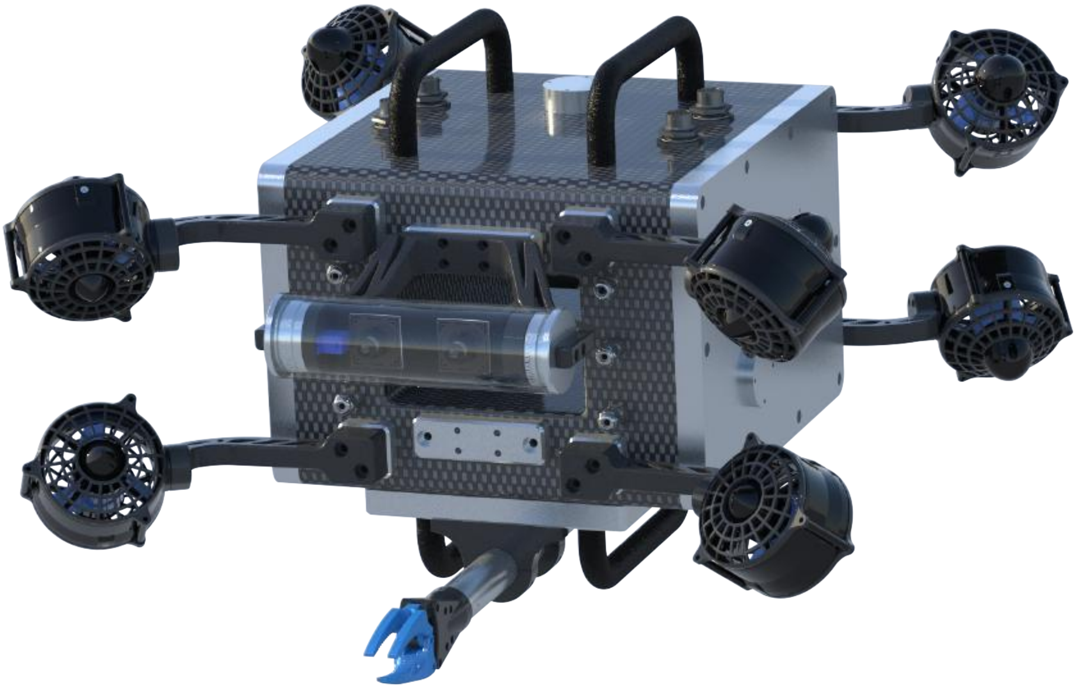
Tethys Robotics

2019 MATE International ROV Competition



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Abstract

This document describes the development, design and manufacturing process of SCUBO 2.0. SCUBO 2.0 is a remotely operated underwater vehicle (ROV) specifically designed for intervention in inshore, underwater environments. It was developed and built in 2019 by Tethys Robotics

Tethys Robotics is a student organization at ETH Zrich Switzerland. It currently consists of eight students studying electrical engineering, computer science and mechanical engineering.

SCUBO 2.0 is an omni directional vehicle, with a sophisticated control algorithm as a key component. This enables easy and precise manoeuvring in tight spaces, such as they are common on hydro electric dams. A quick-change payload system allows to swap different mission sensors and tooling in matter of seconds, to equip SCUBO 2.0 for a variety of different tasks. A strong gripper at the front of the ROV enables it to grab and lift heavy objects in various geometries easily and securely.

With safety as the companys primary concern, special attention was given to the creation and implementation of safe working practices, safe vehicle features and the creation of a team environment where safety is not a nuisance but a central part of every day operations and each and everyones top priority.

Contents

1 Introduction

Who we are?

The desire of exploration and adventure. Finding the last blank spots on the map and go to places where no one has gone before. This has been a dream for many of us since their childhood. But are there any remaining 'blank spots' on our planet? All maps are drawn to completion. Or are they? You simply have to put your head under the surface of the water and you will realize that there are vast areas waiting to be explored and many mysteries still to uncover.

With this desire for adventure in our minds, we founded Tethys Robotics in the summer of 2018. Tethys Robotics is an interdisciplinary team of like minded students, passionate about underwater exploration and technology. Together we want to bring the adventure of sub sea exploration to students in Switzerland and expand our skill set by conducting projects in the field of underwater exploration and technology. Participating in the 2019 MATE international ROV competition is the perfect opportunity for us to get our feet wet. With Switzerland being a land locked nation, one might think that there is no big need for sub sea technology and exploration. But with an abundance of lakes, rivers and a thriving hydroelectric industry, there is plenty of need and opportunity for sub sea innovation. This being said, we could not have asked for a better competition topic, than 'Inshore ROV operations'

Team

Tethys Robotics consists of eight Students studying mechanical, electrical engineering and computer science.

Figure 1: Team of Tethys Robotics (from top left to bottom right: Stefano Marti, Pragash Sivananthaguru, Andrej Studer, Jonas Wüst, Bastian Schildknecht, Christian Engler, Mathis Först, Gallus Kaufmann)

2 Design

While the tasks of this years ROV competition called for very specific design considerations, our goal was to design an ROV that was as versatile as possible and could be used for numerous different tasks in changing environments. Key design requirements were:

- Safety of operator and environment
- Expandable system
- Compliant with MATE specifications
- Intuitive and simple handling
- Being able to accomplish competition tasks efficiently

During conceptual design meetings we evaluated these requirements, looked how to incorporate them into our upcoming design and checked how the design considerations could affect competition performance and system safety. The design we came up with is an omni-directional ROV with easily exchangeable mission payloads and an adaptable electronics and software infrastructure. As a base for our ROV we used the electronics enclosure from another ROV, called SCUBO, built in 2016 by a team of students at ETH Zurich. In appreciation for their work and support during our ideation phase we called our ROV SCUBO 2.0. In the following sections, the individual aspects and sub systems of our SCUBO 2.0 are explained. In general the whole design process was split into mechanical, electrical and software design. These different design areas were then handled by sub groups of team members with the corresponding expertise.

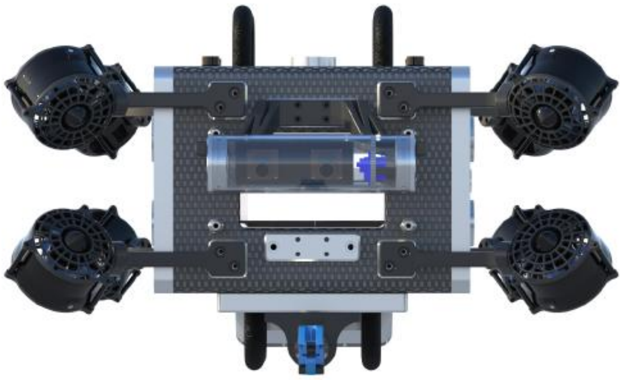

Figure 2: Front view of SCUBO 2.0

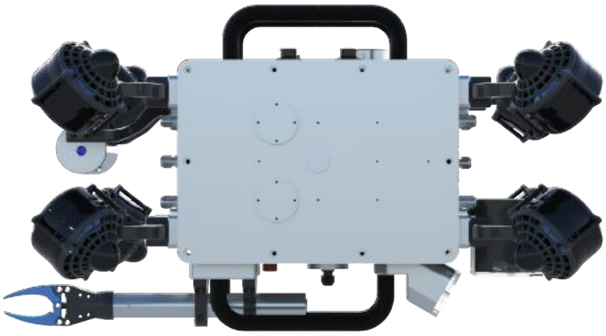

Figure 3: Side view of SCUBO 2.0

2.1 Mechanical

The mechanical design process was split up into the different sub systems, explained in the following sections. All mechanical parts were designed in CAD with Siemens NX12. After assembling them digitally and checking fit and function, they were manufactured and assembled.

Wherever possible, we manufactured our own parts, to keep costs and turn around time low. Therefore our design favours machined and 3D printed components, since this could be done by our team members in-house.

2.1.1 Propulsion layout

To achieve the optimal propulsion layout for our system, following requirements were evaluated:

- Omnidirectional (6-DOF)
- Intrinsic stability, even without controller running
- Good performance in all directions.

To fulfill these requirements in the best possible way, some compromises had to be made and some directions of movement and axis of rotation had to be favoured over others. Since moving rapidly and agile in the forward direction as well as up and down is essential for accomplishing the competition tasks efficiently, these directions were favoured. This also implies that the yaw rotation is favoured, since it is coupled with agile movements in the planar directions. Furthermore, we had to decide whether the roll or the pitch rotation would be more important for us. As we have the gripper installed in forward facing direction, it causes a pitching moment every time something is grabbed. Therefore we need enough torque in this direction to be able to counteract. These decisions led to the current propulsion layout, visualized in figure 2.3.

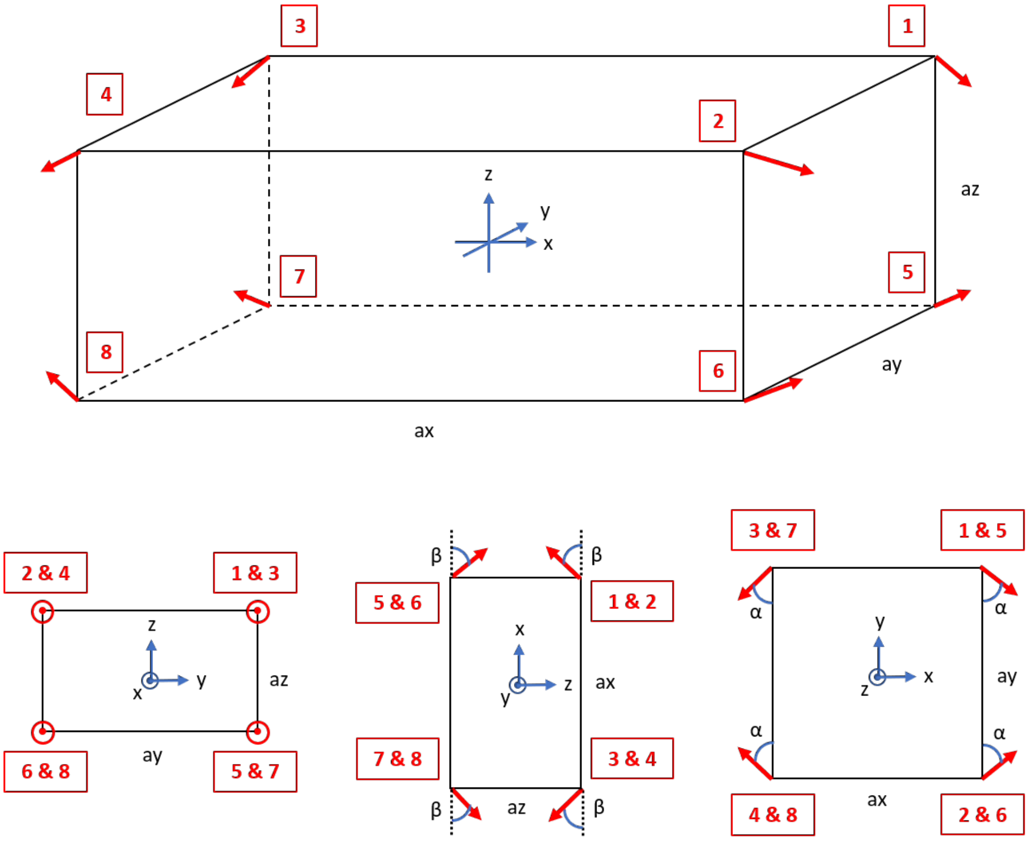

Figure 4: Thruster layout and orientation.

2.1.2 Electronics enclosure


Figure 5: Carbon electronics enclosure

The Electronics enclosure is the core structure of the ROV. It provides ample space for electronics, and tools, thrusters and any mission payloads can be attached to the outside. It also provides buoyancy and holds trim weights to achieve optimal trim in water. It consists of a box made out of carbon fiber, sealed by two machined aluminum plates, with o-ring seals, on either side. Both plates can be removed to provide easy access to the electronics inside. Connectors and penetrators are routed through the enclosure walls. Furthermore, the carbon box does have a channel in the middle, which serves as a docking area for the micro ROV. This box has been reused by our team. It was the core part of SCUBO, a ROV built by students from ETH Zrich,back in 2016. With its beautiful design, accessible interior and perfect garage for the micro ROV it is a perfect fit for SCUBO 2.0. While the carbon box design provides a lot of space for maintenace and expansion, it does however come with some drawbacks. Firstly, the sides of the box are a major weak point limiting the maximum operation depth of the ROV. FEM analysis has shown that at 3 bar absolute hydrostatic pressure, the side plates buckle slightly. This causes the compressed o-ring seal to dislocate and water to enter the housing. Furthermore, the enclosure has a lot of through-holes, interfacing directly with the water. This requires a high number of seals, increasing the risk of leaks. In order to mitigate this risk, adapter plates were machined that can be firmly attached to the ROV. External components can then be attached to to these plates externally, bypassing the need for through-hole seals.

2.1.3 Connectors

To interface sub systems with the inside of the electronics enclosure, different styles of connectors are used. For components that stay afixed to the ROV, bulkhead penetrators are used. For components that need to be detachable (e.g. tether, payload systems, etc.) waterproof circular connectors are used. To keep the cost down, these are IP68 rated wherever possible. Only for the power connection to the tether, a SubCon ciruclar connector is used, since this connection needs to be very reliable.

2.1.4 Propulsion


Figure 6: Thruster arm

For propulsion Blue Robotics T-200 thrusters are used. These provide a lot of thrust for a moderate price. Since they do not have any enclosed air pockets, they can be used down to extreme depths. While the performance of the thrusters was great throughout testing, we had three thruster breaking in short sequence. Further investigation by our team members revealed that the thrusters broke due to the phase wires snapping off at the stem, caused by vibration. This problem was solved by replacing the thrusters with newer models and adjusting the controller to actuate the motors more smoothly. The thrusters are mounted on 3D-printed arms. The use of additive manufacturing enabled us to test several different designs and materials on short notice. After experimenting with arms printed from PLA, ABS and PET, the latter was found to be the material of choice due to its high fracture toughness and low water absorption. The PET thruster arms also serve as a dampener and as a breaking point in case of a crash. This way, bending and torsional loads can be kept away from the carbon electronics enclosure. While the carbon fiber box can handle compression loads very well, bending loads can cause the carbon to fracture at the drilled through-holes.

2.1.5 Manipulator

With the advantage of a omni-directional ROV we were able to rely on a simple, single-function manipulator design. With the ROV being able to obtain and hold any position in the water and move in all directions, only a simple gripping mechanism is needed. The mechanism is composed of an electric motor actuating a spindle that drives a piston rod, which in turn actuates the gripping mechanism. With the reduction through the spindle lifter, high linear forces can be achieved. Using a 6 Watts 12 Volt DC electric motor we are able to create 800N of linear force. Through the gripper mechanism, this results in a gripping force of approximately 20 Kg. For safety reasons, current limiting on the gripper motor controller is used to reduce the gripping force to safe values. The manipulator tool is designed to be easily interchangeable. This way, the jaws can be easily replaced in the case of breakage or a different tool can be swapped in for use on another task. As an example, a larger gripper can be mounted for the retrieval of the degraded rubber tire, while the rest of the tasks can be accomplished with a smaller, fast-acting gripper.

Figure 7: Overview of the gripper mechanism: (from left to right) electric motor, gearing, spindle with bearing, bearing housing with piston rod, exchangeable end effector

2.1.6 Camera

The main navigation camera used on Scubo 2.0 is a low light HD USB camera. This camera provides excellent footage, even in low light conditions, such as they are often encountered in sub sea environments. Two identical cameras are mounted in a stereo setup to provide the pilot with a 3D image, that can be viewed with a virtual reality goggle. This facilitates depth perception and enables the pilot to maneuver more accurately and efficiently. Furthermore it enables the creation of disparity maps for computer vision. The stereo camera can be rotated up or down by the use of a servo motor. At the aft of the ROV there is another fixed mounted camera that enables us to monitor the operation of the rear payload systems as well as keeping an eye on the micro ROV when undocked.

Figure 8: Stereo camera in watertight enclosure with rotation mechanism

2.1.7 Payload system

At the aft end of the ROV, a quick change payload system is mounted. Using a dovetail connector to secure different payloads enables us to quickly and easily change different systems. For the competition, several dedicated payload systems were developed, to ensure that SCUBO 2.0 can perform all tasks required in an inshore environment.

Figure 9: Cannon lift mechanism with pneumatic lift bag

Figure 10: Fish dropping mechanism

Figure 11: Puls Induction metal detector

Cannon lift mechanism: This mechanism consists of a claw that can be placed above the cannon barrel, and then slides over it to cradle the cannon for lifting. A lift bag attached to the gripping mechanism is then pumped full of air, and the cannon rises to the surface.

Fish dropping mechanism: The trout fry is transported in a small box. The box is closed with two trap doors, that are held shut by electric magnets. Once the magnets are deactivated, the trap door opens and the fishes are released.

Cannon ball detector and marker dispenser: A pulse induction metal detector is attached to the front adapter plate of the ROV. If the sensor detects a signal from a ferrous metal, the corresponding marker is released from a hook on the back of the ROV.

2.2 Electrical

The key philosophies followed for the electrical design are modularity and safety. This gives us flexibility and allows for a better component organization within the ROV. Moreover, the main components can be easily exchanged for testing or repair. In order to achieve such a modular system, it is divided into a power and a signal subsystem.

2.2.1 Power Supply

All hardware aboard of the ROV requires a voltage of either 12V or 5V. Since the topside power supply delivers a voltage of 48V over a 25m tether, and the voltage conversion has to be done on board of the ROV, a multiport DC/DC converter, as in Figure 12, is required. Therefore, we developed a DC/DC converter PCB, which takes the 48V and up to 30A from the tether as input and transforms it into 12V and 5V. The 12V conversion is done by our three parallel DC/DC converters, each of which has a maximum power rating of 600W, while the 5V conversion is done by a single 150W converter. We decided to use three 600W converter to build a reliable system, so that if one 600W converter fails the ROV still remains operational.

Furthermore, the stress on the DC/DC converter is reduced. In order to choose the best converters in terms of efficiency, power, size, weight and cost, we analyzed several options with Matlab.

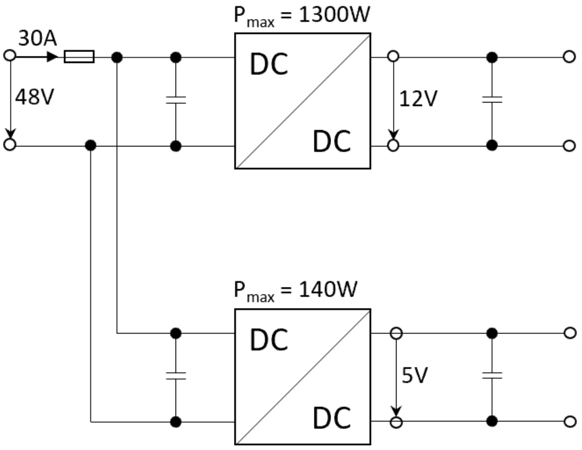

Figure 12: DC/DC converter overview.

Figure 13: DC/DC Converter PCB.

The resulting multiport DC/DC conversion unit has a gravimetric power density of 1.98 $\frac{kW}{kg}$ and a volumetric power density of 1.44 $\frac{kW}{l}$. The power consumption of the ROV is limited by software and furthermore, especially by a 30A fuse by Littelfuse Inc. These two measures ensure that a maximum current of 30A is never exceeded.

The tether, which delivers the necessary energy to the ROV, is 25m long and consists of four wires, where two of them are used for the positive side of the power supply and the other two for the negative side. Two cable per phase reduce the power loss in the wire. The tether is plugged in at our control station.

Even though the the overall efficiency of the multi-port DC/DC conversion unit is approximately 94%, the whole unit gets hot quickly because 6% of 1400W is 84W. In order to prevent overheating, which under full load could warm up to 85° C, we mounted five 15W fans on the aluminum plates, as explained in more detail in section 4. As a result, air is pushed through the whole ROV and allows the heat to be dissipated via the two aluminum side plates into the water. The DC/DC converters have a safety mechanism, which shuts down the power supply if it gets too hot. With the ventilation we are able to keep the temperature of the on-board power supply below 45° C. We carefully measured voltage and current on input and output side and observed the temperature by using an infrared camera and a laser temperature sensor during this testing.

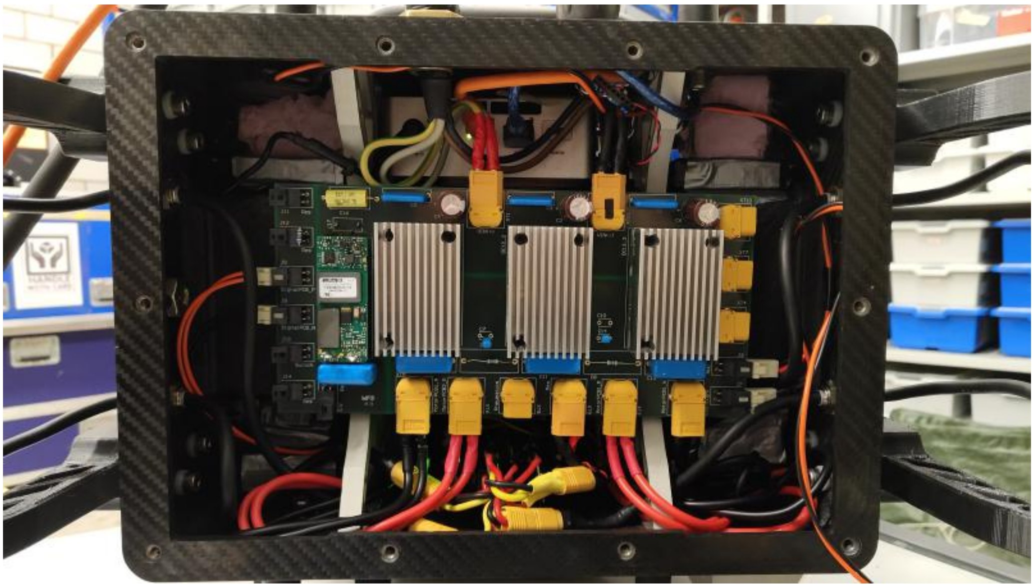

Figure 14: Placement of the DC/DC converter PCB inside the ROV.

2.2.2 Communication and Operating Hardware

Our ROV uses eight BlueRobotics T200 thrusters for propulsion and maneuvering. If we operate these motors at the maximum power of 350W each, we would exceed the maximum allowed current. Therefore, the power consumption of these thrusters is restricted by software. Due to the 12V operating voltage of these devices, they are connected at the 12V output of the multiport DC/DC conversion unit.

As our on-board computer, we use an Intel NUC. This computer is connected to the control station over a 25m long Ethernet cable. Furthermore, the cameras, the depth sensor, the IMU and the Arduino Mega 2560 are plugged into the Intel NUC computer. The detailed implementation of the data processing and communication is discussed in the sub-chapter 2.3. Our Arduino Mega is powered from the 5V output of the on-board power supply. The Arduino Mega is attached on a self-designed shield, which we call the signal PCB. The signal PCB makes the link between the signal cables of the electronic speed controllers (ESC) of the thrusters via the self-designed motor PCB and the Arduino Mega. Besides, the signal PCB has two optocouplers, which allow us to electronically turn on and off the electromagnets, which are used for the fish box. An other important point is that the signal PCB is connected to the signal cable of the 12V linear motor, which is responsible to open and close the grabber. We use two motor PCBs, where each motor PCB is connected to the 12V power supply and the ESCs. Therefore, the motor PCBs are responsible for the power link between the 12V power supply and the ESC and for the signal link between the ESC and the Arduino Mega.

2.2.3 Control Station

The control station is set up in a large case, which offers enough space for two laptops to control and monitor the ROV and facilitates safe transportation. There are two input and two output connections. One of the input connections provides power for the laptops as well as for the router, which enables communication with the ROV. The other one is an Anderson Powerpole connector, which provides the 48V 30A power supply for the ROV. Both inputs are equipped with large, physical switches to switch off immediately in case of emergency.

Figure 15: Control station

On the output side there are also two connections. One connects the router to the ROV, while the other port transmits the given power of 48V and 30A. A big advantage of this control station is that it can be set up very quickly. It only needs to be opened and connected. There is a checklist in the lid of this box with the most important safety information and operation procedures. In addition, there are strain reliefs on the cables to keep the control station in place.

2.3 Software

The whole software setup is built around the "Robot Operating System" (ROS). It is responsible for the communication between the different software components (nodes) running on the ROV and the ground station. For that purpose it provides a message model where each node can advertise topics and subscribe to them. ROS takes care of their correct delivery over network and additionally includes useful debug tools.

2.3.1 Onboard Control Computer (NUC)

The key component of ROS, the ROS-master node, is running on an Intel NUC mini computer in the ROV. This allows the system to stay active and functional even if the data connection to the control station is interrupted. The following nodes are also running on the NUC:

- **rosserial_server** acts as a translator between the ROS messages exchanged over network and the messages sent over a serial connection using the `rosserial` protocol. It is necessary for the connectivity of the Arduino Mega that is connected via a virtual COM port on top of USB.
- **rosbridge** provides a JSON-API for the core ROS functionality. It is the gateway for the C# based Unity control software to the other components of the ROS network.
- **myahrs_driver** is the IMU manufacturers solution to publish the IMU data to the ROS network. The IMU itself is connected to the NUC via a virtual COM port on top of USB.
- The **Simulink Controller** combines the IMU, depth sensor and control input information to calculate the desired power of the thrusters (see section 2.4).
- The **stereo_image_proc** node handles the stereo camera pair. It reads the images from the cameras, publishes them to the ROS network and additionally calculates a disparity map of them that can be used for distance estimation. To limit the CPU usage of the image processing to a reasonable level, we are using a resolution of 640 by 480 pixels. Since these images are only used for the vision tasks, the low resolution does not effect the operators perception.
- Two **GStreamer** instances handle the high resolution video streams for the operator. Our cameras have hardware driven H264 encoder onboard, such that the computational expensive video encoding has not to be done on the NUC. Since ROS does not offer a performant way to stream H264-data, these streams are running independent of the ROS network. To achieve the lowest latency possible for the operator, the GStreamer instances use a very basic pipeline: It hosts a TCP-server that grabs the data from the camera, encapsulates it in TCP-packets and sends it to the connected clients. The decoding is done later on the operator laptop in the control station.

2.3.2 Arduinos

There are two Arduinos inside the ROV, the Arduino Mega and the Arduino Nano. The Mega handles the serial communication with the NUC using the `rosserial` protocol and maps the inputs to the according GPIO pins. Depending on type of hardware it generates either PWM or digital signals. It also reads the values of the leakage sensors and publishes them to the ROS network. The software on the Arduino Mega also includes some safety precautions such as a timer that stops all thrusters when no control message arrive for longer than one second.
The Arduino Nano is responsible only for the depth sensor that is connected via I^2C. Since this sensor seems to have a bug that crashes the I^2C bus and the connected Arduino as well, it was necessary to separate it from the rest of the system. The Arduino Nano is connected over a serial connection to the Mega and sends the depth and temperature data from the sensor over this link. The Mega forwards this data over `rosserial` to the NUC. If it receives no data from the Nano for a certain time, it is likely that the sensor has crashed the Nano. In this case, the Mega, which is also connected to the Nano's reset pin, reboots it.

2.3.3 Control Station

The user interface and control station software is implemented on top of the **Unity 3D** engine in order to greatly simplify support for various human interface devices (HID) and the development of graphical user interfaces (GUI). The solution uses an adapted and partly rewritten version of the `ROS#` software libraries by Siemens AG in order to connect to the `RosBridgeServer` and thus to the ROS core. It furthermore uses `GStreamer` to decode and display the various camera streams in engine.
The key features of the control station software are:

- Fully customizable pilot input
- An extensive, customizable and reactive heads up display (HUD) with information about heading, pitch, roll and depth of the ROV
- Controls and graphical feedback to interact with the control system directly e.g. enabling the depth controller or holding a specified rotation axis
- Controls and feedback for various ROV attachments and tools like the grabber or camera tilt mechanism
- Support for the Oculus Rift virtual reality head mounted display (HMD) and therefore full stereo vision
- Connection awareness i.e. the software detects a lost connection and tries to reestablish it, all by not degrading performance by using multiple threads
- Various warning messages e.g. leaks, safe depth, etc.

The control station software has been reworked multiple times in order to work as one seamless integrated unit and fulfill the needs of various team members. Developing the control station software from the ground up allows for more flexibility and control over all important features.

Sensor Values
Sens. Depth -1.00000
Water Temp. -1.00000
Leak Safe
Real Depth -1.00000
Int. Temp. -1.00000

Tether Counter: -2

Trying to reconnect...

Figure 16: Heads Up Display (HUD).

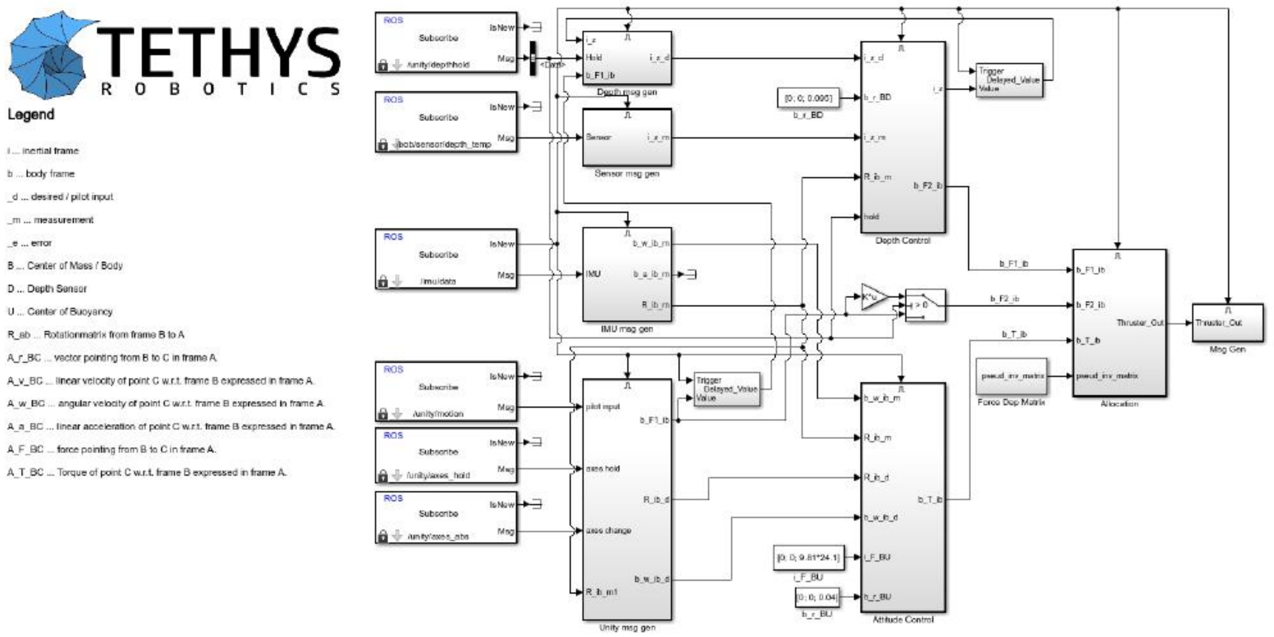

Figure 17: Simulink controller.

2.4 Control

Our goal for this ROV was to be as flexible and agile as possible. It should be able to adopt any position and angle in all directions. Therefore, we built the body and its internal components symmetrical in order to achieve that the center of buoyancy and the center of mass are coincident. This results in more instability of the system, but furthermore minimizes the torque caused by the offset of the two centers. Due to this lack of intrinsic stability the ROV requires a sophisticated controller that keeps it stable in the water. In return we get a system that is very easy to maneuver, actuates quickly and can obtain and hold every possible orientation in space.
The controller was built in Matlab with the tool Simulink. We used the Code Generator Tool to build a ROS Node directly on the NUC aboard the ROV, which runs the control algorithm. The whole controller structure is compromised of two main components. The attitude controller and the depth hold.
The main inputs for the attitude control are the IMU measurements and the desired rotation input by the pilot sent via the pilot control software Unity. The depth control depends mainly on the pressure sensor and our desired depth input sent again by Unity. There are several other messages from Unity that facilitate maneuvering the ROV.
The main output of Unity is the desired linear forces and the change of the angle which are sent as ”motion”. Furthermore, the message ”depthhold” turns the depth-controller on and off. The ”axes_hold” messages blocks the rotation of the selected axes and slows down the linear movement in each enabled direction. And if we still want to rotate with the ”axes_hold” message enabled we just need to use the ”axes_abs” message that sends the exact value of the desired angle.

The controller runs at an update-rate of approximately 60 Hz as well as most of the sensors and Unity except for the pressure sensor. It runs at 24 - 26 Hz. This lower frequency tends to cause oscillations of the ROV and therefore, a Butterworth Low Pass Filter is applied, to achieve a smoother reaction of the depth control.

Our approach for the attitude-control was a nonlinear PD controller. For the linear part, we calculate the error by multiplying the desired rotation matrix from body-frame to world-frame and the actual rotation matrix measured by the IMU. We convert the error to axis angle representation which gives us a vector and an angle. By multiplying these two with an additional gain we get the necessary torque to stabilize the system. And for the derivative part, we just subtract the desired angular velocity by the measured angular velocity of the system given by the IMU. The output gets multiplied by another gain and the result is a torque to avoid oscillations caused by the linear part.

After calculating all forces and torques the controller sends the corresponding signal to the thrusters. This is achieved by calculating an allocation matrix of the system and getting its Moore-Penrose pseudoinverse matrix then multiplying it with the forces and torques. The results of this equation are the thruster forces. But before sending them, we scale their magnitude to 70% due to the limited power budget.

3 Safety

In all our operations, the safety of our team members, other people and the environment has been our primary concern. For the manufacturing and assembly of our ROV system, we were fortunate to be able to rely on safety procedures and precautions already put in place by the workshops and labs we worked in. For all other work conducted on and around the ROV system we relied on the attentiveness of every team member. Being aware that communication is the key to a safe work environment, we strive to create a team culture where every member can voice his concerns and bring in ideas regarding safe work practices. This way we have eight people looking out for dangerous situations and furthermore mitigate those risks by direct action.

3.1 Electrical Testing Safety

When dealing with electrical circuits, dangerous situations can arise easily. Hence, our electrical team always tested the power conversion system in a dedicated lab. It provides easy accessible emergency handles coming from an emergency activation system situated above the working space, emergency off buttons, a lamp signalizing an on-going experiment and a plexi-glass cuboid dome at the working space, see Figure 18. Also, all necessary power supplies, computers, fuses and cables are in this lab.

3.2 Workshop Safety

During the manufacturing phase of parts for SCUBO 2.0 we worked in different workshops around campus and at home where team members worked on various, potentially dangerous, machine tools (e.g. lathes, CNC milling machines, drill presses, etc.). When working on these machines it was of paramount importance that the person handling the equipment was:

Figure 18: Safety precautions in the lab.

Figure 19: Safety precautions during work.

- Properly trained on the equipment
- Wearing correct PPE (safety glasses, respiratory protection, etc.)
- Wearing proper clothing footwear and no dangling jewelery

3.3 Deck Safety

The live testing of our ROV was done at an indoor swimming pool. Here we relied on the so called 'tool box talk' to ensure the safety of all team members. Before every testing event everyone got together and discussed potential safety hazards. Following, we discussed the best practices to avoid and mitigate them. Once everyone was comfortable we proceeded with the testing of the system.

4 Testing

For safety reasons, every subsystem was tested on its own before assembling and integrated testing. Testing is therefore divided in electrical testing, mechanical and assembled system testing.

Testing Electrical

All conceivable safety precautions where taken for the electrical testing. First, testing the system was only allowed having all three electrical team members at the working space, such that two were able to perform the experiments, while the third one would keep an extra eye on the experiment. As a little side-note, there were always experienced master students and postgraduates in the lab, which we could ask for help if we were unsure with anything regarding the test setup. The setup was discussed with our group supervisor before implementing it. After this, the setup was build, strictly having the power supply off and the DC/DC conversion PCB disconnected from it. From this point on, all team members wore safety glasses as well as earplugs. Then, the PCB was connected, the dome closed, the caution lamp turned on and

finally the power supply turned on.
Regarding the soldering, two members were at least required, because it enhanced the process and made it more safe.

Testing Mechanical

Our goal was to test mechanisms as early in the design phase as possible. As an example, the canon lift mechanism was tested before it actually was able to connect with our ROV. This way we were able to get early prove of concepts and make adjustments to our design. Besides the canon lift mechanism, the fish and grout box and also our gripper were tested on land. This is a very important point, since tests within the water were much more complicated and time intensive, depending on how big the tested object was. For the gripper we were doing grip and strength tests to improve the design and material. Obviously we also tested every functioning part later on in water before we assembled it, just to be sure. Small mechanisms like the servo in the camera housing were even easier to test, since it always runs in dry conditions.
During all the tests, two or more team members were required, while one was in charge of the testing itself, the other one was documenting the results, such that nothing was overseen and safety standards were followed. For tests with electrical equipment, a third person was needed to oversee the power supply and shut it off if an unexpected situation arose.

Testing the assembled system

Since the ROV design is modular, it did not take much time to test a first assembled version of the ROV. For this reason we filled a little pool (2x3x0.6m) with water next to our main lab. So it was possible to change the setup and test it within very few time steps. In the beginning most of the testing of the assembled system was used to test a bunch of attitude controllers and to tune them. Later on, as the system got more complex and we first wanted to test its functions, we build the props for the competition itself and tested things like grabbing the trash-rack in bigger pools like indoor swimming pools to get a better feeling for the competition atmosphere. Thus we always focused on early testing and tried to learn from mistakes to improve the finished system.

Troubleshooting experience

During the testing of the DC/DC PCB we noted a serious problem. The soldered 48-12V DC/DC converters were getting very hot, up to 83 °C. This could lead to serious damage inside the ROV during operation, so we had to find a good cooling solution. We tried different things, and finally arrived at heatsinks on each DC/DC converter and five fans, such that 45 °C were never exceeded.
Then, during testing of the complete ROV system, another issue arose. As we were trying out the fish dropping mechanism, we noticed that we had severe water ingress in the electronics enclosure. After long and stressful testing, our Safety Officer came up with the idea of attaching paper towels at each bulk head penetrator. This way we were able to pinpoint the leak and apply countermeasures.

5 Logistics

5.1 Project Management

After a rough draft of the project timeline, the work was mainly conducted in sprints. This meant that the entire team would meet up at the start of the week to asses the goals and tasks for the upcoming week and especially the weekly test. Our weekly test was always conducted on Thursday night. After the test there was another meeting to analyze the results of the test and compile a list of new tasks for the upcoming week and adjust our goals accordingly.

Figure 20: Gantt project management chart of Tethys Robotics

To manage the individual tasks and work packages, the team was divided into three sub teams according to the member's area of expertise and field of study. The three sub teams were mechanical, electrical and software engineering. While the subteams managed their work packages for themselves, all meetings were held with the entire team, to ensure that everyone was up to date and to prevent any problems regarding interfacing of different sub-systems.

5.2 Financial Management

The idea is to continue this and other projects in the field of underwater technology in the future. For this reason we have founded an association for underwater technology and marine research. This association administers a part of our total budget, which comes from different sponsors. Especially for this purpose we have designed sponsoring slides, where we introduced ourselves, the competition and the sponsor categories. With these categories the potential sponsor could choose whether he wanted to belong to the little, big or super fish category depending on the size of the financial, material contribution or amount of work. Depending on the category, we offered various services in return in form of advertising or other services on request.

The special thing about Tethys Robotics is that it is a research project which will be continued in the future. Therefore, the remaining part of the budget is research money from sponsors who maintain a close partnership with our student organization. How big the total costs are and how they are divided can be seen in the appendix under 8.3 Budget Overview.

6 Conclusion

'I would do it all again, but differently'. This statement by one of our team-members serves as a perfect conclusion of our project. Our team's participation in the 2019 MATE international ROV competition has been, first and foremost, a massive learning experience for everyone involved and a lot of fun. Not only did we learn a great deal of new technical skills, but also a lot of interpersonal and project management skills. After this semester, many of our team members will be looking for internships, in order to gain valuable work experience. For this process, the life lessons learned, and skills acquired during this project will certainly be of great value.

6.1 Challenges and Key-learnings

One of the biggest challenges we faced during the project, was the very short time line. Being first time competitors, we made the mistake to wait for the complete competition manual to become available before starting with major design and manufacturing work. In retrospective we would start building the base of the ROV system (e.g. Frame, Propulsion, etc.), based on earlier competition manuals, well before the manual release. We could then adjust this base and create payloads according to the tasks, once the manual is released. Another key learning experience we had was regarding the distribution and definition of work packages. During the project, there were times where members were confused or unsure towards what their current task was. In future projects, we intend to avoid this problem by defining work packages more precisely and assigning a single team member, responsible for the task.

6.2 Outlook

From the very beginning of the project we saw 'Tethys Robotics' as a long term commitment. We want to share our fascination for sub sea exploration with other motivated students and get them involved with the underwater world. That's why we hope to continue on with the project Tethys Robotics. During the development phase of SCUBO 2.0 we had many interested people contacting us and wanting to participate in future projects. Maybe we will be able to participate in next years MATE ROV competition or conduct a project that addresses a need here in Switzerland. But whatever comes next, it's certainly going to be a great underwater adventure.

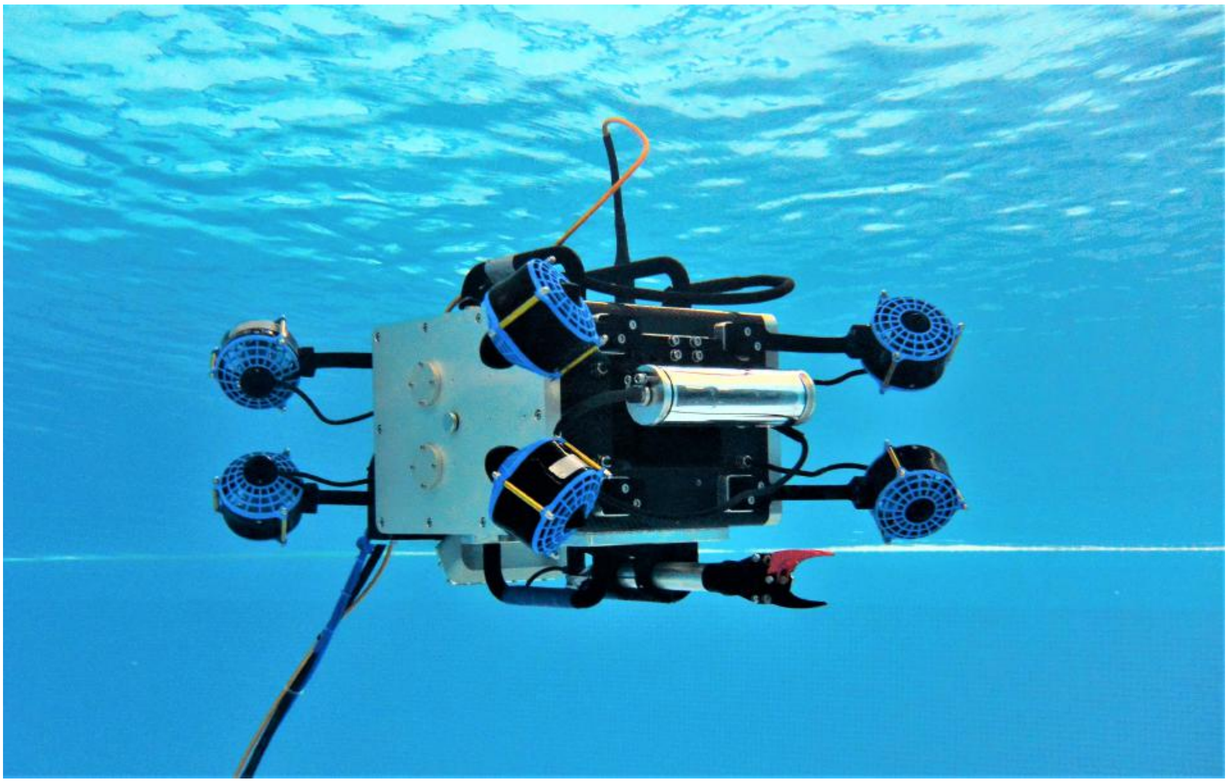

Figure 21: SCUBO 2.0 in in its natural habitat.

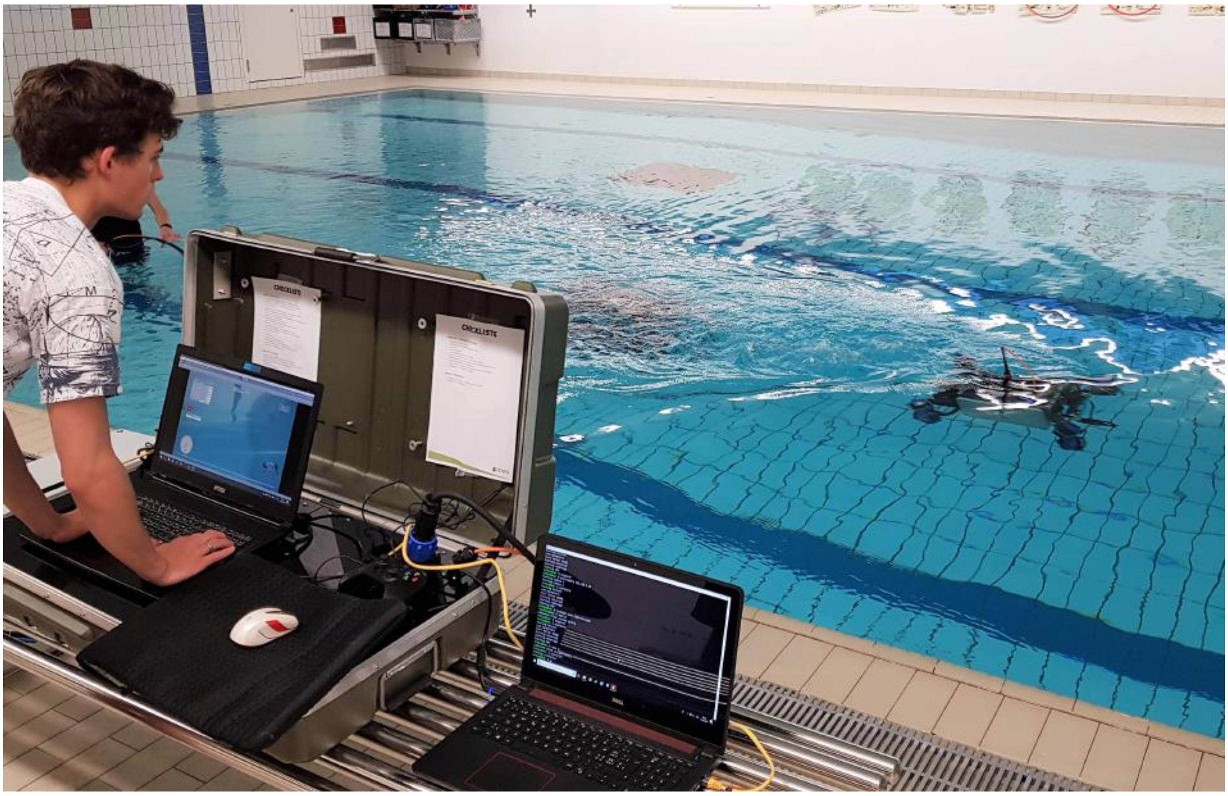

Figure 22: Team Tethys during the testing in their natural habitat.

7 Acknowledgements and References

Acknowledgements

We would like to thank the following people, institutions and companies (In no specific order):

- Swiss Robotics, our main sponsor
- Swiss Engineering for the generous financial support
- Student Project House ETH Zürich
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- Exista for a Powersupply
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- Linda Wüst for some wonderful team shirts
- Our families and friends for their support and patience
- And all other people that joined us on this great adventure, be it by sharing their knowledge, giving us advice or simply giving inspiring and motivating comments.

References

- The ROV Handbook, 2nd edition 2014, by Robert D. Christ and Robert L. Wernli, Sr.
- Handbook of Marine Craft Aerodynamics and Motion Control, 1st edition 2011, Thor I. Fossen
- Underwater Robots, 3rd edition 2014, Giancluca Antonelli
- A Primer on Submarine Modeling and Control, 2019, Yvain de Viragh

8 Appendix

8.1 Power Budget

Device	Quantity	Operating Voltage [V]	Maximal Power [W]	Total Power [W]
Arduino Mega	1	5	0.2	1
Arduino Nano	1	5	0.33	1.65
Bluerobotics T200	8	12	250	2000 [1]
Camera	3	5	1.1	3.3
Electromagnet	2	5	1.25	2.5
Grabber	1	12	6	6
Intel NUC	1	12	65	65
Servo	2	5	1.25	2.5
Ventilator	5	12	15	75
Maximal Overall Power				2156.95

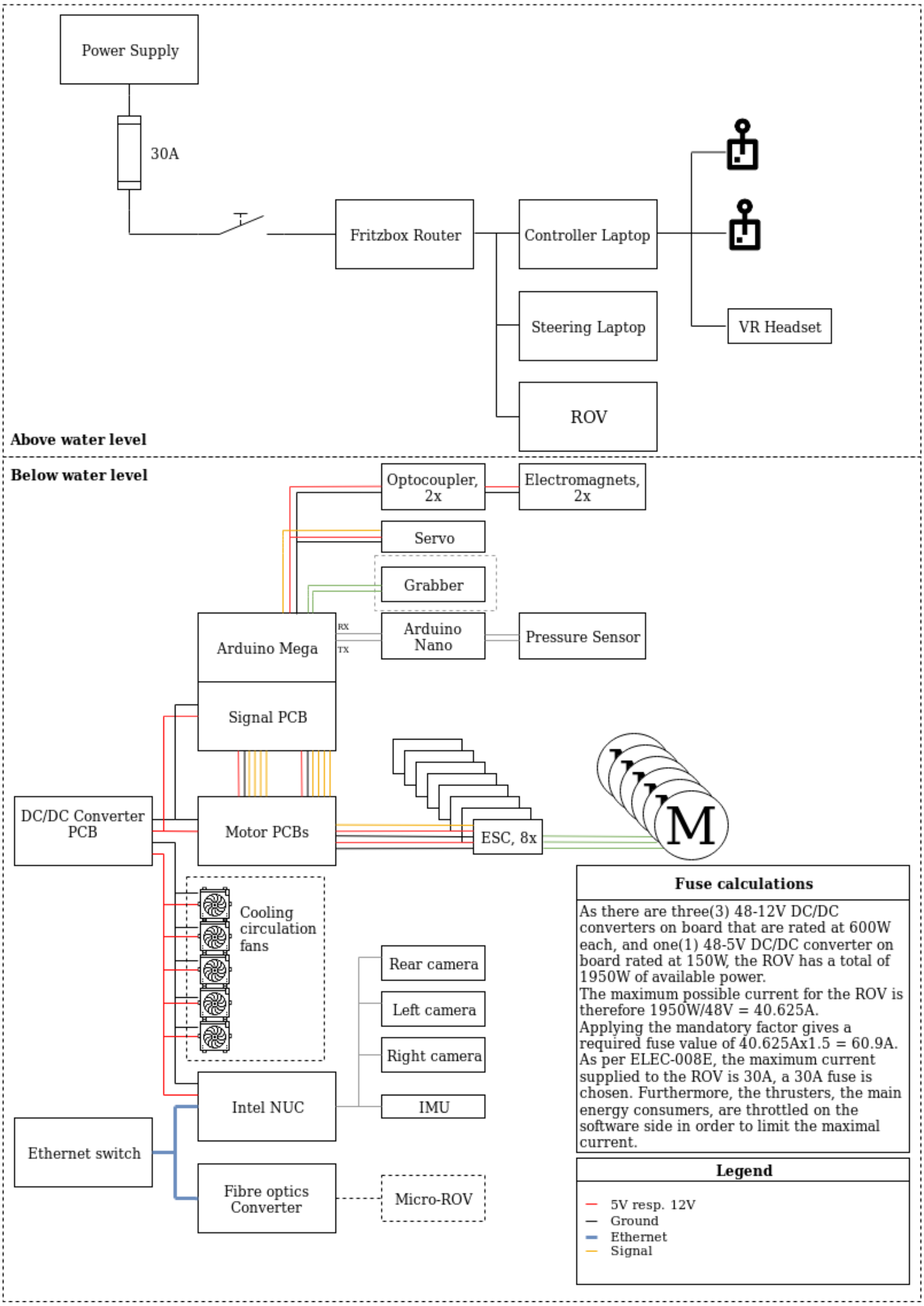
8.2 Safety Checklist

Phase	Check	Approved
Pre-Launch	Surrounding is safe. (No obvious hazards)	
	Power supply is on dry location.	
	Power cable for ROV is connected to control station properly.	
	Tether is connected to the ROV properly.	
	Fuse is intact.	
	Power cable for control station is connected properly.	
	Strain relief is attached.	
	No wires are exposed.	
	Tether is not tangled.	
	All screws of side walls are mounted.	
	All thruster guards are mounted.	
	Perform dry test. (ROV connected)	
	Cameras and grabber are working.	
	At least 2 team members launch the ROV.	
	Surrounding is safe.	
In-water	There are no bubbles.	
	Water leakage sensor.	
	Temperature inside the ROV.	
Retrieval	Power for the ROV is turned off.	
	At least 2 team members lift the ROV.	
	There is no obvious damage.	
	Dry the ROV.	
	There is no water inside the ROV.	

8.3 Budget Overview

Category	Description	Type	Cost [CHF]	Budget [CHF]	Difference [CHF]
Income	Various Donators	Donated	-	30'200	-
ROV	Electrical Enclosure	Re-used	5'000		
	Thrusters, ESCs	Purchased	1'552		
	Power Thether	Purchased	150		
	Ethernet Tether	Purchased	120		
	PCB with Capacitors and DC/DC Converters	Purchased	1'998		
	Microcontrollers	Purchased	30		
	Fiberobtics Converter	Donated	350		
	Fiberobtics Transceiver	Purchased	40		
	IMU, Intel NUC	Re-used	400		
	Connectors, Wires	Purchased	500		
	SubCon Connector	Purchased	270		
	Machined Parts	Self-made	200		
	3D Printed Parts	Self-made	300		
	Ventilators	Donated	100		
	Cameras	Purchased	320		
	Servos	Purchased	20		
	Electromagnets	Purchased	10		
	Fasteners (weight)	Purchased	300		
Total for ROV: [CHF]			11'660	14'000	2'340
Micro ROV	Electrical Enclosure	Re-used	85		
	Thrusters, ESCs, Props	Purchased	258		
	Batteries	Purchased	45		
	Fuses	Purchased	6		
	Connectors, Wires	Purchased	20		
	Fiberoptics Converter	Donated	350		
	Fiberobtics Transceiver	Purchased	40		
	Ethernet Converter	Purchased	21		
	Microcontroller	Purchased	30		
	IMU	Purchased	40		
	Camera	Purchased	10		
	Machined Parts	Self-made	135		
	Fasteners	Purchased	49		
Total for Micro ROV: [CHF]			1'089	1'000	- 89
Testing Material	Pipes, Trout Fries, Tapes, etc.	Purchased	300		
Total for Testing Material: [CHF]			300	200	- 100
Control Station	Case	Re-used	70		
	Switch, Fuse	Purchased	93		
	Connectors, Wires	Purchased	170		
	Ethernet Tether	Purchased	33		
	Router	Purchased	49		
	Multiple Socket	Purchased	12		
	Fasteners	Purchased	30		
	Acrylic	Purchased	120		
	VR glass	Borrowed	350		
	Joystick	Purchased	138		
Total for Controll Station: [CHF]			1'065	1'000	- 65
Total for Material: [CHF]			14'114	16'200	2'086
Total for Material minus Re-used Materials: [CHF]			8'559	16'200	7'641
Travel Expenses	Flights, Visa	Purchased	7'592		
	Transport of ROV	Purchased	2'500		
	Accommodation	Purchased	2'120		
	Competition Fee	Purchased	400		
Total for Travelling: [CHF]			12'612	14'000	1'388
Overall [CHF]			21'171	30'200	9'029
Overall [USD]			21'102	30'102	8'999

8.4 Systems Integration Diagrams (SID)

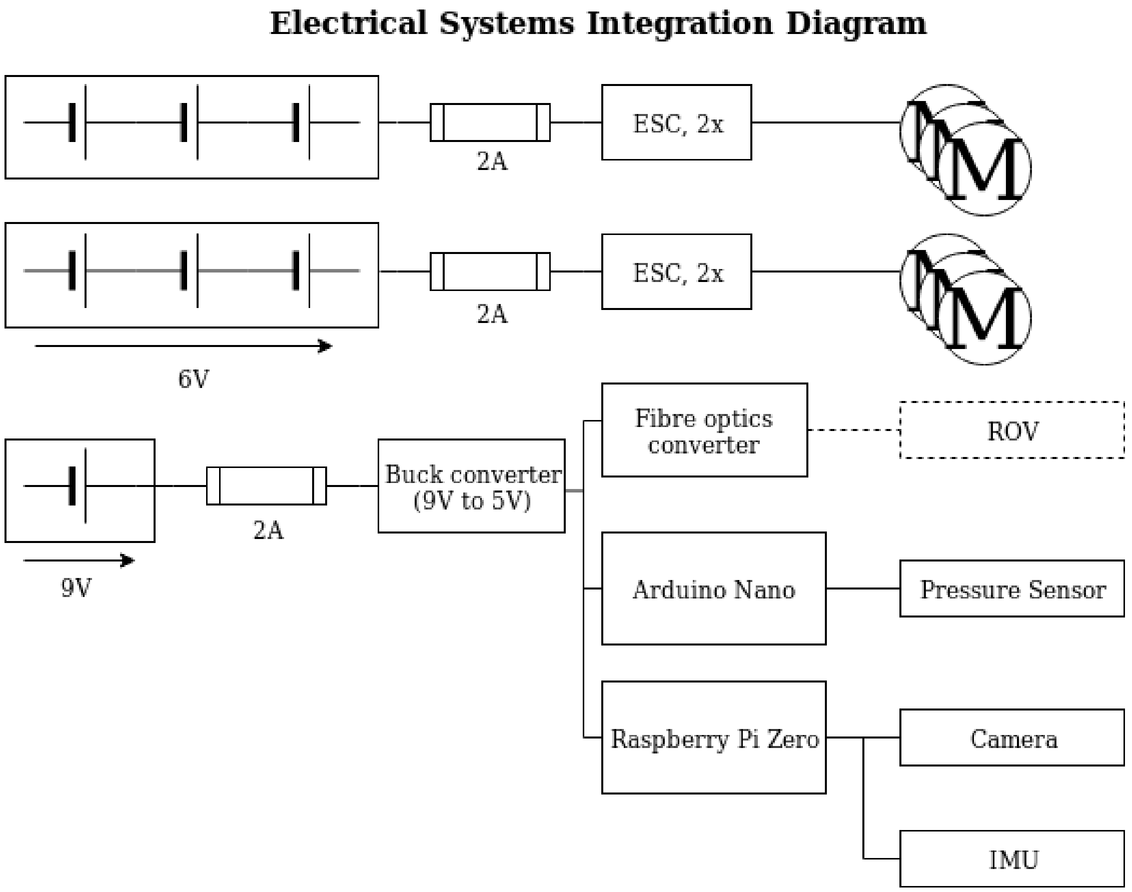


Electrical Systems Integration Diagram

Fuse calculations

As there are three(3) 48-12V DC/DC converters on board that are rated at 600W each, and one(1) 48-5V DC/DC converter on board rated at 150W, the ROV has a total of 1950W of available power.
The maximum possible current for the ROV is therefore 1950W/48V = 40.625A.
Applying the mandatory factor gives a required fuse value of 40.625Ax1.5 = 60.9A.
As per ELEC-008E, the maximum current supplied to the ROV is 30A, a 30A fuse is chosen. Furthermore, the thrusters, the main energy consumers, are throttled on the software side in order to limit the maximal current.

Figure 23: ROV SID.



Fuse calculations

The Micro ROV uses the following battery groups:
- 1 x Battery group A: one(1) 9V Alkaline battery
- 2 x Battery group B: four(4) 1.5V C Alkaline batteries in series

Since the batteries are able to deliver approximately 2A and the thrusters are throttled on the software side, two(2) 2A fuses are used at the positive terminals of the battery groups B.

For the positive terminal of the battery group A the following calculations are done:
- Pi zero: 0.2A
- Pi camera: 0.25A
- Arduino Nano: 0.2A
- Fiber optics converter: 0.4A

The maximal total current is 1.05A. Applying the mandatory factor gives a required fuse value of 1.05A x 1.5 = 1.575A. Therefore, one(1) 2A fuse is use for the battery group A.

Figure 24: Micro-ROV SID.

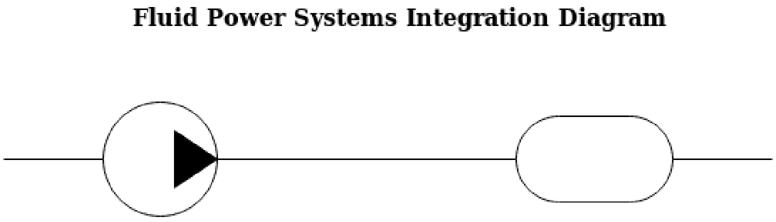


Figure 25: Fluid Power SID.