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1. Abstract

Remotely Operated Vehicles are becoming increasingly important for scientific and industrial applications. In order to extend this technology to underwater applications, the U.Stall was founded at the Esslingen University of Applied Sciences in September 2023. Its focus is to meet all possible requirements for a clean underwater environment and the preservation of biodiversity.

With our ROV, we succeeded in the development of a sophisticated robot with multifunctional tools to improve underwater missions and operations. The name Franz pays tribute to the German engineer Franz Reuleaux who was well known for using triangles in his designs.

The distinctive appearance of the ROV also offers several technical advantages, including reduced weight and the potential for fewer motors to operate the robot in three-dimensional space. The Sandwich design provides additional protection for the engines and the modular toolbox.

With an innovative philosophy in design and technology, we are confident to give scientists a valuable instrument to perform a wide variety of tasks underwater, for example observation of living beings, plants in their natural habitat, data collecting or even healing of an ecosystem.

Thanks to this extraordinary project, we as future engineers were able to broaden our knowledge and put our diligence and determination into the goal of creating a better environment for humanity.

Figure 1: U.Stall- Team

2. Design Rationale

2.1 Goals for the project

The goals we set for our ROV and thus for our final product are the requirements listed below:

Reliability: Establishing a basis for future team members with robust mechanics and durable, modular electronics.

Testing Capabilities: Given our team's lack of experience in underwater robotics, both in building and operating ROVs, maximizing testing opportunities is imperative for driver training and commissioning.

Speed/Agility: Balancing speed and agility are crucial for navigating narrow passages and executing precise maneuvers, necessitating a stable ROV design.

High Quality: Striving for exceptional quality in manufacturing and engineering practices to ensure the longevity of the ROV base.

Modular/Easily Expandable: Designing a modular system that facilitates easy adjustments and flexibility, allowing future university teams to enhance the ROV from its base state without needing to troubleshoot basic motor or communication functionality, enabling them to focus on developing and refining autonomous capabilities and other details.

Knowledge Transfer: Through documentation of all components to facilitate seamless knowledge transfer to subsequent student teams, enabling them to pick up where we left off efficiently.

2.2 Design Evolution and problem solving!

Established in late September 2023, our journey began with the ambitious goal of designing our first ROV to compete in the MATE ROV competition. Starting literally from scratch, we embarked on an extensive design deliberation process. We commenced by carefully dividing up the fundamental components of an ROV and carrying out collaborative brainstorming sessions to explore diverse realization opportunities. Operating in small groups, each assigned specific assemblies, we created a plethora of ideas, generating a minimum of three concepts per group. Our deliberations prioritized factors such as reliability, cost-effectiveness, manufacturing feasibility, quality assurance, weight considerations, and development timelines.

During our designated Design Weekend, each group showcased their proposals and the data and facts, inviting constructive feedback and holding comprehensive discussions. It was through this collaborative effort that the concept of our inaugural ROV, affectionately named Franz, took shape. Concrete design decisions were made when we started with our accurate design of mechanical components using the CAD system, AutoCAD Inventor. Simultaneously, we designed electrical PCBs using Altium and created the framework for the software architecture. For detailed design problems we did reviews on the designed components and gave each other feedback. Subsequently, our focus transitioned to the manufacturing phase, where particular attention was taken to every detail of assembly production.

In the next chapters we give an overview of our ROV-components and the manufacturing process, providing insights into our commitment to excellence at every stage of production.

2.3 Decisions new vs. buy

As a first-year competitor, we had simply no existing concepts, hardware, or materials. With natural limits in manpower, we decided as a group what parts would be our highest priority.

With our unconventional triangular shape, we had no access to many commercially available products, so we had to design and manufacture them ourselves. In the electronic department, we tried to use a simple but powerful platform, so we focused on integrating bought parts to work with this platform. For more detailed information regarding some details, see the section overall vehicle design.

3. Overall Vehicle Design

3.1 Frame

Mechanical Design:

For our first try in the pioneer class with a 48 V system, we decided to construct a new design from scratch. The main goal was to create a very agile and mechanically stable ROV-design. Flexibility was another important aspect in terms of the different use cases it must be operated. For this reason, we concluded that a multiple layer system would be the optimal choice. Our ROV consists of three layers with buoyancy as first, main frame as second and the tools layer as third. The idea behind a separated tools layer, or "tool sled", is a smart way to be able to change out different tools in a short amount of time by just changing the whole sled. Therefore, there is no need to deconstruct the rest of the ROV. The frame layer accommodates the motors and the electrical box. By the name, one can already tell that the first layer will be used to keep the ROV stable in the water by adding just enough buoyancy, so it won't tilt, sink, or rush to the surface without using the motors.

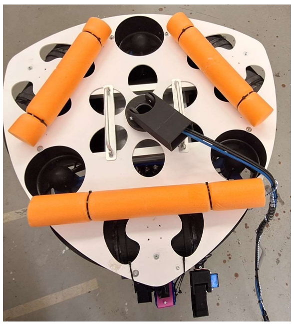


Figure 3: Layer 1 buoyancy

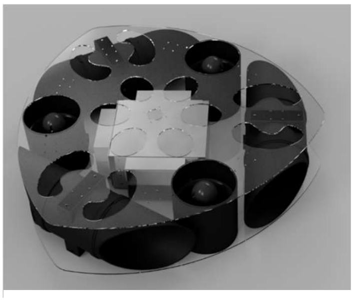


Figure 2: Layer 2 Thruster and basic electronics

The "Rouleaux's" triangular shape of the ROV is another smart feature we added to not only save weight but also reduce the number of motors needed to six to operate the robot in three-dimensional space. It also gives the ROV an unusual and unheard-of design.

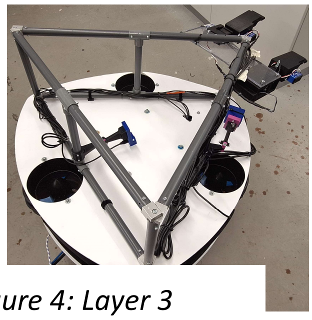


Figure 4: Layer 3 Toolsled

Manufacturing Process:

By implementing the “layer system” we get easy excess in little time to all important parts of the ROV, which also helps with the assembly. The frame layer is sitting in between two plates like a sandwich. These plates are made of PVC and acrylic glass for their light weight, flexibility, and stability traits. The motors are secured in 3D-printed tubes, which hold the two plates together, to give them a more streamline thrust. The electrical box is sitting in the center of the ROV and is made of cast aluminum.

20 mm PVC-pipe together with CNC-milled aluminum fittings are used to create a stable and light-weight tool sled. The sled is connected to the frame by 3D-Printed clamps and Velcro strips so it’s easily removable.

3.2 Propulsion System

Due to our clever triangular design, we only need 6 thrusters instead of the 8 required for rectangular ROVs to move in all directions and along all axes. This makes our ROV not only energy-efficient but also weight- and cost-efficient. Additionally, we can move the ROV in any direction, position and in any possible plane without needing to rotate or turn it beforehand. This results in easy navigation to mission tasks. For this, three thrusters are mounted horizontally at the corners and three thrusters vertically on the sides of the triangle, as shown with the black 3D-print pipes in the render image. We use thrusters from the "T500" series by "Blue Robotics", which operate efficiently and provide enough power to bring the ROV to its target quickly and safely.

3.3 Buoyancy System

To ensure that the ROV does not sink to the bottom in the event of a motor failure, floating noodles are attached to the ROV. The floating noodles provide enough buoyancy to ensure that the ROV always moves towards the water surface. However, the buoyancy should only be slightly greater than the downforce. This ensures that no great force must be exerted when descending.

3.4 Tools

Gripper

The gripper assembly is essential for the ROVs functionality and its sole purpose. The grippers are necessary for the ROV to physically interact with its surroundings and a solution to complete the tasks of the Product Demonstration.

The Grippers are designed to temporarily connect to items of the Product Demonstration that need to be moved by the ROV in any way. Additionally, the gripper assembly is designed to do be as fitting for each task as possible and at the same time versatile enough to as many tasks of the product demonstration as possible. Another aspect to consider is that the gripper assembly must allow for some steering errors, both on the durability side and on the tolerances the driver has, to still be able to grip the target at first try.

The assembly consists of three single grippers, which are all mounted beneath the ROVs body on the tool sled. All grippers are actuated by electric servo motors. The reason to use electrically powered grippers is driven by three factors. First, to reduce the weight of the tether to the surface, which would be a lot bigger and heavier if hydraulic actuated grippers were used. Second, remove the risk of a leak from a hydraulic system, with the negative environmental impacts. Also it is very difficult to make a hydraulic system that can achieve the probiotic valve task, therefore it is not practical to use multiple actuation systems. The third reason for the team to use electrically powered grippers is the increased flexibility and modularity compared to hydraulics and the even greater accuracy which is achievable with a digitally controlled motor.

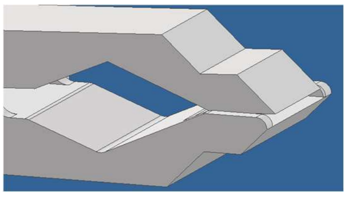


Figure 5: Front part of Gripper

The gripper assembly consists of three different grippers. Two of them are located on the front of the ROV and are designed like a pair of pliers. The front part of the pliers is designed to fully contact, to be able to grab smaller things like cables or hooks. Behind that is the part of the pliers, specifically designed to grab PVC tubes. That is, because all tasks in the 2024 Product Demonstration either need to grab a smaller tube-like object (cable, hook etc.) or a PVC tube. That way the gripper can grip all competition items with the same gripper.

There are two grippers needed in the front of the ROV, for multiple reasons. First, there are objects like the Float that need to be connected to the ROV in a stable way with two gripping points. This is necessary because of the relatively great mass and drag in the water of the Float device. The delivery of the float is valued high for the team because of the 70 Points the task is valued and the fact that the team has a fully functional Float. The other reason to put the grippers in the front is that there is enough space to grab taller objects like the valve to activate the probiotic irrigation system.

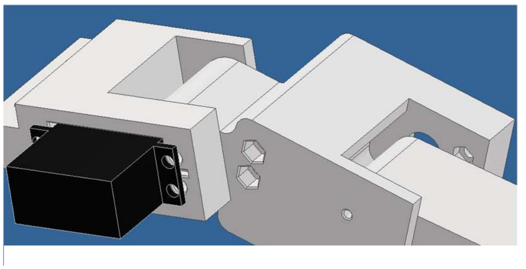
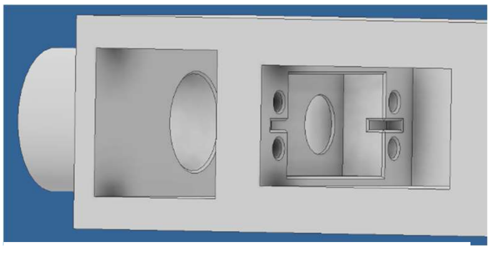


Figure 6: Gripper moveable downwards

The two front grippers are also moveable. One can be angled downwards to grab objects from the top like the Smart Cable or the Smart Cable Repeater. Another reason for that is, so the gripper can make space for the other gripper to grab larger objects.



Figures 7: Gripper adjustable part 1

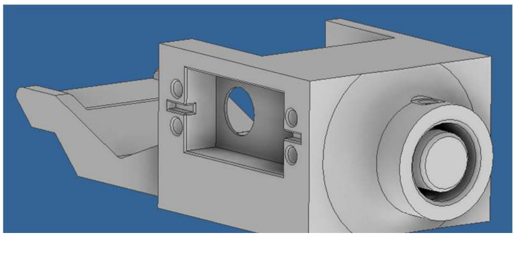


Figure 8: Gripper adjustable part 2

The other one can rotate around its longitudinal axle 360° to turn the probiotic irrigation valve and be able to grab vertical tubes like the branch corral or the acoustic receiver. The grippers are made of 3D printed PLA, because it is an easy and cost-effective way to build the grippers in the desired shape and size. Most importantly it allowed us to integrate the servo motors in an efficient and suitable fashion into the grippers structure.

Innovative Gripper design: For all smaller objects laying on the ground or other things these two grippers cannot grip, we found some inspiration in our own evolution. Our hands are perfectly optimized to grip and handle all objects of daily life. We thought: “Why don’t we try to copy them?”. And so, we did. Our gripper for small things consists of “three fingers”, which are actuated by a servo inside the housing. The finger itself is connected to the motor via a drive shaft, that pulls a string running to the fingertips from the inner side. The strings on the outer side of the gripper are prestressed by a spring, that is also located inside the housing. The main purpose of the spring is to pull the “finger” back into an upright position after the drive shaft has released its pull to reopen the grip. As mentioned above we tried to copy as many parts from the human body as possible. The whole mechanism of actuating the gripper functions just like the tendon in your own hand that actuates the finger. Of course, it is much more simplified, but the core function stays the same.

The housing is built from classic 3D printed PLA to keep costs and weight down. For all parts directly engaged in the mechanism, 3D printed PLA would not work that well because its surface is too rough for good sliding properties in the joints. That is why we went for 3D printed resin. Firstly, its surface is much smoother and secondly resin is not as brittle as PLA is. We also printed the front of the housing from resin for two other reasons: Firstly, threads in resin are more sustainable than those in PLA, secondly resin is transparent to some degree. As a result, you can look inside while the gripper is operating.

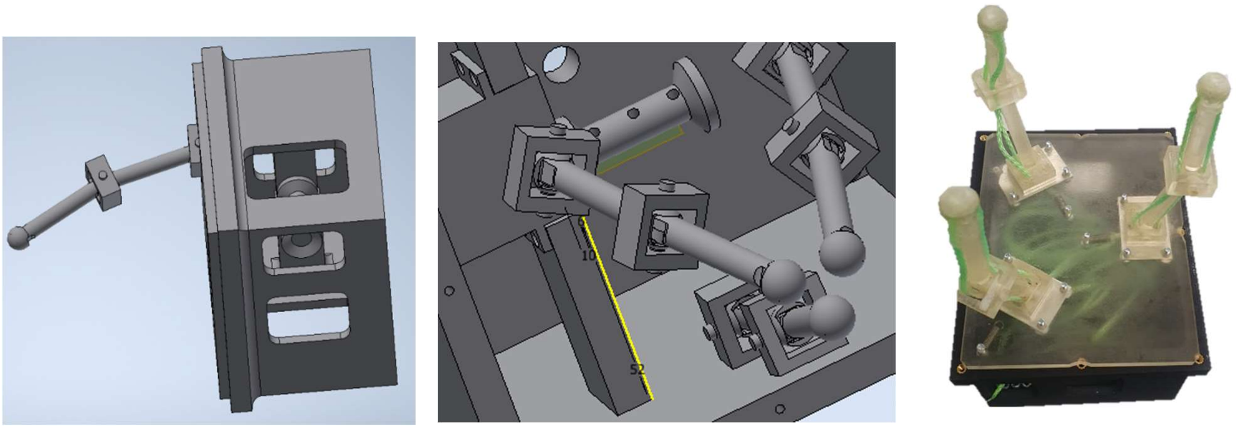


Figure 9: different views of the innovative three finger gripper; right: completed gripper

Improved and self-designed recovery hook
For the recovery of the coastal pioneer array in task one the team needs to attach a carbine to it. This single task is rewarded with 20 Points while not being very time consuming. Therefore,

we paid special attention to solve this task. The main difficulty is to attach the carbine, which is why we redesigned the recovery hook.

It is designed with the intention of hook attaching automatically to the latch of the coastal pioneer array up on contact. To achieve this the hook is pretensioned with one or two springs and is held open with a rod in the middle. As soon as the latch of the array comes in contact, with the rod, the two arms of the hook snap together and attach the recovery rope with the coastal array. The nose of the one arm prevents the hook from sliding of the latch, if not properly closed. The spring keeps the hook closed and prevents it from reopening unintentionally.

The hook is self-designed in CAD and 3D printed to make production simpler and more cost effective. Through holes in the base block, the hook is easily attachable to a PVC tube. With that tube the hook can be placed securely in the gripper of the ROV.

Camera System

For our cameras we used USB-camera modules, as they are quite cheap and do not contain any extra features we do not need. Additionally, the connection to our Raspberry Pi is quite easy. As the electric shields and the camera lens are not waterproofed at all, we waterproofed them using a self-designed 3D-print and epoxy resin. In our first approach, the black one, we did not waterproof the lens and it got wet. That's why we evaluated some improvement ideas in the team and decided to make a second version – the blue one. First we laser cut a quadratic acrylic glass with a hole in it. Then we glued the lens on the acrylic glass. Epoxy resin is filled into the housing and the wire of the camera can be guided through the hole. Our concept provides three cameras with a perspective up to 160°, which means there is a possibility for a complete all-round view around the ROV. Different positions were evaluated with the ROV-Simulation provided by our software department and later, on the complete real ROV. One special feature is the camera mounting on an articulated arm, connected to the tool-sled, so it's easy to adjust the camera position to meet the wishes of the operator. One of the cameras is positioned to look to the front, and the others focus on the gripper from different angles. That enables us a precise control of the grippers in every task. The cameras are connected to a Raspberry Pi, which ensures the communication to the operation station for camera view and control.

Figure 10: different waterproofing designs for the cameras

Sensor selection and requirements

Our main goal was to drive precisely and reliably. To achieve precise control, we implemented an angular and position controller and a flotation depth controller in software. To measure the angular position, we do use an inertial measuring unit with an extra low drift and a high sampling rate of up to 6.666 Hz. For depth control, we use an absolute pressure sensor with a maximum range of 100 kpa, which would be equivalent to a depth of 10 m under water. The competition demands a temperature measurement of the water. Therefore, we’ve chosen a PT100 resistor. We chose the PT100 to save money with the sensor and evaluation electronics. In comparison to thermocouples, a PT100 has better sensitivity, and in comparison to an NTC, its transfer function is linear

3.5 Electrical System

Concept – Keep it flexible.

Keep it flexible – as a goal for the whole Electrical subsystem. This should help us to create an ROV base with the possibility for future teams to change the tools easily. To reach this goal, we designed a system, that…

- Is easy to understand, so future teams can focus on the improving process and not get stuck in old structures.
- Is modular to keep adding and removing additional features possible, depending on the competitions’ tasks.
- Is reliable and testable, so developing gets faster and easier.

In the following chapters we will explain the functionality of the whole electric concept.

Overview

The whole system can be divided into some subsystems on different layers. The two decentralized main systems, the topside control station and the ROV-Underwater-Box communicate via MQTT with each other. In general, the tasks of the topside control station are controlling, logging, showing cameras and doing calculations for the pool actions. The tasks of the ROV-box include the execution of Thrusters, Mapping the USB-Cameras on MQTT and the reading the sensor data. Both subsystems work on their own as one single self-contained system. Via software and the connection with the Ethernet communication both systems are then linked together to one big system. That leads to an extreme flexibility in adding features, sensors, actors, or control elements, as the tether does not need to change. Another advantage is the simplification of the testing procedure. By testing the single subsystems on their own and then joining them, it is more likely to quickly find out the occurring issue and how to solve it. Further downwards the subsystems get smaller. They are all designed to be added or removed as one single module or system.

Topside Control Station

The Topside Control Station is kept very simple. A Laptop deals as our main component with the software. It is shows our Graphical User Interface, descripted in section: Software, and the camera feed. The laptop is connected to a monitor via an HDMI-Line. An X-Box-Controller deals as a control

Figure 11: Topside Control Station

device of the ROV. It is plugged into the laptop via USB.

ROV-Underwater-Box

The underwater box is designed to carry out all instructions of the signals from the control station. We used only one underwater box for all electronic parts, as only one needs to be waterproofed. For a housing we chose an aluminum box as it is usable as a heatsink for the electronic components. The heat can be ideal transported to the outside and then to the cool water. When the housing arrived, we noticed that because it is a cast part, there are demoulding draft angles. To ensure that the sealing ring of the PG-joint contacts the housing level on the surface, we gave the housing to a manufacturing workshop to get it professionally milled in the correct angle. Unfortunately, we got it back with leaning threads. To ensure that it is a completely waterproof, we filled a frame with epoxy resin for three millimeters.

Figure 12: epoxy resined frame

The electronics itself is designed very modular. It consists of self-designed PCBs. All of them fulfil specific tasks. The connection between the different PCBs is made via a backplane, to ensure easy wiring and reliable connections. On the backplane we used different sizes and positions of connectors, to ensure the correct mounting of each PCB. Additionally, there is an arrangement of pin headers to mount the STM32H743 NUCLEO board, that is responsible for all PWM signals of the motors, and the sensors signals. The other embedded controller, the Raspberry Pi, is located over the STM and connected via UART wires. A big advantage of the modular System is that we can keep the basic shields and only need to change the ones that are responsible for sensors (SCU) and the tools (TCU) like grippers, lights and everything that changes over the years, when future teams need to adjust to other tasks. In the following sections we describe the self-designed PCB-modules a bit further:

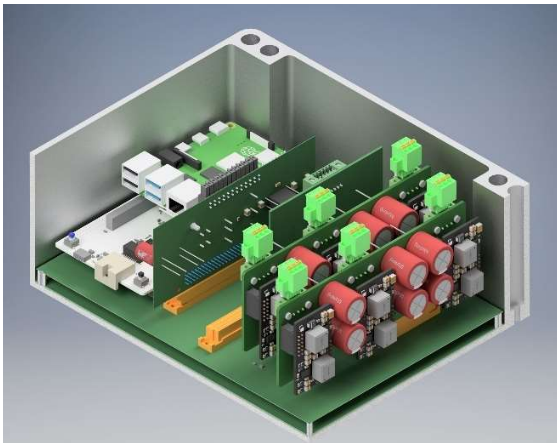


Figure 13: Complete E-Compartment

Power Distribution Unit (PDU):

The power distribution unit provides power for the whole system with different voltages. It gets the 48Volts from the tether and converts them into 5V/6A and 3,3V/1A used for sensors, microcontrollers, and servo motors.

Motor Control Unit (MCU):

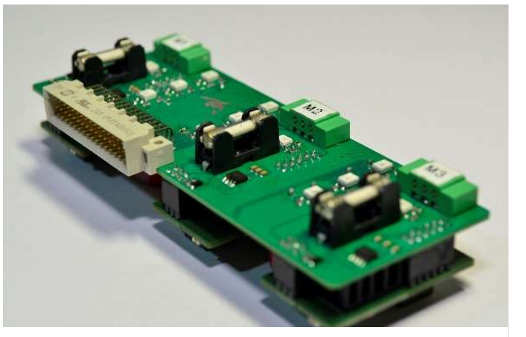


Figure 14: MCU front

The MCU is responsible for the power conversion of the thrusters and is a self-designed buck converter. The goal was to get a small package and high-power density. The chosen IC limits inrush current and has an adjustable rise time to decrease EMC. The unit consists of two main PCBs each with three small motor shields on it. The shields convert the power supply to 22V. The shields could provide a maximum of 12A each that would lead to a thrust of 7kg per motor. On the main shield where the little motor shields are attached one can measure the current, it secures the little shield via a fuse and one can also detect the fuses state. The green LEDs show a proper voltage output. The reason for using a main board and smaller shields was that one can exchange the shields quickly, if there is an error during testing period. To get a good connection between the motor wires and the shields, we use connectors that are secured by screws on the shield itself and via the plug and receptacle as well.

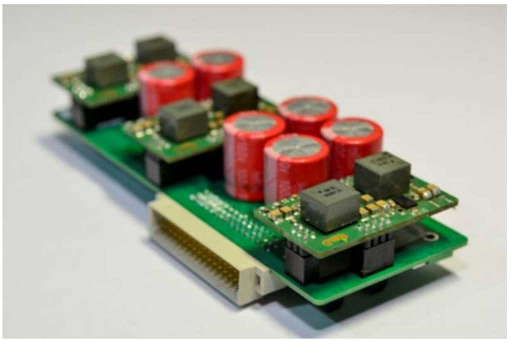


Figure 15: MCU back

Sensor Control Unit (SCU):

Important Components:

- MAX11210 24-Bit analog-to-digital converters
- LM4040 2.5V voltage references
- ASM330LHH adapter board, 6-axis accelerometer and gyroscope

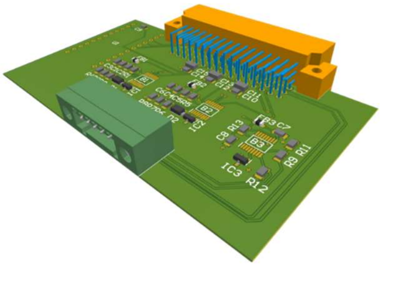


Figure 16: Sensor Control Unit

General Description:

The name of the Sensor Control Unit is not to be understood literally, it has pure signal processing purposes. The SCU design aims to be as multifunctional as possible when it comes to reading all kinds of sensors. Therefor it features three analog-digital converters (ADCs) with appropriate measuring circuits. Two of the ADCs are for measuring 4-20 mA sensor signals, which are common in industrial sensors like hydrostatic pressure sensors

Figure 17: Sensor Control Unit 2

for instance. The remaining ADC with its circuit is for measuring anything that changes its ohmic resistance, as in our application a PT100 temperature sensor.

Current Measurement:

As mentioned, we are using high resolution ADCs to detect a 4-20mA sensor signal. The circuit diagram below shows the application of the current measuring ADCs. The current signal of a sensor flows through R6, R7 and R8 to ground, the fully differential analog inputs of the MAX11210 are connected parallel to R8, so the flowing current can be calculated theoretically with the voltage drop on R8.

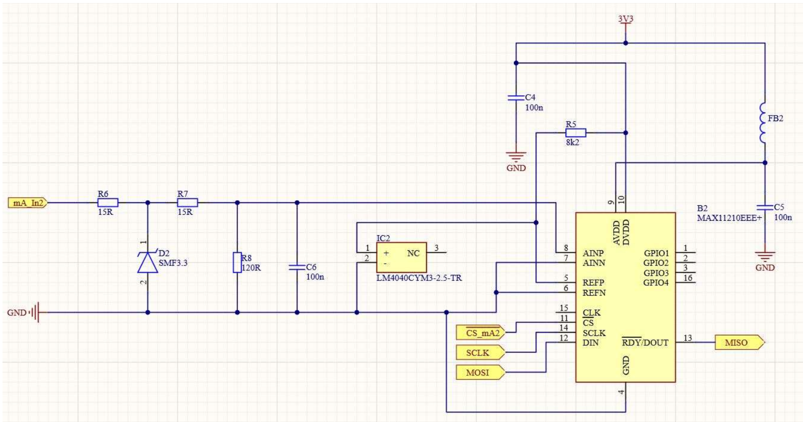


Figure 18: Circuit of one current measurement

Resistance Measurement:

Detecting changes of resistance is still state of the art in sensory, for example in strain gauges or as in our application a PT100 for temperature measurement. For this purpose, we are going with a typical Wheatstone bridge. As should be known, the unknown resistance can be calculated with the potential difference between both sides of the bridge. To detect this voltage, we are using the same ADC as already mentioned in the current measurement.

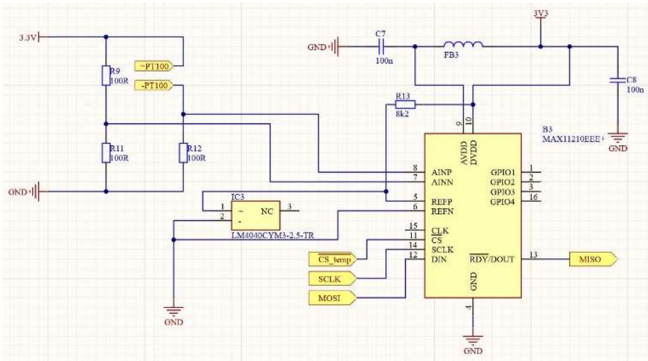


Figure 19: Circuit of the resistance measurement

Inertial Measurement Unit (IMU)

As an IMU we use an adapter board with a ASM330LHH from STMicroelectronics. It is a 6-axis inertial module with 3D accelerometer and 3D gyroscope. This gives us the possibility of better control and other software-based motion optimization, such as wave and flow compensation for example. It features communication with SPI and I^2C.

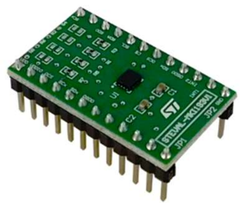


Figure 20: IMU

Tool Control Unit (TCU):

The tool control unit deals as a shield to provide power and signal to all of the tools that are used in the current ROV. In this year we only have gripper, so there are only the power lines and the

PWM lines used. But others such as normal GPIO-Inputs or Outputs, SPI or I2C-Connections to the NUCLEO are provided.

Issues on the Electronic Shields:
Unfortunately, when testing and troubleshooting the PCBs we got a lot of different issues and as the additional cable wiring got too much, we decided to make a second revision of the Electronic-Box.

Following where the issues of the original version:

- MCU - chips got too hot and blew up when using the desired power, much less power was not an option.
- Misrouting in some of the PCBs lead to much of additional soldering.
- PDU – schematics did not work out and we needed more total power to keep the raspberry Pi running.
- Wiring can be improved and placed further to the regarding PG-joint.

Underwater Box 2 Improvements
As the previous concept had its benefits in flexibility we had to work on its limitations and a more structured and dedicated hardware was needed to fulfill the needs of our companies ROV2024.

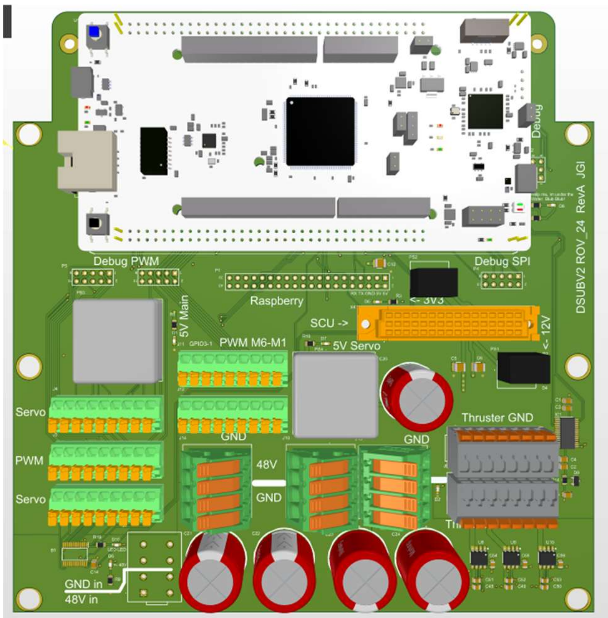


Figure 21: Version 2 of the Electronics Compartment

Needed modifications would result in a rework of several boards and therefore the new and more centralized board results in less redevelopment effort and handles many more wire to board connections to reduce cable splices within the Underwater Box. This major change allows for worker building a ROV2024 to follow a straightforward wiring plan and therefore minimizes errors in construction.

Following features were implemented in the Underwater Box 2 from testing feedback by our engineers:

- **Straightforward wiring** without splices.
- **5V** Power Supply capabilities have been **doubled** from 6A to 12A to separately supply:
  - Critical Power: Raspberry + Cameras + Nucleo Board (6A)
  - Mission Power:Servos (6A)
- **Current Sensors** for all actuators
  - Shunt based current sensors for all servos to estimate the grabbing force.

- Hall effect current converters to measure higher currents of the thrusters to eventually limit power draw if the limits of the 24V Supply is reached.
- Additional **fuses** for individual mission servos to limit compromise during a mission.
- Direct Wiring connections for the **Raspberry** board to encompass a direct UART communication with more reliable wiring connection.
- **Debugging headers** to interface all digital communications to allow easy software implementation and debugging.
- More **Signal LEDs** to allow for faster problem solving when any production issues occur.

We are confident that these improvements will result in a more fleshed out ROV and will result in great mission performance.

Tether Design and Tether Management System

Goals to design a tether are to reduce the drag force of the tether cable due to water movement, waves and underwater currents, but also the tether´s weight itself. This makes it essential to control the negative buoyancy of the tether. Therefore, the negative buoyancy of the tether must be controlled by selecting suitable materials for the tether. Moreover, entanglement of the tether cable to the ROV or underwater obstacles must be avoided. As well as have a look at a good strain relief and not too much voltage drops (decision of a proper length and cross section). Our tether consists of:

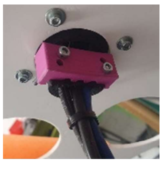


Figure 22: strain relief 1

- Two AWG10 wires for the power supply
- one Ethernet cable

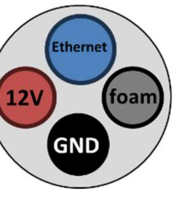


Figure 23: Tether cross section

It is about 15 meters long, according to the competition rules we did the following calculation to estimate the length. According to the manual:

$$maximum\ Pool\ depth: 4m$$
$$maximum\ ROV\ distance\ from\ side\ of\ the\ pool: 10m$$
$$product\ demonstration\ station\ from\ side\ of\ the\ pool: 3m$$
$$minimum\ Tether\ length = \sqrt{4^2m^2 + 10^2m^2} + 3 = 13.77m$$

The cross-section is sufficient for the cable not to heat up beyond a critical temperature threshold. In addition, it lies in the water most of the time and is cooled again here. However, this cross-section was chosen bigger, to keep the voltage-drop as low as possible. For protection and to keep all the lines together, we used a spiral cable wrap. A self-designed strain relief helps to ensure that all cables going out of the ROV are securely fastened to the frame. A self-developed cable guide on a bearing base helps to ensure that the tether does not affect the direction of travel of the ROV. To ensure a reliable and durable assembly the bearings in the cable guide are made of PVC and glass balls. Both solutions would not be possible to buy as such an individual product, so we decided to make it by ourselves.

Figure 24: cable guide

Additionally, we added pipe insulation along the tether to keep it on the surface. This made the Tether naturally buoyant by calculating the correct diameter for the pipe string.

In general, we have paid particular attention to good cable routing that is close to the frame, so that we do not get stuck when operating the ROV.

3.6 Software

Concept – Keep it modular.

The software is responsible for fusing both subsystems, the upper and the lower electronics. The main goal was to do it in a modular way, as that improves maintenance possibilities as well as the possibility to work on it in a team. With this modular structure it is easy to include new members and transfer tasks to new groups. We use three subsystems that communicate with each other: The Graphical User Interface (GUI), the raspberry Pi and the STM32H743 NUCLEO board

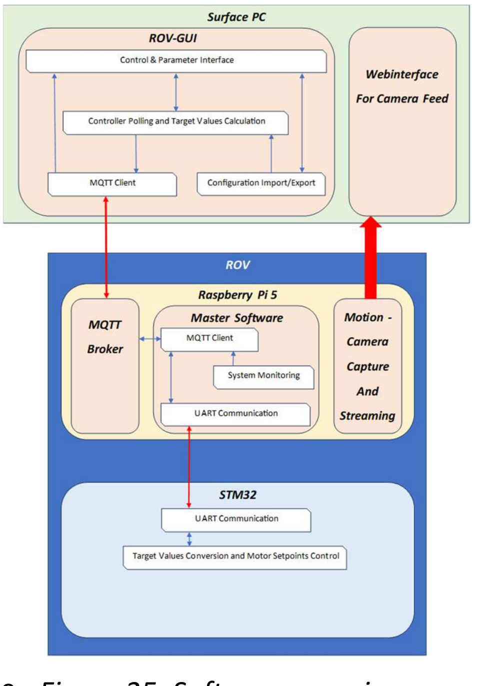


Figure 25: Software overview

GUI, Control Algorithms and Simulation – For a precise controlling

As MQTT plays nowadays a crucial role in Industrial Automation with real-time constraints, we thought to use it as our base for the Communication between the ROV and the Laptop used to control it. With the "ROV-GUI" as the centerpiece, a Windows-Forms App, it polls controller Input, calculates the Motor/Grappler Values and sends it to the MQTT-Broker residing on the Raspberry Pi.

The philosophy of this approach is to implement an easy yet feature-rich in-house tool to accommodate on-the-fly parameter tuning and sensor monitoring. This also placed value on fast startup and low resource usage.

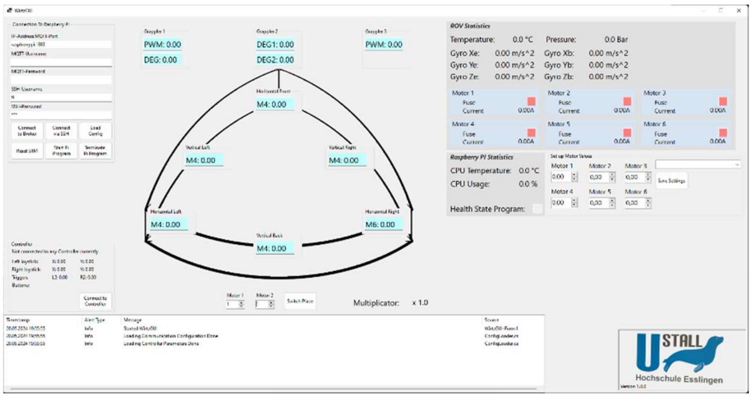


Figure 26: Main window of the ROV-GUI

In the early stages of development, we decided to implement a simple simulation of the ROV to test our unique approach. Making use of the Unity Engine and MQTT, the simulator helped implement the right parameters and test the latency of controlling the model.

Later, we also used it for Pilot training since it provided a realistic model of ROV behavior in the water.

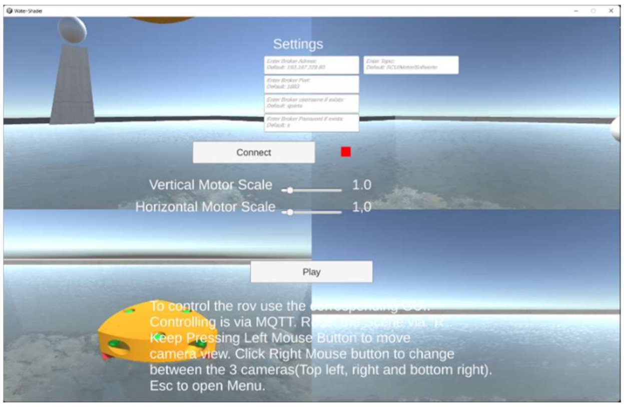


Figure 27: Main window of the ROV Simulator

Raspberry Pi

On the ROV itself, we decided to send the motor values to the raspberry itself then pass it via UART to the STM32 responsible for controlling the whole system. This removed the need for a switch which saved valuable space on the ROV, as a switch requires a lot of space.

The Raspberry Pi serves two distinct roles in this setup. Firstly, it acts as an intermediary between the Graphical User Interface (GUI) and the STM, which handles motor control. In this capacity, the Raspberry Pi intercepts incoming data from the GUI, scales it, and transmits it via UART to the STM. Simultaneously, it receives sensor data from the STM, monitors system information on the Pi itself, and relays it back to the GUI using MQTT.

The second role of the Raspberry Pi involves capturing and streaming camera feeds to a laptop through a web interface. This is achieved using the Motion software and its integrated features.

STM32

The STM32 is responsible for several key tasks such as thruster PWM control, servo PWM control for our gripper motors or sensor data acquisition as it reads the values from our various sensors, including the IMU (Inertial Measurement Unit), pressure sensor, current sensors, fuses states, and temperature sensors. This data is vital for the real-time monitoring and control of the robot and ensures that we can use our safety features.

The decision to use an STM32 microcontroller instead of relying solely on a Raspberry Pi is based on several factors:

- **Real-Time Capability:** The STM32's ability to perform real-time processing makes it suitable as a smart actuator for autonomous tasks, ensuring timely and accurate responses.
- **Extensive Peripheral Support:** The STM32 offers more peripherals, which are better integrated and perform more efficiently compared to those on a Raspberry Pi.
- **Cost-Effectiveness:** Despite its advanced capabilities, the STM32 remains relatively inexpensive, adding minimal additional cost to the project.
- **Sufficient Computational Power:** The STM32 has enough processing power to implement various control algorithms, including those for position, plane, and altitude control.
- **Multiple ADC Channels:** It provides numerous ADC (Analog-to-Digital Converter) channels, which are crucial for continuous monitoring of current and other sensor values.
- **Ethernet Communication:** The microcontroller offers the option to communicate via Ethernet, enhancing its versatility and integration with other systems in future.

The software architecture on the STM32 is divided into three main components:

- **Base Software:** This includes drivers for the chips and other components within the control box, forming the foundation of the system's software stack.
- **Application Software:** This layer consists of the application-specific software responsible for executing the various tasks required by the underwater robot.
- **Runtime Environment (RTE):** Serving as an interchange layer, the RTE facilitates communication and data exchange between different software components, ensuring smooth and efficient operation.

This structured approach allows the STM32 to effectively manage the complex requirements of the underwater robot, from precise actuator control to real-time sensor data processing, thereby enhancing the robot's autonomous capabilities and operational reliability also in future ROVs of U.Stall.

Software Development

Efficient software development can only take place if several developers can work together in a structured way. Therefore, we used the version management tool GitHub. Changes are logged and it is always possible to roll back to earlier versions. Additionally, there is controlled access to the files by several employees. As soon as there is a basic project structure in the form of a functional software version, it makes sense to form branches for individual new features. This way, everyone can work on a different feature without having major merging problems occurring later.

4. Troubleshooting and Testing

One of our biggest concerns was the fact that not everybody could work on the ROV at the same time. Therefore, testing when everything is mounted to the ROV was not an option for us. We've chosen an approach like the V-model systems development style, where every subpart is tested as an individual part and becomes part of a bigger assembly bit by bit. For example, the servo motors were tested standalone in a water tank before being mounted to the plastic grippers. After that, the grippers were tested to work properly with the device before this subassembly was mounted to the tools sled and so on. Due to this approach, all upcoming problems were detected as soon as possible and could be fixed without any pressure of time. Other problems were noticed at our testing facilities and could be fixed via clever software fixes and workarounds.

Software Testing accessories

For testing we always tried to test little modules, that are completely independent from others, separately. That made it possible to test when other modules are not available or not completely developed yet. Troubleshooting gets easier that way as well. For testing the embedded software, we had a spare copy of each PCB.

5. Safety Philosophy and Checklist

Without a safe work environment, successful outcomes cannot occur. Therefore, it was a great concern for us to follow the necessities described by MATE. The risk of injury during project work and test rehearsals was taken seriously and avoided. Every member of our team is responsible for safety. Everyone must make sure that nobody gets hurt and that all regulations are followed. The greatest danger comes from electricity and from motors that have enough power to injure someone. A checklist has been drawn up from the analysis of the potential hazards to reduce the risk of Accidents. This should be carried out before the ROV is put into operation.

Safety-Checklist:

Personal Protective Equipment(PPE): ☐ Wear closed, non-slip shoes. ☐ No jewelry or loose clothing ☐ Safety glasses ☐ Tying back loose Hair ☐ At least one other employee to supervise and assist in operations.
Pre-Deployment: ☐ Put all electrical components on the table

☐ Attach the monitor on the table ☐ Tether is laid out neatly with no knots or tangles ☐ Attach tether strain relief to the table ☐ Ensure that all fittings on the control box are tight and leak-proof ☐ Ensure that no parts could come loose or fall off from the ROV ☐ Poolside is clear of tripping hazards.
ROV Operation ☐ Before turning ON verify that no one touching the ROV and announce: “Power ON” ☐ Check the connection to all on-board systems ☐ Check cameras ☐ Use Handhold to handle the ROV ☐ Retrieval ROV with the security rope

Safety also includes having completed the annual safety briefing to be authorized to work in the university laboratories and machine shops. Furthermore, all laboratory and workshop regulations must be followed. If necessary, specific instruction must be arranged with the university employees. When new members or those interested in acting as support help, we took care to demonstrate the dangers and use of equipment to the newcomers. During such outreach, we were keen to look out for each other and support each other. Newly used tools were operated with caution after reading the instructions with oversight from our mentor.

6. Project Management

Throughout the whole development and manufacturing process we attached great importance to carrying out the project according to PRINCE 2 procedures. Among other things, we structured the team in departments, created a budget plan by the beginning of the season and created a clear task overview, which was distributed to the respective group members.

6.1 Company Structure

U.Stall is the Underwater Robotics Team of the Esslingen University. It all began in March 2023 when a few students took on the challenge for their mechatronics project to build an underwater robot. The mechatronic project is an integral part of the Bachelor's degree program in Mechatronics and covers a wide range of topics, showcasing some of the many different applications of mechatronics in our daily lives. Building the robot sparked significant interest within our university, prompting some students to continue the project, when the mechatronic projects were over. Consequently, in September 2023, our own workshop was established on our Campus. This is where we hold our meetings, and our equipment now even includes a mini pool and a 3D printer. Since then, we've been working almost daily with full enthusiasm and passion on our ROV. We now have 11 members in the U.Stall core team. Julia Würtz has been there from day one and is therefore co-founder of the U.Stall. She enriches our team not only with her excellent knowledge in the areas of software and electronics, but also with her outstanding skills in leading a team. Moreover, our team is divided into smaller working groups focusing on mechatronics, software, electronics, and organization. We meet at least once a week to update each other and to set new goals for the next period of time. Our mentors are Prof. Dürr and Mr. Hoover, who provide us with great support. The name is based on the nickname of our university, “Stall”. The origin of the nickname reaches back to the year 1868. Originally the university was located in Stuttgart next to the royal stables or “königliche Stall”. After the school moved to Esslingen the students took the nickname with them.

6.2 Timeline and other additional software resources

Figure 28: Extract of schedule Planning

For a good overview of the project status, we kept our project scheduling updated and watched out for the deadlines we tried not to miss. Once a week we held our meeting to get everyone updated what is going on, where are the current problems and what we need to do the next week. We used some practical software resources such as Discord to communicate with people in home-office and used the resource management program GitHub for developing the software and a cloud service to exchange our development files in an efficient way.

6.3 Budget plan

At the end of our planning phase, we knew the general concept of our ROV-design and how we want to manufacture the subsections of the ROV. That’s when we estimated the general costs and made a budget plan. When purchasing material, we always updated the excel sheet of our spent costs and if we need to adjust to changes according to problems that occurred while troubleshooting, we had a look at the balance between target and actual value and made the decision considering the advantages in technology, weight and problem solving.

Assembly	Description of main parts	Type of expenditure	Budget	Total price	Team price
ROV Production Expenses					
Frame	plates, lasering, milling, aluminium pipes	Purchased	300 €	290 €	290 €
Toolsled	pipes, aluminium connectors, milling	Purchased/Funding	50 €	725 €	25 €
Thrusters	T500 Blue Robotics thrusters and ESCs (6)	Purchased	2.000 €	4.980 €	4.980 €
Thruster housing	3D-prints, shroud	Purchased	200 €	500 €	500 €
Tether, Connectors and strain reliefs	Ethernet CAT7 cable, SBS50 connectors, 3D-Prints, bearings,48V wire	Purchased	300 €	150 €	150 €
Electronics housing	aluminium box, PG-joints, inserts	Purchased/Funding	200 €	260 €	200 €
Electronics PCBs and materials	Backplane V2, SCU (2)	Purchased/Funding	500 €	1.080 €	880 €
Gripper and servos	3D-prints, rubber, servo 270° (4), servo 360°	Purchased	200 €	190 €	190 €
Control Station	monitore, controler, strain relief, clamps	Purchased	500 €	380 €	380 €
Cameras	3D-prints, cameras (3)	Purchased	500 €	250 €	250 €
microcontroller, single board computer	STM32(2), Raspberry Pi (4), SD-cards	Purchased	600 €	450 €	450 €
sensors	IMU, pressure, temperature	Purchased	400 €	300 €	300 €
Basic materials, consumables	wires, screws, glue, epoxy resin, wires	Purchased	300 €	180 €	180 €
power supply box for testing	power supply, basic electronic material, box	Purchased	1.500 €	1.180 €	1.180 €
Float Expenses					
Electronics	Linear electric motor, wires, batteries, raspberry pi, PCB	Funding	300 €	260 €	260 €
Mechanics	pipe, 3D-prints, inserts, syringe, screws	Funding	150 €	140 €	140 €
Expenses for spare parts	all Grippers, PCBs, Cameras etc. are manufactured at minimum twice	Purchased	300 €	230 €	230 €
Development and Research Expenses	old electronic compartment, old frame, broken cameras, servos, etc.	Purchased	800 €	1.400 €	1.400 €
Organisational Expenses					
Mate Entry Fee		Funding		323 €	0 €
Lodging		Funding		5.200 €	0 €
Plane tickets		Funding		8.500 €	0 €
car rental		Funding		1.500 €	0 €
shipping		Funding		500 €	0 €
Received Foundings	Schmidt Ocean Coalition Travel Stipend for the 2024 MATE ROV			$1.000	used for Organisational Expenses
	SCHULER founding			10.000 €	used for Organisational Expenses
	Endress+Houser founding			1.000 €	used for purchasing material
	Pflitsch PG-joints founding				free ordering for their products
	Würth Electronics				free ordering for their products
		Total Project in €	9.100 €	28.968,00 €	11.985,00 €
		Total Project in $	9.828 €	$31.285,44	$12.943,80
		ROV as a product in €	7.550 €	10.915 €	9.955 €
		ROV as a product in $	8.154 €	$11.788	$10.751

Figure 29: Extract of accounting spreadsheet

7. Conclusion

Our underwater robot project has been a remarkable journey, marked by numerous achievements and invaluable experiences. Bringing together a newly formed team of students from various semesters and academic disciplines, we fostered a rich environment of collaboration and learning. Despite it being our first competition, we demonstrated our ability to work cohesively and overcome challenges. A highlight was establishing our own workshop, providing a dedicated space for design, build, and testing, and instilling a sense of ownership and responsibility within the team. The workshop became a hub of innovation and teamwork, where diverse ideas and skills converged to drive the project forward. We gained a deeper understanding of the complexities involved in developing an underwater robot, from hardware integration to software development and real-time system management. This hands-on experience equipped us with practical skills and a solid foundation for future engineering challenges. In conclusion, our participation in this project has been a profound learning experience. It underscored the importance of interdisciplinary collaboration, perseverance, and innovation. We are proud of our achievements and excited to build on this foundation in future projects and competitions.

8. Acknowledgements

At this point we would like to thank everyone who helped us during this project, and specifically thank the MATE, MATE II and MTS for the organization and sponsoring of the Mate ROV competition.

First, we would like to thank our mentors Thomas Hoover and Prof. Dr. rer. pol. Oliver Dürr who supervised our project and provided us with helpful suggestions as well as constructive criticism.

We would also like to thank Esslingen University for providing us with the necessary working materials as well as a workshop that we gladly used. Major thanks to Ms. Clauß for supporting us with our 3D-printed parts, Ms. Minder who provided us with acrylic plates and the laser and Mr. Frank who helped us in all jobs with mechanical machineries. Another big thank you for the facility management who supported us in every question for our facilities and the universities post office

A special thanks to all the pool attendants for allowing us to use their pool and for supervising us: Cityworks Göppingen, Wellness Wernau Quadrium, the Community of Dürnau, City of Uhingen and the Community of Jebenhausen. Without them we would not have been able to test our ROV.

The whole work would not have been possible without the donations from our sponsors, Würth Electronic, Pflitsch, Schmidt Ocean Institute and

SCHULER Endress+Hauser MAKINO

9. References

1. Roland Kilgus, Roland Gomeringer, Volker Menges, Andreas Stenzel, Falko Wieneke,Andreas Stephan, Stefan Oesterle,Thomas Rapp; Tabellenbuch Metall mit Formelsammlung, Europa-Lehrmittel, 2022.

2. Bernd Schiemann, Klaus Tkotz, Gregor Häberle, Verena Häberle, Konstantin Häberle, Hans Jöckel, Rudolf Krall, Dietmar Schmid, Dieter Isele, Thomas Urian; Tabellenbuch Elektrotechnik, Europa-Lehrmittel, 2024.

3. Ulrich Tietze, Christoph Schenk, Eberhard Gamm; Halbleiter-Schaltungstechnik, Springer Verlag, 2019.

4. Detlef Ridder; 3D-Konstruktionen mit Autodesk Inventor 2024: Der umfassende Praxiseinstieg. Inkl. Übungsbeispielen und Aufgaben mit Lösungen. (mitp Professional), mitp Verlags GmbH & Co. KG; 2023.

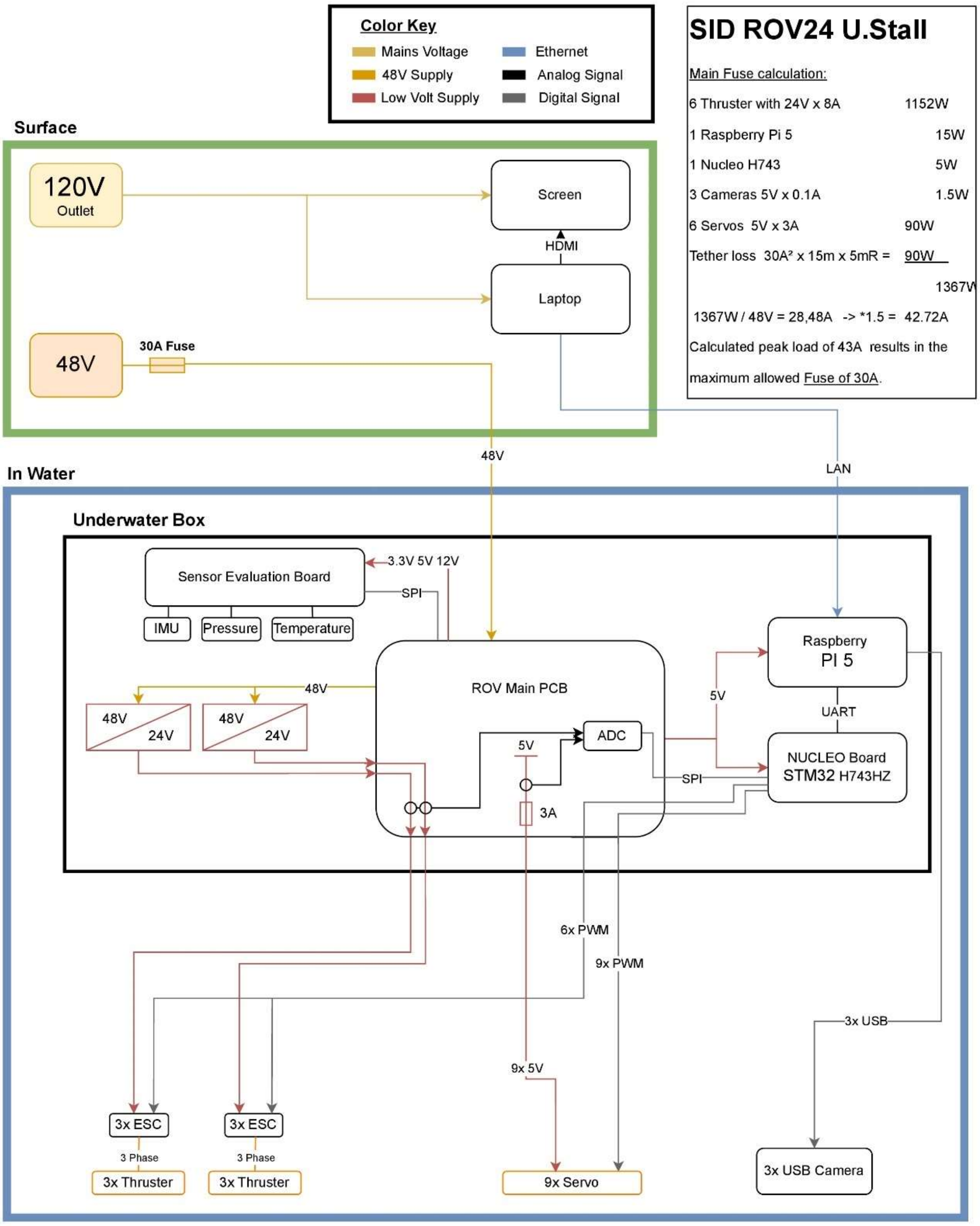
5. Nigel Bennet, AXELOS; Managing Successful Projects with PRINCE 2; Stationery Office, 2017.

6. Healey, P.; Project Management getting the job done within time and budget, Routledge, 1998.

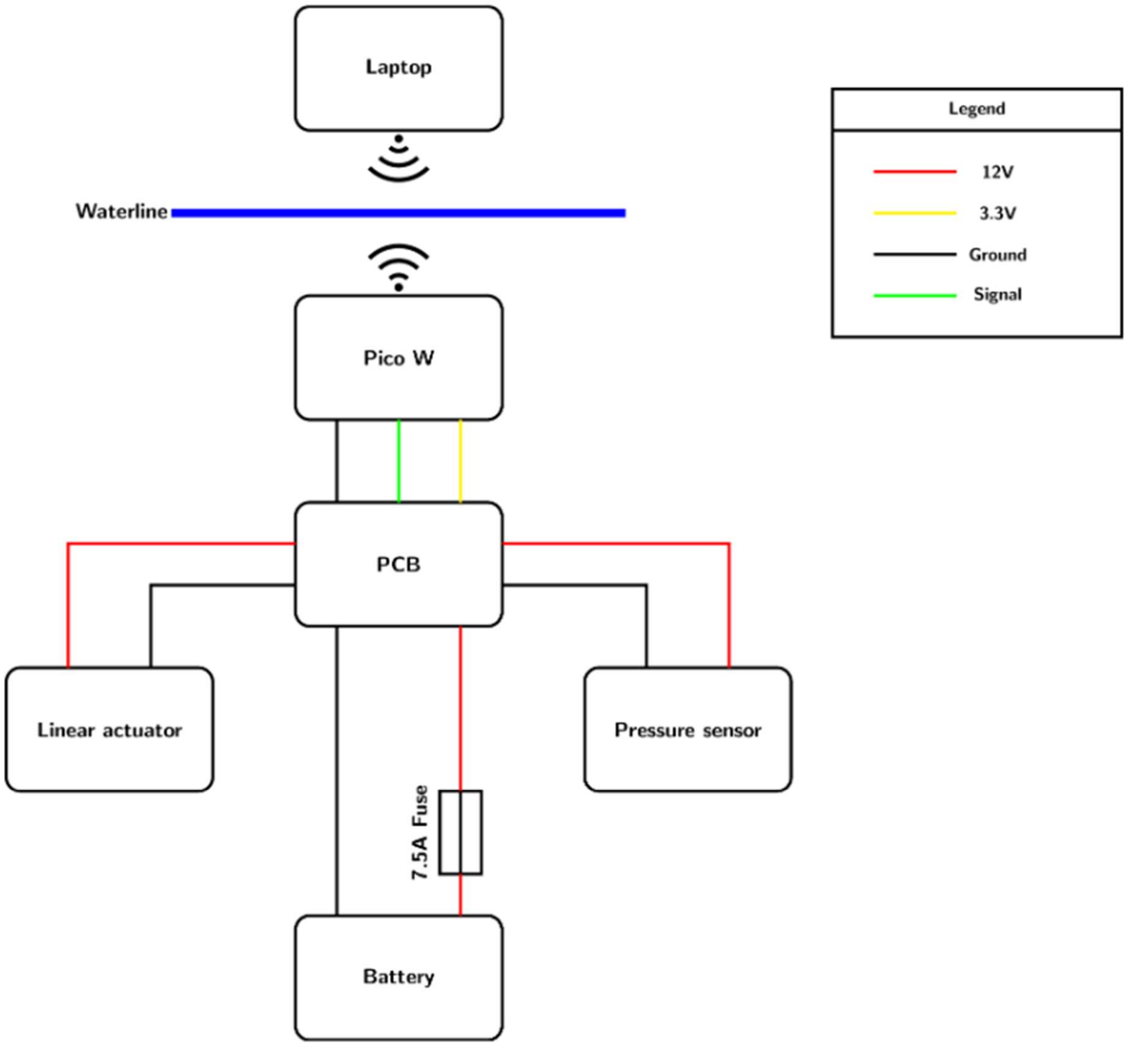
7. Claudius Scholer, Hartmut Fritsche, Bernd Schiemann, Gregor Häberle, Verena Häberle, Konstantin Häberle, Rudolf Krall, Dietmar Schmid, Thomas Urian, Thomas Helmer, Matthias Schultheiss, Heinrich Bröker; Tabellenbuch Mechatronik, Europa-Lehrmittel, 2016.

8. Jürgen Schwarz, Klaus Tkotz, Werner Klee, Ulrich Winter, Monika Burgmaier, Horst Bumiller, Ronald Neumann, Walter Eichler, Thomas Käppel, Bernd Feustel, Olaf Reichmann, Christian Duhr, Christian Gmeiner; Fachkunde Elektrotechnik, Europa-Lehrmittel, 2018

10. SID ROV24


Color Key
Mains Voltage
48V Supply
Low Volt Supply
Ethernet
Analog Signal
Digital Signal
SID ROV24 U.Stall
Main Fuse calculation:
6 Thruster with 24V x 8A 1152W
1 Raspberry Pi 5 15W
1 Nucleo H743 5W
3 Cameras 5V x 0.1A 1.5W
6 Servos 5V x 3A 90W
Tether loss 30A² x 15m x 5mR = 90W
1367W
1367W / 48V = 28,48A -> *1.5 = 42.72A
Calculated peak load of 43A results in the
maximum allowed Fuse of 30A.
Surface
120V
Outlet
Screen
HDMI
Laptop
48V
30A Fuse
48V
LAN
In Water
Underwater Box
Sensor Evaluation Board
3.3V 5V 12V
SPI
IMU
Pressure
Temperature
ROV Main PCB
48V
48V
24V
48V
24V
5V
ADC
3A
5V
SPI
Raspberry
PI 5
UART
NUCLEO Board
STM32 H743HZ
6x PWM
9x PWM
3x USB
9x 5V
3x ESC
3 Phase
3x Thruster
3x ESC
3 Phase
3x Thruster
9x Servo
3x USB Camera

11. SID Float



The max. rated current of the linear actuator is 3.2A and the remaining electronics need about 0.05-0.1A. Multiplied with the factor 1.5, we get a total of

$$(3.2A + 0.1A) \cdot 1.5 = 4.95A.$$

Therefore, we used a 7.5A fuse for functional reliability.