ROS and CAN, use EDA to provide modularity in its architecture. The extensive use of EDA enables services to be modified and replaced easily resulting in rapid and non-blocking development of Manta's software.

Communication Architecture	Request-response	Event-driven
Node Interaction	Polling Based (Blocking)	Interrupt Based (Non-blocking)
Resiliency and Error handling	Complex retry logic	Queue based solving
Coupling	High	Low
Node State Management	Transaction-based	Event-based

Figure 18. Comparison between commonly used communication architectures

Mission Specific Features

Micro-ROV

Manta employs a Micro-ROV to identify areas of muddy water flow inside a drain pipe. The Micro-ROV accomplishes this task with a minimal design consisting of a single acrylic tube as the frame with components such as USB camera, LED, thruster and epoxy-potted electric boards.

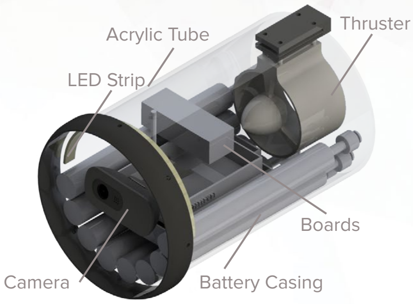


Figure 19. Components of Micro-ROV

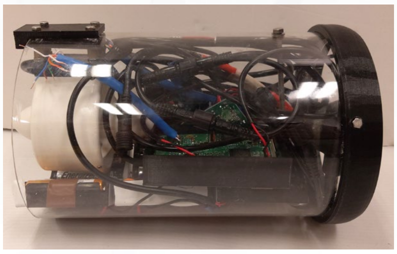


Figure 20. Micro-ROV side view

A 130mm diameter acrylic tube 200mm in length is chosen due to its circular cross-section for more efficient use of space. It also enables easier but more secure mounting of components by drilling and screwing. Additionally, an ROV Maker thruster is selected due to its sufficient amount of power relative to its size and mass. Instead of regular LED light bulbs, LED strips are chosen to allow for more flexible usages.

To enable the Micro-ROV to dock onto Manta, a specially designed docking mechanism is employed. Once the Micro-ROV is deployed and the tether is loose, a motor-powered wheel allows the tether to retract back into Manta. This allows the tether to be easily gathered inside a container without placing strain on the wire.

Tire and Cannon Retrieval

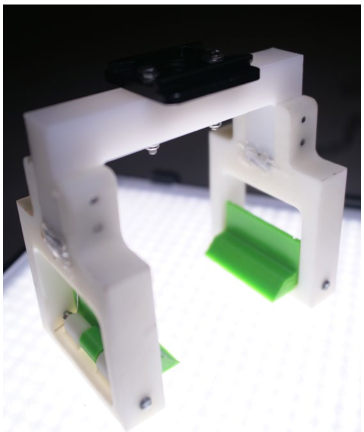


Figure 21. Grabbing mechanism

Manta's grabbing mechanism is designed to retrieve both the tire and the cannon, minimizing the number of manipulators Manta needs. Relying on a passive mechanism, the manipulator comprises of a pair of 3D printed retractable holders and an aluminum frame, carefully designed to be adjustable to fit the size of the two objects.

The grabber involves a locking system to secure the target object. Once the cannon or the tire is fully inside the arch, then, the torsion springs installed in the holders trigger immediate retraction, with the rigidity of the grabber acting as the locking system. Since the grabber can only work when located at the lowest point of Manta, a slide-in mount is implemented to allow for quick uninstallation when not in use.

pH and Temperature Sensor

The dual-functionality module for the pH sensor and temperature probe simplifies the measurement of pH value and temperature level of water samples, which is aligned with Manta's modular design philosophy. Manta collects water samples for the pH sensor using a pneumatic powered syringe to protect the fragile pH probe from being in direct contact with externalities. Consequently, any maintenance effort is further simplified and made cost-effective as only the 3D printed parts need to be replaced. The PCB measures pH values through analog to digital conversion. Meanwhile, the temperature sensor will measure the temperature level and communicate with the PCB using the one wire bus system, a reliable protocol for transmitting digital signal.

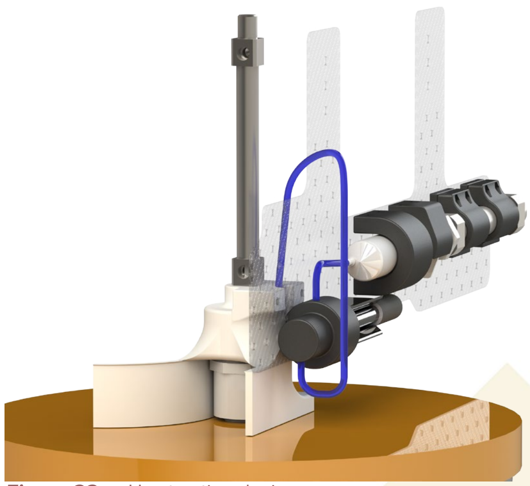


Figure 22. pH extraction device

Grout Inserter

In a bid to balance reliability and compactness, the structural design of the grout inserter relies on magnetic and mechanical forces to achieve a precise passive mechanism. The magnetic enclosures that form a barrier at the bottom of the two-inch PVC pipe securely prevent the grout from flowing out, yet are simultaneously sensitive to a strong mechanical force, allowing the cup to act as its trigger.

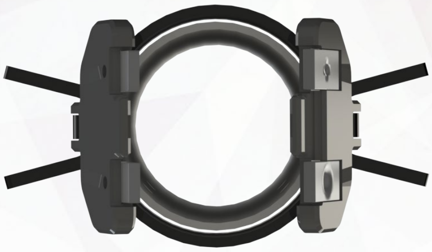


Figure 23. Grout inserter (bottom view)

Figure 24. Grout inserter (lateral view)

Trout Fry Dispenser

Figure 25. Trout fry dispensing mechanism

The trout fry dispenser comprises a push-to-open mechanism and a one-inch PVC container to store the trout fry. The door of the container is mounted on one end of a pivoted aluminum bar while a magnet and a hanging bar are connected on the other end. The magnet counteracts the weight of the trout fry to securely close the door, preventing the trout fry from escaping. The attractive magnetic force is overcome when the hanging bar touches the ground, freeing the trout fry. This design enables the driver to release the trout fry in a short amount of time with minimum effort.

Benthic Species Detection

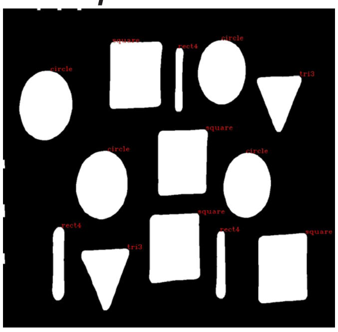


Figure 26. Benthic species detection software

To accurately identify the species of benthic organisms, Manta first identifies the section of the image where the benthic species are located. This decreases the chance of errors and reduces noise. Manta then uses proven image processing algorithms to detect the sides of each detected organism. This information is used together with in-house logical checks to autonomously determine the number of each benthic species. Additionally, safeguards are put in place to inform the pilot of possible irregularities and allow for additional photos to be taken for processing.

Trash Rack Screen Holder

The trash rack screen holder is designed to complete multiple tasks including removing the damaged trash rack screen and installing a new trash rack screen, while concurrently serving as a set of multi-purpose hooks. Its mechanism consists of two 3D printed clips facing upwards to support the trash rack and secured onto an aluminum bar of the manipulator mount. In order to prevent trash rack screens from toppling over, the front portion of the clips is extended for support.

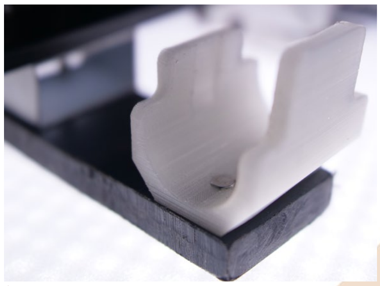


Figure 27. Clip of trash rack screen holder

When removing the damaged trash rack screen, Manta approaches the cradle of the trash rack where the clips can hook onto the screen. As Manta moves up, the upward motion will push the screen onto the holder. Meanwhile, when delivering a new screen to the trash rack, the bottom of the new screen will be aimed to fit inside the cradle of the trash rack. Manta's downward force then releases the new screen out of the clips and into the cradle.

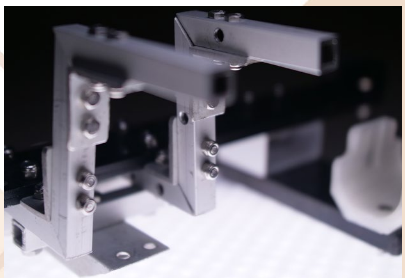


Figure 28. Stabiliser for new trash rack screen

Cannon Measurement

To aid the measurement of the cannon dimensions, Manta utilizes a stereo camera which relies on the duality of lenses. The stereo camera comprises of two lenses with separate image sensors that are mounted together as an integrated system, enabling Manta to mimic human binocular vision. Unlike a regular camera, the stereo camera is able to perceive the environment in a three-dimensional manner. Initially, a comparison between two different perspectives of the same scene is translated into a disparity map, which is then translated to actual measurements of metric distance and size facilitated by a linear regression model built on more than 30,000 data points to ensure its accuracy.

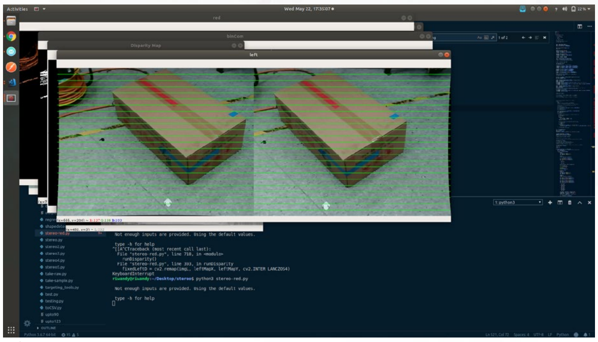


Figure 29. Preprocessed camera input from stereo camera

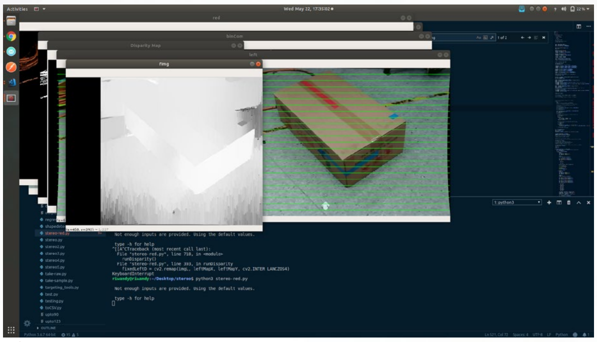


Figure 30. Mapped images to be used in the algorithm

The cannon weight in water is calculated using a formula derived from force balance based on Archimedes' principle:

Cannon weight in water = $\rho gV - \gamma gV$

where ρ = cannon density, g = gravitational acceleration, γ = water density, V = cannon volume

Metal Debris Identification

In order to differentiate metal cannon shells and non-metal debris, Manta is equipped with an identification device made of two sets of aluminum bar with a magnet attached at one end. The two aluminum bars are connected through an axis of rotation at the other end of each bar, which can easily indicate magnetic attraction for debris classification.

Metal Debris Marking

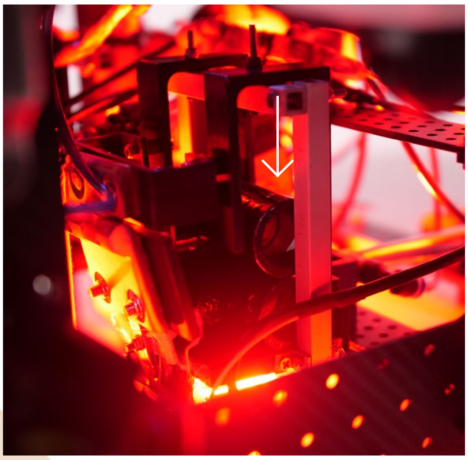


Figure 31. Metal debris marker on Manta

The tee-dispensing mechanism used for metal debris marking is constructed with 10mm thick aluminum bars and 3D printed PLA components. The dispenser resembles a cage-like structure that precisely fits the PVC tees stacked on top of each other. The motion that releases the tees is commanded by a pneumatic cylinder mounted at the back of the mechanism. At every extension and retraction of the pneumatic cylinder, one tee is pushed out of the base platform, with metal hinges controlling the end and acting as a door. Whenever the pneumatic cylinder extends to push a tee out, the tee would sequentially push open the hinged door, exiting the mechanism. A pair of magnets are attached to the bottom of the door and the edge of the base platform to ensure that the mechanism is closed when not in use.

Dam Inspection

In order to reliably follow the red path and measure crack lengths during dam inspection, Manta collects data from an inertial measurement unit sensor to check its orientation in the three rotational axes. This is used to stabilize Manta's movement and is complemented by an algorithm that filters red colors for identifying the path, and blue colors for measuring crack length.

Safety

Philosophy

In upholding safety as a core value, Epoxsea believes it is both a personal and collective responsibility to maintain a safe work environment that prioritizes the protection of people, tools, and the environment. This notion is translated into executable actions through rigorous training, mandatory laboratory practices, incorporation of vehicular safety, and strict testing protocols.

Training

The effort to acquaint new hires with Epoxsea's culture of safety begins from the Induction Day, in which a designated portion was allocated for cross training. This provides an overview of different operations so that employees are aware of possible safety hazards. Veteran employees demonstrated proper safety practices in handling common tools and equipment specific to their departments, while simultaneously sharing their experience on common safety oversights to enable all employees to keep a lookout for one another throughout the ensuing workmanship of Manta. This ensures that all employees have the essential skills to minimize risks of accident and deal with emergency situations.

Figure 32. Mechanical safety training in practice

Figure 33. Safety practices by electronics team member

Following this broad introduction, employees underwent a more in-depth safety exercise in which senior employees closely supervise and monitor the ability of newly-hired employees in operating tools and pieces of machinery in a safe and proper manner. In addition, to keep up with industry standard, Epoxsea engineers attended safety training conducted by external organizations such as the Design and Manufacturing Services Facility.

Laboratory Safety Practices

Prior to undertaking any risk-posing procedures, employees have the responsibility to ensure that they are equipped with the necessary knowledge to prevent accidents and conduct remediation actions. In case of any doubt, multiple copies of the Safety Instructions — detailing hazards related to tool handling, fire, and electricity, as well as proper management of perilous substances and common housekeeping practices — placed in the laboratory may be directly consulted. This not only ensures the lab safety but also offers a more attended environment for employees to work efficiently.

To enhance personal safety, on the other hand, employees have specified work attire that consists of long-sleeved tops, ankle-reaching pants, and covered shoes to prevent direct contact with harmful particulates like epoxy and glass fibers. Furthermore, personal protective gears such as safety goggles and protective earmuffs must be put on when dealing with machinery and power tools. Overhead ventilation systems with intake fans are also installed to ensure safety when soldering electronics components and handling of epoxy by exhausting any fumes generated. The pneumatics pressure levels are also kept at 2.75 bars (275 kPa) for safety measures with respect to the air pump.

Vehicle Safety Features

As early as the research & development stage, Epoxsea examined the MATE safety requirements for the vehicle, attributed each of them to the suitable department, and ensured that safety lies intrinsically in Manta's construction. Besides including basic reminders in the form of visible "moving parts" and "high pressure" safety stickers to notify crew members, inherent technical safety features were incorporated in the conception of Manta.

Electronics engineers make use of a "kill-box" that includes a 30A fuse designated by MATE and an emergency stop button between the 48V power supply and the tether. Additionally, LED indicators and color-coded cables for different tasks are implemented to easily debug error feedback and prevent misconnection of headers. Prevention of dangling and tangled wires is carried out by properly securing all wires with zip ties, velcro, and 3M Dual-Locks.

Mechanical engineers make sure all sharp edges are eliminated through filling and deburring. Thrusters are shrouded with guards to prevent potential safety hazards such as thruster interference from loose components and peripherals. In addition, four metallic locks are installed on the bottom part of the frame to ensure that all manipulators are properly secured to Manta. Visible warning stickers such as "sharp edges" and "electrical hazard" are placed on the components as well. Strain relief is installed to prevent putting stress on the tether.

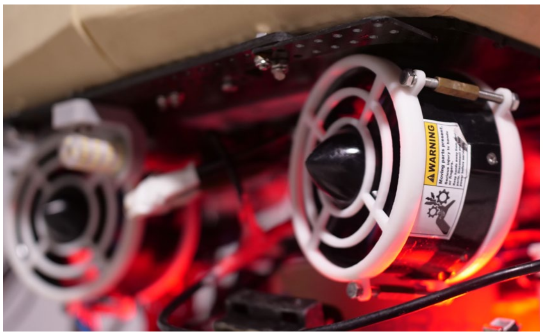


Figure 34. Safety sticker on thruster

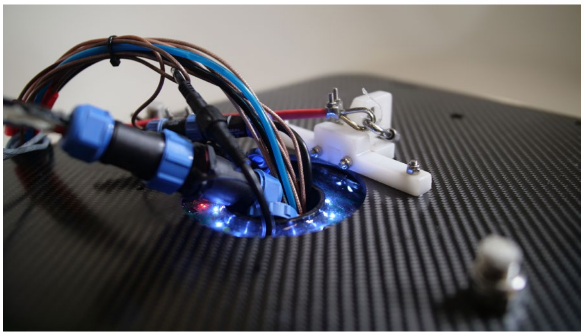


Figure 35. Tether strain relief

Software engineers have programmed each motor driver with watchdog timers that periodically check inbound commands, suspending thruster operations when no valid commands have been received by the board after a specified period of time. With regards to CAN communication, ***candump*** and ***cansniffer*** are two software commands in the Linux can-utils library. These two commands output both the sent and received CAN messages onto the console. By being able to monitor CAN commands broadcasted throughout the system, Epoxsea's software engineers are able to pinpoint critical errors that might cause loss of control of Manta and pose safety risks to the crew members and its surroundings.

Testing Protocols

Epoxsea's testing protocols for operational safety are refined year by year. Systematic dry tests are implemented before any water tests and the operational safety checklist (Appendix A) should be abided by all crew members under any circumstances. For instance, thorough communication protocols between shoreside and ROV-side engineers, such as but not limited to "contact" and "kill", must be put into action since physical injuries may occur from improper activation of manipulators and thrusters. These signals are proved to be extremely useful in making sure the driver is not controlling the vehicle or the ROV is shut down while the shore-side crew members attend any operations so as to prevent electrical shock and wounds caused by moving objects.

If emergencies arise, given exposed ports or ESC restarting, the crew member closest to the 48V power supply must shut down the power to the ROV at once to avoid harm to the crew and damage to the electronics on the ROV.

Testing and Troubleshooting

The modular architecture of Manta motivates employees to continuously propose new solutions in a bid to tackle existing challenges from a different angle. This provides a comparative measurement that equips Manta with a multitude of competitive advantages. Based on a systematic approach, individual components are first assessed to determine the reliability of their performance and ensure that each sub-system incorporated into Manta works in itself, as well as within the entire architecture.

For the software department, every addition to the codebase does not only have to pass rigorous test cases but also complies with the continuous integration algorithm implemented to ensure compatibility. In terms of electronics testing, for every PCB, a digital multimeter is used to check for proper connection among the pins and wires, and ascertain the absence of short circuits that may cause interference to other boards and pose safety hazards. The preliminary manipulator designs were initially 3D printed to ascertain its proof of concept before undergoing a series of prototyping iterations to improve durability, practicality, and ease of use. In fact, this development style contributes to the Manta's core principle of modularity, as parts are easily interchangeable and design options can easily be evaluated.

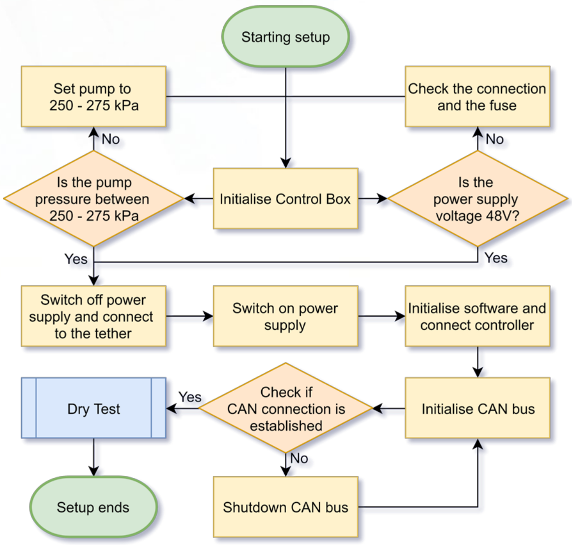


Figure 36. Testing and troubleshooting protocol

In line with our safety protocol, full vehicle testing consists of a two-step verification prior to attempting mission runs. The initial in-air dry test requires checking of each component functionality and identifying potential safety risks such as disconnected ports through powering the machine in a lab-controlled setup. Following this, Manta is brought into the buoyancy test to ensure neutral buoyancy given variable weights of manipulator designs, guaranteeing Manta's stability and maneuverability. Only after passing these tests can Manta proceed to embark onto mission-specific tasks, in which its performance and capability are further scrutinized. Numerous repetitions of this cycle amounted to more than 40 hours of continuous quality inspection and reassurance that allows Epoxsea to deliver the best product possible.

Epoxsea capitalizes on both system-based and human-centric approaches to identify issues and potential solutions. Problems often emerge during water tests and are addressed during debriefing afterward. Epoxsea's tactic to troubleshooting is a step-by-step process that involves reproducing, isolating, and diagnosing the problem, as shown in Appendix B. The engineers will first attempt to reproduce the problem in the laboratory to avoid acting under a false premise. Each component is then isolated to pinpoint the source of the problem down to a single module. Afterward, the defective module would be thoroughly trialed and corrected. Additionally, Epoxsea resorts to deploying a designated diver for each testing cycle as this proves to be useful in identifying situational disturbances unrecognizable by the machine.

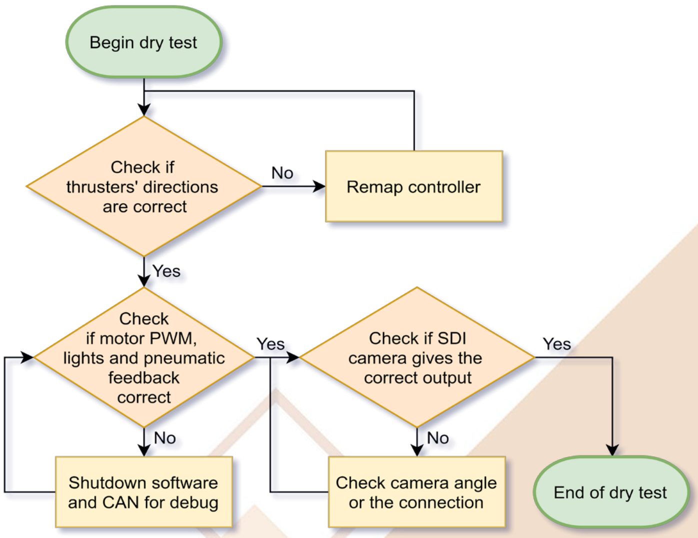


Figure 37. Dry test protocol

Project Management

Organization Structure, Planning, and Procedures

As a multidisciplinary and multicultural company, Epoxsea believes that its core value proposition lies in the quality and capability of its human resources. By capitalizing on the diversity of its employees, culturally divergent perspectives are incorporated in the development of Manta, increasing its robustness in dealing with unexpected situations. Each employee is an integral stakeholder whose opinion is greatly valued, as seen in meetings where everyone is encouraged to speak up. Additionally, the organizational structure within the company is flat, so the majority rule is used for final decision making. In order to bridge cultural barriers and forge strong bonds amongst the employees, team building activities such as Cycling Day and nightly Company Dinners are held. This culture of inclusiveness, combined with the flat organizational structure, serves as a foundation to facilitate a harmonious working environment that contributes to overall productivity.

Company

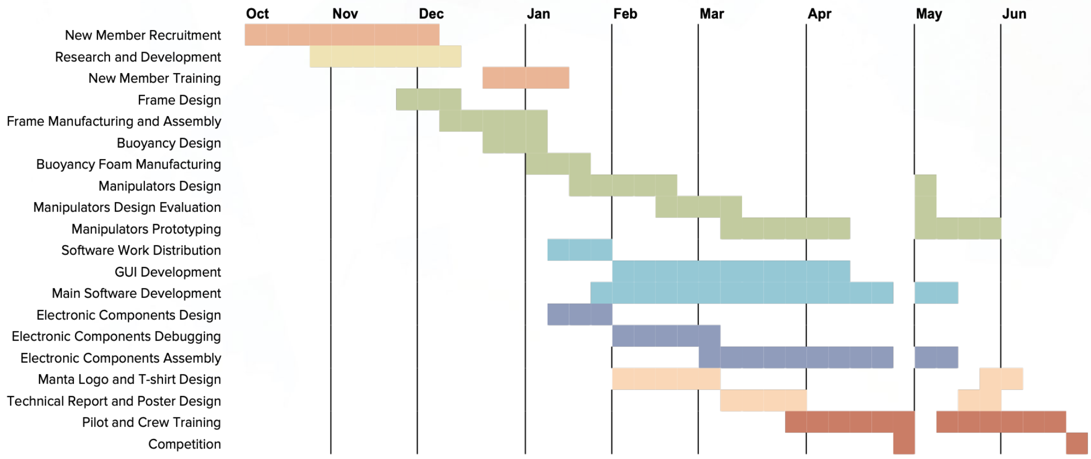


Figure 38. Gantt Chart of Manta's development

From the beginning of the conception of Manta, we use the Gantt Chart to inform the employees of the macroscopic view on the timeline of the project. Google Cloud Platform allows real-time collaboration and immutability of important documents. A Slack workspace is utilized for important updates and aid communication, keeping employees informed of emergency matters and current progress. A detailed view is taken during meetings after water tests, as every department reports back about progress, challenges, and possible solutions which are then refined through discussion with the rest of the company. Every conclusion reached during the meeting will then be translated into specific, measurable, achievable, realistic, and time-based (SMART) goals and assigned to specific employees, with progress tracked in following meetings.

Budget and Cost Projection

The majority of Manta's development budget was allocated for electronics and mechanical parts. A large sum was invested in the electronics needed for high-quality video streaming including serial digital cameras, coaxial cables, and multiplexers whereas the budget for mechanical components was largely used for the manufacturing of Manta's frame and high-quality manipulators. The budget is estimated based on funding from HKUST and sponsorships.

At the beginning of the year, Epoxsea searched for sponsorship as well as conducting a review on the past materials for re-use possibilities. This allows the company to invest more in value-adding items. As a university-based company, the company's budget is limited, hence the budget must be reviewed continuously to ensure the proper use of the budget. The budget projections and cost breakdown of Manta are attached in Appendix C and Appendix D.

Mechanical

Manta's mechanical division aims to not only deliver reliable manipulators but also help its employees grow as a mechanical engineer and a team player. As such, instead of developing each manipulator individually, mechanical engineers are grouped in a manner similar to pair programming whereby the pair conducted research and discussed the alternative design solutions together before sharing their ideas to the division. In addition, this year's cloud-based file storage system on Google Drive allows mechanical designs to be viewed and modified by anyone at any time, along with providing version control for said designs, facilitating a more efficient co-working experience among mechanical employees. Besides fostering a harmonious team dynamics, this approach facilitates early identification of potential problems and allows the mechanical division to take corrective measures during the early stages of development, which would save time and resources.

To further enhance and ensure the performance of each manipulator, all of them are field-tested to ensure driver friendliness and operability. One example would be the design of water sample collection mechanism, which throughout the development and testing stage has undergone several improvement stages. With the driver providing feedback on manipulator performance after each testing day, the engineers responsible would be able to pinpoint the manipulator's shortcomings and enhance its performance and reliability.

Figure 39. Design evolution of the pH manipulator

Electronics

During the first meeting, the electronics division divided responsibilities pertaining to the basic functions of Manta, such as motor control, power distribution, and camera boards. Each electronics engineer is in charge of designing and soldering his/her respective boards, along with the maintenance of sensors and production of backup modules. Furthermore, weekly deadlines are set in place for improving Manta's functions, such as the overhaul of the camera setup from analog cameras to serial digital cameras and debugging problems that arise during water tests.

Software

Manta's software team aims to produce reliable software to support basic controls and mission-specific capabilities. Manta's modular software architecture allows its software members to simultaneously work on multiple software packages. However, various problems occur and hinder the development process when changes on one package affect other packages. To mitigate this problem, the following software development lifecycle promotes clean code, concurrent development, and rigid testing, ensuring the usage of latest software versions in water tests.

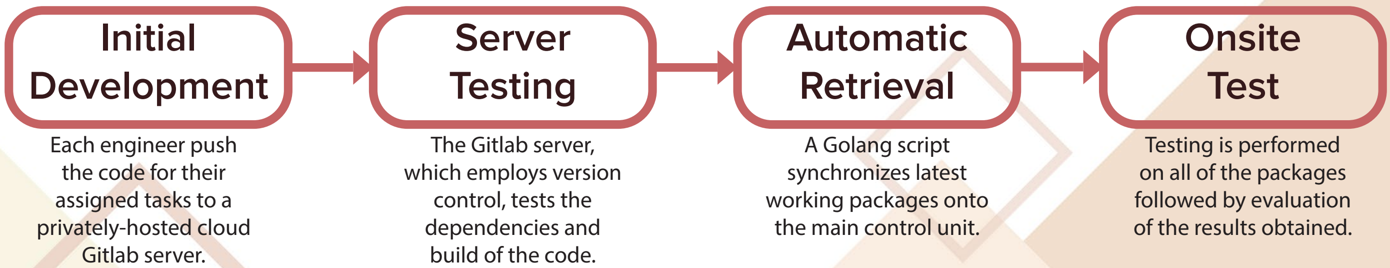


Figure 40. Software development pipeline

Challenges

Technical

Besides the unprecedented constraints on electronics and mechanical design due to its limited size, the Micro-ROV's docking mechanism was initially an insurmountable challenge. Based on the preconceived notion that a rolling motion must be initiated by the tether of the Micro-ROV to return it to its designated spot in the main ROV, an inherent problem of tether entanglement surfaced. Should this be left unresolved, damage to electronics connections can pose a safety hazard of shorted wirings. After long deliberations and intensive prototyping, it was decided that the premise of the docking design principle did not hold ground as a simpler "into the box" mechanism did not require this and was more space-efficient and time-effective in its attempt to pack the tether.

Non-technical

An inherent and expected challenge coming from the multinational — Hong Kong, Taiwan, South Korea, Indonesia, the Philippines, and Belgium — background of Epoxsea's employees was the language barrier. A measure to tackle this, in line with propagating an inclusive culture, was for each member to communicate in English rather than their mother tongue throughout the development of Manta. Although some tolerances were given for technical terms that may be difficult to express in English, conversations in a foreign language would be concluded with an English translation to ensure that everyone is on the same page.

Figure 41. The multinational shoreside crew members, working together to lift up Manta during regional.

Also, a rather unexpected logistics problem was encountered this year due to delays in delivery of purchased components. In the beginning, we have implemented just-in-time inventory management to make cost management efficient, ordering only the necessary parts needed. Unfortunately, due to the extended Chinese New Year holidays between mid-January and mid-February, as well as some confusion amongst the delivery agents that caused our package to be returned to the sender, the shipping of components from Taobao, our long-term supplier, required more time than usual. This hindered development progress for a few weeks. Learning from this experience, Epoxsea started to plan ahead and keep track of possible restocks and future purchases of required essential materials.

Future Improvements

Epoxsea believes in the culture of lifelong learning, which is why at the end of each product life cycle, in this case that of Manta, employees share constructive feedback on potential enhancements that can be made in every cycle. One major technical improvement to be introduced is in terms of software testing, as errors are often encountered after integrating new components. Although some processes have been automated through integration of build testing in the server, extending this to the whole architecture can improve software quality. This can be implemented by specifying test cases with expected outputs given a certain input. For every change made to the code, all test cases must be passed to ensure that these changes do not break the existing base. However, much effort must be put into ascertaining that the base itself is error-free and only then can this test-driven development be confirmed to work. Otherwise, new changes may be rejected due to an inherent problem of the foundational architecture, raising confusion and prolonging debugging processes.

Lesson Learned

A fundamental challenge related to the design of Manta is the usage of analog cameras. The company chose to use analog due to past experiences and a lack of willingness to change. However, analog cameras have proven to be a major detriment to both driver skills and mission task testing because of its lackluster image quality and susceptibility to signal noise. The electronics division had especially encountered difficulties in remedying the complications related to the aging analog camera system. As such, the company concluded that the costs to fix the analog cameras outweigh its benefits. The alternative was to overhaul the camera system into a serial digital system, allowing for high definition images as well as the direct transmission of digital signals, negating the drawbacks of converting from analog. Furthermore, the overhaul has resulted in benefits that include the direct implementation of camera vision algorithms for mission-specific tasks, as well as allowing the pilot to simultaneously drive while the co-pilot operates software needed for camera-related mission tasks.

Figure 42. A software engineer monitors the SDI feed on the control box for camera vision purposes.

The overhaul of cameras to the serial digital system has also contributed to the growing development of Epoxsea's knowledge base. Not only do electronics engineers need to learn how to work with the multitude of new technologies such as digital video multiplexers and coaxial wiring, but mechanical engineers also need to learn how to work with the bulky models of serial digital cameras, along with new mounting mechanisms that differ greatly from the previous analog cameras. The adaptation of serial digital cameras and its companion technologies such as coaxial wiring meant that both the senior and junior members had to familiarize themselves with the more delicate piece of technology, being mindful towards the drawbacks that come with using serial digital cameras, such as over-exposure to the lens, along with frail wire connectors and modules. To combat said drawbacks, Epoxsea engineers have used multiple extreme conditions to simulate real-life situations, such that each problem can be identified through trial and error. One such example was the usage of a pressure chamber to simulate deep-water conditions along with the use of a freezer to hasten condensation, testing waterproofness. Other electrical tests were used, including varying camera power to simulate power fluctuations, along with testing direct signal transmission as opposed to through waterproof ports.

Epoxsea also gained invaluable insights into management, especially regarding problem-solving. Undeniably, Epoxsea's engineers, each eager to apply theoretical knowledge towards solving mission-related tasks, are motivated to propose a solution from a technically sophisticated angle. In approaching the identification of metal cannon shells, the initial solution was to use a magnetic sensor along with an interface board that converts the analog signals. However, this poses its own challenges, especially due to the limited range of the magnetic coil, requiring objects to be within 1 cm. This needs perfect alignment between the sensor and the cannon shells. It was only after multiple discussions did the much simpler solution of attaching magnets to Manta's surface. This change to a mechanical solution resulted in the dismissal of the previous electronics solution. However, without the previous electronics solution, engineers would not have learned about its potential benefits and weaknesses, and the company would not have come upon the mechanical solution.

Reflections

Figure 43. Tsz Ho Wong, senior mechanical engineer

Having been a mechanical engineer of Epoxsea for two years, my participation this year is a vastly different one from that of my first. To begin with, compared to my first year's experience, I have the responsibility of not only designing manipulators and finishing my assigned tasks, but also the pressure of managing the mechanical division's technical progress and bearing responsibility for its performance. This is a totally new and especially challenging task for me due to the expansion of the team and the complexity of this year's tasks. Other than the mental pressure, I also learned a lot from designing and drafting for the year's plan. As the only returning mechanical engineer, I am also responsible for Manta's frame, which allowed me to gain many valuable insights with regards to the whole product design and manufacturing process. Last but not least, in catering to the relatively large number of new hires, other experienced employees and I spent a lot of time in managing Manta's technical progress and in our pursuit to create a very passionate and harmonious company atmosphere — all of which lead to Epoxsea's competitive performance.

Through my participation as an employee of Epoxsea, I feel that I am gaining valuable experience that I would not be able to gain elsewhere. Working on Manta together with other employees does not only hone my teamwork skills but also aid my intrapersonal development through the ability to be considerate towards others and think from their perspectives. Since the development of Manta is an arduous process with deadlines after deadlines, it is crucial to set my priorities straight and manage my time in an efficient way. It is indeed difficult to always maintain a good balance between my academics and the work at Epoxsea. However, I feel that my time management skills have significantly improved over the past months of working on Manta. The motivation that drives me forward would definitely be the sense of achievement we get from successful testings of Manta. Especially being a member of the mechanical division, the feeling of thrill and satisfaction when my own mechanical design works are beyond words.

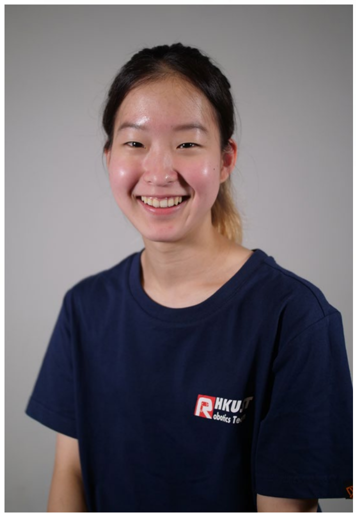


Figure 44. Jung Eun Ahn, junior mechanical engineer

Figure 45. Clyde Wesley Ang, junior software engineer

Joining Epoxsea as a software engineer has so far been the best decision I have made in university. After several long nights spent on improving design and algorithms, I was able to develop skills in various fields through delving into the different areas of software development. Besides empowering me to become a more holistic engineer through the hands-on experience, the feeling of satisfaction after all our hard work culminates in Manta is just irreplaceable. After working in this company for a few months, I know that problems can never be avoided, but we should always do our best to find a way to fix this. All of those sleepless nights have given me this mindset, and I know that I have my teammates to back me up if I will ever encounter new problems.

Acknowledgements

- HKUST School of Engineering — for their continuous assistance, sponsorship and providing laboratories for Epoxsea
- Center for Global & Community Engagement (GCE) — for supporting Epoxsea
- HKUST Design and Manufacturing Services Facility (DMSF) — for helping Epoxsea in mechanical design, providing technical advice and guidance
- HKUST Student Affairs Office (SAO) — for granting us permission to use the university's swimming pool for testing Manta
- Dr. Kam Tim Woo — our supervisor for his persisting guidance and counseling that helped point us to the right direction
- Chun Yin Leung and Sau Lak Law — our mentors for their recommendations and technical help during the design process of Manta
- 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 through 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 2019 and educating the Hong Kong public on marine technology
- RS Components Ltd. — for sponsoring electronic components for Epoxsea
- Gigabyte — for providing computer components for the overhauled main control unit of Epoxsea
- Milwaukee — for sponsoring machining tools for Epoxsea

References

Blue Robotics. (2015, August 22). T200 Thruster Documentation. Retrieved from http://docs.bluerobotics.com/thrusters/t200/.

Commercial Video Security Products. (n.d.). Retrieved from https://www.supercircuits.com/lp/compare-hd-analog-video-formats.

Garrett, P. H. (2013). Advanced Instrumentation and Computer I/O Design: Defined Accuracy Decision and Control with Process Applications. Piscataway, NJ: IEEE Press.

Greig, J. (2014, December 18). What type of material should I use: Epoxy, urethane or silicone? Retrieved from https://lordelectronicmaterials.wordpress.com/2013/10/29/what-type-of-material-should-i-use-epoxy-urethane-or-silicone/.

HD-SDI: Basic information for HD-SDI camera. (2014, August 20). Retrieved from http://support.hkvstar.com/knowledgebase.php?article=19.

Hill, R., Madden, C., Hengel, A. V., Detmold, H., & Dick, A. (2009). Measuring Latency for Video Surveillance Systems. 2009 Digital Image Computing: Techniques and Applications. doi:10.1109/dicta.2009.23

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.

HKUST Epoxsea. (2018). Narwhal Technical Report. [PDF]. Retrieved from https://www.marinetech.org/files/marine/files/ROV%20Competition/2018%20competition/Team%20Documentation/EXPLORER/HKUST_EPOXSEA_TechReport_2018.pdf.

LAST-A-FOAM® R- 3300 RIGID POLYURETHANE FOAM [PDF]. (2018, April 4). Tacoma: General Plastics Manufacturing Company.

Nayak, R. K. (2018, November). Comparison of Properties of the Materials. Retrieved from https://www.researchgate.net/figure/Comparison-of-Properties-of-the-Materials_tbl1_328802058

Appendices

Appendix A: Operational Safety Checklist

General

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

Before mission run

- All connections are secured and correctly connected
- Cameras are not blocked
- Cables and tether are properly tightened
- Air pressure is below 275 kPa
- Tether area has no obstructions
- 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 Manta
- Status of Manta is monitored
- Tether is not too loose or too tight

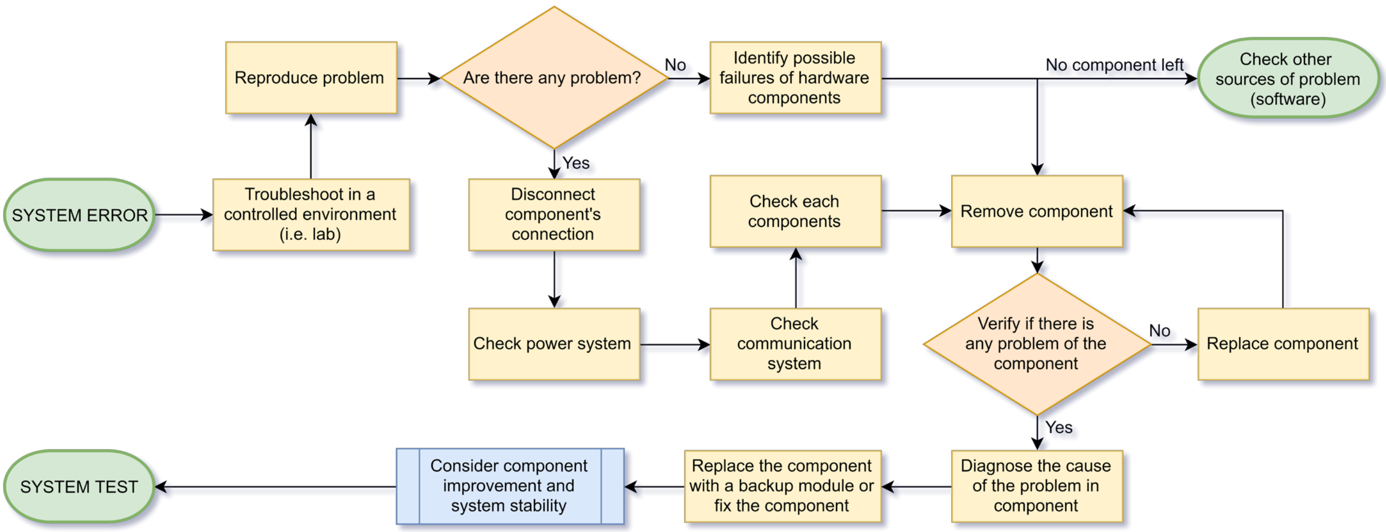
Protocol

- “Kill” when power needs to be cut immediately
- “Contact” when anyone is going to touch Manta
- “Launch” when ROV is safe to operate underwater
- “Release” when shoreside crew open the gripper

After mission run

- Power supply and air pump are 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	$ 16790.00
Sponsorship	RS Components (Electronic Components)	$ 3820.00
	Milwaukee (Tools)	$ 2550.00
	Gigabyte (Electronic Components)	$ 300.00
Total Income		$ 23460.00
Research and Development	Mechanical	$ 600.00
	Electronics	$ 700.00
	Software	$ 300.00
Tools		$ 400.00
Machine Development	ROV Frame	$ 600.00
	Buoyancy Foam	$ 500.00
	ESC	$ 200.00
	Thruster	$ 1350.00
	Camera	$ 320.00
	Sensor	$ 200.00
	Remaining Miscellaneous	$ 500.00
Micro ROV	Frame	$ 50.00
	ESC	$ 25.00
	Thruster	$ 50.00
	Camera	$ 70.00
	Remaining Miscellaneous	$ 10.00
Shipment		$ 700.00
Props		$ 400.00
Traveling Expense		$ 16400.00
Total Expense		$ 23375.00

Appendix D: Cost Projection

Category	Type	Description / Example	Price (USD)	
Electronic Components	Purchased	T200 Thruster (6 pcs)	$	1014.00
	Purchased	30A Electronic Speed Controller (6 pcs)	$	150.00
	Purchased	48V to 12V Regulator (4 pcs)	$	67.96
	Purchased	Printed Circuit Board	$	100.00
	Purchased	Anderson Plug	$	17.50
	Purchased	Serial Digital Camera (8 pcs)	$	440.00
	Purchased	USB Stereo Camera	$	27.00
	Purchased	Waterproof LED (4 pcs)	$	8.00
	Purchased	Waterproof Connector	$	265.00
	Purchased	Tether Wire	$	214.00
	Purchased	Surface Mount and Through-hole Device	$	89.00
	Purchased	pH and Temperature Sensor	$	24.30
Hardware Components Sub-Total [1]			$	2416.76
Control Box Components	Re-used	LCD Display (Orca, Epoxsea 2016)	$	177.45
	Purchased	Keyboard	$	15.64
	Purchased	Xbox Controller	$	14.80
	Re-used	Power Supply (Beluga, Epoxsea 2017)	$	45.37
	Sponsored	CPU, Motherboard, SSD & Cooling Fan	$	300.00
	Purchased	RAM, Power Supply for Computer	$	222.96
	Re-used	Control Box Case (Stingray, Epoxsea 2015)	$	150.00
	Purchased	Monitor for Serial Digital Camera	$	267.45
	Purchased	Multiplexer	$	476.53
	Purchased	HDMI Capture Card	$	142.36
	Purchased	USB Hub	$	22.34
Control Box Components Sub-total [2]			$	1834.90
Mechanical Components	Purchased	Manta Carbon Fiber Frame	$	297.83
	Purchased	SMC Valve Manifold	$	27.00
	Purchased	CNC Service	$	372.29
	Purchased	Buoyancy Foam	$	384.00
	Purchased	3D Printing Material	$	163.81
	Purchased	Mechanical Components Miscellaneous	$	292.32
	Purchased	Epoxy	$	152.89
Mechanical Components Sub-total [3]			$	1690.14
Total Cost for Manta [1] + [2] + [3]			$	5941.80