# INVICTUS

Arab Academy for Science and Technology
Alexandria, Egypt

MATE 2019

# TECHNICAL DOCUMENTATION

# BROTTA

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# ABSTRACT

Hailing from the country of the Nile and the Aswan High Dam, Invictus is excited to present a Remotely Operated Vehicle (ROV) to help authorities inspect and repair dams, monitor water quality and habitat-diversity of rivers, and recover historical artifacts thought lost in the riverbed.

The company was founded in 2015 with a mission to provide the industrial and research sectors with low-cost high-quality ROVs. Our company comprises of passionate makers from the Mechanical, Electronics, and Computer Engineering departments. With three ROVs under our belt, our newest ROV, *Brotta* is highly optimized.

This report illustrates how the company designed and built *Brotta* to be able to efficiently achieve those tasks. *Brotta* was designed specifically to maneuver with great speed and ease, it has an acrylic electronics housing, 8 high-quality Blue Robotics T100 thrusters. Our chassis was manufactured using purposefully-chosen manufacturing techniques such as CNC milling, Laser cutting, 3D-printing and electroplating.


*Invictus 2019 company mentors and members*

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# DESIGN RATIONALE

## Design Evolution

Invictus is proud of its 4 years of experience designing and building ROVs. As firm believers in the advantages of iterative design, the design process begins by asking "What can we do better?". The previous year's design is then reviewed to decide which elements of it to keep and which to improve upon. This year, tangible improvements were warranted for our vehicle's total acceleration and control authority; namely, the shape of our vehicle's frame and type of thrusters used to propel it.

*Figure 1 – Real picture of Brotta*

Consequently, we decided to abandon our previous upright cylindrical design philosophy and rather stick with the rectangular one. The leading motive for such a mighty evolution was the exceedingly unstable heaving of the cylindrical model, which in turn significantly increased the execution time of some tasks. Moreover, the company's mechanical team decided to dedicate a massive research and development effort into replacing last year's bilge pumps-turned-thrusters with faster, more powerful ones that would better serve our customer's needs.

## Design and Manufacturing Process

After thoroughly reviewing the tasks required by our vehicle, the Mechanical team brainstorms different design ideas for the vehicle's frame and thruster arrangement. Next, they present a mockup or mechanical drawing (Figure 2) to discuss with the company's other departments and accommodate their feedback and suggested modifications. The process repeats until the design is deemed optimal by all departments.

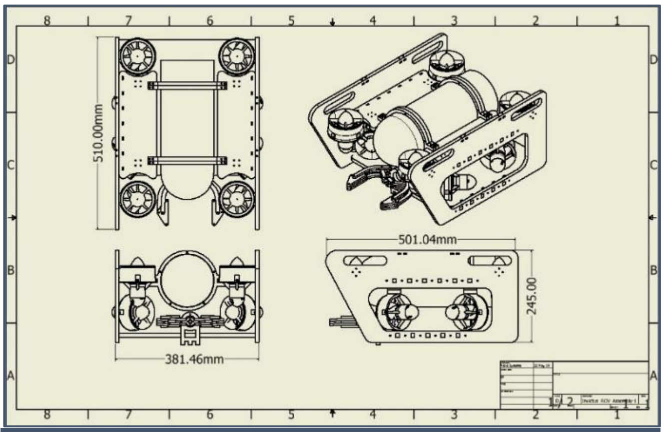


*Figure 2 – Mechanical Drawing of our Initial Design*

One factor that heavily influenced our company's mechanical design process is our mission to provide our customers with cheap and efficient ROVs. Hence, heavy consideration was paid to the available materials in the market along with the different manufacturing techniques available in our locality; i.e. The acrylic parts were cut out of a 10mm thick Acrylic sheet using a CNC laser cutter.

To help the company's different departments easily view the design and suggest any beneficial modifications, a computer aided design (CAD) was created using SolidWorks and viewed at a company-wide meeting. Finally, the designs were converted into Drawing Exchange Format (DXF) and Standard Tessellation Language (STL) files in order to be sent to our CNC router, laser cutter and 3D printer.

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# Mechanical Design

## Frame

Designed to be lightweight and compact, *Brotta's* frame comprises two main vertical sides (Figure 3) connected by two horizontal plates (Figure 4) to form the cubic outline of our frame (Figure 5). The top horizontal plate carries the four surging thrusters while the four heaving thrusters are attached to the vertical sides. In the heart of vehicle, two T-shaped links carry rings to encapsulate the power conversion and control electronics housings.

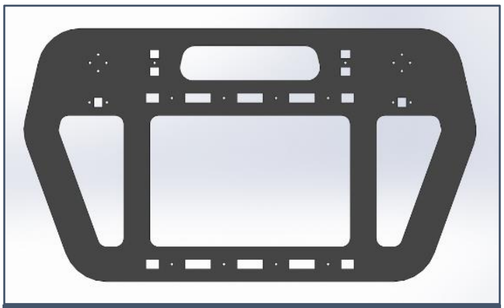

Figure 3 – HDPE Main Vertical Side

High-density polyethylene (HDPE) was used due to its low density to strength ratio. It offers a density of 970 Kg/m3, which is lower than the PVC used in Eddy (*Brotta's* predecessor). PVC has a density of about 1300 Kg/m3. The difference in strength and rigidity between the two materials was far less than the difference in density. This meant that the HDPE would enable us to design a lighter, but equally strong frame.

Using the table of fits and tolerances, we were able to create parts that easily yet robustly fit into each other, eliminating the need for an inventory of nuts and bolts.

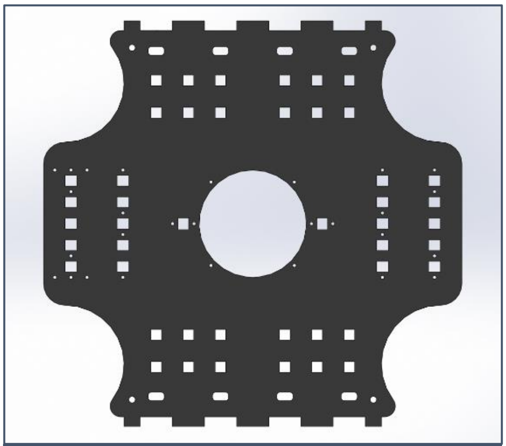

Figure 4 – HDPE Lower Horizontal Plate

## Thrusters

Our company elected to replace last year's repurposed bilge pumps with an alternative that utilized brushless DC motors due to their reduced mechanical wear, longevity, far superior power-to-weight and power-to-size ratios, inherent insulation and water-readiness.

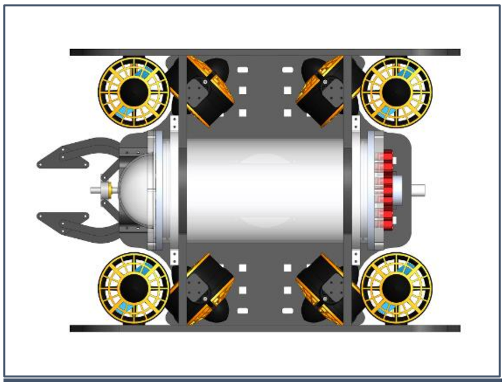

Figure 5 – Brotta's Thrusters Layout

This was a vital build vs. buy decision; our company first built a custom-made thruster option that used brushless DC motors equipped with BlueRobotics' highly reliable propeller and kort nozzle. This was done in order to obtain commercial performance at a cheaper price. After several in-water tests and experiments, this option proved to be unreliable. Our engineers noticed that the motors' Electronic Speed Controllers (ESCs) would heat up and automatically stop all motors after a short period of continued use.

Our mechanical team then concluded that the only way to obtain a reliable performance was to search the market for ROV thrusters. BlueRobotics T100 thruster was found to be the cheapest and most efficient thruster commercially available.

*Brotta* employs 8 BlueRobotics T100 brushless DC thrusters. To achieve stable vector control, the 4 surging thrusters are mounted at 45° angles, allowing all thrusters to contribute to the total propulsion in all cardinal directions and minimizing flow interference with the electronics housings in the center of the vehicle. Four -rather than two- thrusters were used for vertical control to allow the pilot to roll and pitch whenever needed while executing the missions, as shown in Figure 5.

*Figure 6 – BlueRobotics T100 Thruster*

### Buoyancy

As shown in Figure 7, *Brotta* relies on the two voluminous electronics housings as its major pieces for providing buoyancy. They both occupy a total volume of 6,650 cm3 - 44% of the vehicle's total volume of 15,300 cm3 - generating a buoyancy force of 15.3 Kg-force. Since our vehicle weighs nearly 16.0 Kg, we were in need of adding about 700 cm3 of foam to make our vehicle neutrally buoyant. Conveniently, the two horizontal HDPE sheets in our frame are built with a dozen places where weights and foam can be added to readily adjust the vehicle's buoyancy.

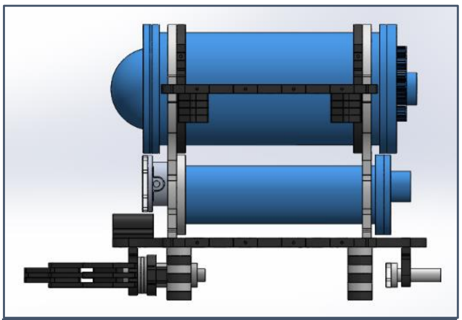

*Figure 7 – Two voluminous tubes*

## Insulation Housings

### Cameras

Due to the fact that high quality waterproof cameras are costly, our company was faced with an interesting build vs. buy decision; spend a large percentage of the company's financial resources on one, or buy an HD security camera and seal it ourselves. We chose the latter option and sealed the front end of the electronics housing with a transparent acrylic dome instead of a cap and placed 2 cameras inside, as shown in Figure 8. Moreover, a Polyamide-6 (PA6) cylinder was machined to house the third camera with a transparent 8mm thick acrylic sheet acting as a lens cover.

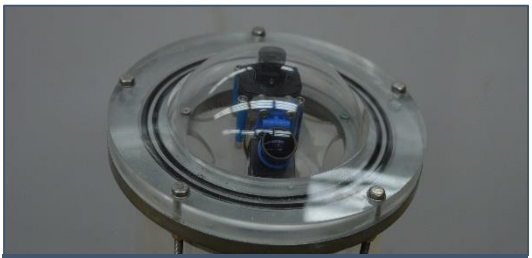

*Figure 8 - Sealed dome containing 2 cameras*

### Gripper's DC Motor

To design a reliable gripper, we were in need of a reliable submersible motor that provides a high gripping force to the gripper assembly. Since the torque generated by a brushless DC motor wasn't enough for our gripper's requirements, it was a must to seal a geared DC motor that would provide more torque.

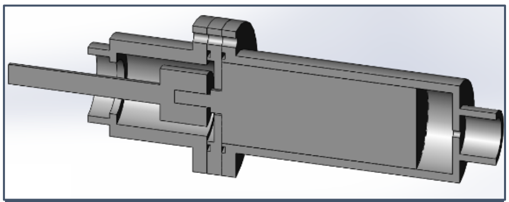

*Figure 9 - CAD model of the sealed motor*

After witnessing its unparalleled reliability whilst performing the 2017 and 2018 product demonstrations, it was optimal to re-use our previous vehicle's DC motor to rotate the lead screw actuating our current gripper assembly. The 8.8 kg.cm-torque, 250 rpm geared DC motor was sealed in an aluminum housing, using a mechanical single-spring shaft seal to isolate the rotary shaft of the motor from water.

*Figure 10 – Mechanical spring shaft seal*

## Electronics Housings

### Control Electronics Housing

At the heart of our vehicle, a transparent Poly(methyl methacrylate) (PMMA) acrylic cylinder houses the electronics responsible for handling all the vehicle's operations save the power conversion. It is 300mm long, with a 140mm external diameter and a 3 mm wall thickness. We chose PMMA acrylic as it is both transparent and lightweight.

*Figure 11 – Assembled Electronics Housing*

Two aluminum flanges enclose our acrylic cylinder. Each flange has two radial grooves that house O-rings, which are responsible for the sealing between the flanges and the acrylic tube. In addition, two acrylic end-caps complete the mechanical sealing of our electronics housing. Another two surface O-rings seal the region between the flanges and acrylic end-caps.

The front end-cap is dome shaped to decrease surging drag and house the vehicle's 2 front cameras, while the rear one carries all the cables' penetrators. A surface O-ring was used to seal between the penetrators and rear acrylic cap while Loctite Marine Epoxy was cast to seal the area around the cable.

These components achieve complete mechanical sealing of the electronics housing while enabling incredibly effortless plug-and-play replacements.

The design of *Brotta's* electronics housing was re-used from last year due to the latter's numerous advantages:

**1- <u>Durable:</u>**

Aluminum was selected for the flanges because of its low density and high rigidity, while PMMA acrylic was the material of choice for the tube and end-caps. PMMA acrylic is superior to the PA6 used in our previous vehicle in that it has higher rigidity. The Buna-N/NBR rubber O-rings are installed in suitable grooves in the flange to ensure total mechanical sealing of the electronics housing.

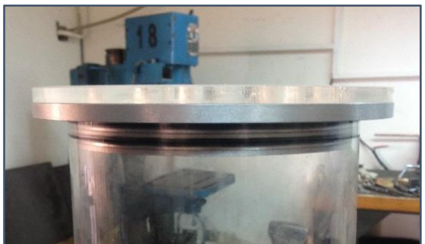

*Figure 12 – O-rings sealing*

**2- Modular:**

Previously, our company encountered a considerable amount of trouble whenever we wanted to test or replace any cables sealed inside the end-cap. It was too difficult to make changes as we used the inflexible Scotchcast to seal our cables. As a result, penetrators were used in order to facilitate easy modification of the components inside both electronics housings. Installing a new mission-specific tool, replacing or upgrading a component was just as simple as adding or removing a bolt.

*Figure 13 - Cables Penetrators*

**3- Transparent:**

The presence of transparent PMMA acrylic in the tube and end-caps is again superior to PA6, as it enables us to monitor the electronic components inside for quick and easy debugging or detecting electronic component failure.

**4- Maintainable:**

In order to be able to test the effectiveness of our insulation system, we plugged a metal tyre valve in our acrylic end-cap. This helped us readily compress air into the control electronics air and monitor the pressure gauge, which would ensure that our box is completely sealed and would aid in identifying the source of any leakage.

*Figure 14 - Tyre Valve*

## Power Conversion Housing

An aluminum tube carries our power conversion electronics. Unlike the acrylic that encapsulates other electronic components, aluminum was chosen as (through conduction) it acts as a giant heatsink for all the DC-DC converters inside. This would then be further cooled through conduction and convection by the surrounding water.

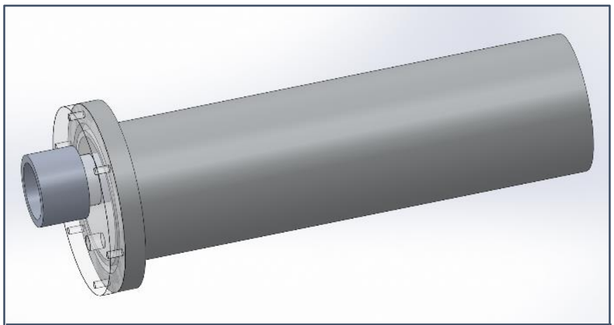

Figure 15 - Power Conversion Housing

The housing was designed by machining a bore into a solid aluminum cylinder from one side to make space for the DC-DC converters while the other side was kept intact to provide sealing. A groove was cut into the machined side to house an O-ring and the seal was completed using an acrylic cap while the same modular approach of employing penetrators was used for the cables.

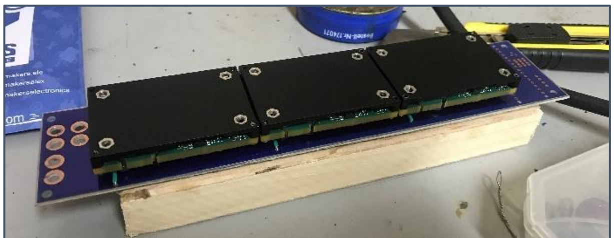

Figure 16 - DC-DC Converters

# Electrical Design

## System Overview

Our company's electrical team aimed for a customer-oriented design that would optimize performance while maintaining flexibility, modularity and most importantly ease of use. The electrical system consists of three major units, the surface control station, tether system, and onboard electronics.

Arduino boards were chosen for use throughout the system as they come with their support circuitry built-in, thus simplifying its carrier board design. Moreover, their economic price means that replacing a faulty Arduino board as a whole is often easier and cheaper than replacing discrete components.

## Topside Electronics

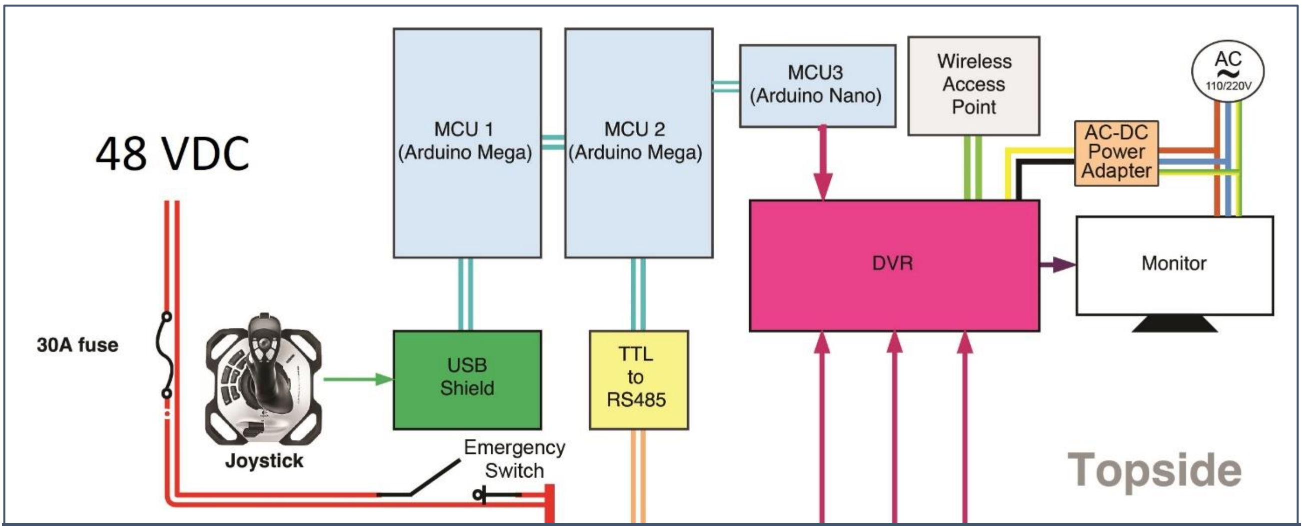


*Figure 17 - Topside Electronics Interconnection Diagram*

Having seen the incredible mobility and ease-of-use of this design last year, the topside control unit (TCU) was again built by placing all the topside electronics within a four-channel Digital Video Recorder (DVR) enclosure to make for a cheap and highly compact solution.

*Figure 18 - DVR casing before modifications*

*Figure 19 - DVR casing after adding topside electronics inside*

The TCU incorporates the tether interface electronics and connects to the tether with a Registered Jack 45 (RJ-45) and three coaxial Bayonet-Neill Concelman (BNC) connectors which where chosen not only for their electrical properties but also their quick connectivity. As per our in-house standards, the BNC connectors are also numbered to allow the operators to quickly and easily connect them and set-up the system.


*Figure 20 – Camera feeds*

The pilot controls the ROV using a Logitech 3D Pro Extreme USB joystick, chosen for its versatility and ergonomic design. For a seamless piloting experience, the three camera feeds and telemetry data received from the ROV are displayed in a four-quadrant split-view-style on the LCD monitor. Telemetry data includes various sensor information including temperatures, pressures and voltages. Through the TCU, a laptop computer can be used to change various settings, such as the vehicle's power limit, which allows easy troubleshooting.

Finally, at the business end of the surface control station, an enclosure splits the tether into a power cable with an inline 30A fuse as a safety measure and a signal-carrying-cable bundle that goes to the TCU. This makes it even more mobile as this reduces the setup time by keeping the relatively fragile signal cables separate and free from the heavy 12 AWG power cable. The same enclosure also has an emergency power cut off switch that is easy to reach.

## Tether System

The tether system consists of 2 main parts, the tether itself and the tether interface electronics.

VideoRay tether was selected as it has a good electrical layout as well as neutral buoyancy and flexibility that allows the ROV worry-free maneuvering. A section of VideoRay contains two pairs of 16 AWG silicon wire to carry power, two 120 ohm twisted pairs for data transmission which are are inherently immune to noise and one 75 ohm pair which is ideal for signal integrity and is suitable for video transmission.

*Figure 21 – Three lengths of VideoRay tether attached using braided sleeve*

Three lengths of VideoRay tether are used in parallel to increase the total current-carrying capacity for the tether system and have redundant paths for data transmission. This also enables us to have three direct analog video feeds without multiplexing or loss of quality, for the lowest possible latency video which drastically improves the piloting experience.

## Onboard Electronics

Onboard the ROV, there are three subsystems: a power subsystem, the Vector Control Engine (VCE), and an Auxiliary Management Computer.

*Figure 22 - Control Electronics Tray*

Power conversion from 48V to 12V is handled by three quarter brick digital DC-DC isolated bus converters with an excellent nominal efficiency of 95%. Having proven their reliability in our ROV systems for the past two years, they were re-used for their small size, low weight, and their ability to share loads by being connected in parallel. Their protection features allow us to more confidently experiment with thruster power output compared to conventional DC-DC converters and unleash up to 75% of the T100 thruster total power.

As the power conversion housing required the DC-DC converters to fit in a tight space, a challengingly small PCB was designed in-house. It carries the converters, handles the required current, and provides us with monitoring capabilities. This is possible as we can communicate to each converter digitally over industry standard Power Management Bus (PMBus) to monitor the conversion process. For troubleshooting purposes, a bluetooth link was installed to output a detailed report when protection circuits are triggered.

After conversion, the 12V bus is distributed with another in-house manufactured PCB to thruster electronic speed controllers (ESCs) and other power demanding components. ESCs were needed to power the thrusters as they require three-phase power as opposed to regular brushed motors that require simple H-bridges. Each ESC powers one thruster with high efficiency for optimal throttle response. Each thruster is programmed with an ID number and has its input and output cables numbered as per our in-house standards. Temperature sensors are attached to ESCs for monitoring and added safety. Only ESCs with overcurrent and over temperature protections are used to prevent as much failures and their consequent power surges as possible.

The Vector Control Engine is a microcontroller based unit that is dedicated to controlling all the ROVs' thrusters in unison and gives the ROV its smooth maneuvering abilities.

The Auxiliary Management Computer is the Arduino responsible for communicating data up and down the tether on the ROV side. It also controls auxiliary non flight-critical sensors internal and external to the ROV's insulation boxes as well as the lights, gripper mechanism, and the laser array.

As per our in-house standard, foolproof electrical connectors are used everywhere where disaster can happen should any of these connections become cross connected during assembly, testing or maintenance for safety. We also use color and numerical codes for similar connections which can only cause temporary malfunction without permanent harm to the system should two become cross connected.

## Software and Control

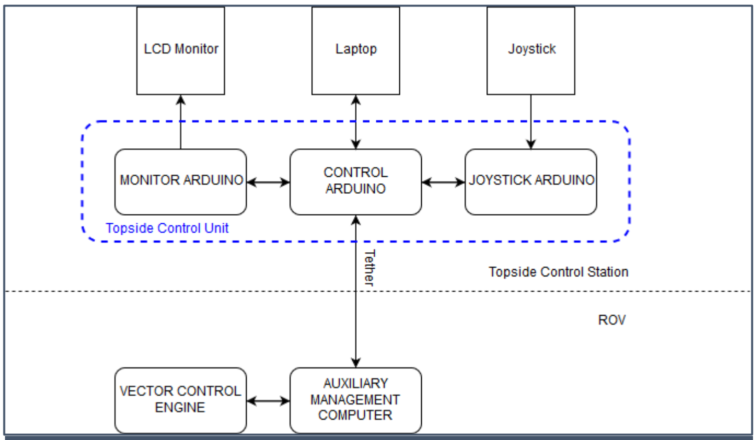

*Figure 23 – System Control Flow Diagram*

Joystick button states and axes values are read by its dedicated Arduino (JOYSTICK) so it can handle the Joystick's interrupts without disrupting the rest of the system and introducing unnecessary delays. It interfaces with a USB host controller over serial peripheral interface (SPI) connection. Easy Transfer (ET) library is used throughout the system to assemble the data into a packet and send it to the next Arduino (CONTROL). The packet includes two nested Cyclic Redundancy Check (CRC) values calculated both before transmission and at the receiving end. The receiving controller then compares both and rejects the packet if they don't match.

After comprehensive testing, this error checking algorithm proved to be robust enough and was immediately implemented all around the system. The vehicle is halted if packet rejection rate becomes too high for operation to remain stable and safe.

CONTROL in the TCU communicates with the Auxiliary Management Computer on the ROV through the tether. CONTROL formats the Joystick data into the proper ranges and converts it to translational and rotational commands before sending it to the ROV along with navigation modes and peripheral feature activation commands. When the ROV transmits telemetry data, CONTROL is responsible for relaying the received data to the MONITOR Arduino which displays it on the monitor and the laptop debugging terminal.

The Auxiliary Management Computer controls auxiliary non-navigational and body control functions. These include the lights, gripper and laser array. It also relays commands and telemetry data to and from the Vector Control Engine as well as its own associated set of sensors to be sent to the TCU.

Onboard the ROV, the Vector Control Engine mixes the input positions coming from CONTROL through the Auxiliary Management Computer, this include movements from the Joystick itself, the Point Of View (POV) hat switch, and depth control buttons. Then it outputs a specific speed vector for each thruster so that all inputs are merged. This is key to *Brotta's* excellent maneuverability. For all current-hungry motor functions, a soft acceleration function is implemented to start the motor from full stop or accelerate it from a previously achieved speed, thus avoiding tripping the overcurrent protection of the DC/DC converters by the inrush currents.

The MONITOR Arduino outputs a PAL video signal to the DVR to display values and value placeholders on its designated quadrant on the screen. The data displayed includes pitch, roll, and heading angles, along with internal and external pressures and temperatures.

## Mission-Specific Tools

**Gripper**

To be able to grab items from the pool bed with ease, *Brotta* features a gripper in the bottom of the vehicle. The gripper assembly comprises PVC parts that are bolted together and powered by a mechanically-sealed DC geared motor.

*Figure 24 – Gripper*

Since an undesirable forward tilt was experienced while holding objects with Eddy, our current gripper is placed exactly below the front heaving motors. This allows us to generate a reaction force equivalent to that of the load carried by the gripper, stabilizing the ROV.

### Vision System

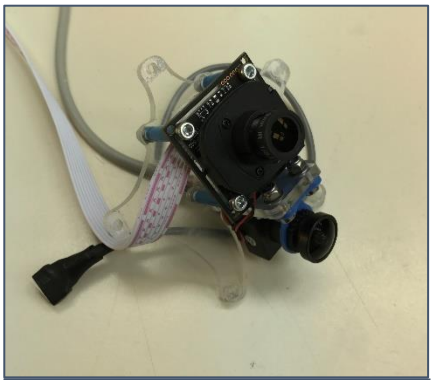

Figure 25 – Front cameras positions

In order to be able to accurately insert items in their desired locations, the cameras were placed on the vehicle in such a way that allows the pilot to view the gripper and the object it's holding. This was achieved by placing a camera pointed at the vehicle's heading, another that is perpendicular to the gripper, and a wide-angle one secured on the vehicle's lower horizontal plate.

The 3 camera feeds, including two analog high definition (AHD) cameras and one analog 700TVL camera, are fed into the DVR. The DVR divides the screen into 4, displaying the feeds along with on-board sensor data for a better piloting experience. a view that includes the gripper with respect to different objects horizontally and another, vertically.

Headlights with three brightness levels were designed and built in-house to illuminate the scene for easier piloting and allow the image processing applications to perform better.

### Cannon Lifting Mechanism

Figure 26 - Slip knot

Figure 27 - Lift Bag

In order to easily return the cannon to the surface, it was crucial to design a mechanism that would enable the pilot to secure the cannon at any point, regardless of the cannon's diameter. The simplest solution was found to be the most effective one in this case. The vehicle would carry a simple cable tie in its gripper, secure it around the cannon at any point, and simply pull it up. The cannon's weight ensures that the cable is tightened around it.

After calculating the volume of the cannon, its weight in water is calculated. Finally, based on our vehicle's thrust output, the pilot and co-pilot decide whether or not they will pull the cannon to the surface using the ROV or through the help of a lift bag.

### Cannon Shells Identifying and Marking System

Figure 28 – Rotating Spiral Motor

To rapidly detect the presence/absence of a cannon shell and mark its location, the ROV is equipped with a magnet along with two motors, each rotating a spiral that carries four red and black markers.

The presence of cannon shell is detected by placing the magnet against each pipe and slowly moving the vehicle. This helps determine whether the magnet is attracted to the pipe. To drop a distinct marker into its genuine location, the pilot simply rotates one of the motors until the proper marker moves towards the end of the spiral and descends into its designated area.

### Autonomous Line Following and Crack Measurement Application

As shown in Figure 29, the algorithm works by first dividing the Image into four rectangular masks at each corner and one central rectangular mask at the center of the image. The corner masks are used to determine the next move based on the presence of a red line at a given corner. The vertical rectangular mask is used to detect any line segment and compute its centroid and angle. These are used to adjust the position and orientation of the ROV. If a line segment is not found in the central rectangular mask, the whole image is scanned for any red lines.

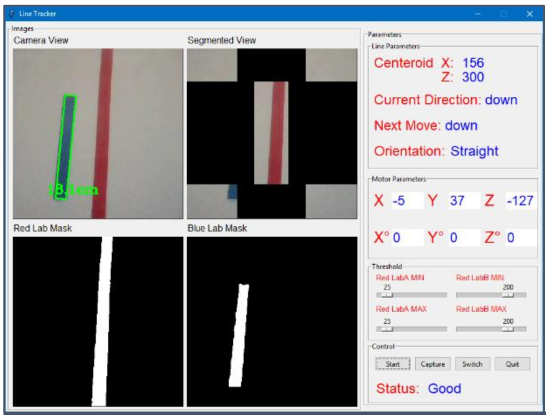


*Figure 29 – GUI of Line Following Application*

### Autonomous Benthic Species Recognition

A Species Recognition Python application implements a computer vision algorithm using OpenCV that automatically detects, counts, and classifies the different species, as shown in Figure 30.

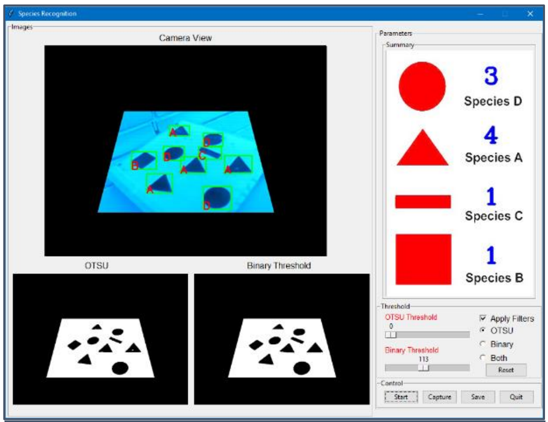


*Figure 30 – GUI of Benthic Species Recognition*

A raw image is captured, masked, and thresholded using OTSU or Binary thresholding to better detect the shapes' external contours. Contours that have an area below a certain threshold are discarded and the corners of the remaining ones are counted. Contours with three corners are a Triangle (Species A), while those with four have the ratio between their width and length checked to differentiate between a Square (Species B) or a Rectangle (Species C). If the number of corners is more than four then it's classified as a Circle (Species D).

## TESTING & TROUBLESHOOTING

All independent systems that make up the ROV are tested individually before assembly to ensure that they are fully operational and ready for integration. After the assembly process is complete, each subsystem is tested again to guarantee a fully functional integration. Our vehicle's insulation and structural integrity are tested by submerging the vehicle underwater for long periods at rated depth. To test mission-specific tools, Invictus designed PVC structures that mimic the missions the ROV is designed to execute. For a testing environment, Invictus reserved a swimming pool during the afternoons over a period of 5 weeks, in which we timed the simulated missions to ensure that the pilot was able to execute all required tasks efficiently within the allowed time.

To help us debug the crucial problem of communication between the surface control station and the ROV, two LEDs were added on our custom-made printed circuit board (PCB) that light up under three conditions, as shown in Table 1. This debugging method is more convenient than constantly connecting all Arduino boards to a single laptop and then manually monitoring the feed.

| Green LED | Yellow LED | Status |
|---|---|---|
| ON | OFF | Initializing |
| OFF | ON | Data packet from Control station is corrupted |
| ON | ON | No communication with ROV |

*Table 1 - Communication debugging LEDs states*

# SAFETY

## Safety Philosophy

"Humans over machines". At Invictus, employee safety is the senior concern. Our employees' well-being is paramount to any raw material, component, or task. Our high regard for safety stems from our belief that one would not be able to learn, work, and innovate freely if one feared for their safety. The company's senior members actively instruct newer members to follow safety protocols. The Safety officer constantly updates the Job Safety Analysis (JSA) and the Safety Checklist documents throughout designing, building, handling, and testing the ROV.

*Figure 31 - Mechanical team leader Abdallah*

## Lab Safety Protocols

Our labs are located within the Arab Academy of Science, Technology and Maritime Transport (AASTMT). These on-campus labs were designed and equipped with all necessary safety features to keep us as well as our fellow students safe. Appropriate personal protective equipment (PPE), such as hard hats, safety goggles, ear protection, gloves, safety vests and footwear, are employed when handling power tools. Our labs are fitted with carefully fixed drilling and cutting tools in order to avoid any serious injuries. Ventilation fans are used for clearing soldering fumes, driving particulate matter and smoke outside the lab, leaving the air in the lab cleaner and fresher for company members.

## Training

For the safety of our members in the field, at least two of the personnel must be present when lifting or transporting the ROV, and they must be wearing safety gloves and footwear. In addition, all hands must clear off the ROV before power is applied. Most importantly, the attached safety checklist is rigorously followed during every water test to ensure both the safety of members and optimal operation of the ROV.

*Figure 32 – Our pilot Youssef while training*

## Safety Features

In order to prevent cuts during handling the ROV, all edges of the ROV are designed as fillets, and cap nuts cover any exposed bolt threads. Even before deployment, sensory data is provided to the pilot on the station's LCD screen, to double check that the vehicle is stable for operation. An emergency stop pedal at the station allows for a quick shutdown mid-operation if the need arises. Furthermore, In case the pilot loses control of the vehicle, automatic software lock-out prevents any motors from running until control is restored to the pilot. For overcurrent protection, the ROV is allowed a maximum current of 30 A at which point the fuse on the tether breaks the circuit.

# LOGISTICS

## Company Structure and Teamwork

### Company Structure

Invictus features an almost-flat organizational structure. The employees can generally be classified into two departments; the Mechanical department, and the Electrical and Software Department. Each department has a head, and the CEO and the CFO each belongs to one of the noted departments respectively. This offers a unique advantage in strategic-level meetings between the CEO, the CFO, and the department heads, as they are perfectly in sync with the progress of the team each of them belongs to.

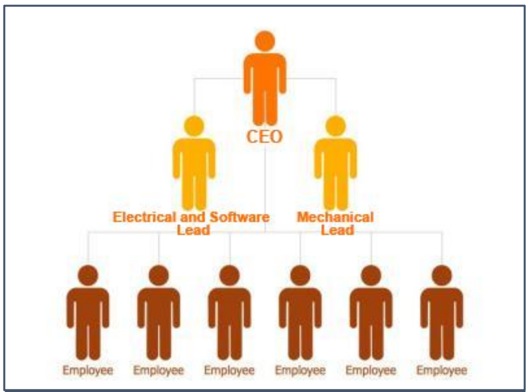

*Figure 33 - Invictus' Company Structure*

### Work Flow

Invictus holds frequent meetings on the strategic and operational levels. Strategic-management meetings have to do with where the company stands on the technical and financial levels. This is accomplished by comparing expenditure with the project costing, comparing the current progress to the Gantt chart, and making appropriate decisions based on the current state.

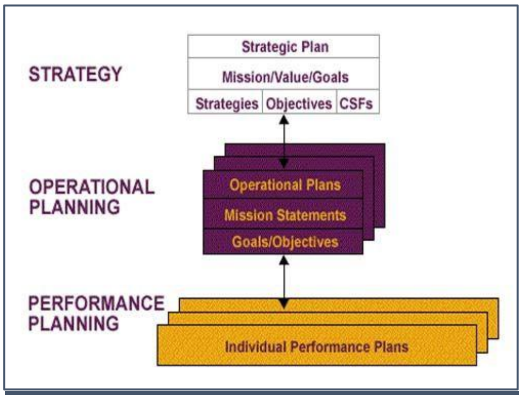

*Figure 34 - Work flow between Invictus' management levels*

Operational meetings encompass employees who belong to either departments including the CEO and the CFO, and the department heads. These meetings entail conveying and distributing the company's operational objectives, as actionable tasks, to each employee. For the more challenging tasks, cross-department team-ups are created, which opens opportunities for teamwork between employees of different departments. Communication between both departments is facilitated by the fact that Invictus's employees possess vast experiences from previous projects and practical knowledge beyond the scope of their specializations.

## Project Management

Since the summer of 2018, even though it was off-schedule, Invictus began designing its newest, most compatible vehicle to mission-specific tools; *Brotta*. The aim behind this timing was to get through the vehicle design phase as quickly as possible, leaving enough time for the iterative design and testing of integrable mission-specific tools once the manual comes out. As an added bonus, that afforded the pilot enough time to get as familiar as possible with the new vehicle, to be able to successfully execute the required missions efficiently within the specified time limit. Consequently, the company planned to dedicate a minimum of 200 hours for testing and training and actually clocked in 360 over a period of 5 weeks as illustrated in the Gantt chart.

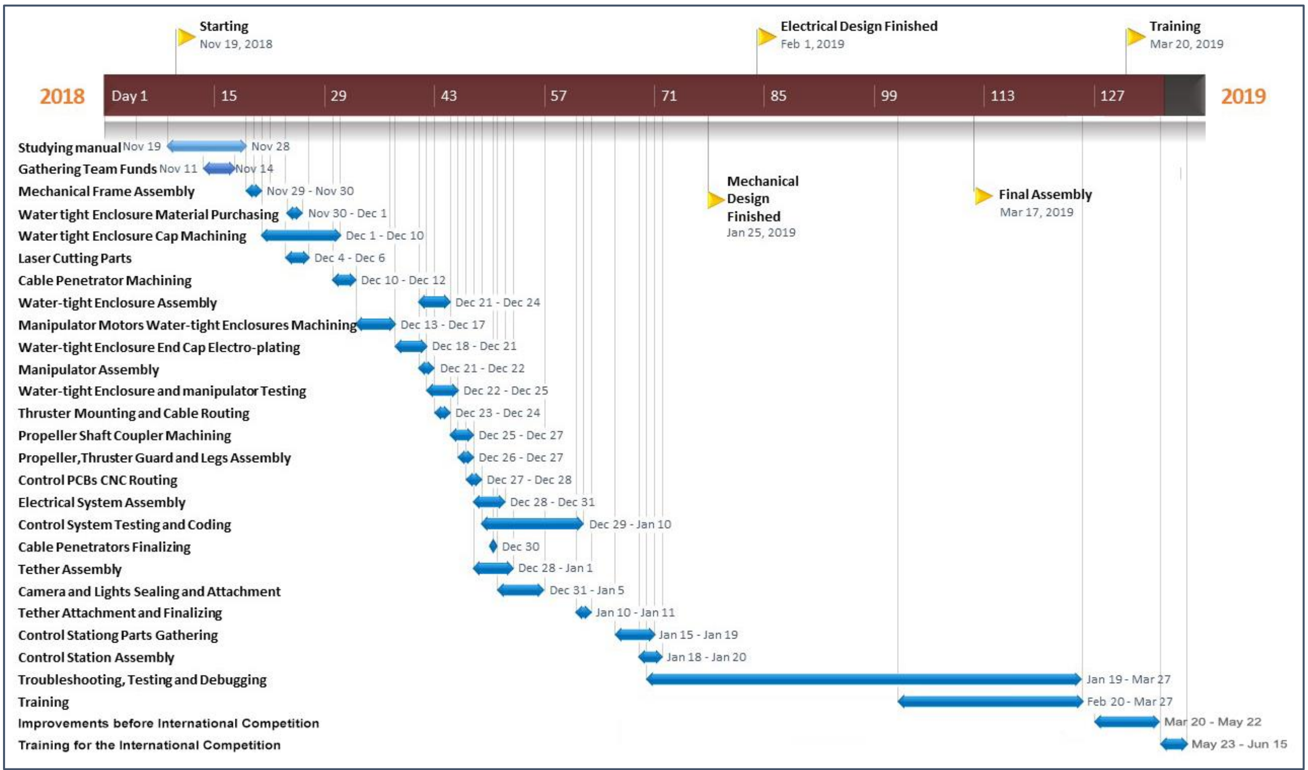


*Figure 35 - Gantt Chart that illustrates tasks breakdown and timeline*

## Budget and Project Costing

We calculated the total amount spent on our 2018 vehicle ($ 1,866.20), reviewed the competition manual, and based on our experience from the international competition, projected the amount of money required to prototype and manufacture new mission-specific tools. Next, we accounted for the fact that our university would pledge a total amount of $ 2,200.00 for vehicle development. Our team planned the design and build process accordingly.

Many components proved their worth and reliability over the past two years and were re-used.

Invictus is forever grateful to the Arab Academy for Science and Technology and their decision to generously cover the costs of accommodation during as well as travelling to the MATE ROV International Competition ($ 7,700.00).

| Category | Item and Description | Type | Amount | Qty. | Total | Category Total | Budget Allocated |
|---|---|---|---|---|---|---|---|
| Mechanical Body | HDPE Sheet (Used to build the frame) | Purchased | $ 66.70 | 1 | $ 66.70 | $ (132.70) | $ 300.00 |
| | Acrylic Parts (Used in minor parts) | Purchased | $ 11.00 | 1 | $ 11.00 | | |
| | Assembling Components | Purchased | $ 20.00 | 1 | $ 20.00 | | |
| | *CNC Router Cutting (Done by AAST Workshops)* | *Donated* | *$ 40.00* | *1* | *$ 40.00* | | |
| | Laser Cutting | Purchased | $ 10.00 | 1 | $ 10.00 | | |
| | *Geared Motors (To actuate grippers)* | *Re-used* | *$ 17.00* | *1* | *$ 17.00* | | |
| | *Aluminum Housings (Seals geared motors)* | *Re-used* | *$ 15.00* | *1* | *$ 15.00* | | |
| | O-Rings (To seal enclosures) | Purchased | $ 25.00 | 1 | $ 25.00 | | |
| Thrusters | Blue Robotics T100 Thruster | Purchased | $ 119.00 | 9 | $ 1071.00 | $ (1218.06) | $ 1300.00 |
| | DYS 40A Electronic Speed Controller (ESC) | Purchased | $ 11.43 | 6 | $ 68.58 | | |
| | Afro 30A Electronic Speed Controller (ESC) | Purchased | $ 19.62 | 4 | $ 78.48 | | |
| | *3D Printed Guards (Done by AAST Workshops)* | *Donated* | *$ 5.50* | *12* | *$ 66.00* | | |
| Tether | *VideoRay Neutrally Buoyant Tether 50 feet* | *Re-used* | *$ 50.00* | *3* | *$ 150.00* | $ (9.00) | $ 0.00 |
| | *Tether Nylon Sleeve* | *Re-used* | *$ 25.00* | *1* | *$ 25.00* | | |
| | *Ethernet Cable (Connecting RS485 to station)* | *Re-used* | *$ 12.00* | *1* | *$ 12.00* | | |
| | *Coaxial Cable (Connecting video to station)* | *Re-used* | *$ 6.50* | *3* | *$ 19.50* | | |
| | Video Balun | Purchased | $ 3.00 | 3 | $ 9.00 | | |
| Control Box | Acrylic Tube (Containing all electronics) | Purchased | $ 25.00 | 1 | $ 25.00 | $ (185.00) | $ 300.00 |
| | Aluminum Flanges (Seals radially with the tube) | Purchased | $ 20.00 | 2 | $ 40.00 | | |
| | Aluminum Penetrators (Seals the cables) | Purchased | $ 5.00 | 20 | $ 100.00 | | |
| | Acrylic Caps (Carries the penetrators) | Purchased | $ 15.00 | 1 | $ 15.00 | | |
| | *Flanges Machining (Done by AAST Workshops)* | *Donated* | *$ 10.00* | *2* | *$ 20.00* | | |
| | Laser Cutting for Caps | Purchased | $ 5.00 | 1 | $ 5.00 | | |
| Onboard Electronics | *DC/DC Converters (Murata 420W Converters)* | *Re-used* | *$ 86.60* | *3* | *$ 259.80* | $ (48.50) | $ 200.00 |
| | *Arduino MEGA 2560* | *Re-used* | *$ 23.00* | *1* | *$ 23.00* | | |
| | *Arduino Nano* | *Re-used* | *$ 9.00* | *2* | *$ 18.00* | | |
| | *IMU (Gets vehicle's orientation)* | *Re-used* | *$ 11.50* | *1* | *$ 11.50* | | |
| | Pressure Sensor (Gets vehicle's depth) | Purchased | $ 21.50 | 1 | $ 21.50 | | |
| | PCBs (The main board and power board) | Purchased | $ 17.00 | 1 | $ 17.00 | | |
| | *RS485 Modules (Communication protocol)* | *Re-used* | *$ 30.90* | *2* | *$ 61.80* | | |
| | Wires and Connectors | Purchased | $ 10.00 | 1 | $ 10.00 | | |
| Cameras | *Security HD Cameras (Analog High Definition)* | *Re-used* | *$ 16.10* | *2* | *$ 32.20* | $ (79.50) | $ 100.00 |
| | Wide Angle Analog Camera (Analog Signal) | Purchased | $ 17.50 | 1 | $ 17.50 | | |
| | Cree X MK-R LED Cold White Lights | Purchased | $ 7.00 | 6 | $ 42.00 | | |
| | Artilon PA6 Enclosures | Purchased | $ 11.00 | 1 | $ 11.00 | | |
| | Acrylic Transparent Caps | Purchased | $ 7.00 | 1 | $ 7.00 | | |
| | *Housing Machining (Done by AAST Workshops)* | *Donated* | *$ 5.00* | *2* | *$ 10.00* | | |
| | Laser Cutting for Caps | Purchased | $ 2.00 | 1 | $ 2.00 | | |
| Piloting Station | *DVR (To display cameras' feeds)* | *Re-used* | *$ 36.00* | *1* | *$ 36.00* | $ (0.00) | $ 0.00 |
| | *Logitech Extreme 3D Pro (To control the vehicle)* | *Re-used* | *$ 28.90* | *1* | *$ 28.90* | | |
| | *Arduino MEGA 2560* | *Re-used* | *$ 23.00* | *2* | *$ 46.00* | | |
| | *Arduino Nano* | *Re-used* | *$ 9.00* | *1* | *$ 9.00* | | |
| | *Monitor (Displays video and data)* | *Re-used* | *$ 32.50* | *1* | *$ 32.50* | | |
| | **Total Expenses** | | | | $ (1,672.76) | | --- |
| | **Total Re-used and Donated items** | | | | $ (867.20) | | --- |
| | ***Travel and Vehicle Transportation*** | | | | *$ 7,700.00* | | *Donated* |
| | **Total Cash Income** | | | | $ 2,200.00 | | --- |
| | **Net Balance** | | | | $ 527.24 | | --- |
| | **Next Year Investment** | | | | $ 527.24 | | --- |

*Table 2 – Invictus 2018 Project Costing Sheet*

# CHALLENGES

## Technical

Before we compartmentalized the Control and the Power Conversion housings, both sets of circuitry were contained in a single sealed acrylic tube. During that time, we faced a problem where our vehicle would go into lockout mode a few minutes after deployment, preventing any motors from running. After a lengthy troubleshooting process, we arrived to the conclusion that the DC-DC converters and the ESCs were generating a lot of heat, which triggered the overheating protection on the ESCs, which in turn, prevented the motors from running.

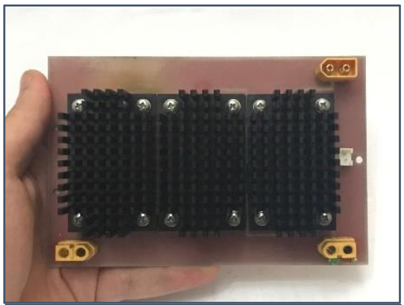

*Figure 36 – Old Converters Board*

In order to minimize the heat the ESCs get exposed to, we decided to house the power conversion circuitry and the control circuitry in separate insulation boxes. That itself presented a new challenge, as our vehicle was not originally designed to accommodate two insulation boxes. However, our mechanical engineers came up with a solution that minimized the manufacturing needs and preserved our vehicle's compactness. Only the T-shaped plates - that connect the vertical side plates to the horizontal plates, were redesigned to accommodate the newly added Power Conversion Housing. As such, these surgical modifications successfully enabled the ESCs to run the motors throughout longer dives without the risk of overheating.

## Non-Technical

The largest challenge in this category must be the departure of more of our strong members. Given our small company size in terms of manpower, our former-members-turned-mentors have tried their best to keep supporting us. However, that came with challenges in the form of time-zone differences, that range between 1 to 8 hours, since two of our mentors are now pursuing master's degrees in the USA and three others in Europe. As such, it has been challenging to coordinate meetings that unite us and our supervisor with the mentors abroad. In order to overcome this challenge, we have utilized cloud-based software, such as Google Drive to synchronize our contributions on the same platform, and VOIP software, such as Discord to hold video conferences and share screens while we collaborate.

*Figure 37 – Our team in 2017*

# LESSONS LEARNED

## Technical

This year, we have faced a challenge attempting to select the type of thrusters most suited to our design. We decided not to buy commercially available thrusters if we can realistically build our own. To power our DIY thrusters, we selected brushless DC motors. However, since they pull high current intensities regardless of their rotational speeds, they generated enough heat to trigger the overheat protection on our ESCs within minutes, rendering all the motors motionless. We re-assessed our decision not to buy commercially available thrusters, having wasted a lot of time and research & development effort avoiding it. We reached the conclusion that the BlueRobotics model T100 thrusters would be the best for the job. That experience nudged us never to dismiss the commercially available options beforehand, as one of them may turn out to be the best choice.

*Figure 38 – Customized Thurster*

### Interpersonal

This year marked the departure of the last of the founding members from the team roster. The founding members had always been more involved in determining the flow of work and other managerial tasks. Consequently, we now had to adapt to taking up such responsibilities as allocating ourselves and the two new members who have joined us to the most appropriate tasks. It took us some time to understand this new dynamic. Nonetheless, we now know each other better, understand our strengths and how to make the most out of them and our weaknesses and how to shore them up together as a team.

## REFLECTIONS

### Mohamed Samir, former Mechanical Team Leader, current Mentor

Throughout my work with this team, I have constantly been intrigued by the possible upgrades we can apply to our underwater vehicles, especially complementing them with elements of autonomy. Motivated by my goal of creating AUVs to aid in preserving marine life, I am now doing a Master’s of Science degree in Robotics and Control Engineering in Sapienza University of Rome. Learning exactly the things I had explored my interest in working with Invictus, I am one now step closer to fulfilling a dream which started with a shark documentary “Sharkwater” and a team of college students who just wanted to better themselves. And for that, I have MATE, Hadath, AAST, my teammates and mentors; everything this competition is, to thank.

## FUTURE IMPROVEMENTS

### Orientation-and-Depth Hold Mode

Thus far, our control system is in an open loop configuration. It can be thought that the pilot reacting to the current position of the ROV - as perceived from the video feed, closes the control loop by taking corrective actions. However, this open-loop configuration does not support a lot of features we would love to implement. One such feature is rejecting disturbances due to water currents and only executing the pilot’s commands, or simply maintaining the ROV’s current position and orientation regardless of external disturbances.

These features require closing the control loop using more sensors, such as shaft encoders to measure the motors rotational velocity, and an IMU to measure the ROV's position and orientation. We have not had a chance to implement these features yet, but we're working towards it.


## ACKNOWLEDGMENTS

Invictus would have not been founded nor able to overcome the challenges it faced without the help of these organizations and individuals:

- **MATE Center -** for creating such a highly competitive and professional competition, that allows makers to explore their passions and develop their engineering skills along the way.
- **Arab Academy for Science and Technology -** for funding our company in 2017 and 2018, as well as funding our new *Brotta* and supporting us, and also for hosting this year's regional competition.
- **Regional Informatics Center (RIC) -** at AAST Alexandria.
- **Industry Service Complex (ISC) -** at AAST Alexandria.
- **Our supervisor, Eng. Amr Khamis -** for his constant concern for us to perform better.
- **Prof. Amr Ali Hassan, Prof. Mohamed Abbas Kotb, Prof. AbdelMoneim AbdelBary and Prof. ElSayed Saber -** for their relentless support and continuous encouragement.
- **Dr. Ahmed ElShennawy from the RIC -** for organizing the regional competition.
- **Our current mentors and former team members Mohamed Samir, Hossam Samir, Abdelrahman Elkanishy, Hesham Fadl, Abdelrahman Elshoura, Ahmed Eldawansy, Omar Hammouda and Mohamed Lotfy.**


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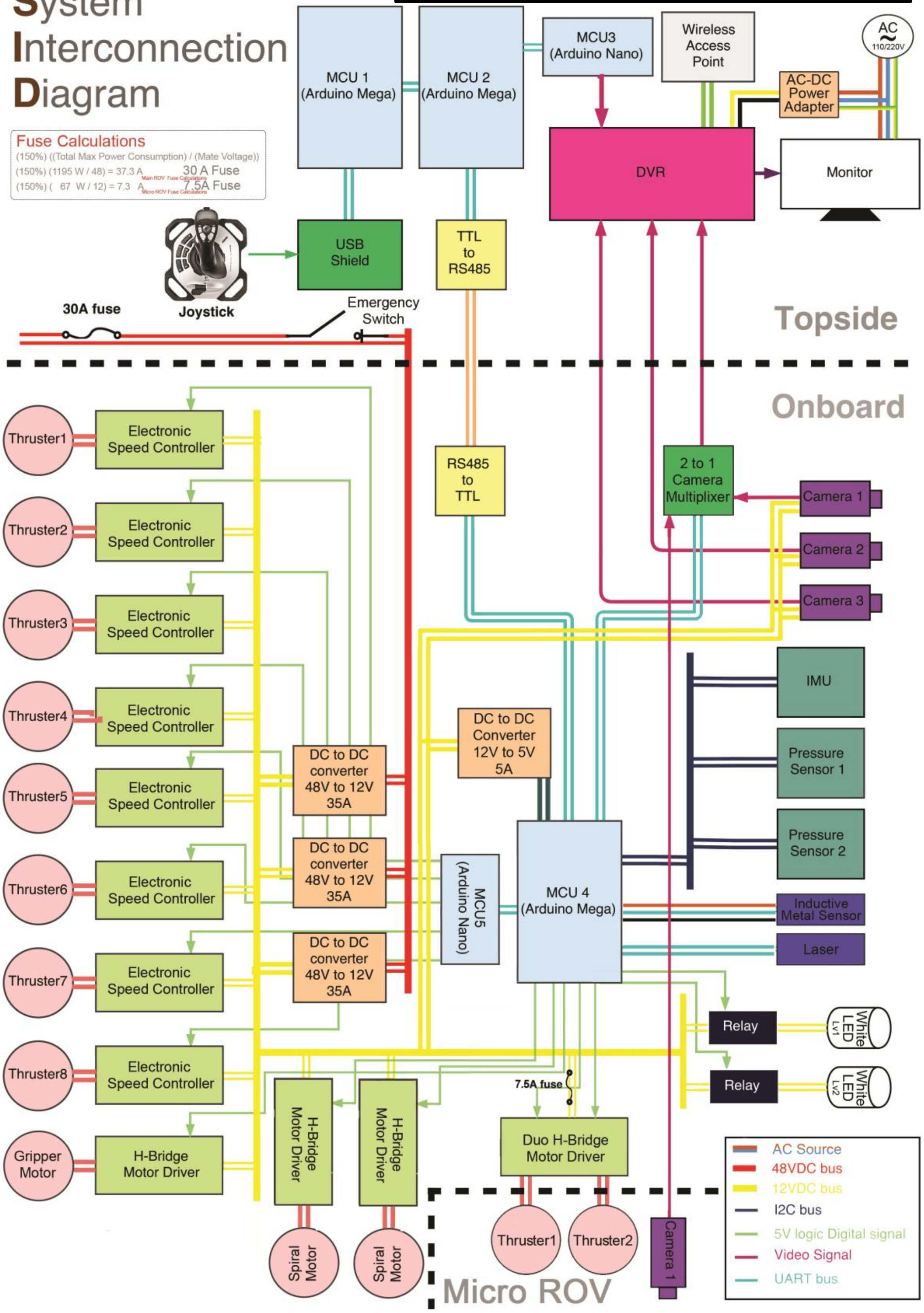
# APPENDICES

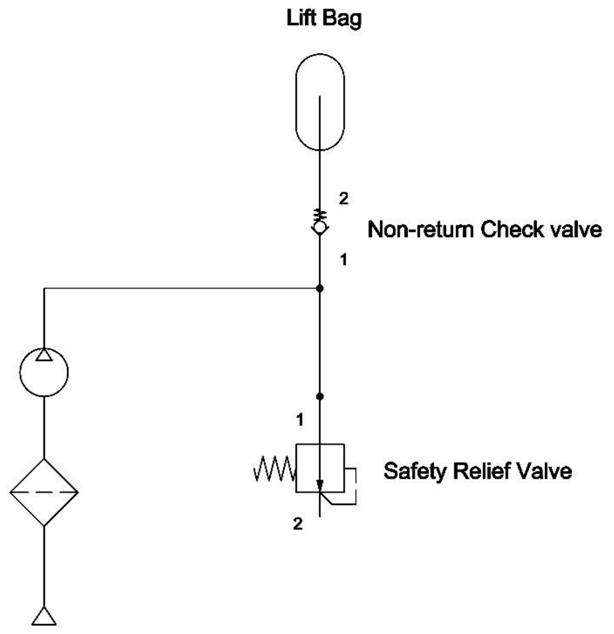
## Appendix A Electrical SID

| Device | Nominal Voltage (V) | Max. Current (A) | Max. Power (W) | Qty. | Total Max. Power (W) |
|---|---|---|---|---|---|
| Thrusters | 12 | 8.8 | 105.6 | 8 | 845.0 |
| Geared Motors | 12 | 5.0 | 60.0 | 1 | 60.0 |
| Cameras | 12 | 1.0 | 12.0 | 3 | 36.0 |
| LEDs | 12 | 1.25 | 15.0 | 5 | 75.0 |
| Control Boards | 5 | 0.35 | 1.75 | 6 | 10.5 |
| Micro ROV | 12 | 6.0 | 72.0 | 1 | 72.0 |
| Conversion Losses | - | - | 31.8 | 3 | 95.6 |
| Total Power Consumption | 1195 W | | | | |

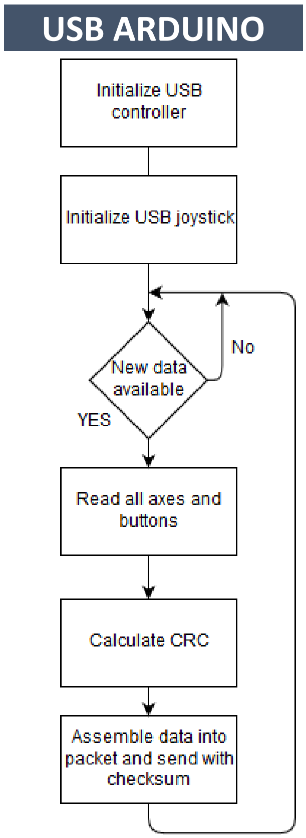
### System Interconnection Diagram

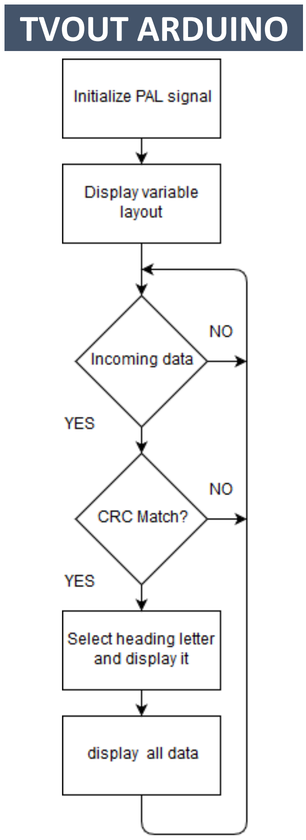


## Appendix B Fluid Power SID

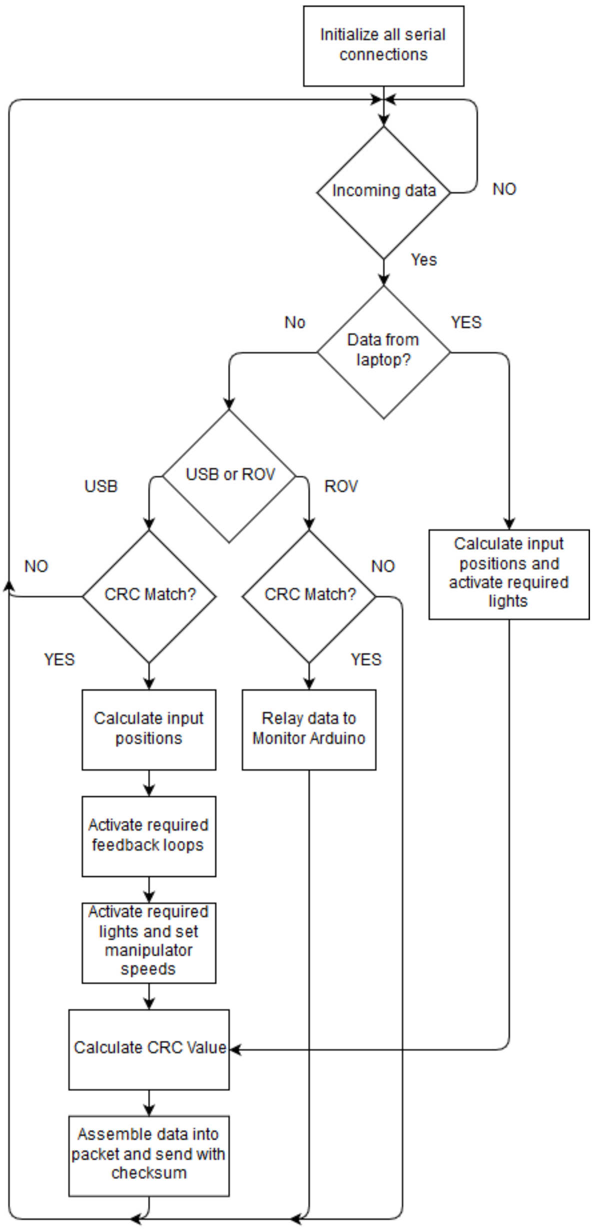



## Appendix C Flowcharts

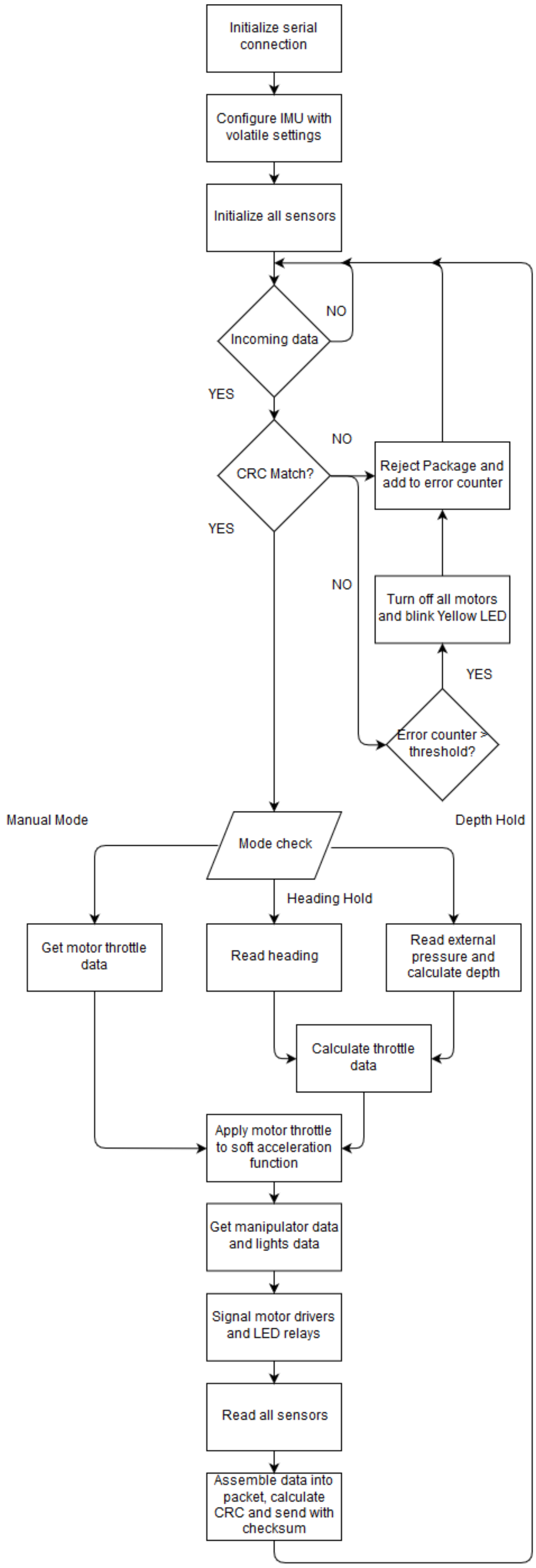


## CONTROL ARDUINO




## ONBOARD ARDUINOs



## Appendix D Safety Checklist

| Procedure | Check Mark |
|---|---|
| **Pre-Power Checks** | |
| All crewmembers are wearing safety gear | |
| Power is disconnected before conducting safety check | |
| Check fuse is not blown | |
| All mechanical structures fastened securely | |
| All sharp edges covered and cap nuts installed | |
| Propellers, shafts and manipulators clear of obstructions | |
| Video gear clear of obstructions | |
| Cables are tied down and electrical connections are waterproofed | |
| Check all seals are installed correctly | |
| Check electronics enclosure end caps are fastened correctly | |
| Check pressure valve needle is fully screwed in | |
| Check operating environment is clear of obstacles | |
| Call out “Safe” | |
| **Pre-Water Checks** | |
| Connect tether to control station and power the system | |
| Check video system | |
| Pressurize the electronics enclosure for the rated depth for the called dive | |
| Check internal pressure reading at control station is correct for the dive | |
| Power down the system and call out “Water Ready” | |
| Two crewmembers and the tether man lower the ROV in the water | |
| Call out “In Water” | |
| **In-Water Checks** | |
| Power up the system and check warning lights | |
| Check internal pressure is stable at surface | |
| Call out “Pilot In Command” | |
| **Recovery Checks** | |
| Check ROV is at surface, facing away from pool wall | |
| Power down the system and call out “Crew In Command” | |
| Two crewmembers and tether man lift the ROV from the water onto land | |
| **Safety officer signature:** | |