4th Year Project - Project Initialisation Report

Group 1

Design and Manufacture of Electrical and Control Systems for an Underwater ROV

Contributors: Benjamin Griffiths
George Osmond
Henry O'Keeffe
Joseph Orford

Supervisors: Dr. Dan Gladwin
Prof. Martin Foster

Word Count: 4674

1. Project Description

1.1. Background (*JO*)

Avalon is a multi-disciplinary project encompassing engineers from multiple backgrounds to create an underwater Remotely Operated Vehicle (ROV). This ROV will compete in the MATE 2020 ROV competition taking place in Pennsylvania next year competing with teams from all over the world. The ROVs are tasked with exploring underwater terrain and completing numerous challenges, each based on a real-life scenario in order to score points.

The electronics system for the ROV is responsible for the control of all systems on board the rover, be it regulating, actuating or sensing. Enclosed inside the control enclosure, a clear, watertight tube, the electronics is the beating heart of the ROV and is the bridge from ROV to the surface. Battling thermals and moisture, the conditions are harsh, making a disciplined design of utmost criticality.

The applications of underwater ROVs are numerous. They allow scientists and engineers to survey areas which would either be too expensive to visit, too dangerous to visit, or would simply damage the environment you wish to look at. Examples of this includes monitoring corral welfare, extracting waste from rivers and waterways, and taking video footage or photos for studies of waterways.

1.2. Specification & Aims (BG)

The overall objective of this project is to design, manufacture and test a complete electronics control system for an ROV, with the ability to control electromechanical devices on the ROV such as thrusters and pneumatic solenoids. Accompanying the electronics control system will be low level software embedded on the ROVs microcontroller, as well as a desktop GUI for operating the ROV and monitoring the camera feeds.

The functionality requirements of the ROV are partly dependant on the tasks outlined in the 2020 MATE ROV Competition Mission Brief, which include tasks such as collecting plastic, using computer vision to determine the health of coral reefs and collecting samples. The full list of tasks is listed in Appendix Table 1.

The full mission specification, which includes the exact layout of the mission area and the physical dimensions of the task props will be released in early November, which will allow the mission to be fully simulated before the competition.

The ROV being developed will align with the EXPLORER class technical specifications, which are outlined below:

- Powered by a +48 V, 30 A DC power supply, any DC-DC conversion must be done on the ROV, not on the surface.
- Pneumatics and hydraulics are permitted, but must comply with competition regulations, such as using a pneumatic regulator.
- Camera feeds are required.
- ROV must be able to handle a depth of 4 m.
- Maximum size is 0.92 m in diameter.
- Maximum weight is 35 kg.

Using this information, with the experience gained through previous competition attempts, an initial specification for the ROVs electronics control system can be determined.

The electronics control system on board the ROV will build on last year's design, with the system being broken down into a modular, interlocking PCB assembly containing 'data', 'power', 'ESC' (electronic speed controller) and 'interface' boards, as shown in figure 1.

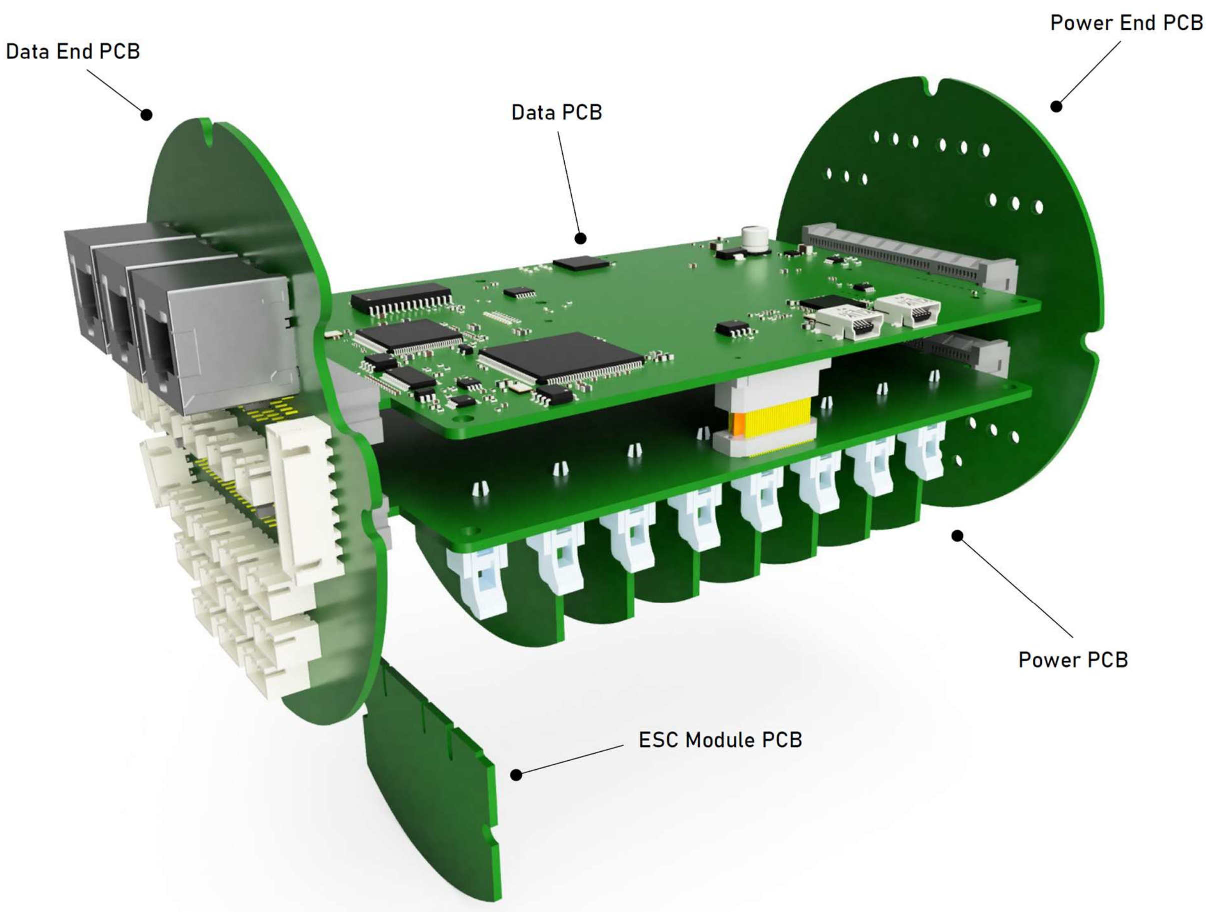


Figure 1: Proposed PCB arrangement inside electronics capsule.

There will also be a 'surface' board that is located above the water and a board mounted inside a Mini-ROV. The surface board handles communication between the control program running on a computer and the ROV via the tether, and the Mini-ROV board will connect to the main ROV via a tether and will control the Mini-ROVs functions.

Table 1 outlines the specification of each board.

Board	Specification
Data	• Powered off +48 V, with an on-board DC-DC converter to provide +5 V for the microcontrollers. • Communicates with the control program via serial commands using RS422 protocol. • Receives, switches and transmits analogue camera signals up the tether via twisted pairs. • Outputs 4 PWM and 8 DIRECTION digital signals to drive H-Bridges on power board. • Sends speed commands to ESC modules via RS485 protocol. • Reads values from temperature, depth and gyro sensors on an I2C bus.
Surface	• Contains a serial transceiver and differential line driver to transmit serial commands from USB down the tether to the ROV. • Receives input data via mini-USB socket from control program. • Transmits data down a CAT5e cable via an RJ45 connector. • Routes video feeds from the tether to a digital video recorder (DVR) for analogue to digital conversion via RCA connectors.
Power	• Mounts 8 custom ESC modules via individual edge card connectors. • Routes ESCs motor phase connections to interface board with 8 A capable traces. • Contains 4 full H-bridges, which can be configured into 8 half-bridges to drive solenoids and motors. • Generates 12 V at 10 A using 48-12 V DC-DC converter to power H-bridges and analogue cameras. • Generates 5 V at 5 A using a 48 V to 5 V regulator to power logic onboard ESC modules.

ESC	● Powered from +48 V and +5 V rail. ● On-board 5 v -3.3 V regulator to power logic. ● Drives a single brushless DC (BLDC) thruster at a maximum power of 200W. ● Modular design - easily replaceable in the event of failure.
Interface	● Mounts on each end-cap of the electronics capsule, with one handling power connections, and the other handling data connections. ● Power end interface board connects to 8 thrusters and one main power connector via through hole solder terminals. ● Routes external devices such as thrusters, sensors, and the tether to the data and power board. ● Data end interface board connects to camera, sensor, mini-ROV, tether and solenoid connectors via JST XH and RJ45 connectors. ● Connects to and mechanically supports the data and power boards inside the capsule using PCI-E 98 pin connectors.
Mini-ROV	● Receives power and data over a ‘power over ethernet’ cable, which contains 4 twisted pairs and 2 power conductors. ● Drives a single thruster, a headlight LED and a camera. ● Receives motor commands and sends camera feed up mini-ROV tether using differential line driver via RS422 protocol.

Table 1: Individual PCB specification.

The software for the system is split into software that runs locally on the ROV, and software that runs on a computer on the surface. The software running on the surface will be written in Python using the PyQt5 library for the GUI elements, and the software running locally on the ROV will be written in C using the Arduino environment. Table 2 outlines the specification of each software element.

Software	Specification
ROV	● Programmed in Python, using the PyQt5 library and Qt Designer for the GUI. ● Using OpenCV2 library for computer vision. ● Connects to surface board via USB using serial library. ● Connects to XBOX controller via Bluetooth. ● Control ROV functions using ASCII commands. ● On-screen buttons to turn on/off actuators. ● Displays sensor readings. ● Displays and allows switching between camera feeds. ● Uses thrust vectoring algorithm to calculate speeds of 8 thrusters to achieve any thrust direction in XYZ plane. ● Uses inertial measurement unit (IMU) to read ROVs angular position and incorporate active stability control. ● Switch between ROV and Mini-ROV control. ● Allow for easy configuration to add more sensors/thruster etc without modifying base code. ● Generate configuration file to save program setup. ● Allows easy remapping of XBOX controller buttons.
Mini-ROV	● Programmed in C using Arduino programming environment. ● Receives ASCII serial commands. ● Extracts and returns sensor readings using I2C library. ● Outputs thruster speeds to all 8 thrusters using RS485 library. ● Outputs digital and PWM signals to H-Bridges drivers to control actuators and motors. ● Controls camera switcher.

Table 2: ROV and Mini-ROV software specification.

There were a range of problems with last year's design, which led to failures of some crucial parts of the electronics system during the competition. The new electronics system design aims to address these problems, with a key focus on system reliability and ease of maintenance.

The first major problem with last year's design was the lack of underwater electrical connectors to connect the thrusters, tether, sensors and actuators to the electronics capsule. Cable glands were used, which restricted access to the electronics capsule due to the cables being non-removable. Furthermore, the cable glands were not designed for underwater use, hence the capsule suffered from water ingress, damaging the electronics.

The second major problem with last year's design was the use of multichannel ESCs, which are designed to be compact for use in quadcopters, with forced air cooling. In the use case of the ROV, the ESCs were contained in a small capsule, with no air flow, which led to several of the channels failing due to overheating.

To address the first major problem, the new electronics control capsule will replace basic cable glands with MacArtney SubConn underwater connectors. This will prevent water ingress from damaging the electronics, and will enable the external devices to be connected/disconnected for easy access to the capsule.

To address the second major problem, the multi-channel commercial ESCs will be replaced with a custom, individual ESC per thruster. This has two major benefits, with the first being modularity, enabling individual ESCs to be swapped out in the event of a failure, whereas with a multichannel ESC, the whole unit would have to be replaced. The second benefit is thermal performance, where the power density will be spread throughout the whole electronics capsule, rather than in one concentrated area, which should delay the temperature rise and greatly reduce the likelihood of failures caused by overheating.

The aims of the project are shown below:

1) **Define functional requirements of electronics control system**
    a) Identify required number of thrusters.
    b) Identify sensor types required.
    c) Identify number and type of cameras required.
2) **Design electronics control system**
    a) Use CAD to design the physical structure of the electronics control system to be housed inside the capsule.
    b) Research and source required components such as microcontrollers and PCB connectors.
    c) Design user interface for ROV control program using Qt Designer.
    d) Write back end code for GUI.
    e) Design circuit for data, power, interface and surface boards.
    f) Route PCB for each circuit within the designated dimensions for each board.
    g) Design breakout board for each PCB to allow individual function testing.
3) **Manufacture**
    a) Send of PCBs for fabrication.
    b) Populate PCBs with necessary components.
4) **Test system**
    a) Write low level C code to run on microcontrollers.
    b) Test functionality of each board separately using breakout boards.
    c) Thermal test individual ESC module under a range of operating conditions.
    d) Construct the complete electronics system inside the capsule and run thermal tests under a range of operating conditions.
    e) Test ROV control program with electronics.
5) **Re-design**
    a) Identify errors and redesign necessary areas of the system.
    b) Make improvements to software.
6) **Test complete system**
    a) Send of new PCB designs for manufacture.
    b) Manufacture necessary mounting plates for the underwater connectors.
    c) Integrate electronics control system into the ROV and connect electro-mechanical devices.
    d) Test full system functionality with the thrusters, sensors and actuators.

2. Project Breakdown

2.1. Benjamin Griffiths

The arrangement of the electronics system is designed to be securely housed inside the watertight capsule, whilst being highly modular to allow the data, power or ESC boards to be individually replaced in the event of damage. This is achieved by using PCI-E connectors on the interface boards, that connect to the data and power boards via an edge card connection. The interface boards, mounted on each end cap, simply act as a pass through for power, thrusters, cameras, sensors and the tether signals, which are routed to their designated pins on the PCI-E connectors.

The power end interface PCB is circular in shape and mounts to the capsules end cap. It is responsible for routing the main +48 V power bus to the data and power board, and also routes the 24 thruster connections to the power board. Due to the high currents involved (30A power input and 10A per thruster), the board uses 2oz copper layers and routes each track on both copper layers to improve thermal performance.

The data end interface PCB is also circular in shape and mounts to the opposite capsule end cap. It is responsible for routing the tether, cameras, solenoids, motors and sensors to the data and power boards. Due to the large number of connections on this one PCB, with 11 cameras, 4 sensors, 4 solenoids and ethernet, using solder connections would make maintenance difficult. Instead, small JST connectors will be used, to allow the devices to be connected/disconnected easily.

The pair of PCI-E connectors on each interface board are spaced apart so that the distance between the data and power board is 16mm, connected together into a parallel stack using threaded hex pillars. This distance was chosen because it allows the size of the data and power PCBs to be maximised inside the capsule, and a connector can be placed in between the boards to route the motor control signals. Furthermore, the space in between the data and power boards can be used to mount components for the DC-DC converter on the power board.

The Python GUI interface will be the means of controlling the ROV from the surface. The program will have 3 high-level tabs that the pilot can access. The first tab will be the 'Control Panel', and will only contain the necessary objects to control the ROV, such as camera feeds, actuator control buttons and sensor readouts. The second tab will be a 'Configuration' menu, where the programs settings can be configured to suit the ROV. The aim of this GUI is to act like a platform, enabling the program to adapt to future ROV designs without having to modify the base code. To achieve this, the configuration settings include number of thrusters, thruster arrangement, number of sensors/sensor type, number of cameras, key bindings and communication settings. These settings will be saved to an XML configuration file, allowing the program to be adapted for different pilots with differing key binding preferences.

The third tab is 'Function Testing' interface, which allows every device on the ROV to be individually tested, such as driving each motor separately to ensure their direction is correct and checking camera feeds.

An early mock-up of the GUI is shown in Appendix Figure 1,2 & 3.

2.2. Joseph Orford

Due to the rules of the competition, only power and data can be sent from the control PC and thus the ROV must take data from the surface PCB and send back camera data and feedback. Camera data is high bandwidth and control data must be low latency.

To provide adequate bandwidth, a fibre optic communications link with greater than 100Mb/s will be used with a latency of under 10ms. This system should be robust in that it can deal with the relatively high temperature of the control enclosure and high moisture level. The system should also be physically robust, as the ROV will move around and possibly result in cables becoming dislodged or damaged.

For the main data connection, only a low bandwidth is required as it will be simple thruster values and simple feedback. There will not be any camera data sent along this as it is just to control the ROV's movements. To solve this a full duplex RS-422 connection will be used which allows for reduced noise in the communications over long distances with simple implementation. The full duplex allows for a higher data rate to be achieved over half-duplex and as the bus does not require a processor intensive protocol; ultra-low latency can be achieved.

For the camera signals, analogue cameras allow for high bandwidth video signals to be sent with a relatively simple set of electronics and does not require processing by a computer which results in very low latency video feeds. These video feeds will be sent up to the surface over a differential pair which are more flexible than coaxial cable for transmission down the tether. As the tether must have its size kept to a minimum, to reduce the number of differential pairs sent up, an analogue camera switch will be used to change between cameras.

For the main control of the ROV, an Arduino supported microcontroller will be implemented which will allow for control loops and low-level operations to be run locally to reduce latency. This will send data signals throughout the ROV and read all sensor data. There will also be a backup microcontroller on board which will monitor the main data lines to check for errors or will be able to take over in the event of an issue.

As image recognition is required though, a Raspberry Pi compute module will be included with a Spartan-6 FPGA to process images from an onboard camera. This will allow for low latency on board image recognition to be completed inside the ROV, which alleviates stress on the data connection down the tether.

To program the Arduino module and Raspberry Pi modules, it is key that the control enclosure is not opened during this process once the ROV is wet. Opening the control enclosure can reduce the integrity of the sealing and takes it time to ensure the enclosure remains watertight. This means the Raspberry Pi will be connected to the Arduino via its programming USB and thus both can be programmed via the tether. Failing this a wireless module will be included so that the Arduino can be programmed wirelessly. There will also be the facility to use a USB cable to program everything when the electronics are being developed or in an emergency.

On board there will be a host of sensors which will be relayed back to the surface, this includes temperature, humidity, air-quality, water pressure, water temperature and the speed/direction and orientation of the ROV at any given time. There will also be indicator LEDs to light up the enclosure, this will allow the operator to detect issues whilst the ROV is deep underwater, such as turning red in the event of water being detected.

Due to the many sensors, and sensitive electronics on board, a stable and clean power supply will be needed at multiple voltage levels. Multiple switched mode regulators will be employed with sufficient filtering so as to reduce noise and increase efficiency.

2.3. Henry O'Keeffe

The ROV requires thrusters vectored to allow it to move with 6 degrees of freedom. To achieve this, the mechanical sub team has decided on 8 thrusters, 4 applying force along the X-Y plane, and 4 applying force perpendicular to the X-Y plane. These thrusters have been designed as BLDC (Brushless Direct Current) motors which each require a motor driver, aka Electronic Speed Controller, ESC, to operate.

As a BLDC motor can be driven as a PMSM (Permanent Magnet Synchronous Machine), and custom ESCs are required to be made to fit into the control enclosure with maximum integration, two control systems will be designed, one driving the motor with a PMSM control scheme and one using a BLDC control scheme.

The PMSM controller will be designed with FOC (Field Orientated Control) and sensor less control with a SMO (Sliding Mode Observer) using feedback from current and voltage sensors. This should result in smoother operation (lower torque ripple) and lower acoustic noise than a BLDC scheme which will be designed later as a backup due to its simplicity.

In addition to the control schemes (software), two PCBs will be designed, one using GaN (Gallium Nitride) MOSFETs from Texas Instruments, and one using Silicon MOSFETs. The characteristics of GaN will allow it to run at a higher frequency, and so the performance will be evaluated and the most suitable used in the competition.

48 V is received on the ROV from the tether but the thrusters are optimised for < 20 V. In order to remove the need for a high-power DC/DC converter, the thrusters will be run from the 48 V line, with the ESCs taking the task of ensuring current and voltage remains within safe levels for the operation of the thrusters.

2.4. George Osmond

With all the requirements of the ROV, there needs to be a way to power them all. The ROV is supplied with 48 V at a maximum of 30 A from the surface via the tether, it was decided that a separate power board would be required to route high voltage and high current traces to the respective components while keeping them away from the sensitive components located on the board that handles all the data processing. Although the ROV is supplied with 48 V, most of the components require much less than this, so we need some DC-DC convertors to step the voltage down to a usable level. However, the competition rules state that any conversion done to the initial supply must be done on board the ROV. This means that as well as the motor traces, the board will have a 48 V to 12 V regulator which will be capable of up to 10A as well as a 48 V to 5 V which will be capable of up to 5 A.

The 5 V regulator will be used to power the logic on board the ESC's which is fed back to the power board as 3.3V via the connectors, This 3.3 V will be used to address each ESC individually in hardware, so that they can be programmed to recognise what socket they are sat in based on the address they are given, this will tell the ESC which motor it is controlling. This increases the modularity by not having to reprogramme each ESC every time you need to move them round. As well as the ESC logic supply the 5 V regulator will have a jumper that will be able to link the 5 V rail on the power board to the 5

V rail on the data board so that if one of the supplies stops working then the jumper allows power to be routed to the board which has the faulty supply. This ensures that if one supply goes down then the board will still be able to function.

The 12 V regulator will be used to power all the solenoids, cameras and motors (not thrusters) which are connected to the board. In order to control the solenoids and motors, h-bridges will be used on the board with a supply from the 12 V regulator. These H bridges will be fed a PWM signal and two enable signals from the data board via the board to board connector. This allows the h-bridges to be configured as either one single full H bridge capable of driving a motor, or two half bridges which would be used to control the pneumatic valves for the solenoids. Figure 2a shows how the H bridge would be configured to operate as a full H bridge with a motor between Out_1 and Out_2 and figure 2b shows the two half bridge configuration which allows the two solenoid valves to be operated.

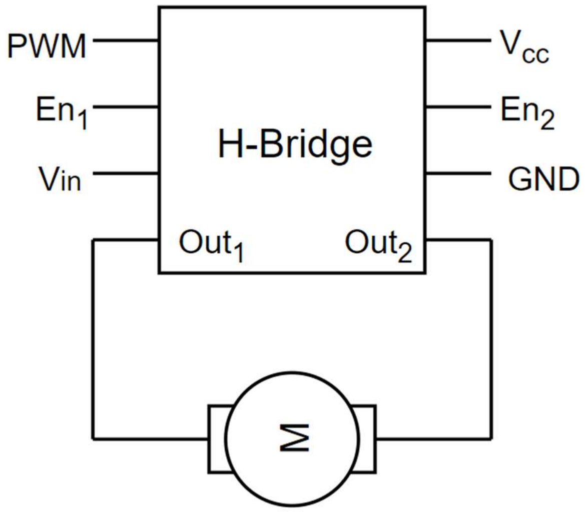


Figure 2a: Full H-Bridge for Motor Control

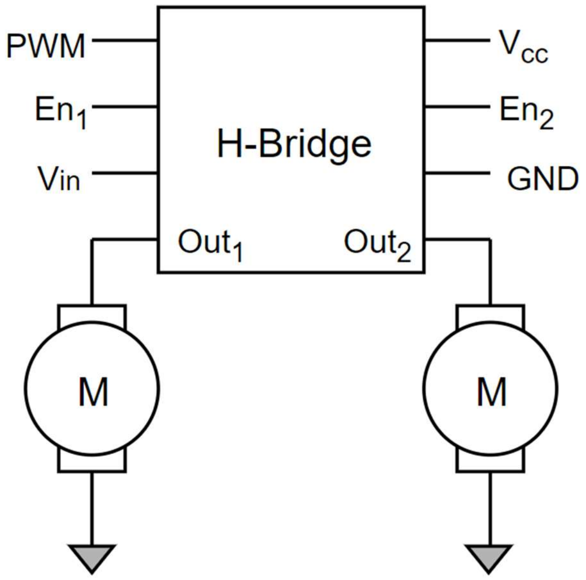


Figure 2b: H-Bridge Configured as Two Half Bridges for Solenoid Control.

It was decided that a 48 V to 5 V regulator would be used rather than a 12 V to 5 V regulator because then if the 12 V regulator becomes faulty or gets damaged, then it doesn't bring the 5 V regulator down as well so that we keep at least some of our functionality. If this were to happen and the supply did become faulty then the ROV would be stuck in the water incapable of completing any tasks as all the power for all the external components comes from these regulators. This was a necessary decision to ensure that the ROV has better reliability.

3. Project Schedule (GO)

In order to ensure that the project stays on track and milestones are met a Gantt chart was created where each phase of the project was noted down and split up into all the subtasks that need doing within each phase. These were then organised into a timeline of events and then allocated time slots with hard deadlines which will allow us to ensure the project doesn't run on. Figure 3a and Figure 3b show the Gantt chart with milestones shown by a red bar at the end of a timeline. These milestones are parts of the project which must be finished in order for the next stage of the project to either be started or finished. One of the major milestones is 'Phase 2 - manufacture' as these must all be done in order to test the final ROV and get it ready for competition.

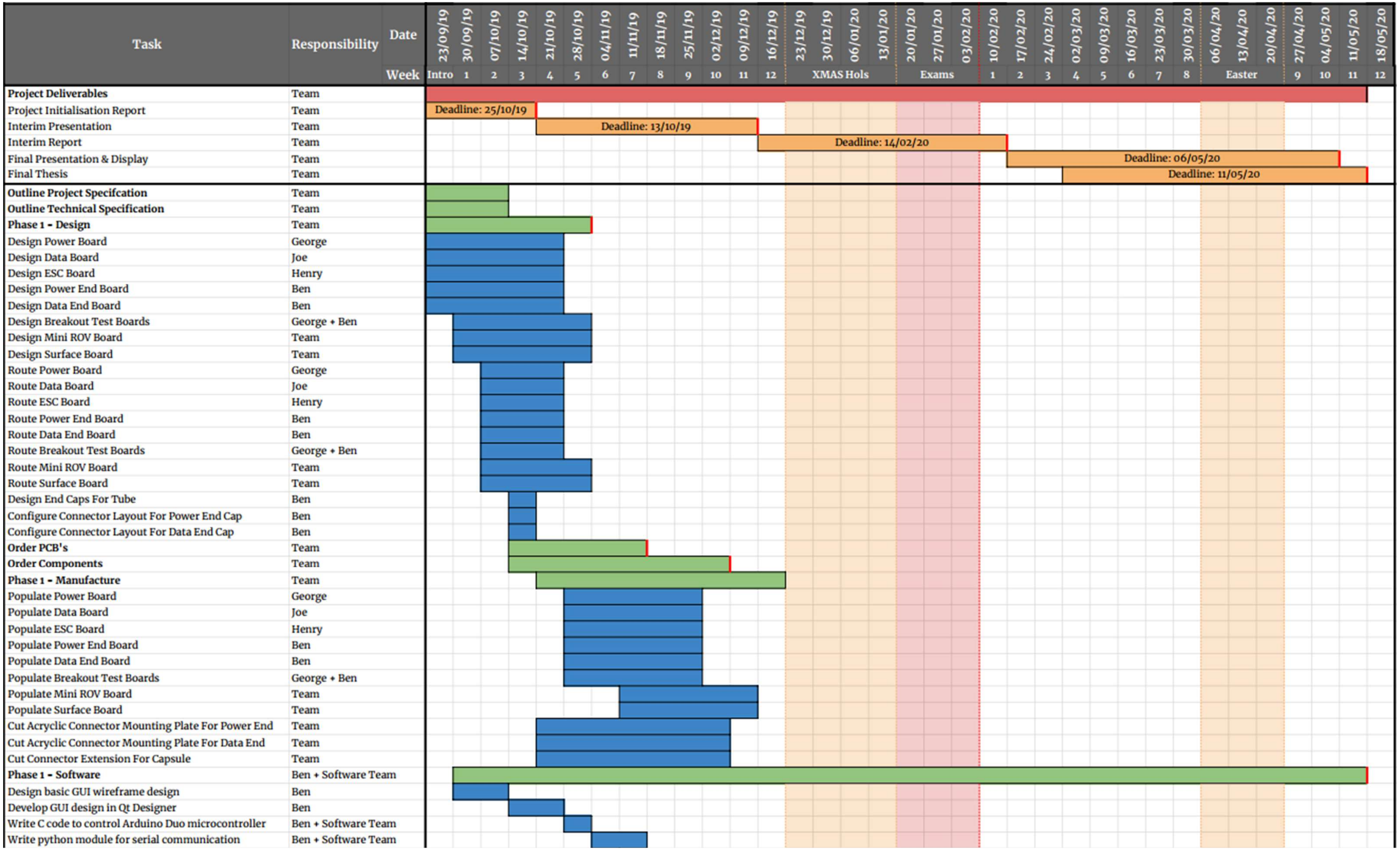


Figure 3a: Gantt chart showing project progress and milestones (part 1)

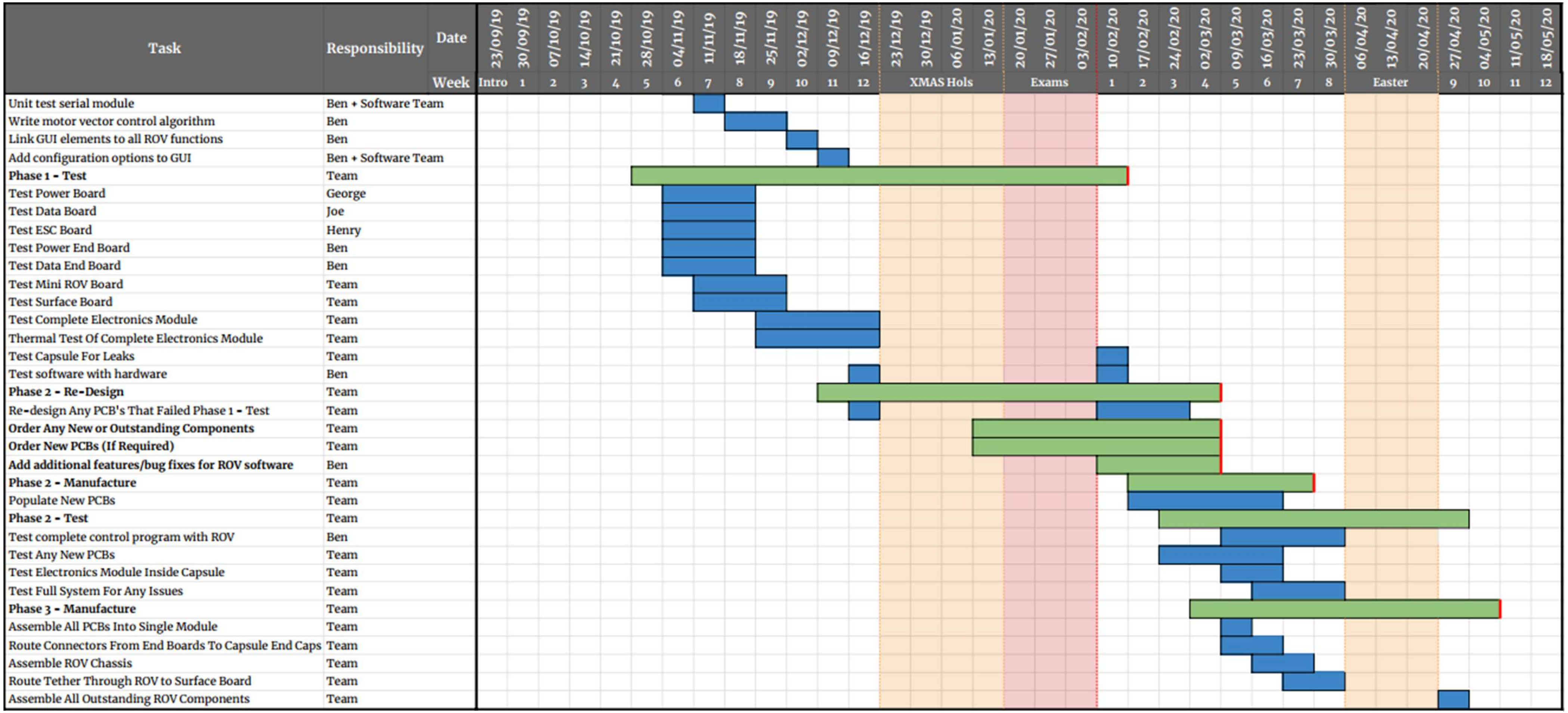


Figure 3b: Gantt chart showing project progress and milestones (part 2)

4. Risk Register (*HO*)

No.	Risk to Project	Severity	Likelihood	Risk Rating	Mitigation	Updated Severity	Updated Likelihood	Final Risk
1	Scope Creep increasing workload, causing delays in task completion.	4	4	16	Properly define a fixed specification at the initialisation of the project (in this document) and refer to it frequently.	4	2	8
2	Poor understanding of project requirements.	5	3	15	Spend additional time ensuring the project requirements, then write the specification to ensure full coverage.	5	1	5
3	Pressures from other projects and exams.	4	4	16	Ensure other events (exams, etc.) are accounted for in the project planning phase.	4	1	4
4	Delays due to late or slow ordering of components / PCBs.	5	3	15	Use the schedule to plan ahead component ordering once requirements have been identified. After final checks, order PCBs at the next available opportunity.	5	1	5
5	One or more tasks are not known at the planning stage.	4	3	12	Ensure full coverage by cross-checking specification against aims.	4	1	4
6	Communication between team members breaks down, causing task duplication or loss.	4	4	16	Conduct regular meetings in person and avoid the use of social media to conduct important conversations.	4	1	4
7	Time pressure due to nearing deliverable deadlines causes non-functioning / poor quality work.	3	4	12	Adhere to the project plan, completing work earlier if possible, to ensure an acceptable workload immediately before deadlines.	3	1	3
8	Knock-on delays build such that the lost time is unrecoverable.	5	4	20	Plan extra time into the schedule to act as contingency for any unexpected delays.	5	1	5
9	MATE Specification, on release, reveals incorrect assumptions about tasks, leading to a lack of requirement planning.	5	3	15	Design for additional features in the electronic systems to cover all possible specification variations; ensure system is expandable.	5	1	5

10	Testing does not cover the boundary conditions of the electrical system, and discrepancies with the specification are not noticed.	**3**	**4**	**12**	Use unit testing, where tests are built before the module concerned. This ensures that, provided the test is accurate, the product meets the specification.	**3**	**2**	**6**
11	Data loss	**5**	**4**	**20**	Use online services such as google drive to synchronise personal data.	**5**	**1**	**5**

Table 3: Risk Register Showing Major Risks and Attempted Risk Mitigation

		Likelihood				
		1	**2**	**3**	**4**	**5**
Impact	**1**	1	2	3	4	5
	2	2	4	6	8	10
	3	3	6	9	12	15
	4	4	8	12	16	20
	5	5	10	15	20	25

Table 4: Risk Rating Based on Likelihood & Impact of Risk

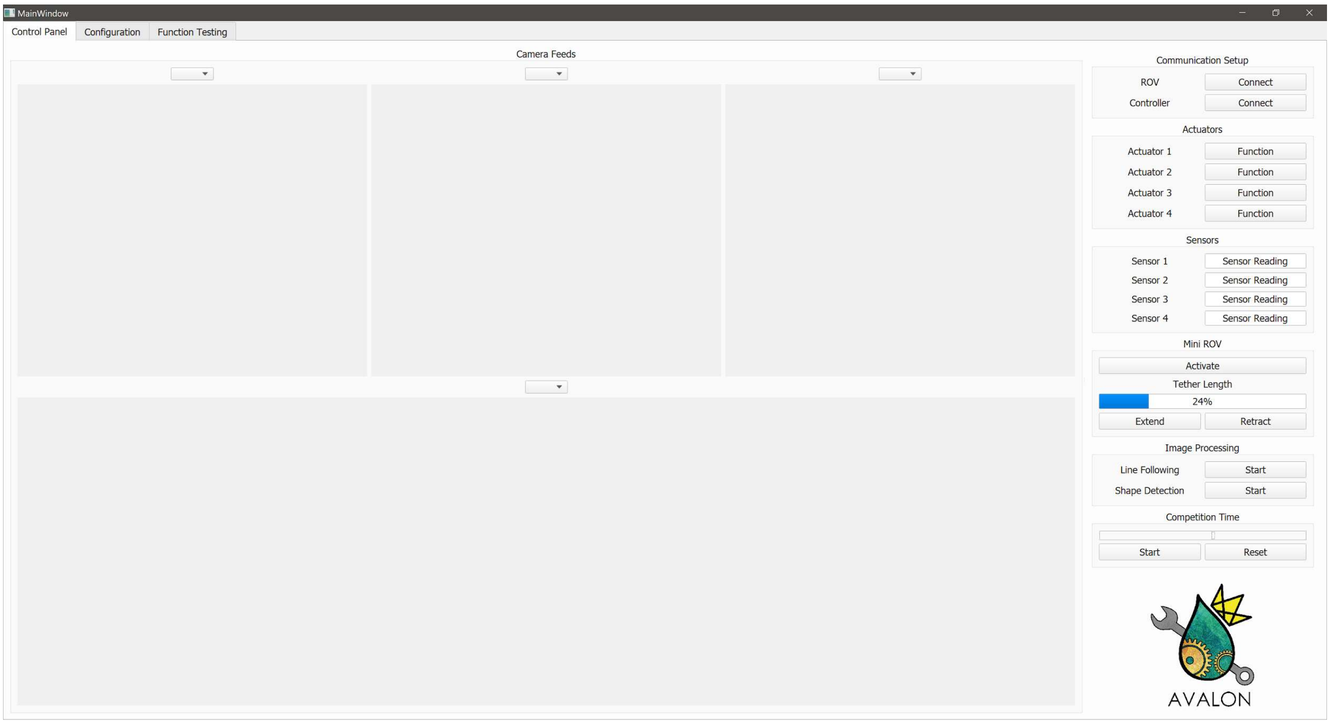
Risk Rating	**Description**
1-2	Low priority risk - risks we are willing to take and won't affect project progress.
3-6	Moderate risk-risk will need monitoring but not a large threat to project completion.
8-12	High risk - risk will need monitoring and action will need to be taken to prevent risk from affecting project progress.
15-25	Critical risk - risk is detrimental to project progress and processes must be put in place to prevent it.

Table 5: Description of Risk Rating

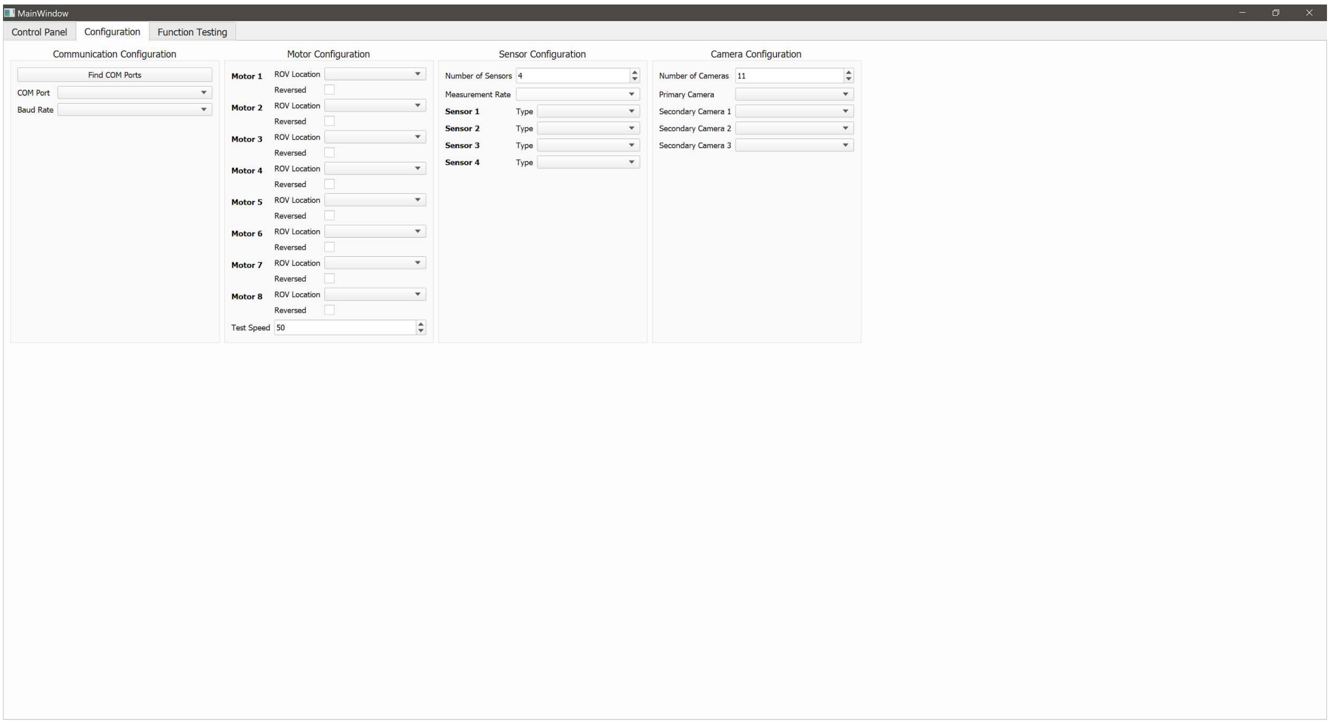
5. Appendix

Task	Description
Plastic Pollution	● Seabin: ○ Disconnect old power connector from recently installed seabin ○ Remove mesh catch bag from previously installed seabin ○ Install new mesh catch bag into seabin ○ Reconnect power connector to recently installed seabin ● Remediation: ○ Remove floating plastic debris from the surface ○ Remove a ghost net from midwater ○ Remove plastic debris from bottom of trench
Effects of climate change on Coral Reefs	● Autonomously fly a transect line over a coral reef ○ Autonomously/manually map points of interest on the reef ● Use computer vision to determine the health of coral reef by comparing current conditions to past data ● Propagate corals onto the reef ○ Remove coral fragments from nursery structure ○ Outplant coral fragments to designated locations on coral reef ● Cull an outbreak of sea stars ● Collect samples of sponge species
Maintaining healthy waterways	● Retrieve sediment sample from inside drain pipe to analyse for contaminants ○ Deploy a device into pipe and collect sediment sample ○ Return sample to the surface ○ Determine type of contaminants present in sample ● Estimate number of mussels in mussel bed ■ Deploy a quadrat ■ Count number of mussels in the bed ● Estimate the total amount of water filtered by mussel bed ■ Eel restoration ● Remove a trap full of eels from a designated area ● Place empty eel trap in a designated area ■ Autonomously/manually create a photomosaic of a subway car submerged to create an artificial reef.

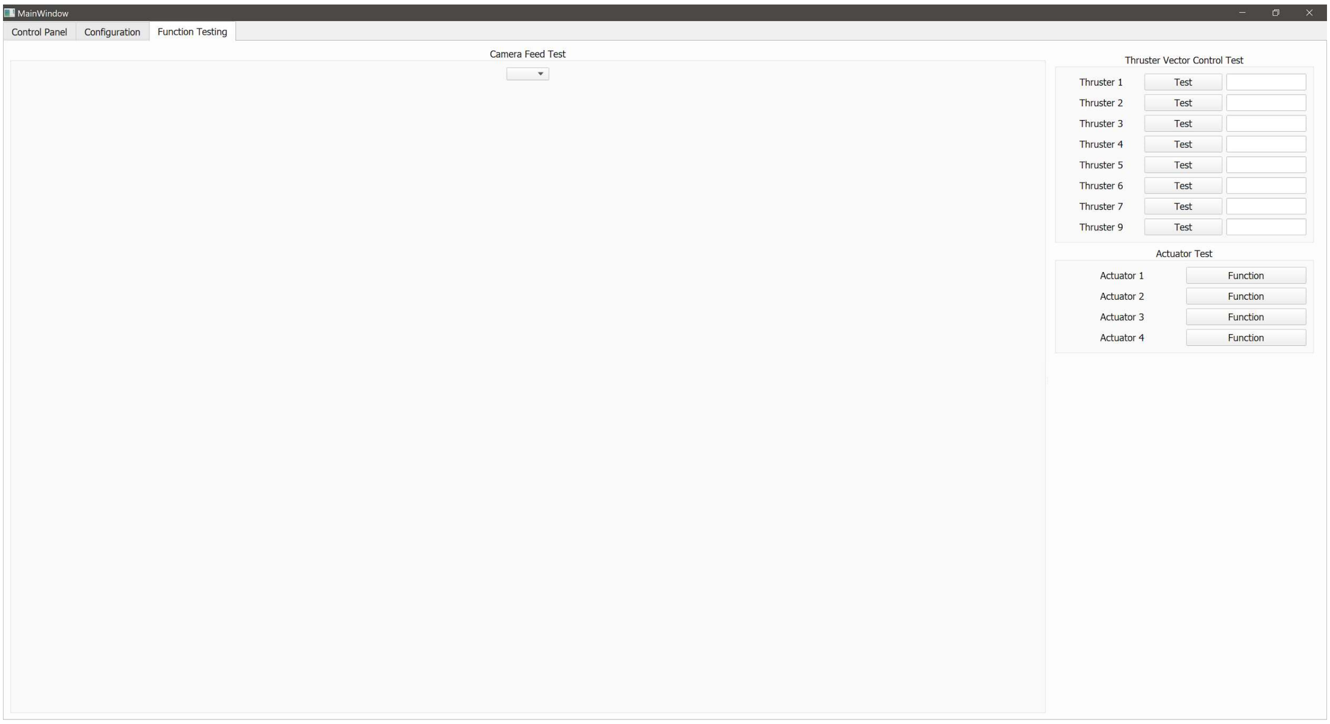
Appendix Table 1: Basic mission brief.



Appendix Figure 1: GUI Control Panel Tab.



Appendix Figure 2: GUI Configuration Tab.



Appendix Figure 3: GUI Function Testing Tab.