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Design of ROV Frame, Enclosures and Manipulator

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Preface

This bachelor thesis was crafted in partnership with the student organization UiS Subsea. The Subsea team includes 27 members, spread across 10 distinct bachelor thesis projects. This year's project is cross-disciplinary, involving mechanical-, electrical-, and computer engineering. The primary aim of this bachelor thesis is to develop a fully functional ROV and manipulator, able to execute the given tasks for the upcoming TAC Challenge. The group has high desires for the competition and have therefore incorporated certain design elements based on criteria established during last year's TAC challenge.

We want to express our sincere gratitude to the Faculty of Science and Technology at UiS and the UiS Subsea organization for granting us the opportunity to be part of this project and its associated challenges. This project has provided us with an incredibly enriching and demanding experience, marked by significant learning opportunities. It has served as an outstanding platform to further develop our mechanical-, collaborative-, imaginative-, and hands-on skills, all of which will prove invaluable for our future career paths.

We are deeply thankful to all our sponsors, advisors, and former bachelor students whose invaluable insights and inspiration have facilitated the successful completion and delivery of operational products. A heartfelt appreciation is extended to Professor Yihan Xing, our supervisor, Senior Lab Engineer Emil Mannes Surnevik, and Senior Lab Engineer Jan-Tore Jakobsen, from the University of Stavanger, for their unwavering guidance and support throughout the project. Additionally, we extend our gratitude to the university's machine shop lab engineers and the lab engineers at the 3D-printing workshop, for their contributions, ideas, and assistance in the manufacturing process of essential components.

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Nomenclature

PDP: Product Development Process

ROV: Remotely Operated Vehicle

RCV: Remote Controlled Vehicle

Thruster: A device that create forward motion for spacecraft and vessels, allowing them to maneuver and manage their direction in either water or space

FEM: Finite Element Method

FEA: Finite Element Analysis

CAD: Computer-aided design

CNC: Computer Numerical Control

DVL: Doppler Velocity Logger

Ballast: A weight strategically positioned within a vessel or aircraft to maintain stability and equilibrium

Manipulator: An ROV manipulator is a robotic arm used to perform tasks or manipulate objects in underwater environments

Clamps: A component used for fastening and tightening

O-ring: A component used for sealing

UiS: Universitetet i Stavanger

CAD: Computer-aided design

TAC: Tau Autonomy Center

CAM: Computer-aided manufacturing

Summary

This bachelor thesis is written in collaboration with the student organization UiS Subsea, a project that requires joint effort between the different engineering disciplines to be able to manufacture a functional end product. The thesis addresses the mechanical aspect of the project, and entails the design, production, and assembly of the ROV frame, electronics enclosure, battery enclosure and the manipulator. Ensuring the functionality of the ROV requires proper sealing of all electronic devices. A new aspect of this year's project is that the mechanical group were responsible for the design, manufacturing, and assembly of a waterproof battery enclosure. The main purpose behind the idea of utilizing batteries for this year's project was due to the long term goal which is to run the entire ROV on battery power. A ROV operated on battery power, would enable utilizing a longer tether as the voltage drop issue would have been eliminated.

The objective for this year's ROV was to manufacture a robust ROV. This also suggest that a heavier vehicle was likely for this year's project, which in turn would impact its velocity. On the other hand, due its robustness, the vehicle will be well-suited for executing tasks requiring stability and strength. The transition phase that the world is experiencing today's is a part of revolutionizing the subsea industry. This thesis is highly relevant for the industry nowadays as the market is experiencing significant growth and substantial investments from both private and public sector.

The product development process is highly relevant for this thesis, due to the fact that this thesis deals with manufacturing of a product. Therefore, both the project execution and the thesis are based on this process. Additionally, frequent communication with students from last year's project were maintained. Their knowledge has been absolute central as the project seek continuous development. Consultations with field expertise were conducted during the design phase. These consultations involved team members from Energy X, Seal Engineering, IKM Industrigravøren, and Djuvik Maskinering. This way of working has presented with the opportunity of looking at problems from new angles, a valuable experience throughout the project. Proper testing of critical components was absolutely crucial for the project. A vacuum test was conducted in order to discover potential water intrusion in both the electronic- and battery enclosure. These tests concluded that both enclosures had passed inspection and therefore ready for further testing in a water environment. There are room for improvements for future projects. One valuable insight gained was the importance of avoiding focusing on too many details early in the concept generation phase. It is easy to fall into the trap of trying to envision the completion of the concept all the way through, from the design phase to the final product. If, at this stage, determined that it was not feasible, the process would pivot to exploring other concepts. The key lesson learned is that while an overall concept fell short, there may be individual solutions to particular problems that can be used in other concepts.

The chosen product development process was followed strictly during the project. Some steps were left out, as these were not as relevant for a non-commercial product. Without such organized way of structuring the strategy for the 2023/2024 bachelor project, the results would probably not have been adequate, given limited time and resources. The planning phase started as early as fall 2023, with the project management team setting goals and boundaries for the overall project. The product development process played a significant part in accomplishing the main goal of this bachelor thesis, which was developing a fully functional remotely operated vehicle.

1 Introduction

The bachelor thesis is part of a large project in collaboration with UiS Subsea. The introduction chapter has been written together with the several project teams in the organization. UiS Subsea designs and develops a Remotely Operated Vehicle (ROV) every year. An ROV is a remotely controlled underwater craft, and the objective of the organization is to participate in competitions. MATE ROV Competition in the USA has been the main focus these previous years, while TAC Challenge is a competition that is held in Tau this year. The organization won the TAC Challenge with the ROV Yme last year, and the main target of this year's project is to design and develop an ROV that performs and excels as the ROV Yme.

The introductory chapter will provide insight into the student organization UiS Subsea and the TAC Challenge. Additionally, this chapter will include a presentation of this year's ROV with the various systems and groups within the project.

1.1 About UiS Subsea

UiS Subsea, shown in Figure 1.1, is a student organization that was established back in 2013/14. The objective of the organization is to motivate students to participate in large projects and to affiliate with several companies. Stavanger is known for its large industry within oil and gas, both on- and offshore. Therefore, being a part of this project will help students to get exposed to the oil and gas industry.

UiS Subsea is primarily a bachelor project. Each year, a new ROV is developed by the organization. However, this year's design of the ROV is already an existing model that expanded and optimized for the TAC Challenge. At the final stages of the project, the organization participates in a competition to test the performance of the ROV that is produced. Additionally, participating in a competition gives opportunities for the project members to affiliate with several universities and organizations on both a national and global scale.

Figure 1.1: UiS Subsea logo

1.2 TAC Challenge

Tau Autonomy Center (TAC) is held just outside of Stavanger. This competition organizes an annual AUV/ROV competition for both Norwegian and foreign students. The purpose is to promote new ideas and innovations related to underwater technology for unmanned vessels. By challenging interdisciplinary groups of students to conduct both self-directed and autonomous tasks in an industrial underwater environment. Moreover, students acquire the opportunity to display their learning and to obtain project work experience that is related to their future careers in the oil and gas industry. Social events are also organized for all contestants, which makes it possible to meet people from all over the world. Thus, this helps to promote social and professional connections between future engineers and organizations related to autonomous and remotely controlled underwater technologies [1].

The challenges to the student groups are to plan, design, develop, and construct a fully functional ROV that will compete by performing certain tasks given by the TAC Challenge. The objective of these tasks is duplicated and approximated regarding the realistic issues and problems of the oil and gas industry. These tasks have been developed by TAC in combination with sponsors or other bidders. The competition will be held at TAC and lasts for 5 days, from June 10th to June 14th. Over this period, everything from social activities and testing for the actual competition content occurs [1]. Due to the close location and the fact that UiS Subsea also won the TAC Challenge last year, it was decided to focus on the TAC Challenge this year as the only competition for the ROV.

1.2.1 This year's competition

Details of the competition tasks The competition consists of various tasks which are divided into the categories of static and dynamic tasks. For the static tasks, all teams must hold a group presentation and deliver a technical design report, which is evaluated by a jury within the field. The dynamic part of the tasks consists of 4 different tasks, where the objective of the evaluation is based on the result and the execution method [1].

1. **Subsea docking and data transfer** (TAC Rules and Regulations 2024 rev 1, §7.1.1.) A docking station is positioned in an indoor training pool in the TAC building. The vessel must locate the docking station and attempt to dock. The docking station is equipped with an inductive 250W Subsea Power Puck, which can transfer data and power to the vessel. The ROV will demonstrate power transfer by having a light that is turned on and connected to the power puck, mounted to the ROV, and at the same time establish communication to the docking station. The docking station is also equipped with predefined visual indicators, that are ArUco brands. Specific autonomous behavior can also obtain points.

2. **Pipeline inspection** (TAC Rules and Regulations 2024 rev 1, §7.1.2.) A pipeline is positioned on the seabed within the operational area and needs inspection. The pipeline has an unknown path and length, and there is also an unknown number of ArUco marks along the pipeline to be identified. Delivery of the tag code in the correct orders is needed to achieve maximum points, and specific autonomous behavior can also provide points.

3. **Visual inspection of underwater structure** (TAC Rules and Regulations 2024 rev 1, §7.1.3.) An underwater structure is positioned on the seabed within the operational area and requires inspection. Different ArUco brands are positioned on the structure itself and must be recognized to gain points. Specific autonomous behavior can also earn points.

4. **Valve intervention** (TAC Rules and Regulations 2024 rev 1, §7.1.4.) An underwater structure positioned on the seabed within the operational area and requiring inspection. Different ArUco brands are positioned on the structure itself and must be recognized to gain points. Specific autonomous behavior can also earn points.

1.2.2 Point distribution

1. **Technical requirements**
   The ROV must also be compatible with TAC Challenge's Launch and Recovery System (LARS), where the drone can be attached to a carabiner or barrel. The drone cannot weigh more than 100kg either, and lower weight classes are awarded extra points in the static part. Moreover, there is a maximum limitation of 60V from any battery systems mounted on the ROV, as well as a 50V limitation for the power cable from shore. There is also a requirement for positive buoyancy. These requirements are checked via the technical report and the group presentation in addition to the TAC having the opportunity to carry out pre-competition inspections.

2. **Static tasks**
   Each group in the competition must produce a separate technical report detailing the competition strategy, security measures, system architecture, testing, and validation. These points are thus evaluated based on technical depth and innovative solutions to the technical challenges in the competition. Additionally, the organization and the literary presentation of the report are also taken into account in the final scoring.

3. **Dynamic tasks**
   The previously mentioned assignments are evaluated based on implementation and strategy. As mentioned, points can also be given for both fully or partially autonomous implementation.

The entire distribution of points for both the static and dynamic tasks is summarized in Table 1.2.2 below [1]. These points are distributed by the judging panel when performing the static and dynamic tasks during the competition days.

Table 1.1: Overview of the distribution of points at TAC (TAC Rules and Regulations 2024 rev 1, §2.4)

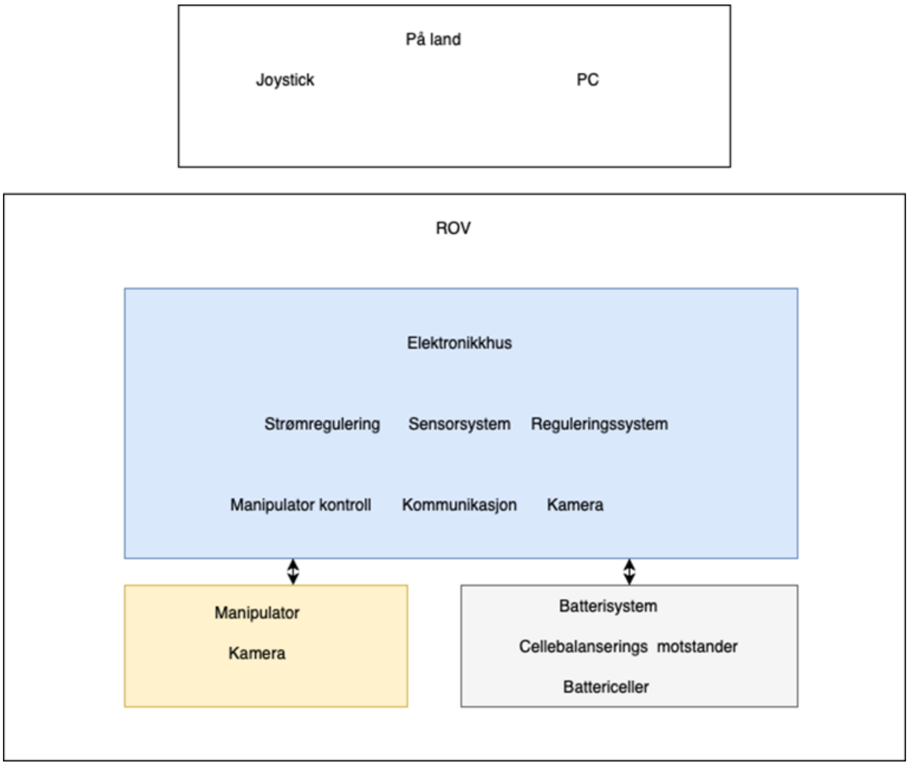
Competition scoring			
Static tasks	**Standard points**	**Bonus points**	**Total**
Technical documentation	100	No bonus points	**100**
Group presentation	100	No bonus points	**100**
Dynamic tasks	**Standard points**	**Bonus points**	**Total**
Docking	120	100	**220**
Pipeline inspection	100	300	**400**
Visual inspection	120	120	**240**
Valve intervention	100	200	**300**

1.3 This year's ROV: Draugen

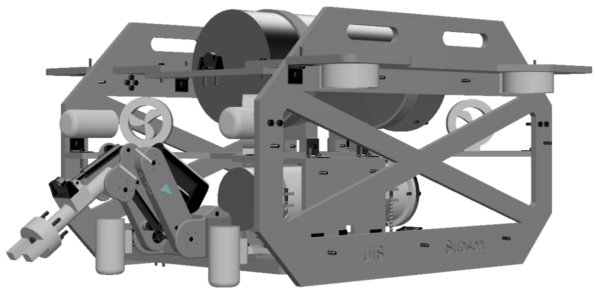
The ROV developed by this year's team has been named Draugen. The block diagram and design of the ROV are shown in Figure 1.2.

The objective of this year's ROV design was stability, hydrodynamic properties, and environmentally friendly production and machining methods. As Draugen will be the first ROV with a fitted battery, this required extra space and a somewhat larger ROV than last year's. This led to a heavier ROV, which was a concern at the initial phase of the project. However, this proved not to be a problem in the final phase of the project, when the ROV became significantly stable, both on land and in water.

[0]Exact values are not provided, due to an unknown number of markers to be identified in the tasks [1] [2].



(a) Block scheme for this year´s ROV



(b) This year's ROV Draugen

Figure 1.2: Group structure and ROV 2024

1.3.1 The project management for the 2024 project are:

Project manager: Sveinung Laupland Høyvik

Competition manager: Bjørge Zagros Rysstad

Technical manager, Electrical: Ingvild Bortheim

Technical manager, Data: Christofer Juul

Technical manager, Mechanical: Magnus Dolmen

Project Manager The project manager's responsibility is to mainly ensure that the project milestones are completed within the given deadlines. This involves a general overview of what the various groups' areas of responsibility are on the ROV, as well as follow-up of these. The communication between the project management and the various groups is a critical factor. The project manager is also responsible for arranging the weekly meetings throughout the project. The meetings have usually consisted of a short review from each group of what has been done and what needs to be done until the next meeting. It is then up to each group to ensure that these points are carried out, but here the project manager must also have a certain overview.

Competition manager The main objective of the competition manager is to ensure that the ROV meets the technical requirements that have been set to be able to participate in this year's competition and to acquire as many points as possible from the given tasks. This primarily means that the overall system stays within the overall restrictions set for participation. Since the given tasks in the competition also have issues and problems within the industry, the competition manager's goal is to communicate to the relevant groups within the same work and that has the responsibility for implementing a solution. It is also the competition manager who undertakes communication and registration for the competition. Moreover, the competition manager is the contact person between the TAC and UiS Subsea.

Technical manager, Electrical The main task of the technical electrical manager is to get all the electrical groups to cooperate and be interdisciplinary with the other disciplines so that the end product is finalized. Since the electrical department in UiS Subsea is the largest, more personnel management follows. The electrical manager handles any challenges, whether of a technical nature within the project or related to the combination of the electrical team and the various subgroups.

Technical manager, Data As the technical data manager, the most important task is to ensure good communication internally between the data groups and with the rest of the Subsea team. The technical manager for data is also responsible for ensuring that the data groups deliver what is expected of them for the project to reach its goal. In the case of data-related technical choices, it is the technical data manager who is responsible for the decision, and for ensuring that good solutions are chosen.

Technical manager, Mechanical The technical mechanical manager has the responsibility for checking that the tasks related to the mechanical students are complied with and carried out. One of the main tasks is to create concrete sub-goals, linked to the overall goal, which for the mechanical group, is to produce a functional ROV and manipulator. Because this is an interdisciplinary project across three engineering disciplines, the technical mechanical manager's objective is to maintain good communication within the groups that may be affected by any design changes to both the ROV and the manipulator.

1.4 Design of the ROV

1.4.1 Data, GUI, and operating system

The main objective of the GUI group is to develop a monitoring and control system for the ROV. A graphical operator interface (GUI) must be produced that shows all relevant information from the ROV, such as sensor data, and streams the video for the operators clearly.

The GUI group is also responsible for implementing control of the ROV and the manipulator. This is accomplished by receiving data from a controller and sending the data down to the ROV where it will be processed by the respective project groups.

For all of this to work, a system that can send data between the ROV and the Top Side is needed. This system must be implemented in collaboration with the communications group.

1.4.2 Data, Autonomous Docking

The purpose of the task of the autonomous docking group is to develop a program that allows the ROV to locate a docking station positioned underwater in a pool and attempt to dock the station autonomously. The ROV is equipped with a camera and DVL-sensor that can be used to navigate the surroundings. The docking station is fixed on a pallet which is equipped with ArUco brands in each corner which are used for positioning and recognition.

1.4.3 Electrical, Autonomous Driving

The objective of the autonomous driving group is to develop programs that enable the ROV to autonomously inspect a pipeline and a workbench underwater. The ROV will read AruUco codes placed along the pipeline and on the bench surfaces. Autonomous driving is achieved by estimating the ROV's position using a video stream from cameras and position data from DVL-sensor.

1.4.4 Electrical, Regulation

The task of the regulation group is to develop the control and regulation system for the ROV. To be able to perform the tasks most optimally for the TAC Challenge. The ROV is dependent on good maneuverability, which is the result of a functional control and regulation system.

1.4.5 Electrical, Manipulator

The manipulator arm's design is prepared as a collaboration with the mechanical group. The manipulator group aims to solve the tasks described in TAC Challenge - Valve intervention. The main task of the group is to design the control system using kinematics and implement it by programming in C.

1.4.6 Electrical, Sensor system

The assignment for the sensor system group is to develop the ROV's sensor system. The system will collect raw data from various sensors and process this to be able to control and monitor the ROV. Processed data is sent to the superior system via the communication interface, CAN FD. For regulation and autonomous- driving and docking of the ROV, data for the orientation and position is required, and at the same time, it must be supervised if there is a leak or excessive temperatures in the electronics enclosure. The sensor system group focuses on developing circuit boards with microcontrollers and relevant sensors.

1.4.7 Electrical, Power supply

The power supply group has the overall responsibility for making sure that all other modules receive the voltage it need and that these modules receive enough power to be able to operate. The system consists of 2 circuit boards and a cable from shore. There are monitoring functions for circuits with a high current draw in addition to general monitoring via fuse circuits on each outlet. These measurements are then sent to the communications card from a microcontroller on the circuit board, which then passes the data onto the topside. The ROV also has a battery on board which will automatically be used as a power source if no power is supplied from the power cable.

1.4.8 Electrical, Communication

The communication- and video transmission group objective is to develop the interface for internal communication between the circuit board modules and externally between the topside and ROV. The interface for communication is implemented using the CAN FD- and Ethernet protocols respectively. Simultaneously, the group will process video streams from the cameras attached to the front and below of the ROV, and on the manipulator's arm, before they are transmitted to the topside. Like last year's group, the communications group is responsible for developing the electronics enclosure. The team will develop a template in the form of a circuit board that includes a circuit for a CAN FD transceiver, which will be used by the groups that will have a circuit board inside the electronics enclosure.

1.4.9 Electrical, Battery

The battery group is responsible for developing the battery and lighting system of the ROV. The battery system must ensure the delivery of power to the ROV so that it can operate without an external power supply. The lighting system must provide visibility underwater in varying conditions and must be dimmable. The battery is built in its enclosure with battery cells and management system (BMS), while the lighting system is to be built in cooperation with the power supply group with floodlights and associated electronics.

The mounted battery on the ROV is a new venture for UiS Subsea and it is the first time such a system has been developed. The goal of this venture is to develop an ROV that is fully functional without an external power supply. This year's ROV has been designed so that the battery system is not required during normal operation and can be disconnected should problems arise.

1.4.10 Mechanical, ROV and manipulator design

The mechanical students on this year's project are gathered in a group consisting of three students who are respectively responsible for the ROV design, the electronics- and battery enclosure, and the manipulator. The main goal for the group is to design and produce a fully functional ROV and manipulator, which has the functional properties to be able to perform the challenges given at the TAC Challenge.

The ROV design lays the very foundation of the project. The ROV has mainly been designed concerning the requirements for the TAC Challenge. The design is also determined by the requirements and wishes of the other bachelor groups. A new component for this year's project is that a battery enclosure will also be produced. Both the battery- and electronics enclosure must protect the interior components against water ingress. As a result of this, the requirement follows that both electronics- and battery enclosures must be waterproof.

The task of designing and developing the manipulator is an interdisciplinary combination of two engineering disciplines, respectively the mechanical group and the electrical group. These groups are responsible for the manipulator. This collaboration opens up the possibility of developing a more advanced manipulator than in previous years. The goal for this year's manipulator is to develop and manufacture a robust manipulator, capable of executing the challenges associated with the TAC Challenge.

2 ROV - Theory

2.0.1 Forces

In the domain of subsea vehicles, the dynamic forces can be categorized into five distinct groups: Thrust, drag, lift, weight, and buoyancy. Thrust, the propulsive force, is harnessed by propulsion systems to propel or navigate the vehicle within its local x-y plane. Conversely, drag, acting in opposition to the vehicle's motion, is influenced by various factors including shape, velocity, size, fluid density, and the drag coefficient. Following the principles of Newton's second law, the weight force, dictated by the vehicle's mass, exerts a downward force. Mathematically, it can be expressed as: [3]

$$F = mg \tag{1}$$

In the given equation, F represents the force, m denotes the mass, and g stands for the acceleration due to gravity.

When submerged in water, objects experience a multitude of forces depending on their state of motion. Even in a state of rest, two constant forces persist: buoyancy and gravity. However, in the context of this project, the ROV is often required to maneuver. These movements are facilitated by the propulsion of the thruster engines, strategically positioned to enable both horizontal and vertical mobility. Consequently, these movements trigger "action-reaction" force pairs. For instance, propulsion forward is achieved through the exertion of thrust force, countered by water resistance force. Similarly, the installation of thrusters for vertical movement yields a lifting force, met with its corresponding counterreaction force from the water resistance. Figure 2.1 is a visual representation illustrating the diverse forces influencing the ROV [4].

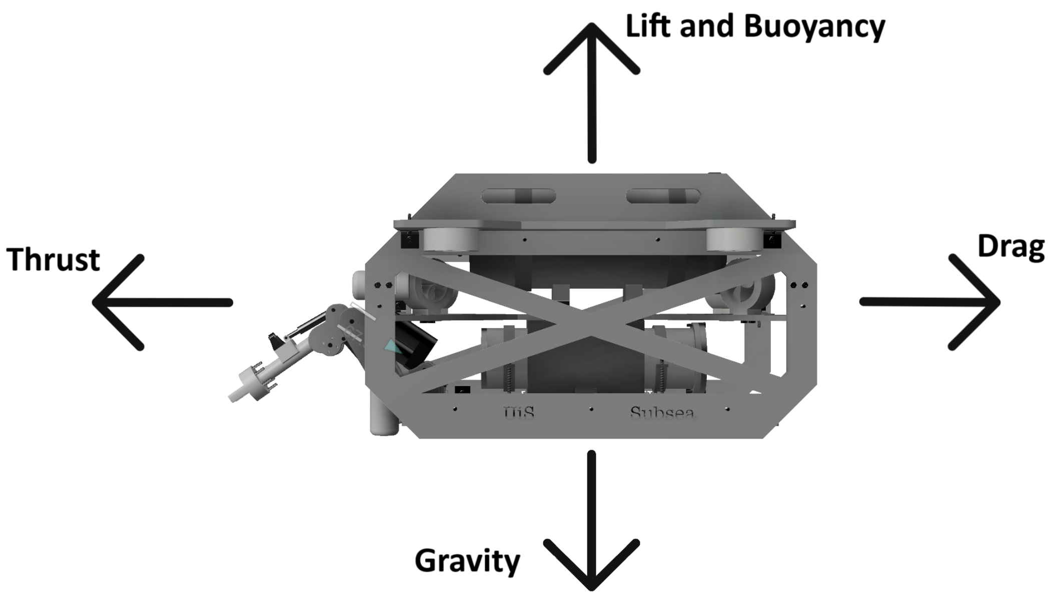


Figure 2.1: Forces acting on the ROV

2.0.2 Buoyancy and Stability

Buoyancy Archimedes' principle, often associated with the phenomenon of buoyancy, is a fundamental aspect of fluid mechanics. It describes how the upward force exerted on an object of uniform density submerged in a fluid equals the weight of the displaced fluid. This force operates in an upward direction, originating from the centroid of the displaced volume. Mathematical representation of the buoyant force is expressed as: [5]

$$F_B = F_{\text{bottom}} - F_{\text{top}} = \rho g(s+h)A - \rho g s A = \rho g V \tag{2}$$

In this scenario, FB symbolizes the buoyant force, while ρ represents the density of the liquid, g stands for gravitational force, s is the top of the body submerged, h is the bottom of the body submerged, and V denotes the volume of the submerged segment. When fully submerged, this volume equals that of the object itself. Another crucial consideration in buoyancy discussions involves the material density of the immersed object. If the average material density aligns with the fluid density, the object remains stable, maintaining its position without sinking or rising. Conversely, if the average material density surpasses that of the fluid, the object will descend. Contrary, if the average material density falls below the fluid density, the object will ascend to the fluid's surface [4] [5].

Stability Ensuring an object's stability in aquatic environments is pivotal for its operational efficacy. To assess the potential stability of a structure submerged in water, certain considerations must be taken into account. Primarily, identifying the precise locations of the center of gravity (G) and the center of buoyancy (B) is vital. Stability depends on the alignment of these centers: an object achieves stability when its center of gravity lies directly beneath the center of buoyancy. Conversely, a deviation from this alignment results in instability, posing significant risks. Take, for instance, a vessel such as a boat: if the center of gravity surpasses the center of buoyancy, the potential for catastrophic consequences, such as capsizing, becomes imminent. Nevertheless, there exists a unique scenario where stability persists despite the center of gravity positioned above the center of buoyancy [6].

The gravitational midpoint of an object remains constant relative to the object itself, though its positional values vary based on the selected coordinate framework. For example, the gravitational midpoint of an item typically aligns with its geometric center, resulting in positive $\bar{x}$ and $\bar{y}$ values. However, should the object shift left of the y-axis or the coordinate system undergo a translation to the right, the $\bar{x}$ value would turn negative. When considering the object in three dimensions, the mathematical representation of its gravitational midpoint is expressed as follows: [7]

$$\bar{x} = \frac{\sum_i x_i W_i}{\sum_i W_i}, \quad \bar{y} = \frac{\sum_i y_i W_i}{\sum_i W_i}, \quad \bar{z} = \frac{\sum_i z_i W_i}{\sum_i W_i} \tag{3}$$

In these equations, $\bar{x}$, $\bar{y}$ and $\bar{z}$ represent the centroid coordinates of the object, while W_i stands for the weight of part i, and x_i, y_i and z_i denote the coordinates of the gravitational center of element i.

The center of buoyancy, situated at the centroid of the submerged region of an ROV or any floating entity, acts as the point where the upward buoyant forces is exerted on a submerged object. In scenarios of full immersion, it aligns with the center of gravity of the displaced fluid. Yet, in the case of a partially submerged floating entity, the center of buoyancy aligns with the center of gravity of the submerged part, positioned directly beneath the overall center of gravity [6] The mathematical depiction of center of buoyancy is expressed as: [8]

$$\bar{x} = \frac{\sum_i x_i W_i}{\sum_i W_i} \tag{4}$$

In this context, $\bar{x}$ indicate the centroid coordinates of the object, while W_i represents the weight of part i, and x_i denote the coordinates of the buoyancy center of element i [8].

This relationship between the center of buoyancy and the center of gravity, depicted in Figure 2.2, carries implications for stability. When both align vertically and the hull maintains an upright position, stability is attained. This stability, termed as "meta-stability", persists, when the center of buoyancy lies beneath the center of gravity. As the hull inclines, the center of gravity remains stationary relative to the hull, whereas the center of buoyancy adjusts to the altered volume of displaced water. Consequently, the combined forces of gravity and buoyancy generate a corrective torque, striving to realign the hull to its upright position [6].

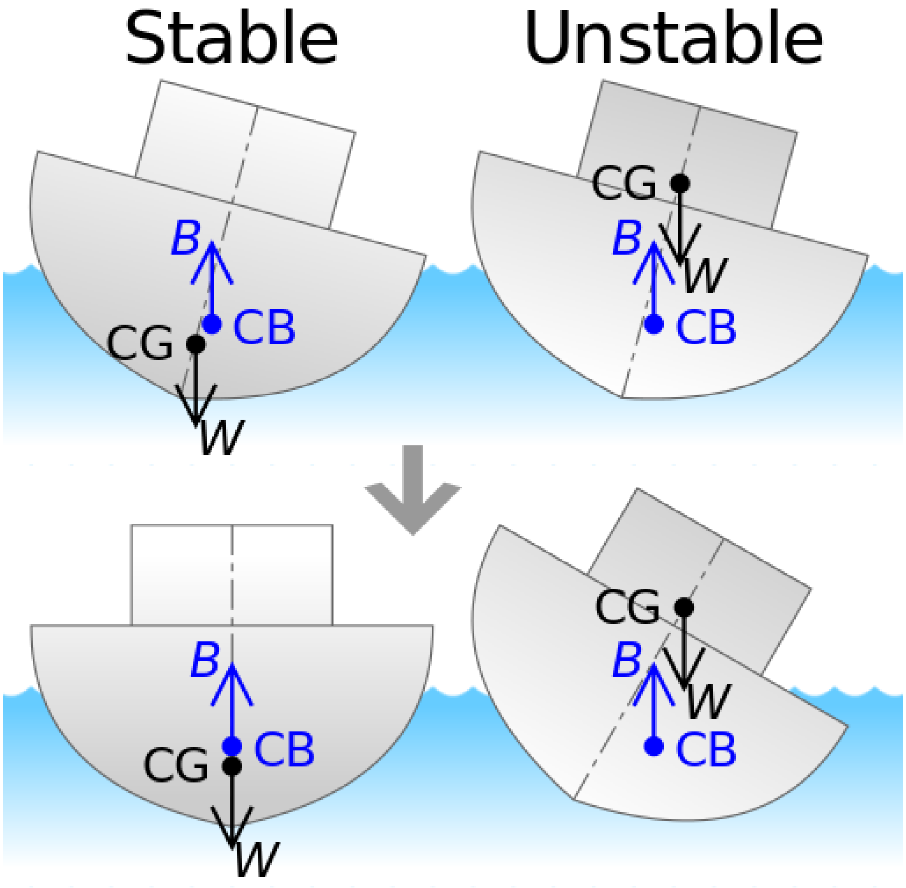


Figure 2.2: Relationship between the CG and CB [9]

2.0.3 Drag Force

As a subsea vehicle navigates underwater, its propulsion system faces the challenge of countering the resistance imposed by the surrounding water. This resistance, known as drag force, occurs when an object moves through a fluid, displacing the fluid in the process. The drag force acts in opposition to the direction of movement between the object and the fluid. Reducing drag requires significant power consumption, underscoring the importance of designing vehicles with optimal hydrodynamics to minimize this effect [10].

Among the various types of drag forces, parasitic drag holds particular significance for this project. Parasitic drag primarily arises from factors such as the object's shape, material composition, and construction, leading to the displacement of water during motion. This type of drag includes both form and skin drag. Form drag is closely linked to the object's shape, with some shapes exhibiting greater hydrodynamics than others. For example, a simplofied half-body experiences a lower drag coefficient compared to a cube, rendering it more hydrodynamic. Skin drag, on the other hand, emerges from surface roughness, with increased roughness resulting in higher drag. To minimize drag on a hydrodynamic body, maintaining a smooth surface with elegant geometrical transitions is crucial. While skin drag is considered, its impact is often outweighed in calculations by the larger contribution of form drag. Mathematical representation of the drag force is expressed as: [10]

$$F_D = \frac{1}{2} C_D \rho A v^2 \tag{5}$$

In this equation, FD represents the drag force, ρ denotes the density of the fluid, A stands for the cross-sectional area of the object, v represents the relative speed between the object and the fluid, and CD signifies the form drag coefficient.

The form drag coefficient CD is depicted in Figure 2.3. This visual representation serves to determine the extent of form drag.

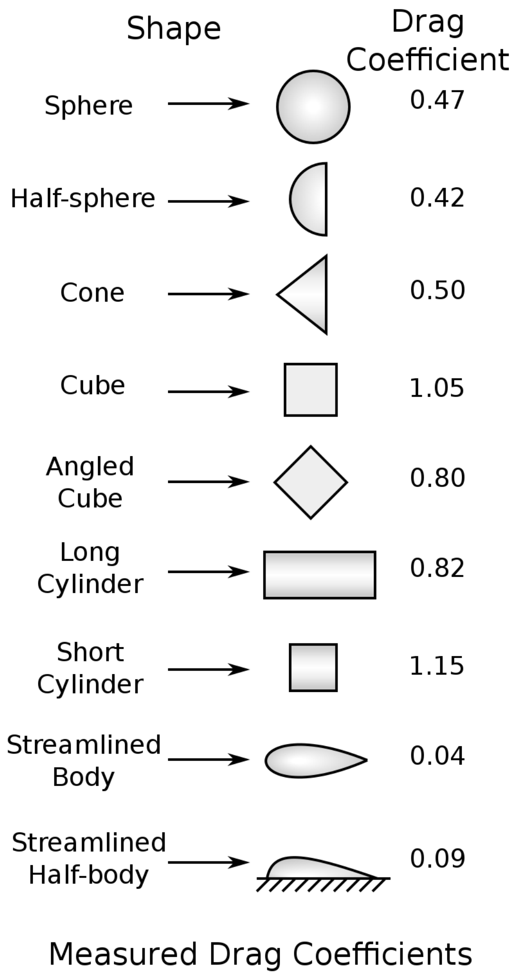


Figure 2.3: Drag coefficients [11]

2.0.4 Hydrostatic Pressure

As the submersible vehicle dives into the deep, it experience increasingly pressure. Understanding the principles of hydrostatic pressure theoretically anticipates the pressures which would confront the ROV at such depth, thus potentially avoiding malfunctions [12].

Hydrostatic pressure refers to the force exerted by a fluid in a state of balance at a given moment due to gravity's influence. It correlates directly with depth, as the fluid's weight enhancing with the application of a downward force, resulting in an increase in pressure moving deeper from the surface [12]. The concept of hydrostatic pressure is depitcted in Figure 2.4.

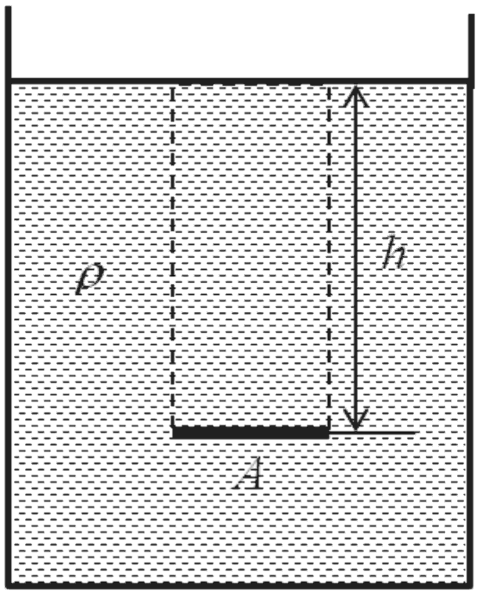


Figure 2.4: Hydrostatic pressure [13]

Fluid pressure can arise from various factors such as gravity, acceleration, or internal forces within a sealed vessel. Let's envision a column of water spanning from the surface to the bottom of the ROV. At any given depth, the water exerts pressure on the surrounding surfaces of the ROV. Descending from the top to the bottom, the cumulative effect of the water layers above adds to the pressure at each successive depth. This accumulation of pressure is accountable for the increased pressure experienced at the bottom of the ROV. The mathematical depiction of hydrostatic pressure is expressed as: [12]

$$P = \rho g h \tag{6}$$

In the equation, P represents the pressure applied by the liquid, while ρ denotes the density of the liquid. The variable g stands for the acceleration due to gravity, and h signifies the vertical distance between the uppermost and lowermost points of the submerged object [12].

2.0.5 Propulsion System

The propulsion system of a Remotely Operated Vehicle (ROV) comprises multiple thrusters designed to guide the vehicle to its designated work area. These thrusters are strategically positioned to ensure precise control and maneuverability, considering the moment arm generated by their thrust in relation to the vehicle's central mass. Thrust vectoring serves as the primary propulsion method for an ROV, with various position options available for thrusters to enhance maneuvering capabilities. Maneuvering involves asymmetrical thrusting, leveraging both thruster placement and output variations. ROV propulsion systems are commonly classified into three main types: electrical, hydraulic, and ducted jet propulsion [14].

6 degrees of freedom The six degrees of freedom, as depicted in Figure 2.5, concerning thruster setup denote its capacity to navigate fluidly in a three-dimensional space. These freedoms consist of translational movements along the x, y, and z axes, alongside rotational motions: roll, pitch, and yaw. Movement along the x-axis involves horizontal thrusters on the ROV's sides, propelling it forward or backward. For the z-axis, vertical thrusters on the top and bottom permit upward or downward movement. Lateral thrusters along the ROV's body enable movement along the y-axis. Roll entails rotation around the x-axis, adjusted by opposing thrusters for sideways motion. Pitch, revolving around the y-axis, is controlled by altering forward and backward thruster capacity. Yaw, rotating about the z-axis, is regulated by opposing side thrusters. Mastery of these freedoms via precise thruster manipulation enables the ROV to traverse complicated underwater terrains, execute tasks, and maintaining stability [15].

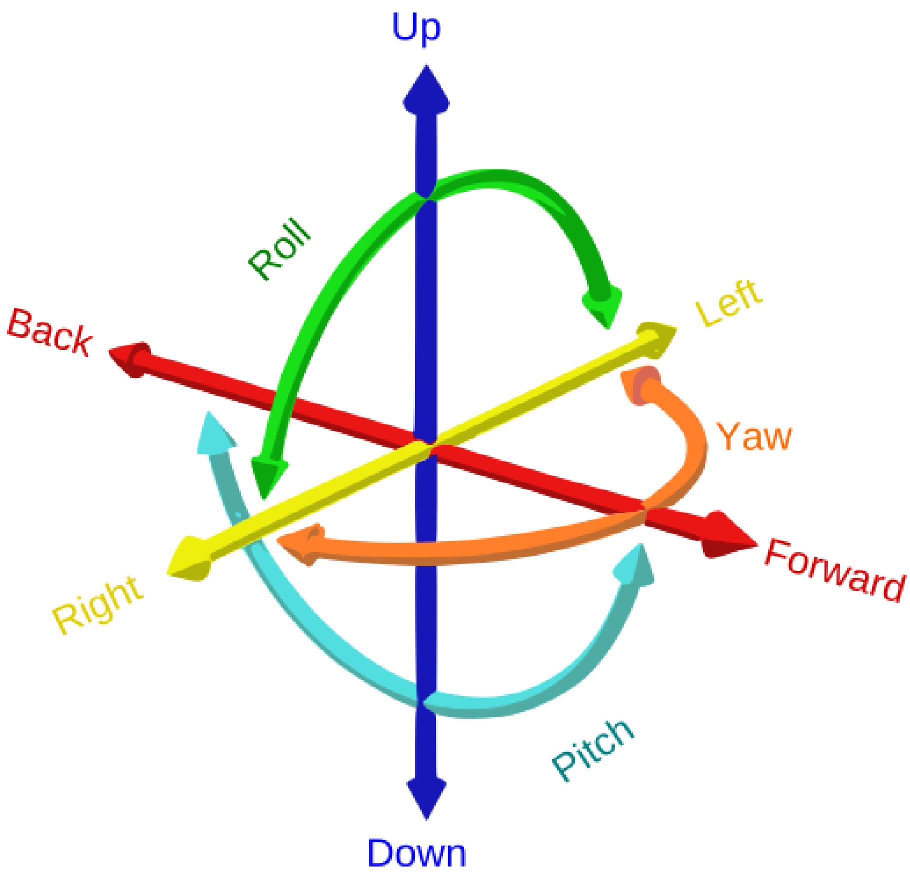
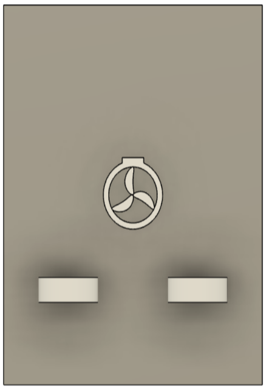
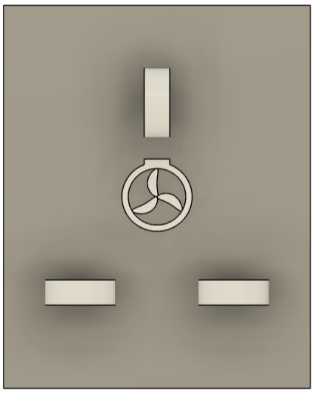
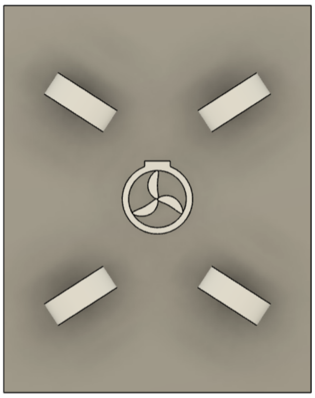


Figure 2.5: 6 degrees of freedom [16]

Horizontal Propulsion System Achieving the optimal orientation for lateral thrusters necessitates a thorough evaluation of multiple factors, encompassing hydrodynamics, thrust efficiency, and operational stability, shown in Table 2.1. Engineers strive to position these thrusters in a manner that maximizes their efficiency while minimizing resistance and potential interference with other ROV components. Extensive research and computational modeling have highlighted an approximate angle of 33 degrees from the horizontal plane, shown in Figure 2.6, as a prime orientation for lateral thrusters. This angle facilitates efficient propulsion by directing thrust in a manner that balances forward momentum with stability, fostering optimal performance without yielding excessive drag or turbulence [14].

Table 2.1: Alternatives for horizontal propulsion system

		
Three propulsion version	**Four propulsion version**	**Five propulsion version**

Moreover, the 33-degree inclination aids in reducing pressure differentials between thrusters, thereby optimizing overall ROV functionality. Through strategic deployment of lateral thrusters at this angle, engineers can elevate the ROV's maneuverability, velocity, and responsiveness [14].

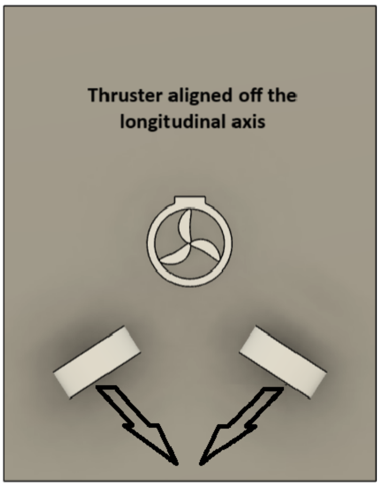


Figure 2.6: Optimal horizontal propulsion configuration [14]

Vertical Propulsion System Understanding the principles encompassing the positioning of the vertical thrusters is essential for refining the configuration of thrusters in an ROV. Vertical thrusters are pivotal in facilitating both upward and downward propulsion, which is essential for regulating the vehicle's buoyancy and managing its depth in aquatic environments [14].

Achieving the optimal positioning of vertical thrusters necessitates a comprehensive evaluation of various factors, encompassing hydrodynamic forces, buoyancy considerations, and equal to the horizontal thrusters, the experts find it challenging maximizing efficiency. Moreover, it is crucial to strategically position vertical thrusters to maintain the stability of the ROV and minimize excessive tilting or rolling during operational maneuvers. Ensuring the precise alignment of the thrusters enables engineers to effectively distribute the propulsion forces, thereby enhancing the overall performance of the vehicle [14].

Propulsion Force Grasping the fundamental principles behind thruster dynamics, pressure interaction, and water flow management is pivotal for optimizing an ROV's propulsion system.

Thruster Dynamics: The operation of thrusters depends on creating pressure differences to propel the ROV through water, shown in Figure 2.7. This complex process entails converting energy, electric or hydraulic, into kinetic force. As the thruster blades rotate, it induce directional water movement, thus generating thrust. The detailed design of thrusters, encompassing factors such as blade geometry, size, and rotational velocity, which influences pressure dynamics. Engineers analyze these dynamics to fine-tune propulsion efficiency and maneuverability [17].

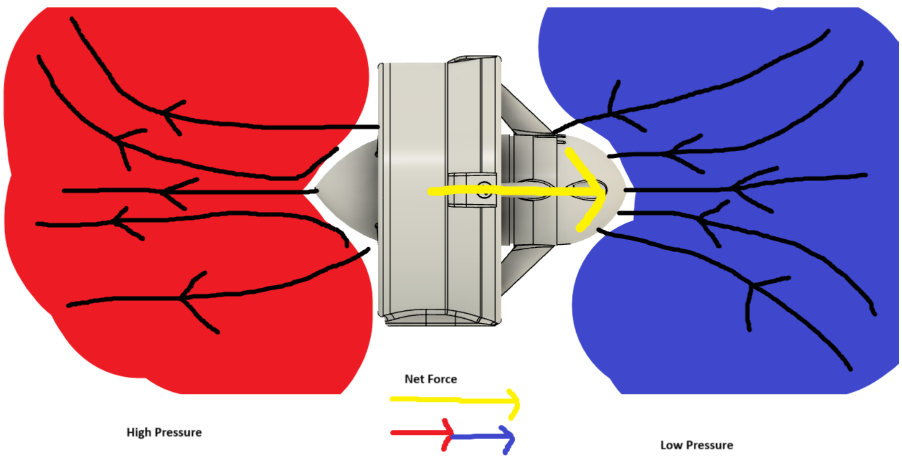


Figure 2.7: Thruster [18]

Pressure Interaction: When multiple thrusters are at play, pressure interference arises as the thrust from one unit interacts with the flow of another. This interaction can disturb flow patterns, illustrated in Figure 2.8, resulting in suboptimal thrust generation. To reduce pressure interference, engineers strategize the arrangement and alignment of thrusters. Advanced computational fluid dynamics (CFD) simulations aid in forecasting and mitigating potential interference effects [17].

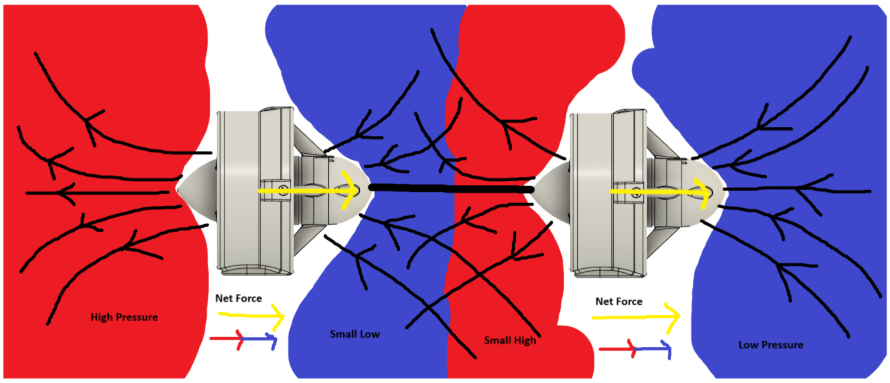


Figure 2.8: Thruster [18]

Water Flow Obstruction: Hindrances in the water flow surrounding thrusters, depicted in Figure 2.9 present a substantial challenge to performance. Buildup of debris, marine organisms, or misalignment of the ROV can obstruct water intake or discharge, resulting in reduced thrust output and compromised maneuverability. Engineers employ various methods to prevent and mitigate water flow obstructions, such as fitting protective grilles, following scheduled maintenance routines, and thorough cleaning procedures. By ensuring unhindered water flow, engineers maintain the reliability and effectiveness of thrusters in a variety of underwater environments [17].

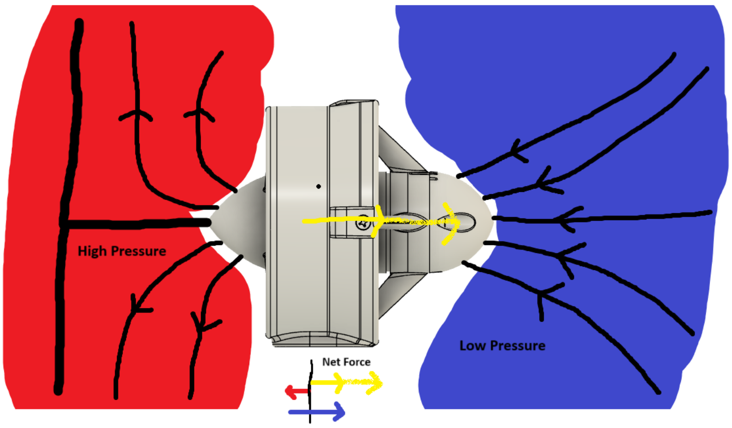


Figure 2.9: Thruster [18]

2.1 Sealing

For operating a ROV, it is crucial that certain components remain dry and protected from water. In this case, the electronics enclosure, battery house, and the electric motor for the manipulator all required some sort of sealing mechanism for waterproofing. This was achieved through the use of o-rings. O-rings have been in use for almost a century, invented by the Danish inventor and machinist Niels Christensen in 1936. An important invention in the second world war, but just as popular today. When correctly sized, o-rings can prevent almost any fluid or gas from escaping their enclosure, or this case, from entering it. The o-rings are suited for static workloads, but in some cases, it‘s used under dynamic applications as well. For optimal o-ring functionality, the grooves must be designed according to the specified o-ring cross section. The group followed SealEngineering´s o-ring catalog for guidance, whom also offered sponsoring UiS Subsea with the chosen o-rings. When installed, the o-rings compress between the two surfaces and seal all gaps around the area of interaction. These are available in various materials, depending on the exposed temperature and pressure [19].

2.2 Manipulator - Theory

A manipulator functions much like a robotic arm mounted on an ROV. The manipulator is designed to perform tasks in challenging underwater environments. Resembling a human arm, it typically consists of six joints. The different parts can be translated into the shoulder, elbow, and wrist of the human body. A typical robotic arm is made up of seven segments which are joined by six joints. The arm is powered by motors which in turn is controlled by computer programs. The primary role of the manipulator is to maneuver its end effector to a precise location for task execution. Various end effectors can be attached depending on the required tasks. A common end effector resembles the human hand, capable of grasping and manipulating different objects. Some end effectors are highly advanced and could be equipped with advanced sensors, such as pressure sensors, to gather relevant data, like the force exerted on objects during manipulation [20].

2.2.1 Production methods - 3D printing

3D printing is an efficient manufacturing method for creating components directly from CAD software, such as Fusion360. This process is additive, meaning the object is built layer by layer. It is particularly useful for rapid prototyping and concept development, as it eliminates the need to order individual components. The 3D printing process begins with a 3D model created in CAD software. This model is then imported into a slicer program, where parameters such as layer height, infill percentage, and support structures can be adjusted to optimize the print. While plastics are the most common material used in 3D printing, suitable for prototyping and low-load parts, the industry is expanding rapidly. Now it is possible to print in more robust materials like steel, although this requires special technical expertise, and comes at a higher cost. Therefore, these materials are less suited for prototyping purposes [21].

2.2.2 Production methods - Lathe machining

Lathe machining is a versatile production method used for manufacturing cylindrical mechanical elements from various types of materials such as metals, wood, and plastic. Unlike a milling machine which involves the cutting tool rotating while the workpiece remains stationary, lathe production methods entail the workpiece rotating around a fixed axis while the cutting tool moves parallel to the rotation axis. Optimizing the lathe machining process involves adjusting several settings, including the rotational speed of the workpiece. Larger workpiece typically requires lower rotational speeds. Additionally, the choice of cutting tool is crucial, considering factors such as the material being used and whether the surface finish should be rather fine or coarse. For significant material removal, there is typically recommended to begin with a coarse cutting tool, before proceeding with the finer cutting tool when the desired diameter of the workpiece is approaching. Various techniques can be employed when using the lathe machine, depending on the desired final product. Some of the techniques are namely turning, facing, grooving, parting, and threading. By using the turning method there are different approaches to consider. Step turning is advisable if the goal is to create a workpiece consisting of two different diameters, where there is an abrupt change in diameter. While chamfer turning provides a smoother transition between surfaces. This method may be quite helpful for applications such as bearing housings where sharp edges must be avoided to assemble the bearing correctly [22].

Facing is a lathe machining technique used to shape the ends of a workpiece to specific requirements, such as creating a right-angled end or making small adjustments to the length of the workpiece. By using this method, the cutting tool moves perpendicular to the rotational axis of the workpiece, removing material along its radius. Grooving is employed when grooves need to be added to the workpiece. The depth of each groove can be adjusted relative to the center of the workpiece. To prevent cutting the workpiece into two parts, the cutting tool must be positioned below the center if it penetrates the workpiece from beneath [22].

This point leads to the next technique namely parting. This technique involves executing clean cuts, allowing the workpiece to be separated into desired lengths. In most cases, the products should be produced at specific measurements and therefore, this method is crucial for obtaining the requirement. In some cases, it is necessary to be able to create threaded surfaces. For performing this operation, the lathe technique threading can be used. The cutting tool moves along the rotating workpiece at the correct speed, forming helical grooves [22].

It's important to note that the lathe machine poses significant safety risks and must be used with caution. Therefore, several safety measures must be implemented when operating the lathe machine in the UiS workshop. The documentation and approval of the SJA are mandatory prerequisites for utilizing the lathe machine. The SJA serves as a vital tool working towards safer operations. This enhances personnel awareness of potential hazards associated with the operations that are due to be carried out. Among the safety measures outlined, it is strictly prohibited for individuals to operate the lathe machine alone in the workshop. The reason behind this is the risk of entrapment without immediate assistance. Loose clothing and gloves are to be avoided as these represent an increased risk of becoming entangled in the machine. Ensuring the safe operation of these machines entails the use of appropriate personal protective equipment, with safety glasses being the minimum requirement. Safety shoes are also recommended to reduce the risk of an injury in the event of a workpiece loose during operation [22].

Lastly, proper placement, attachment, and securing of the workpiece according to safety standards are essential for safe operation. Any incorrect or careless use of the lathe machine can lead to serious damage to the body and in the worst case fatality [22].

2.2.3 Production methods - CNC machining

CNC machining distinguishes itself from manual machining by its preprogrammed process, ensuring an automatic operation. It is possible to produce components through CNC machining in different kinds of materials such as metals, plastics, and wood. Similar to 3D printing, CNC machines utilize G-codes to determine the sequence of the production process. Dimensions for the intended 3D model are specified through a computer-aided design program, also known as CAD software. Once the 3D model is created in the CAD software, it is transferred to a computer-aided manufacturing (CAM) program. From the CAM software, it is possible to manufacture the 3D model in the CNC machine. Before proceeding, all settings need to be verified, followed by a test run, confirming that all settings and tools are correct for a specific manufacturing process. CNC systems mainly fall into two categories, namely open-loop systems, and closed-loop systems. In an open-loop system, communication occurs solely between the CNC controller and the motors. In contrast, closed-loop systems allow for feedback to the controller, making error correction possible during the manufacturing process. Various types of CNC machines exist in the industry, including CNC mills, lathes, plasma cutters, electric discharge machines, and water jet cutting [23].

2.2.4 Production methods - Water jet cutting

Water jet cutting is a versatile production method used for machining components in various materials. This process relies on the use of water and pressure where water is forced out of a rather small nozzle at high speed, resulting in a high-pressure impact on the workpiece. This pressure allows the water jet to penetrate the material, making it possible to manufacture desired mechanical components. There are two main production processes in water jet cutting: pure water jet cutting and abrasive water jet cutting.

In pure water jet cutting, water pressure can reach a pressure of approximately 4000 bars, and together with a 0.3mm nozzle, a water velocity between 3000 m/s and 4000 m/s can be obtained. This produces an exceptionally hard and sharp water jet, strong enough to penetrate thin metal plates. Abrasive water jet cutting differs from pure water jet cutting by mixing the extremely sharp water jet with silicate particles. Mixing particles into the strong water jet enhances the water jet's robustness. This mixture of particles and water jet enables the jet to penetrate most materials as such as stones, metals, and composites. Traditional machining methods often generate significant heat in the processed area, leading to abrupt changes in the material properties, and potentially causing catastrophic failures if material weaknesses aren't addressed properly. This heat could cause thermal shrinkage, and eventually cause errors or inaccuracies to the geometry of the mechanical component. Water jet cutting eliminates this issue by not introducing any heat into the material. This production method allows for detailed geometries and high dimensional accuracy, making it a highly attractive production method for a wide range of materials [24].

2.3 Main types of robotic arms

In general, there are six main types of industrial robot arms. The different types are the articulated robot arm, the cartesian robot arm, the cylindrical robot arm, the delta robot arm, the polar or spherical robot arm, and the scara robot arm. Each of these types will be covered in this theory section These different types will be covered in detail in this theory section [25].

2.3.1 Articulated robot arm

The articulated robot arm utilizes six different axis points for movement. While it may resemble a human arm, the articulated robot arm has three additional joints, granting it significantly more flexibility than the human. The different axes are as follows: 1. Axis 1: Rotates the robot at its base. 2. Axis 2: Controls the forward and backward extensions of the lower arm. 3. Axis 3: Raises and lowers the upper arm. 4. Axis 4: Rotates the upper arm and rolls the wrist. 5. Axis 5: Raises and lowers the robot's wrist joint. 6. Axis 6: Rotates the wrist joint. This configuration of joints allows the articulated robot arm to perform different tasks with precision [26].

2.3.2 Cartesian robot arm

A cartesian robot arm utilizes a 3D cartesian system to navigate the arm around to locations specified by the user. The 3D cartesian system consists of the x-axis, y-axis, and the z-axis. Companies seeking to automate their warehouse systems find cartesian robots highly beneficial due to their ability to perform automated tasks with both speed and precision. While the articulated robot arm also can perform similar automated tasks, the crucial distinction lies in the flexible workspace and speed of the cartesian robot arm [27].

2.3.3 Scara robot arm

SCARA is an abbreviation for Selective Compliance Assembly Robot Arm and is commonly utilized for tasks requiring flexibility, such as pick and place, assembly, and sorting. One of its key advantages is that its simple design enables high production rates. Additionally, these possess high precision while these are also well-suited for working in tight areas. These qualities make this type of robot well-suited for the food industry. However, the high speed and precision also come at a cost of other aspects. The maximum load a SCARA robot can handle is between 30-50kg, compared to 6-axis robot arms that can accept payloads of up to 2000kg [28].

2.3.4 Cylindrical robot arm

The cylindrical robot arm features a primary arm capable of both upward and downward movement, driven by motors, gears, and pneumatic cylinders. Motors and gears provide the rotational movement of the arm, while pneumatic cylinders facilitate the vertical motion. This design makes the cylindrical robot arm well-suited for different applications such as spot welding automation, general machine handling, and material handling tasks [29].

2.3.5 Delta robot arm

The delta robot arm is a type of parallel robot that consists of a distinctive triangular base, and arms that are connected to an end effector located in the center of the robot. These arms can move in all three dimensions. Furthermore, it consists of joints that are necessary for the robot's kinematics, actuators for driving force, and lastly controllers for coordination. Tasks suited for the delta robot arm include gripping and cutting, and because of their high precision and speed, these are highly desired in today's market. In particular, the Delta robot arms are highly relevant for the 3D printing industry, which has been experiencing rapid growth in recent years [30].

2.3.6 Polar or spherical robot arm

The polar or spherical robot arm represents one of the oldest robot designs. This type of robot arm is characterized by three particular movements: rotation, elevation, and extension. These movements are acting from a stationary base, with rotation occurring around a vertical axis connected to the base. Elevation provides both upward and downward movements, while extension extends or contracts the arm. Thanks to their spherical coordinate system these arms can cover a large area around their base, and these are renowned for their high precision. However, this type of robot arm also has its limitations as one of them is that it requires a large area due to its size. It also has a limited allowable payload compared to a 6-axis or a Cartesian robot. Therefore, industries requiring greater payloads may opt for other alternatives. Nevertheless, due to their need for a large area, while also providing high precision in their work, these types of robots are usually utilized in industries with large workspaces, such as the automobile or aerospace industry [31].

2.4 Mechanical components and motors

The manipulator consist of several mechanical components, as well as motors, to secure its functionality. This section serves as an introduction for all components included on the manipulator, in addition to a few components that were evaluated for this project, however found excessive.

2.4.1 Shafts

A shafts is a rotating element of a circular geometrical shape, which is primarily used for transmitting power. Shafts are well-known machine elements and can be used in households as well as in the industry. In general, shafts serve two purposes, transmitting power through rotation or supporting different loads, such as those from gears. Over time, shaft technology has evolved into three main categories: longitudinal shafts, torsion shafts, and flexible shafts. Longitudinal shafts carry loads along their length and are subjected to shear stress, bending stress, or both. Due to their high strength, the application of longitudinal shafts can be found in heavy-duty machinery. Torsion shafts, as the name suggests, are designed to withstand torsional forces, also known as twisting forces, making them ideal for power transmission applications. The last category of shafts involves flexible shafts, that possess elastic properties and are capable of transmitting power around objects. These type of shafts offers flexibility where alignment of shaft holes may not be feasible. The choice of shaft material is critical for withstanding applied loads. Common materials to be used in manufacturing shafts include steel, cast irons, and composite materials. Steel shafts offer high strength and machineability, making them highly regarded among engineers [32].

Composite shafts provide a high strength-to-weight ratio and are also resistant to corrosion. On the other hand, composite shafts are rather ductile, possibly leading to sudden failure, in contrast to steel shafts that would yield before they eventually break [33].

2.4.2 Linear Actuators

A linear actuator typically consists of a motor, gears, lead screw, and a rod shaft. A linear actuator converts rotational motion into linear motion, allowing for pushing or pulling actions. These types of actuators offer both static and dynamic load capacities, indicating the amount of load these can handle while stationary or in motion. There is a wide variety of applications where linear actuators are used, such as adjusting car seats in horizontally. Various type of linear actuators exists, each with its characteristics. Mechanical actuators, hydraulic actuators, pneumatic actuators, piezoelectric actuators, coiled actuators, telescoping actuators, and electro-mechanical actuators are among the different types available. Examples of mechanical actuators include ball screws, lead screws or rack and pinion mechanisms. The hydraulic actuators utilize incompressible fluid to generate pressure for piston movement. The piston will pull back when the pressure is eventually released. In contrast to hydraulic actuators, pneumatic actuators utilize compressed air to produce the same piston movement, while piezoelectric actuators convert electrical energy into mechanical energy to perform the same task [34].

Coiled actuators consist of magnets that create a magnetic field. This magnetic field creates current which in turn moves a coil to create linear motion. Finally, electro-mechanical actuators, resembling mechanical actuators, utilize various motors such as brushless DC motors, servo motors, or even stepper motors to generate rotational movement. The key distinction lies in how electro-mechanical actuators employ motors to generate rotational movement, which translates into linear motion. These types of actuators are programmable, allowing for adjustment of force and motion as needed [35].

2.4.3 End effector

Compared to a human arm, the end effector of a robot arm serves as the equivalent of the human hand. This component of the manipulator comes into contact with the objects that the robot arm is supposed to interact with. The design of the end effector can be tailored to perform various tasks, such as grasping, rotating, or both. Additionally, end effectors may incorporate sensors to enhance the robot's understanding of its surroundings beyond direct object interaction [36].

2.4.4 DC motors

Direct current motors converts electrical energy to mechanical energy by utilizing a magnetic field. The rotor initiates rotation as the magnetic field attracts magnets located on the rotor. DC motors are highly regarded due to their ability to control rotational speed. There are different types of DC motors, including DC motors, brushless DC motors, and servo DC motors. Brushed DC motors aren't design for operating in aquatic environment, however, it is possible to encase them in a sealed housing for subsea operation. The same regards the BLDC motors, however these can be submersible by using epoxy, a simpler and more weight-efficient way of sealing the motor.. However, a problem with the BLDC motor is that it doesn't provide any holding torque. A holding torque can be achieved with methods such as worm gears. Unlike brushed DC motors, the brushless DC motors have a longer life due to the absence of brushes that will wear out over time. The last motor covered in this section is the servo DC motor. This type of motor consists of four different parts: a DC motor, a gearbox, a control circuit, and a position-sensing unit. Like BLDC motors, servo DC motors often utilize gearboxes to convert high rotational speed into lower speed, more practical speeds. DC motors can be utilized in various applications such as electric vehicles, cranes, and elevators [37].

2.4.5 Bearings

A sleeve bearing is mainly utilized to facilitate rotation or linear motion between components. Unlike ball bearings, sleeve bearings do not feature rolling action. In a ball bearing, the balls between the inner and outer rings allow the inner ring to rotate while the outer ring is stationary. On the other hand, the sleeve bearings remain stationary and are press-fitted into a housing with a given tolerance. Sleeve bearings provide a low coefficient of friction by employing specific shaft tolerances and lubrication. Sleeve bearings find frequent use in applications requiring linear, rotational, or oscillating movements. These are also particularly useful in heavy-load machinery as robust sleeve bearings can withstand heavy loads while exhibiting low wear. This combination of attributes makes them highly desirable in the industry. There are various types of sleeve bearings available in the market, each designed to offer versatility. These are often categorized as flange sleeve bearings, cylindrical sleeve bearings, and thrust washers. Flange sleeve bearings can accommodate both axial and radial loads while cylindrical sleeve bearings are designed for radial loads only [38].

As mentioned earlier, a ball bearing primarily consists of three parts: the outer ring, the inner ring, and steel balls. These steel balls enable the inner ring to rotate while the outer rings remain fixed in their housing. A common application of ball bearings involves connecting a shaft to the inner ring, with the hardened steel balls providing extremely low frictional resistance for smooth rotation. Press fitting is commonly used to connect the bearing to the housing and the shaft to the inner ring, emphasizing the importance of following the specific tolerances for these bearings. There are different types of ball bearings specialized for specific tasks such as the deep groove ball bearing and the angular contact ball bearings. The deep groove ball bearing is perhaps the most commonly used, offering both axial and radial supports. Angular contact ball bearings facilitate relative motion between the outer and inner ring, designed to accept simultaneously acting radial and axial loads [39].

As mentioned, shafts and housing fits play a critical role in maximizing the performance of the bearing. Fits that are too loose may result in vibrations, leading to excessive wear and premature bearing failures. Conversely, excessively tight fits can lead to failure due to yielding. The pressure from such tight fits may exceed the yield limit of the steel balls, failing. Achieving proper shaft–housing fits is essential for optimal bearing performance. Following standards provided by SKF can help ensure proper fits are obtained [40].

When dimensioning a ball bearing, several factors must be considered to ensure optimal performance. It is crucial to identify the expected lifespan of the bearing, considering factors such as rotational speed and expected. For bearings subjected to little or no rotation during operation, it is important to identify the static load that the bearing can withstand. Additionally, for bearings subjected to both axial and radial loads, it is necessary to calculate the static bearing load using appropriate equations. This helps ensure that the bearing can withstand the combined forces acting on it. The static bearing load can be calculated using this equation: [41]

$$P_0 = X_0 F_r + Y_0 F_a \tag{7}$$

where,

P_0: Equivalent static bearing load
X_0: Radial force factor
Y_0: Axial force factor
F_r: Radial force
F_a: Axial force

The radial and axial force factors continue to vary depending on the type of bearing. For a single-row deep groove ball bearing, it is recommended that the radical force factor is equivalent to 60% of the radial force and the axial force factor is equivalent to 50% of the axial force. Leaving the equation for the equivalent static bearing load for a single row deep groove ball bearing given as: [41]

$$P_0 = 0.6F_r + 0.5F_a \tag{8}$$

Because the cylindrical roller bearings aren't able to handle axial loads, the axial force factor for this type of bearing is equivalent to zero. Leaving equivalent static bearing load equation for a cylindrical roller bearing given as: [41]

$$P_0 = F_r \tag{9}$$

However, the equivalent static bearing load alone is not enough to conclude with anything. By combining the static bearing safety factor, S_0 with the equivalent static bearing load and the static bearing capacity C_0, it is possible to conclude if the bearing is going to fail or not. This can be obtained by utilizing the equation: [41]

$$S_0P_0 \leq C_0 \tag{10}$$

The static bearing safety factor also varies depending on the operating conditions. The recommendation is that under normal operating conditions, the static bearing safety factor is equivalent to 1.

After identifying the static bearing load for the relevant bearing, the process continues toward identifying the dynamic bearing load. The equation for the equivalent dynamic load is given as: [41]

$$P = XF_r + YF_a \tag{11}$$

where,

P: Equivalent dynamic bearing load

X: Dynamic radial force factor

Y: Dynamic axial force factor

F_r: Radial force

F_a: Axial force

Determining the dynamic factors X and Y is a process that involves identifying the constant f_0, which is further determined by the inner and outer diameters of the bearing, depicted by Figure 2.10.

d	D	f_0	d	D	f_0
20	32	15	30	42	14
	37	15		47	14
	42	14		55	15
	47	13		62	14
	52	12		72	13
25	37	14	35	47	14
	42	15		55	16
	47	14		62	15
	52	14		72	14
	62	12		80	13

Figure 2.10: Calculation factor f_0 [42]

In addition, it is necessary to identify the ratio, given by the equation below to identify the dynamic factors: [41]

$$f_0 F_a / C_0 \tag{12}$$

For a single-row deep groove ball bearing, it is recommended to use the equation $P = F_r$, which states that the dynamic bearing load is equivalent to the radial force. However, this assumption is only valid if $F_a/F_r \leq e$. Often, the C_0 value is unknown because the type of ball bearing is unknown, and because of this it is not possible to evaluate if $F_a/F_r \leq e$ is valid. If this is the case, it is necessary to assume that this mathematical relationship is correct. This opens up for determining a possible bearing that can withstand both the dynamic load bearing and the static load bearing. If so, it is necessary to cross-check if this assumption was correct to do in the end. If the opposite is true, which means that $F_a/F_r \geq e$, then $P = XF_r + YF_a$ [41].

Another critical bearing calculation involves its expected lifetime. The expected lifetime of a ball bearing is given by the equation: [41]

$$L_{10} = (\frac{C}{P})^a \tag{13}$$

where,
L_{10} = Expected lifetime with 90% reliability given in million revolutions
C = Dynamic bearing capacity
P = Dynamic bearing load
a = A constant equal to 3 for ball bearing and equal to 10/3 for roller bearings
The expected lifetime in hours of a bearing is given by the equation: [41]

$$L_{10h} = \frac{10^6}{60 * n} * L_{10} \tag{14}$$

where,
n = rotational speed with units revolutions per minute

Nevertheless, machines don't operate continuously at full capacity. Sometimes these may work at reduced capacity due to various reasons. Therefore, it becomes necessary to introduce fatigue calculations for bearings subjected to variable loads. These calculations involve determining the average load that the bearing is subjected to during its operational time. The expected lifetime (in million revolutions) due to the average load is given as: [41]

$$L_m = (\frac{C}{P_m})^a \tag{15}$$

where P_m is the average load given as: [41]

$$P_m = \sqrt[a]{\sum_i \frac{l_i}{l} P_i^a} \tag{16}$$

where,

l_i = revolutions in millions at one specific capacity

l = total revolutions in millions

a = 3, recommended for both ball bearings and roller bearings by SKF.

By following these calculations, it is possible to obtain an estimate of the type of bearing needed for a specific application.

2.4.6 Gears

Gears are essential mechanical components commonly used in pairs to transfer motion. These play a crucial role in various industries by providing speed reduction while increasing the torque output of a motor. This is achieved through the gear ratio, which represents the number of revolutions that the output shaft completes relative to one revolution of the input shaft. This ratio is particularly important for the smaller motors that normally provide high rotational speed while the output torque is normally low. Gears can be divided into several categories including spur gears, helical gears, bevel gears, and worm gears. The spur gears are probably the most common type of gears. By creating a gear system of spur gears it is possible to obtain a large reduction ratio. The teeth profile on a spur gear is straight, while the helical gear teeth are manufactured at an angle relative to each other, which provides a smoother operation. In contrast to spur gears and helical gears, bevel gears possess the ability to change the direction of the shaft's rotation. The teeth on a bevel gear can be straight, but as the spur gear, this would provide noise while operating. If a large speed reduction or additional output torque is needed, then the worm gear is the choice to pick. The worm gear could provide a reduction ratio of 300:1 or even greater. Another interesting characteristic of the worm gear is that the worm can easily rotate the gear, but the gear is not able to turn the worm. This introduces holding torque to the equation, which is highly relevant for a motor such as the BLDC motor which has close to zero holding torque [43].

Operating gears are subjected to loads at all times, and therefore the failure modes of gears often involve fatigue failures, where its teeth are specifically at risk. Over time, the gear teeth will wear out and eventually break. Because of this, it is crucial to determine if the teeth will fail due to pitting and/or bending fatigue in the transition between the tooth base and the foot circle. When gears are working in pairs, their respective teeth would interact at a contact point. In time, the teeth would experience pitting in the contact point because of the contact force. To conclude, it is necessary to compare the max contact pressure with the allowable pressure that the teeth can withstand.

The max contact pressure is given by the equation: [44]

$$P_{max} = 0.418\sqrt{\frac{FE}{b\rho}} \tag{17}$$

where,

F = Contact force between the teeth E = Modulus of elasticity of the relevant material b = Tooth width ρ = Equivalent radius of curvature

Because of the angular contact force between the teeth, it can be decomposed into two force components. One tangential force component which is given by: [44]

$$F_t = Fcos\alpha \tag{18}$$

and one radial force component which is given by: [44]

$$F_r = Fsin\alpha \tag{19}$$

where,

α = Angle of engament between the two gears.

As mentioned earlier it is necessary to identify the maximum allowable pressure that the teeth can withstand. This can be obtained by the equation: [44]

$$P_{till} = 1.75HB \tag{20}$$

where,

HB = The Brinell hardness of the teeth.

The force from each tooth can be decomposed into two force components, a tangential force F_t, and a radial force F_r. It is the tangential force that creates the bending stress in each tooth, and this force is given by the equation: [44]

$$\sigma_{bmax} = \frac{M_b}{W_b} = \frac{6F_tH}{bs_f^2} \tag{21}$$

where,

M_b = Bending moment

W_b = Cross sectional modulus for bending

F_t = Tangential force component

H = Distance from the foot circle to the point where the force is acting

b = Tooth width

s_f = Tooth thickness at the foot circle

The radial force produces a compression force, and therefore the tooth is subjected to a compressive stress. The compressive stress is given by the equation: [44]

$$\sigma_{trykk} = \frac{F_r}{A} = \frac{F_t tan\phi}{bs_f} \tag{22}$$

where,

F_r = Radial force component

A = Cross section where the force is acting

ϕ = Angle of engament

b = Tooth width

s_f = Tooth thickness at the foot circle

By calculating the bending stress in each tooth, some assumptions are made. The radial force is neglected, H = 2m, where m = tooth modulus, and the angle $\varphi = \alpha$. By doing these assumptions it is possible to calculate an estimate of the bending stress that the tooth is subjected to in the transition area between the foot circle and the tooth. The nominal stress at the foot circle is therefore given by the equations: [44]

$$\sigma_f = \frac{M_b}{W_b} = \frac{12F_tm}{bs_f^2} = \frac{F_t}{mbY} \tag{23}$$

where,

Y = Lewis form factor, which is a constant based on the number of teeth of the relevant gear. This factor can be found in a table or by using a graph. An example of the Lewis form factor table is given in Figure 2.11.

Tanntall	Y	Tanntall	Y
12	0.245	28	0.353
13	0.261	30	0.359
14	0.277	34	0.371
15	0.290	38	0.384
16	0.296	43	0.397
17	0.303	50	0.409
18	0.309	60	0.422
19	0.314	75	0.435
20	0.322	100	0.447
21	0.328	150	0.460
22	0.331	300	0.472
24	0.337	400	0.480
26	0.346	Rack	0.485

Figure 2.11: Example of Lewis form factor [45]

2.4.7 Connecting elements

To eliminate one or more degrees of freedom from a mechincal part, a connecting element is necessary. These connections are commonly categorized as either dissolvable connections or non-dissolvable connections. Bolted connections represent dissolvable connections and are widely used in industry today due to their ability to handle axial forces effectively. Available in various sizes, bolts enable versatile use in different settings, often accompanied by nuts and washers to prevent loosening from vibration. Additionally, fastener sets help to distribute force on contact surfaces, reducing the risk of material failure [46].

To ensure waterproof enclosures, the following formulas were utilized: [46]

$$n_k = \frac{F_0}{F_0 - F_k} = \frac{F_0}{F_m} \tag{24}$$

where n_k is the safety factor for leakage.

F_m can be found from:

$$F_m = (1 - \phi) \times F \tag{25}$$

where:

$$\phi = \frac{k_s}{k_s + k_m} \tag{26}$$

and F is the external force.

k_s is the screw stiffness which can be found from:

$$k_s = \frac{k_{s1} \cdot k_{s2}}{k_{s1} + k_{s2}} \tag{27}$$

and k_m is the surface stiffness:

$$k_m = \frac{\pi \cdot (D^2 + d_h^2) \cdot E}{4 \cdot L_k} \tag{28}$$

The k_s1 and k_s2 values are the screws threaded and non-threaded stiffness, respectively:

$$k_{s1} = \frac{A_s \cdot E}{L_k - L_{st}} \tag{29}$$

$$k_{s2} = \frac{A \cdot E}{L_{st}} \tag{30}$$

F_0 also has to be determined, and can be found from:

$$F_0 = \frac{M_T}{k \cdot d_s} \tag{31}$$

where M_T is the bolt torque and k is a constant factor.
d_s is found from:

$$d_s = \sqrt{\frac{4 \cdot A_s}{\pi}} \tag{32}$$

Welded connections, on the other hand, represent non-dissolvable connections, providing permanent joining of components. Press and shrink connections offer versatility as these can function as either dissolvable- or non-dissolvable connections. A spring is another type of connecting element, often utilized in cars. Cars today include a suspension system, where springs absorb the shocks and vibrations enhancing driving comfort. Unlike bolted connections and welded connections, springs provide an elastic connection, contributing to the overall flexibility and functionality of mechanical systems [46].

2.5 Failure modes

A mechanical component that is constantly subjected to multiple forces and stresses is at risk of failing at some point in its life cycle. Therefore, it is highly relevant to address different failure modes that are likely to happen during the lifetime of a mechanical component. Failure due to yielding, buckling, and fatigue all need to be addressed before it is safe to say that the mechanical component can withstand the forces that are expected to act.

2.5.1 Failure due to yielding

When materials are subjected to high loads relative to their yield strength, material yielding would likely occur. It is possible to perform material tests to identify at which point the material starts to yield. However, this can be rather time-consuming, and therefore some calculations can be useful. A mechanical component can be subjected to normal stress and/or shear stress. All these loads must be accounted for to be able to conclude whether the mechanical component would yield or not.
The normal stress can be a result of an axial force or a bending moment. The normal stress due to an axial force and due to a bending moment is respectively given by the equations: [47]

$$\sigma_n = \frac{F}{A} \tag{33}$$

$$\sigma_b = \frac{Mc}{I} = \frac{M}{W_b} \tag{34}$$

where,

F = Axial force

A = Cross sectional area

M = Bending moment

c = Distance from the neutral axis to the point where the force is acting

W_b = Cross sectional modulus for bending moment

The shear stress could act in two different ways, either from a shear force or from a twisting force known as a torsional moment. The equation for shear stress due to a shear force and shear stress due to torsion is respectively given as: [47]

$$\tau = \frac{Q}{A} \tag{35}$$

where,
Q = Shear force

and,

$$\tau_v = \frac{M_v}{W_v} \tag{36}$$

where, M_v = Torsional moment W_v = Cross sectional modulus for torsional moment

When a material has started to yield it has started its plastic deformation. This means that when the material is stretched even more, it won't retract to its original length. Reversely, this means that when the material is elongated below its yield limit, it will retract to its original length when the force applied is released. As mentioned earlier, the yield limit of a material can be shown experimentally with a tensile test. The test can be carried out by placing the material of choice in a tensile testing machine. After securing it properly and every safety measures are completed, the test can begin. The results from the test can be read from a computer connected to the testing machine. The result of the test is displayed as a graph, and it is possible to read the elongation of the material as a function of the force applied. Most materials will have a clear point on the graph where their yield limit is exceeded. The graph before the material yield limit is more or less a linear graph. The material yield limit can be localized where the graph is experiencing a sudden break. This is the point of no return, and the plastic deformation of the material has as this point started.

2.5.2 Buckling

Another failure mode to consider is the failure due to buckling. The risk of buckling occurs when an axial load is acting on a column. There are different factors to consider when determining whether there is a risk or not, among other things the choice of material, how the column is supported, and whether the column is completely straight or not. The critical value when discussing buckling is called the Euler load. When this load is exceeded, the material starts its elastic deformation due to the acting axial force. Due to the axial force and because the column is supported, the column will bend. The type of support determines how the column deforms. For example, if the column is supported with two fixed supports or with two pivoted supports, the maximum deformation will occur in the middle of the column.

The Euler stress can be determined by the equation: [47]

$$\sigma_E = \frac{F_E}{A} = \frac{\pi^2 EI}{AL_k^2} = \frac{\pi^2 Ei^2}{L_k^2} \tag{37}$$

where,

F_E = Euler load

A = Cross sectional area of the column

E = Material modulus of elasticity

I = Moment of inertia

i = Radius of gyration

L_k = Length of the column depending on how the column is supported.

As mentioned earlier, the Euler load is the critical load where the column is giving in as a result of the axial force. The Euler load can be determined by the equation: [47]

$$F_E = C^2 \frac{\pi^2 EI}{L^2} = \frac{\pi^2 EI}{L_k^2} \tag{38}$$

where,

C = Constant depending on how the column is supported

2.5.3 Fatigue

Over time, some machine components are subjected to variable loads. Both static and dynamic in addition to different intensities. As a result of this scenario, it is necessary to identify the risk of failure due to fatigue. There are multiple factors to consider by designing mechanical components against fatigue failure. Among other things type of material, the design of the component, and the quality of the surface. The question regarding fatigue is highly relevant for rotating axles and bearings. Even though the acting force is not causing any remarkable deformation when static, it could be highly detrimental when the same force is acting on a rotating component and therefore the expected lifetime of this component is drastically reduced. In general, two principles are relevant to dimension a component against fatigue failure, namely the safe-life method and the fail-safe method. By using the safe-life method, the mechanical components are designed to be able to withstand the expected loads during the construction lifetime. By using the fail-safe method, the component is designed in a way that if it fails, it won't lead to catastrophic consequences. There is also a possibility to build in spare parts, which will take over the job for a short period, while the main part is being fixed. This method also leads to continuous production, which should be highly appealing to the production industry [47]

2.6 Product Development Process

The product development process is a guide of how an idea becomes a viable product. Companies employ this strategy to develop products the firm can offer and profit from in the consumer markets. It‘s not that different for the bachelor project in UiS Subsea. Here, the UiS Subsea border are the clients or customers, and the bachelor team has to deliver a fully operating ROV by the end of the semester. A general product process involves a planning phase, a concept development phase, system-level design and detail design phases, testing and refinement, and a production ramp-up. The process varies from one product to another, but usually follows the common thread running through these phases.

Delving further into the foundational elements of the product development process, one realizes that it‘s not as straightforward as it might seem. Each phase has several sub phases, and often overlap with one another. With that being said, it‘s important to follow some sort of development process. Tracking progress, establishing checkpoints and having a common understanding of responsibilities are some advantages, but it´s also easier to make future improvements if the process is thoroughly documented [48].

2.6.1 Phase 0: Planning

The planning phase can be divided into 5 different steps. Starting with observing and identifying opportunities, which is step one. The more ideas, the better. Step two involves evaluating and prioritizing the most promising projects. After choosing the projects with the greatest potential, it‘s important to allocate recourse’s and time, also known as step three. An idea remains just an idea if no resources, both human and material, are applied. The fourth step is completing the pre-project planning, which involves creating a mission statement. The fifth and final allows for reflection on both the results and the process [48].

2.6.2 Phase 1: Concept Development

The concept development phase can also be divided into several steps. The main goal is to generate different concepts and ideas which are based on addressing some need in society, or an opportunity in the market. The phase begins with identifying and interpreting the customers needs, and then establishing target specifications based on this data. Following the specifications, the team can start generating concepts. The most promising concepts can be identified using screening and scoring matrices, and then tested to see if these match the given requirements. If so, the final specifications can be set, and a plan for the development process are made [48].

2.6.3 Phase 2: System-level design

The system-level design phase consists of rough sketches and drawings of the product, as well as early plans for production. The key-points in this phase is to showcase the projects architecture and divide it into smaller groups, which is crucial for the production phase. Obviously, you can‘t have everyone working on everything, so it‘s important to divide the responsibility for the project and ensure everyone knows who‘s in charge of what [48].

2.6.4 Phase 3: Detail design

Phase three of the product development process is detail design. During this stage, the drawings from system-level design are finalized, incorporating accurate measurements and tolerances. This allows for acquisition of the right tools and materials, as well as the purchasing of standard parts. Additionally, the earlier plans for production are further developed [48].

2.6.5 Phase 4: Testing and refinement

The drawings and specifications from detail design lay the foundation for the fourth phase, testing and refinement. This phase involves the development and testing of prototypes. There are two main forms of prototypes, alpha and beta. The alpha prototypes are initial assemblies of all the components that the product consists of. These prototypes are mainly tested ”inside” the company's walls, to ensure that the basic requirements are met. If successful, beta prototypes are developed and prepared for testing in customer environments [48].

2.6.6 Phase 5: Production ramp-up

In the fifth phase of the product development process, known as the production ramp-up, the final preparations for productions are evaluated and completed. The product is deemed ready for production, and any flaws or problems with the production system are addressed during this phase [48].

3 PDP - Planning

The first step in developing a product is the planning phase. The planning phase consists, as mentioned earlier, of five sub-phases. The first two sub-phases, identifying opportunities and evaluating and prioritizing projects, could be argued to have already been addressed before the project launch on January 3rd. When choosing to write the bachelor thesis for UiS Subsea you should have an understanding of what the project involves, namely designing and constructing a ROV. The ultimate goal is to deliver a fully functional ROV, as requested by the UiS Subsea border, but the path to achieving that goal is completely up to the different bachelor groups. These initial phases were also considered during meetings with the project management team last year. An idea that could have altered the perspective of the project was designing and building two ROV´s. One smaller and more maneuverable, and another larger, more standard, ROV. This idea was not pursued further because of limited resources. It was concluded that the machine group, consisting of only one bachelor group, already had sufficient workload, with the new additional battery house and the optimization of the manipulator.

3.0.1 Frame

The frame would consist of a bottom plate, top plate and two side walls. After realizing that this year´s ROV was going to be quite heavy, a solid and robust frame was needed. This deviated from the original idea of keeping the ROV under 25 kg. However, after discussing the size and weight of the battery house, as well as the optimization of the manipulator, maintaining this weight limit was not a realistic goal any longer. There were also early discussions with previous year´s machine groups. Last year´s focus was mainly stability and compactness, as that was something the bachelor group from 21/22 struggled with. Stability remained an important consideration for this year´s group as well. An early goal was for the ROV to be capable of performing sub-sea tasks without stability concerns. Regarding compactness, last years group had some issues with space and maintenance inside the frame. All of these factors were taken into consideration in the concept generation phase.

3.0.2 Battery and electronics enclosure

The electronics enclosure also underwent some changes in plans. Initially, the idea was to use a design somewhat similar to the previous year´s, with the cylindrical shape and dome. However, after learning about the challenges the previous year´s group faced with waterproofing the dome, this idea was not pursued. This problem could have been addressed by the use of o-rings, but there was no advantage of having a dome when there are waterproof cameras which can be placed outside the enclosure.

Regarding the battery, this year´s ROV was the first to have a battery enclosure. It was early decided that the ROV should be a hybrid, capable of running on both the tether and the battery. The battery enclosure was designed in close cooperation with the battery group, as was the electronics enclosure with the communication group. The method for connecting the back- and front ends was also discussed during the planning phase. Possible solutions was either bolting the two together, or to use vacuum or press fit for the front ends.

3.0.3 Manipulator

The objective for this year's manipulator project was to build upon the solutions implemented in the previous year while advancing its capabilities. The original plan was to design a two-jointed arm to facilitate reaching objectives right in front of the ROV, and at the seafloor. As one of the tasks at TAC Challenge involved turning two separate valves located both at the seabed and at a wall, this was a critical criterion. However, during the planning phase, a significant challenge was faced, related to the electro-engineering group's bachelor thesis. The manipulator is based on cooperation between the mechanical engineer group and the electro-engineering group. Therefore, it was necessary to redesign and incorporate an additional joint.

Throughout the planning process, open communication was maintained with the manipulator group from the previous year's project. Their insights, particularly regarding material selection, were valuable. For instance, the former bachelor students warned the group about the brittleness of 3D printed material when exposed to a combination of salt and sunlight. This experience led to exploring materials more suitable for this operating environment.

Insights from last year's project and the specific requirements of the competition, established the foundation for this year's manipulator project. The aim was to create a manipulator that excels in both performance and durability.

3.1 Allocation of Resources and Plan timing

When the product design and development book talks about allocation of resources and plan timing, it refers to a broader process of choosing projects with greater diversity among them [49]. For UiS Subsea this process could involve choosing between various projects. A ROV project, like this year´s, an offshore wind power project, or even a seabed subsea installation. These options were not available when the group was introduced to UiS Subsea, but might be an opportunity for future bachelor groups. Since the main project was already chosen, the group opted to use the allocation of resources and plan timing phase on the the different components of the ROV. Considering there being only one group from the machine department in this year´s bachelor project, the group quickly realized the importance of early resource and time allocation. This led to one group member having main responsibility of the manipulator design, with contribution from one of the electronics groups. The other two was in charge of designing the frame, electronic enclosure and the battery enclosure.

The first week after the project kick-of was mainly spent on completing GANTY charts and "needs matrices", as advised by previous bachelor students. The GANTT chart, as depicted in Figure 3.1, represents an overall plan of the projects different phases, heavily influenced by the product development process. These are a valuable tool for tracking progress, and making sure deadlines are met. The goals and deadlines on the GANTT chart might seem somewhat optimistic at this point, but not impossible to achieve.

The "needs matrices" are lists of needs and necessities, where some parts are required for a fully functional ROV, while others may not be as critical. The needs are ranked from high, middle and low in both difficulty and importance. Last year, the project management team completed the GANTT chart and needs matrix for the overall project, but it was also deemed necessary for each bachelor group to have individual ones.

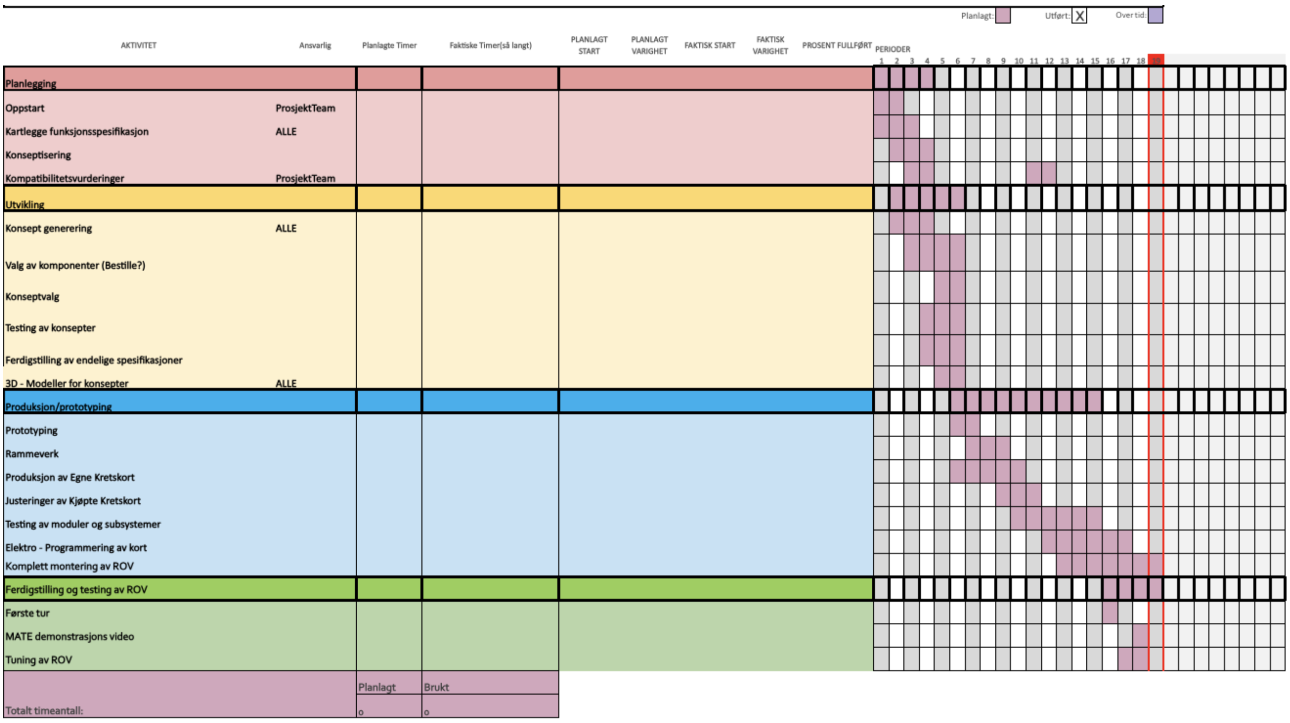


Figure 3.1: GANTT chart

In terms of capital resources, the machine group has been allocated a budget of 22 500kr, 15 000kr for the ROV design and 7500 for the manipulator. There is also a shared post in the budget on 50 000kr, which makes room for additional expenses. The budget this year is not as strict as previous years. There‘s no flight overseas since this year‘s bachelor group is not participating in the MATE competition, which is located in Tennessee, USA. This has been a huge item of expenditure in previous year´s, but talking to former bachelor students, in terms of the academic benefit, the trip was deemed unnecessary. However, having funds available, doesn’t mean it has to be spend.

3.1.1 ROV

The ROV, illustrated in Figure 3.2, was a process solely developed and completed by the machine group. The other groups brought forth wishes and demands for components which either had to be installed on the frame, or integrated to it. This led to a lot of time and resources being allocated to the frame, not just because of the designing process, but since effective communication between the groups were crucial at this stage. Communication within the group was also important. It´s one thing to divide responsibility within the group, but the real challenge lay in integrating all the components and making sure everything fits seamlessly together.

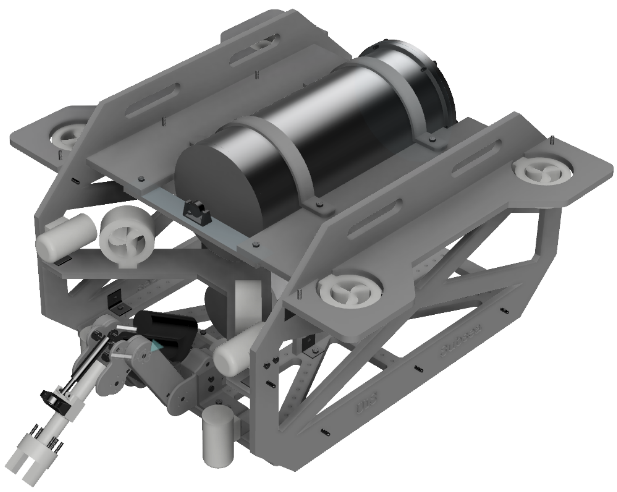
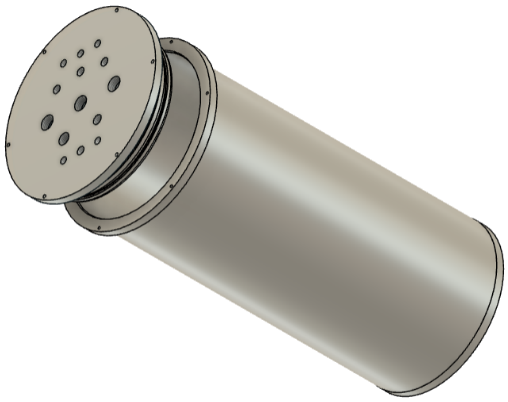


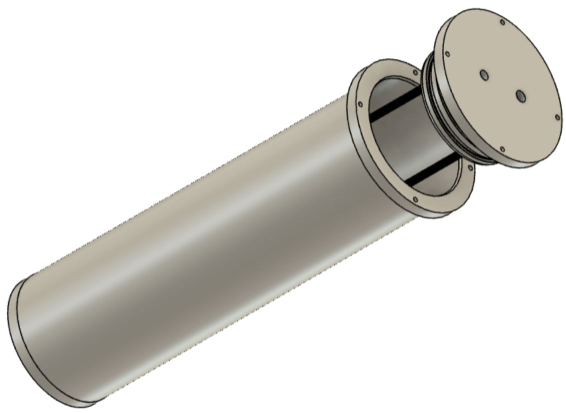
Figure 3.2: Assembled ROV

3.1.2 Electronic enclosure and battery enclosure

The electronic and battery enclosures, as shown in Figure 3.3 also required communication between several groups. Similar to the frame, most of the groups had demands for the enclosures, with the major one being the back end of the electronics enclosure. Based on previous year´s knowledge, this task was assigned a substantial amount of time. The production part at the workshop was also assigned a considerable amount of time. Using the lathe to achieve the chosen diameters of the enclosures required both precision and concentration.



(a) Assembled electronics enclosure



(b) Assembled battery enclosure

Figure 3.3: Assembled enclosures

3.1.3 Manipulator

Given the constraints of limited time and resources, it was necessary to allocate both time and resources effectively for the manipulator project. In the planning phase, a long-term goal was established, which included water testing the ROV by April 10th, a milestone crucial for the manipulator's development. To facilitate efficient allocation of time and resources, responsibilities were carefully distributed between the groups. The mechanical group was assigned the responsibility of designing a manipulator, depicted in Figure 3.4, capable of executing the tasks required for TAC Challenge 2024. A GANTT chart was established early on, providing a visual representation of each group's responsibilities. In pursuit of the project's end goal, weekly individual goals were set to track progress. Since this part of the project was a collaboration between two groups, it was necessary to communicate regularly. Additionally, a needs matrix was established during the planning phase. For the manipulator, this matrix was based on the requirements regarding the TAC Challenge valve intervention task. This created the foundation for developing a functional manipulator that meets the project's objective.

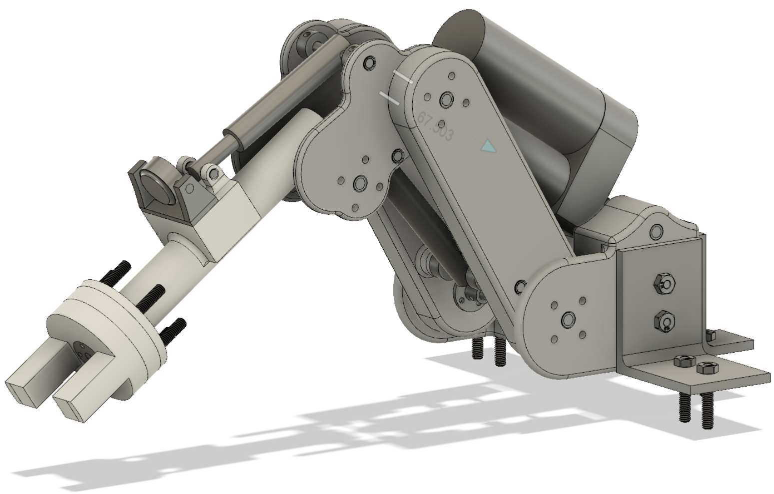


Figure 3.4: Assembled manipulator

3.2 Finalizing pre-project planning

The pre-project planning phase began with the project management team in October 2023, with considerable assistance from previous bachelor students. Weekly meetings were held up until the beginning of the exam period in December. The primary goal of these meetings was to provide an introduction of how the process of designing and building ROV‘s works, and to prepare the team for the kick-of on January 3rd. As mentioned earlier, the GANT charts and needs matrix for the overall project was also established during this phase.

There was not a specific time or date set for the finalization of the pre-project planning phase, it merged with the planning phase when the project launched this year.

3.3 Mission Statement

The mission statement use a couple sentences to inform about the product. It offers a description of the product, benefit propositions and key business goals. It also addresses the market, assumptions and constraints, and stakeholders. When feeling lost or overwhelmed during a product development process, referring to the mission statement might give clarity on the development status, and the next steps. This year´s mission statement goes as following: UiS Subsea is a student organization at the University of Stavanger that focus on the development of remotely operated vehicles for the subsea industry. Each year, new bachelor students are welcome to join this exciting, yet challenging process, on working towards a common goal of developing a fully functional ROV during the spring semester. The overall design was entirely up to this year´s machine group, but within certain boundaries set by both the organization and the group. Stability was a focal point this year, while keeping it under the weight and size regulations required for competing in the TAC challenge. Maintaining an environmental friendly and economic development process were other key points. By integrating these and several other points, the ROV will hopefully be ready for it´s first underwater test on April 10th. While this might be an ambitious goal, it would certainly not be achievable without the support from our stakeholders and sponsors.

4 PDP - Concept Development

If the planning phase is referred to as phase zero, then concept development is phase one of the product development process. The concept development phase compromises several sub-phases. The process begins with identifying customer needs, with the goal of ending up with one or more concepts, which are taken further into the product development process. For UiS Subsea, the customer needs depends on which competitions are participated in. The final concepts will include one for the ROV design and one for the manipulator.

4.1 Identify Customer needs

Being able to identify customer needs is a crucial aspect of the product development process. Like many of the other sub-phases, identifying customer needs also consists of a series of steps for guidance. However, since the primary objective of this project is to design and assemble a fully functional ROV, these are not followed as strictly, in contrast to a product intended for a product market release. As mentioned earlier, the customer needs taken into consideration by UiS Subsea are mainly based on the competition requirements, which originates from the TAC challenge on Tau. The various tasks were acquired quite early in the project process, which was advantageous because it resulted in early requirements that the ROV had to achieve. This activity can be linked to step two in the identifying customer needs phase, which is interpreting raw data in terms of customer needs. Combining this with the next two steps, organizing the needs into a hierarchy and establishing the relative importance of the needs, lays the foundation for the needs matrices, which are commonly utilized throughout the thesis.

When interpreting raw data in terms of customer needs, certain criteria should be followed. The product has to be expressed in terms of ”what” and not ”how”. An example of a need statement would be that the ROV can perform underwater tasks without significant stability concerns. Note that the need does not specify how the ROV should achieve stability. Another important criterion is that the needs should be as specifically expressed as the raw data. Additionally, one should also avoid the words ”must” and ”should”, use positive phrasing and, if possible, and express the need as an attribute of the product.

Acquiring tasks from TAC challenge was considered a part of gathering raw data from customers, which is step one in the process of identifying customer needs. It was a straightforward procedure, the organizers informed that the challenge would be almost the same as last year, with insignificant changes. However, this was not the only source of raw data. Some groups conducted interviews with previous bachelor groups, the machine group included, and last year‘s project management members gave a demonstration of their ROV in use. All former ROV‘s have been stored in the UiS workshop, providing easy access for inspiration regarding design and assembly.

The group decided to divide the ROV into three categories. The ROV frame, the battery and electronic enclosures and the manipulator. This division is utilized in most chapters because the group determined it as the most effective way of dividing the ROV into several sub-problems. It also allows for a more structural and organized bachelor thesis.

4.1.1 ROV Frame

As mentioned earlier, during the initial project management meetings, some basic requirements and targets were established for all bachelor groups. A ROV weight limit of 25 kg was one of the first goals for the machine group, which would grant extra points at TAC challenge. However, after a couple weeks of planning and discussing with other bachelor groups, the team realized this goal was somewhat optimistic. While TAC challenge allows for ROV‘s up to 100 kg, keeping transport of the ROV in mind, the group settled for a weight range around 30-40 kg. As long as the weight remains below 50 kg, there are still opportunities to earn extra points.

The frame had both external and internal requirements. Externally, a salt and chlorine water resistant material, which were capable of carrying the structure of the ROV and weight of components under transportation, was required. Internally, the frame had several requirements. It needed space for cameras, lights, a doppler velocity logger, battery and other components. The maximum depth was set at 50 meters. The needs matrix for the ROV frame is found in Table 4.1.

Table 4.1: Needs Matrix ROV-Frame

Needs Matrix ROV-Frame		
Nr	**Needs**	**Priority**
1	The ROV weighs less than 50 kg	**5**
2	The ROV weighs less than 25 kg	**2**
3	The ROV-frame exhibits hydrodynamic properties	**4**
4	The ROV-frame is capable of operating at a depth of 50 meters	**2**
5	Straightforward process for adding and removing floatation system	**2**
6	Straightforward process for adding and removing ballast	**2**
7	The ROV-frame is engineered for assembly purposes	**4**
8	The ROV-frame is capable of operating in saltwater environments	**5**
9	The ROV-frame is capable of operating in chlorine environments	**5**
10	The ROV-frame features mounting points for the manipulator	**5**
11	The ROV-frame features mounting points for the thrusters	**5**
12	The ROV-frame features mounting system for electronics enclosure	**5**
13	The ROV-frame features mounting system for battery enclosure	**4**
14	The ROV-frame features mounting points for the lights	**5**
15	The ROV-frame features mounting points for the cameras	**5**
16	The ROV-frame features mounting points for the DVL	**5**
17	Transportation of the ROV is convenient	**3**
18	The ROV can be lifted with ease	**2**
19	The ROV-frame fits within the docking place	**5**
20	The production of the ROV-frame is cost-effective	**3**
21	The ROV maintains stability both on land and in water	**5**
22	The ROV-frame enables excellent maneuverability	**4**
23	The vertical thrusters are positioned at the corners	**3**
24	The weight on the ROV-frame is evenly distributed	**4**
25	The ROV-frame safeguards essential components	**5**
26	The ROV-frame is manufactured using environmentally sustainable methods	**4**
27	The ROV-frame maintains a positive buoyancy	**4**

4.1.2 Battery and electronic enclosure

The battery and electronics enclosures were designed for dives down to 50 meters depth. This was not a requirement from TAC. The TAC challenge tasks would not exceed depths of 4-5 meters. Given that the tasks would take place in both the sea and pool, the material had to be resistant to salt and chlorine water. Other requirements were waterproof enclosures to ensure the safety and dryness of the electronics, with some form of cooling system to prevent overheating. Ordered by the electronic groups, the rear plates had to be connected to the internal electronic module, which also required the opportunity for disassembly. The needs matrix of the enclosures is shown in Table 4.2.

Table 4.2: Needs Matrix Enclosures

Needs Matrix Enclosures		
Nr	**Needs**	**Priority**
1	The enclosures are waterproof	**5**
2	The enclosures can resist pressure upto 50 meters deep	**5**
3	The enclosures conduct heat	**4**
4	The enclosures fits the requirement of the electronics group	**5**
5	The enclosures fits the requirement of the battery group	**5**
6	The enclosures withstand saltwater enviroment	**5**
7	The enclosures withstand chlorine enviroment	**4**
8	The enclosures' backplate has room for a pressure relief valve	**5**

4.1.3 Manipulator

The transition from the planning phase to the concept development phase proceeded smoothly. The concept development started as soon as the specifications for this year's project were stated. Multiple concepts were generated throughout this phase, as some of the specifications changed during the planning phase. Extensive discussions and meetings between the two responsible groups were integral to this process, aligning the concepts with the mission requirements of the TAC Challenge and the demands regarding material selection.

Furthermore, identifying the specific needs of the manipulator was another crucial aspect of this phase. Given the environmental conditions it would face, including exposure to saltwater and chlorine from indoor test pools, the material selection process was paramount. The initial plan included that the manipulator was supposed to be driven by electric motors. However, high costs tied to buying sealed linear actuators led to opt for regular linear actuators.

Additionally, an essential requirement for the manipulator was the ease of assembly and disassembly from the ROV frame. Once all the manipulator needs were identified, these were organized into a need matrix, prioritizing each requirement. This facilitated resource allocation, enabling more time and resources on critical components.

Table 4.3: Needs Matrix Manipulator

Needs Matrix Manipulator		
Nr	**Needs**	**Priority**
1	The manipulator can grab objects	**2**
2	The manipulator can provide support for camera	**3**
3	The end effector can rotate +/- 90 degrees	**5**
4	The manipulator can reach a switch at both the seafloor and a wall	**5**
5	The manipulator will not lead to a total ROV weight of 40 kg	**4**
6	The manipulator can provide protection of critical components	**5**
7	The manipulator is easy to assemble and disassemble from the ROV	**4**
8	The manipulator is easy to assemble	**4**

4.2 Establishing target specifications

Establishing target specifications involves translating the previously stated customer needs into specifications. On larger teams, the customer needs are generally understood by all group members, while target specifications are more directed towards the engineers. These specifications, like the customer needs, does not dictate how the problem should be solved, but rather what has to be included in the solution. Different from the needs, the target specifications usually involves numeric values, which are related to a specific metric. The metric can be weight, time, cost and so on, while the value sets the constraint for the metric.

When establishing target specifications, there are three steps to follow. Prepare the list of metrics, collect competitive bench marking information and set ideal and marginally acceptable target values. The groups main focus was on the first and last steps. Preparing the list of metrics can be compared with the interpretation of raw data during the identifying of customer needs process. The needs should be stated as specific as the raw data, while the list of metrics should closely reflect the customer needs. Setting ideal and marginally acceptable goals were important for narrowing down the possible solutions to the specifications. An example is the depth for which the ROV is designed. The customer need is described as following. "The ROV can resist the pressure from the given depth". The need is then transformed into a metric, which could be as simple as operating depth. The metric is constrained by the marginally acceptable and ideal values, which are the depth specified in TAC challenge, and the depth set by the group. The target specifications matrix for the ROV-frame, enclosures, and manipulator are shown in Table 4.4, 4.5, and 4.6.

Table 4.4: Target Specifications ROV-Frame

Target Specification Matrix ROV-Frame						
Target Specification (No)	**Need (Nos)**	**Target Specification**	**Importance**	**Units**	**Marginal value**	**Ideal value**
1	1,2	Max Weight	5	kg	40	> 25
2	3,4,8	Operate within salt water enviroment	5	Subj	OK	OK
3	3,4,9	Operate within chlorine enviroment	5	Subj	OK	OK
4	1,2,4,5,21,24,27	Positively buoyant	5	N	1	1
5	1,2,21,22,24	Maintain stability on land	4	Subj	OK	OK
6	1,2,3,21,24	Maintain stability during underwater operations	5	Subj	OK	OK
7	10,11,12,13,14,15,16,25	Safeguard vital components	5	Subj	OK	OK
8	1,2,17,18,21,24	Suitable transport	3	Subj	OK	OK
9	4	Withstands pressure at specified depths	5	bar	1.5	5
10	3,4,8,9,21,22,24,27	Hydrodynamic	5	Subj	OK	OK
11	5,6,7,10,11,12,13,14,15,16	Facilitates easy component replacement	3	Subj	OK	OK
12	5,6,7,10,11,12,13,14,15,16	Assembly friendly	3	Subj	OK	OK
13	10,11,12,13,14,15,16	Mounting system for additional components	2	Subj	OK	OK
14	10,11,12,13,14,15,16	Mounting system for critical components	5	Subj	OK	OK
15	11,23	Propulsion configuration	5	Subj	OK	OK
16	20,26	Enviromentally friendly	5	Subj	OK	OK
17	7	Smooth edges	3	Subj	OK	OK
18	1,2,5,6,22,24	Distance CM and CB in x- and y-plane	4	mm	> 10	0
19	1,2,5,6,22,24	Distance CM and CB in z-plane	4	mm	> 20	30-40

Table 4.5: Target Specifications Electronics- and Battery enclosure

Target Specification Matrix Electronics- and Battery enclosure						
Target Specification (No)	**Need (Nos)**	**Target Specification**	**Importance**	**Units**	**Marginal value**	**Ideal value**
1	1	Waterproof	5	Subj	OK	OK
2	4	Internal length	5	mm	430	430
3	4	Internal length	5	mm	180	180
4	3	Thermal conductivity rating	5	W/m x K	180-200	> 200
5	4	Hydrodynamic shape	3	Subj	OK	OK
6	2	Operating depth	4	m	5	50
7	5	Operate in salt water	4	Subj	OK	OK
8	6	Operate in chlorine water	4	Subj	OK	OK
9	N/A	Enviromentally friendly	5	Subj	OK	OK
10	7	Pressure resistant	5	bar	1.5	5

Table 4.6: Target Specifications Manipulator

Target Specification Matrix Manipulator						
No	**Need (Nos)**	**Target specification**	**Importance**	**Units**	**Marginal value**	**Ideal value**
1	5	Max weight	5	kg	7	> 3
2	1,3,4	Able to execute intended operations	5	Subj	OK	OK
3	7	Easy assembly / disassembly from the ROV	4	Subj	OK	OK
4	6	Properly sealed linear actuators	5	Subj	OK	OK
5	6	Properly sealed 3. joint	5	Subj	OK	OK
6	8	Ease of assembly	4	Subj	OK	OK

4.3 Concept generation

The concept generation phase was a period marked by numerous hours of work, where the group experienced both challenges and moments of satisfaction. Initially, the goal was to generate as many concepts as possible, considering the constraint of being the sole machine group. In previous years, separate groups were responsible for the design of the ROV and the manipulator. The concept generation phase was structured as a five-step method, involving a thorough understanding and clarifying of the problem, conducting both external and internal research, systematic exploration, and reflection. The group opted to primarily focus on the first three steps of this process.

4.3.1 Clarify the problem

In the initial step, clarifying the problem involved gaining a more detailed comprehension of the process of developing an underwater remotely operated vehicle. At the beginning, the project appeared overwhelming, but breaking down the problem into more manageable subproblems facilitated progress. As previously mentioned, these subproblems involved the frame, battery, electronics enclosure, and manipulator. In the previous year, the ROV exhibited stability both on land and at sea, largely attributed to a compact frame and the optimal positioning of the center of mass relative to the center of buoyancy. The greater the distance between these two centers, the greater the stability achieved. This aspect received significant attention during the design phase. Additionally, careful consideration had to be given to the placement and protection of critical components. Of particular concern was the Doppler velocity logger, the most expensive component, which needed to be mounted in a manner that minimized the risk of damage from obstacles. Moreover, the DVL required a sight angle of 65 degrees to ensure that its signal would not be interfered with by the bottom frame.

Early on, it was determined that the cameras would not be housed within the electronic enclosure. Based on past experiences, the transparent dome used to mount the cameras posed challenges in maintaining waterproofing of the enclosure. Additionally, given that there was no practical advantage to having the cameras inside the enclosure, a new solution for camera placement was sought.

4.3.2 Search externally

Searching externally refers to exploring solutions already developed by others. This step was important for progressing with the bachelor project since none of the group members had any experience in the subsea field. When searching externally, there are five main categories that should be considered:

- Interview lead users
- Consult experts
- Search patents
- Search published literature
- Benchmark related products

Since this is a bachelor project, the group decided to primarily focus on consulting experts, searching published literature and bench-marking related products.

Consult experts Fortunately for this year´s machine group, last year´s group had a lot of valuable information regarding both design and production. In the early phases of the project, these were the main source of information and knowledge. Later on the group started contacting professional firms and experts for further guidance. One of them were EnergyX located at Ålgård technology park. The visit started with a tour on the facilities, providing insight to the daily activities of a mechanical engineer. It was inspiring for the group to observe similarities between their projects and working methods and those of the ROV project, in a much larger scale of course, but the product development process was very much present. After the tour, the group presented the early designs for both ROV and manipulator. There was room for questions regarding design and calculations, and the engineering manager, which led the tour, had a lot of great inputs. They were also open for assisting the project in the production phase, which the group was deeply grateful for, considering the lack of machine engineer students on the bachelor project.

Another firm that was contacted for expertise support was SealEngineering. They were recommended by last year´s group, which had a very positive impression of them. The primary reason for approaching SealEngineering was their expertise in waterproof enclosures. The dialog between SealEngineering and last year´s group proved valuable for this year´s machine group, as they already laid the foundation on the necessary information regarding o-rings. The group was provided with a catalogue from SealEngineering with all standard sizes and dimensions for the o-rings. This resulted in an easy and relatively quick process of waterproofing the two enclosures. The drawings of the battery house were sent to SealEngineering for inspection, ensuring consistency in o-ring sizes and groove dimensions across the enclosures. The two enclosures used the same o-rings and groove dimensions.

Search published literature The team delved into the previous year's research on the bachelor thesis, focusing on the ROV-frame, enclosures, and manipulator. This exploration provided insights, knowledge, and innovative solutions for this year's ROV project. Drawing from the findings, the team formulated a refined and robust concept, building upon the foundation laid by the prior research. Notably, the team encountered uncertainty surrounding the ROV's thruster configuration. However, by utilizing insights from published articles on thruster configurations, the group successfully devised a viable solution. Furthermore, the team investigated bachelor theses from preceding years to pinpoint any recurrent issues with particular components. As a result, the group developed an enhanced concept that addressed past challenges.

Benchmark related products UiS Subsea's victorious entry in the 2023 TAC challenge became a pivotal reference point for this year's project. Despite its success, the 2023 ROV faced certain issues that demanded improvement. Thus, the group's objective was to refine last year's ROV concept. By benchmarking the 2023 model, the team drew inspiration to enhance performance and quality for the current iteration. While some design elements were retained, problematic components from the 2023 version, such as the manipulator's design and material choice, were omitted in the 2024 ROV.

During the concept generation phase, the team encountered challenges in designing certain components for the ROV. The group looked to past models for inspiration on mounting solutions for the electronic enclosure, ultimately refining a solution form the 2023 ROV. However, when it came to the battery enclosure, the group sought inspiration from designs sourced online, such as mounting systems used for pipelines.

4.3.3 Search internally

The internal search consisted of working alone, searching and brainstorming within the machine group, and discussing and sharing ideas with the other bachelor groups. Five key points should be considered when searching internally:

- Suspend judgement
- Generate a lot of ideas
- Welcome infeasible ideas
- Make sketches
- Build sketch models

Suspending judgement in the concept generation phase could refer to the group members not feeling nervous to share their work, or withhold concepts in fear of criticism. Since the group has been working together on previous projects for almost three years now, this should not be a concern. As mentioned earlier, the goal was to come up with as many ideas and concepts as possible. This proved valuable because the final design of the ROV consisted of ideas and combinations of several early concepts. This key point is more easily achieved when keeping the third one, welcome infeasible ideas, in mind. What this means is that no concept is deemed wrong, no matter how absurd it may seem. These concepts might trigger parts of creativity that "normal" concepts could not. The last two key points were mostly executed using computer-aided design programs, like Fusion360.

4.3.4 Frame

Following several weeks of planning, the group initiated the frame design phase. The plan was to dedicate the initial weeks to generating as many concepts as possible, followed by a selection of the most promising ones for further development. After three weeks of design work, the group had formulated nine distinct concepts. The primary considerations for the frame design revolved around ensuring stability, strength, and hydrodynamics.

The initial concepts posed challenges due to the continuous addition of new components, which were demanded by other groups. These components included lights, cameras, a wiring house and a Doppler velocity logger. Additionally, the larger-than-expected size of the battery house presented early difficulties. However, after identifying suitable placements for the components, the design phase proceeded more smoothly. As the group progressed through the initial concepts, the team also recognized the importance of maximizing the distance between the center of gravity and the center of buoyancy, for stability reasons. Consequently, the electronic enclosure was mounted at the top of the ROV. Heavy objects, such as the battery enclosure, were positioned on the bottom plate.

The decision was made to maintain a vertical thruster placement somewhat similar to that of the previous year, with the thrusters mounted on the outside of the side walls. This choice was primarily influenced by stability considerations, as noted by the previous year's group. Regarding the horizontal thrusters, two options were considered. The group could either be directly mounted to the frame or positioned on a cross stiffener situated just above the battery house.

The most challenging aspect of the frame wasn't generating concepts or ideas, but rather integrating them cohesively. An exception was the side walls of the frame, where angled brackets provided an early solution. Two particularly challenging aspects were determining how to attach the battery house to the bottom frame and preventing movement of the electronics enclosure. One proposal to prevent the electronics enclosure from sliding involved cutting rectangles on the edges closest to the enclosure on the top plate, creating a mechanical lock mechanism for the flange. However, this solution wouldn't work as effectively for the battery enclosure due to obstructions above, requiring it to be slid into place. Another idea involved using clamps to prevent both rotation and sliding, which would be optimal for the battery enclosure.

4.3.5 Battery and electronics enclosure

After a few weeks of planning, the group began conceptualizing designs for enclosures. It was decided early on that the enclosures would likely be cylindrical in shape, similar to designs from the previous year. The notable change would be the elimination of the transparent dome, previously used to house cameras. The role of the stereo cameras, which required vision through the dome, was replaced by a Doppler velocity logger, while standard cameras were replaced with waterproof ones.

The group considered both square pipes and spherical enclosures. Spherical enclosures would have been optimal in terms of pressure resistance, but the enclosures posed challenges in terms of connecting and fastening to the frame. Additionally, there was uncertainty regarding the feasibility of placing the internal electronic and battery modules within spherical enclosures, as this had not been attempted before. Square pipes, although less optimal in terms of pressure resistance, offered advantages in terms of mounting. This solution should probably have been explored and tested more thoroughly, but it was not taken any further because of time and limited work force. The pressure would not be a problem for the operating depth at TAC challenge, and less time would be spend on the assembly part.

The battery enclosure was collaboratively designed with input from the battery group, similar to the collaboration with the communication group for the electronics enclosure. To ease the process, the battery house was designed to resemble a scaled-down version of the electronics enclosure. Initially, the first sketches of the enclosures proposed using bolts for fastening both end plates. However, after discussions within the group and with previous bachelor students, it was determined that press fitting could also be a viable solution for the front ends, as well as welding.

4.3.6 Manipulator

With the needs matrix as foundation, the concept generation phase initiated, exploring a wide range of possibilities. Recognizing the importance of diverse concepts, opting not to invest too much time working on all ideas early in the process. Instead, the goal was to generate as many concepts as possible, allowing to identify and refine the most promising solutions for further development.

The first concept was significantly based on the manipulator design from the previous year, incorporating two joints, instead of one. However, a challenge arose with the use of stepper motors and worm gears due to their lack of waterproofing. While a waterproof housing could solve this issue, it would introduce additional weight and complicate the manipulator's operation, particularly regarding lifting capabilities. In addition, these had a problem with last year's manipulator, as the stepper motor struggled with pulling the weight of the arm.

The second concept introduced rotation capability to the manipulator, but similar challenges were encountered with the need to seal the motors which provide both lifting- and rotation mechanisms. Additionally, the base rotational movement of the entire manipulator proved unnecessary for the objectives.

These initial concepts prompted to explore alternative solutions, leading to concept number three which proposed a combination of hydraulic actuators and a BLDC motor for end effector rotation. However, the lack of experience with hydraulic systems and concerns about potential environmental impact, such as oil leaks, posed significant obstacles. At this point, identifying solutions that would enable both rotation of the end effector and gripping mechanism, remained challenging.

This resulted in the final concept. Concept number four consisting of electric linear actuators, a BLDC motor for the rotation of the end effector, and a DC motor for the gripping mechanism. This configuration addressed the challenges encountered with the previous concepts. This concept also aligned with the project objectives as well as the technical capabilities.

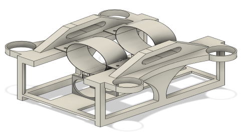
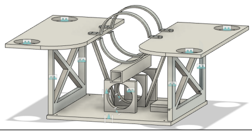
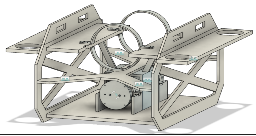
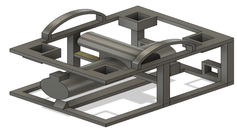
4.4 Concept selection

After a couple weeks of concept generation, it was time to narrow down and choose the most promising ones for further development. The concept selection step was a relief for the group, as the generation phase was more comprehensive and time consuming than expected. The method for choosing concepts involved using the selection matrix, introduced to the group by the product design and development book. The selection matrix was chosen for a structured and organized concept selection, rather than choosing concepts based on intuition, voting or other methods. The matrix rates the concepts with respect to several selection criteria, which are based on the customer needs and the target specifications. The ratings are plus, minus and zero. The plus signs are assigned a value of one, and the minus signs equals minus one. The concepts are all summarized in the last row, and ranked according to the points collected.

4.4.1 ROV Frame

The selection matrix for the ROV, shown in Table 4.7, frame comprised four different concepts. None of them turned out to be the final design, but the process was about choosing the foundation or base of how this year´s ROV was going to look like. Some important criteria for the frame selection was stability, protection of critical components and weight. Another important criteria, which wasn't directly mentioned in the selection matrix, was space for improvements and additional components. As seen on the four concepts, none had a clear spot for mounting of cameras, lights and the the Doppler Velocity Logger. However, this was addressed later in the development process. After carefully evaluating each concept, concepts A and C was taken into further development. However, the group realized there was simply not enough time and resources to continue the development of both concepts. This would mean one concept per group member, considering the responsibility delegation mentioned earlier. After discussing within the group, concept C was chosen as this year´s ROV rough design.

Table 4.7: Screening matrix - ROV frame

Screening matrix - ROV frame				
Selection criteria	A 	B 	C 	D 
Hydrodynamic	+	0	+	-
Weight	0	0	0	0
Maneuverability	+	-	+	-
Buoyancy	+	0	+	0
Salt water resistant	0	0	0	0
Chlorine water resistant	0	0	0	0
Stability on land	0	0	0	0
Stability in water	+	-	+	-
Component replacements	+	-	+	-
Assembly	+	0	+	-
Secure critical part	0	0	0	-
Support wall	+	+	+	+
Protection of critical components	+	+	+	-
Flowing system	+	0	+	0
Mounting for battery	0	0	0	0
Mounting for electronic enclosure	+	+	+	-
Mounting for manipulator	+	+	+	-
Thruster configuration	+	-	+	-
Sum +'s	12	4	12	1
Sum 0's	6	10	6	7
Sum -'s	0	4	0	10
Net score	12	0	12	-9
Rank	1	2	1	3
Continue to develop	**Yes**	**No**	**Yes**	**No**

4.4.2 Battery and electronic enclosure

Both the battery and electronics enclosure was evaluated using their own selection matrix, but the criteria was the same. As seen in the selection table, the group developed three different ideas for design of the electronics enclosure, and two for the battery enclosure. Waterproofing the enclosures was considered the most important aspect in the matrices. Other important criterias were a hydrodynamic design, simple assembly and disassembly, and the ability to withstand the given pressure, which the project team decided on earlier in the process. Although the ROV wouldn't be exposed to the pressure at a depth of 50 meters, it was still a theoretical goal, and all parts were designed accordingly. The screening matrix for the electronic enclosure is illustrated in Table 4.8, and the screening matrix for battery enclosure is depicted in Table 4.9.

Table 4.8: Screening matrix - Electronics enclosure

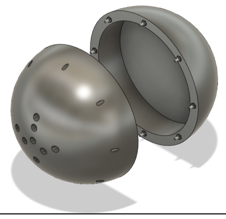
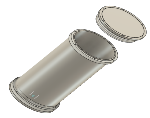
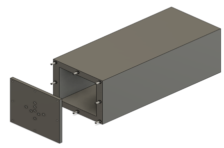
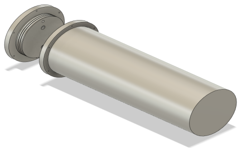
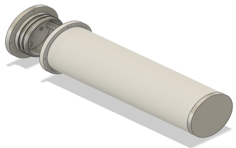
Screening matrix - Electronics enclosure			
Selection criteria	A 	B 	C 
Hydrodynamic	+	+	-
Salt water resistant	0	0	0
Chlorine water resistant	0	0	0
Assembly	-	+	+
Pressure resistant in 50 meters	+	+	-
Waterproof	0	0	0
Heat Dissipation	0	0	0
Room for output	+	+	+
Sealing capacity	0	+	-
Dissassembly ability	0	+	+
Mounting system	-	+	0
Pressure relief valve placement	-	+	+
Weight	-	+	+
Maintance	0	0	0
Sum +'s	2	9	5
Sum 0's	8	5	6
Sum -'s	4	0	3
Net score	-1	9	2
Rank	3	1	2
Continue to develop	**No**	**Yes**	**No**

Table 4.9: Screening matrix - Battery enclosure

Screening matrix - Battery enclosure		
Selection criteria	A 	B 
Hydrodynamic	0	0
Salt water resistant	0	0
Chlorine water resistant	0	0
Assembly	-	+
Pressure resistant in 50 meters	-	+
Waterproof	0	0
Heat Dissipation	-	+
Room for output	0	0
Sealing capacity	-	+
Dissassembly ability	0	0
Mounting system	-	+
Pressure relief valve placement	-	+
Weight	0	0
Maintance	0	0
Sum +'s	0	6
Sum 0's	8	8
Sum -'s	6	0
Net score	-6	6
Rank	2	1
Continue to develop	**No**	**Yes**

4.4.3 Manipulator

The concept generation phase proved to be iterative, with concepts often building upon each other as various possibilities were explored. The concepts selected to proceed with, were subjected to thorough evaluation in the concept selection phase. These evaluations were based on both the needs and the functionality of this year's manipulator. The result from the evaluation process is depicted in Table 4.10. It was essential not to limit exploration to just one concept at this stage, as some concepts might offer clever solutions in specific areas despite not being overall viable. This is also the reason why two concepts went through the first selection, for further evaluation, in addition to complete strength calculations on both concepts.

Concept A did not progress to the next round due to concerns regarding robustness. The weight of the motors at a distance from the anchoring point between the manipulator and the ROV created significant bending moments, increasing the risk of material failure. Also, sealing the motors posed another challenge, with the proposed solution of waterproof housings adding even more stress to the structure.

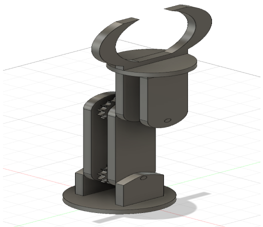
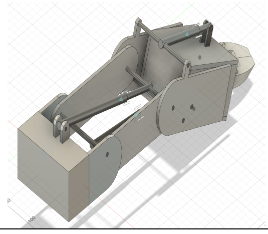
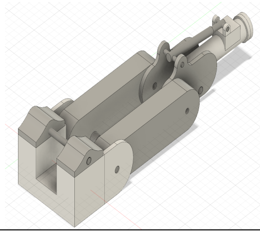
Concept B, however, offered a solution where the motors could be protected while providing both rotation and gripping functions, making it a logical choice for further development.

Concept C is a result of the iterating process performed on Concept B, due to the challenges experienced regarding the sealing of the third joint. This concept was a more robust solution for the intended task, as the removal of the gripping function enabled utilizing a circular enclosure for the DC motor, providing an easier seal for the lid. It was possible to do this improvement as it wasn't a requirement for being able to grip objects for the tasks at the TAC Challenge.

The two concepts that were selected after completing the first concept selection process, were further evaluated based on new criteria, including feasibility. This stage marked the decision-making process for determining which concept to pursue for this year's project.

One significant challenge encountered during this evaluation was the sealing of joint 3 in concept B. A square box, with continuous shafts, is difficult to seal properly. The sealing of this joint was an absolute requirement. After group discussions, it was decided to remove the gripping function for this year's manipulator, allowing for the implementation of a circular third joint, as depicted by Concept C. A circular geometry facilitated easier sealing using o-rings. Through this concept selection process, it was decided to manufacture Concept C for this year's project.

Table 4.10: Screening matrix - manipulator

Screening matrix - Manipulator			
Selection criteria	A 	B 	C 
Easy assembly and disassembly	+	-	+
Suitable placement of the camera	-	+	+
End effector is able to rotate +/- 90 degrees	+	+	+
Able to hold an item of 10N in extended position	0	0	0
Able to perform TAC challenges	+	+	+
Protection of critical components	-	-	+
End effector is able to grab an object	-	+	-
Easy assembly and disassembly onto the ROV	+	+	+
Total -'s	3	2	1
Total 0's	1	1	1
Total +'s	4	5	6
Rank	3	2	1
Continue to develop	**No**	**Yes**	**Yes**

4.5 Concept testing

Concept testing entails a range of efforts aimed at analyzing a concept's viability in the target market. This stage involves examining the mechanical characteristics of each chosen concept and collecting input via interviews involving organizational leadership. In essence, concept testing plays an important role in refining and verifying concepts, guaranteeing that the selected concept stands the highest chance of success in the intended market. It also serves to mitigate risks and form the final product to fulfill both the market's and organization's requisites and anticipations.

4.5.1 Testing of mechanical properties

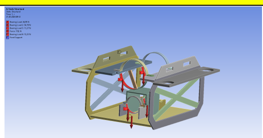
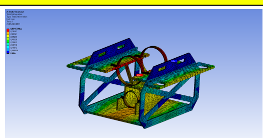
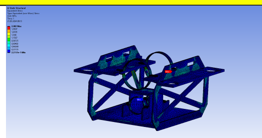
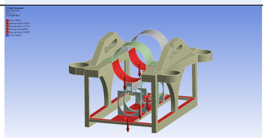
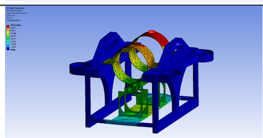
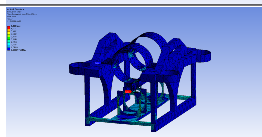
To determine if the concepts were possible and needed improvements, the group used Finite Element Analysis. The software utilized for FEA simulations was ANSYS Workbench. This method helped the team to test the feasibility of the concepts. The chosen concepts were thoroughly tested and analyzed for further development.

Autodesk Fusion 360 was used for creating 3D models of different concepts in the initial phase of concept generating. Utilizing this software helped the group create accurate representations for 3D-printing and technical drawings. Afterwards, the concepts were analyzed in ANSYS Workbench for FEA to understand the forces, pressures and supports acting on the models. Consulting experts and conducting thorough research before simulating the models helped the group to input parameters which produced the most precise results possible.

4.5.2 ROV-Frame

In the testing of mechanical properties of the ROV-frame, the team examined different forces, focusing especially on the weight from the electronic enclosures and the manipulator. The group simulated how these forces would affect the frame when lifted by inputting the supports inside the handles of the side plates and inserting the bearing loads and forces downward.

Table 4.11: ROV frame - Concept testing

Concepts	**Forces and supports**	**Total deformation**	**Equivalent stress**
Concept 1			
Concept 2			

In the developmental process of the project, the team chose High-Density Polyethylene (HDPE) for the frame's material. The team chose to go through with HDPE due to its low water absorption rate, as well as it is approximately neutrally buoyant. The safety factor of the models was a top priority for the group, therefore considering uncertain forces on the structure is important to be inputted in the analysis. Additionally, considering the asymmetric forces generated by the electronics and battery enclosure, the team carefully divided the forces of the components for the model, to ensure structural integrity. By considering these variables, the team was able to assess the total deformation and equivalent stress of the model through FEA, to evaluate the stress distribution.

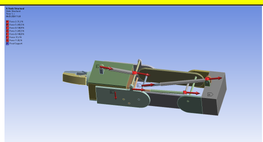
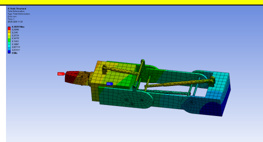
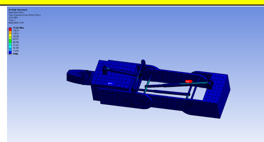
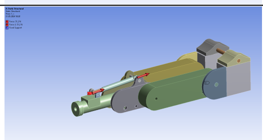
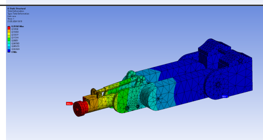
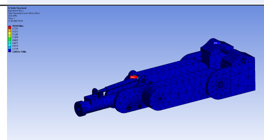
The results of the FEA, shown in Table 4.11, indicated that Concept 1 exhibits superior structural integrity compared to Concept 2. While neither Concept showed signs of failure, the maximum total deformation of Concept 2 was found to be higher. Specifically, the maximum total deformation of Concept 2 was observed to be concentrated on the rear clamps of the electronics enclosure. It should be noted that in this analysis, the clamps were modeled using HDPE material. By selecting a stronger material for the clamps, it is possible to decrease the total deformation. This alternative material choice for the clamps provides valuable insight for the group and offers the opportunity to enhance the sturdiness of the system. Additionally, the stress concentrations in Concept 2 were identified to be greater than in Concept 1. Furthermore, reducing the thickness of certain components during the detailed design phase could lead to material savings without compromising the structural integrity of the models. Through an evaluation of the findings, the team identified potential for further optimization and improvements in material selection.

4.5.3 Manipulator: Forces in pull direction

The manipulator was carefully tested using ANSYS Workbench to gather insights of its strength and performance in different situations. The group decided that it would be optimal to have two sets of FEA for the manipulator. One for forces in pulling direction and the other one for forces in pushing direction. Additionally, the manipulator's position was examined at its most critical stance to assess its sturdiness in a vulnerable position.

The materials that were used for the components of the manipulator was PA6 plastic in order to achieve the most precise outcome possible. The fixed support was inputted on the base of the manipulator where it will be positioned on the bottom plate of the frame. The team's concern was the deformation and stress acting on the side plates and linear actuators of the manipulator. Therefore, examining the total deformation and equivalent stress caused by the weight of the manipulator was critical. These simulations provided a safety factor to avoid failure.

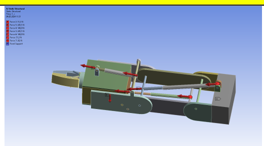
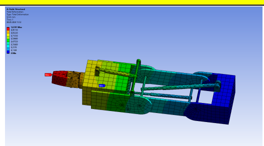
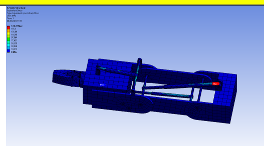
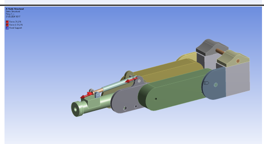
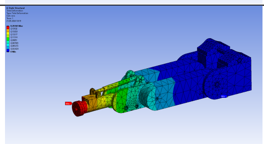
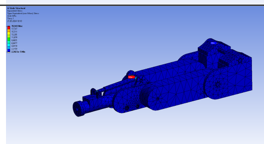
Table 4.12: Manipulator concept testing - Pull force

Concepts	Forces and supports	Total deformation	Equivalent stress
Concept 1			
Concept 2			

4.5.4 Manipulator: Forces in push direction

The outcome of the FEA, illustrated in Table 4.12 and Table 4.13, indicated that Concept 2 exhibits superior structural integrity when compared to Concept 1. Specifically, Concept 2 demonstrated lower maximum total deformation than Concept 1. The maximum total deformation of both concepts is located at the front of the manipulator. Additionally, Concept 2 displayed lower levels of stress concentrations in comparison to Concept 1. The perceived sturdiness of Concept 2's design can be attributed to its utilization of a single linear actuator, as opposed to the three linear actuators present in Concept 1. By carefully examining the results, the structural integrity of the ROV manipulator can be maintained with thinner side plates for Concept 2. Through these analysis's, the team was able to identify potential areas for improvement in material selection and streamlining the design process.

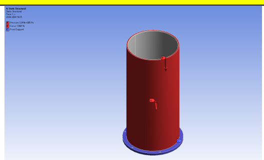
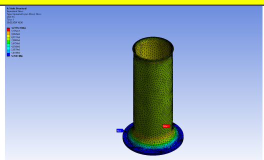
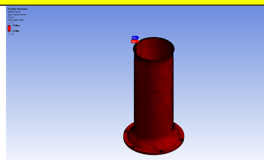
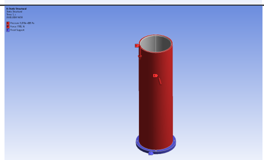
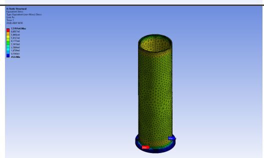
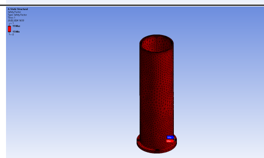
Table 4.13: Manipulator concept testing - Push force

Concepts	Forces and supports	Total deformation	Equivalent stress
Concept 1			
Concept 2			

4.5.5 Electronics Enclosure and Battery Enclosure:

The group designed the electronics and battery enclosure to mimic the deep-sea pressure at depths of 50m and 10m. The main focus was on analyzing the thickness of the bodies of these models.

Table 4.14: Electronics- and battery enclosure - Concept testing

Concepts	Forces and supports	Equivalent stress	Safety factor
Electronic enclosure			
Battery enclosure			

Firstly, the group measured the slimness of the body for the electronics and battery enclosure and found it to be below the critical level of buckling. This meant that the body of the models was not at risk of buckling underwater despite the pressure acting on the enclosures in the axial direction. To determine the critical stress needed for proper sizing of the enclosures, the team conducted an FEA and set the wall thickness at 5 mm for both electronics and battery enclosure. The simulations analyzed the total deformation and equivalent stress caused by external pressure, providing results and a safety factor to prevent failure.

The analysis showed in Table 4.14, that the enclosures were able to handle the underwater environment's stress with a 5 mm wall thickness. By carefully assessing the results, the team found that using a thinner wall is a possibility for further improvement of the models. This analysis gave the team insights to adjust the size of the material to reduce weight and save material without compromising the structural integrity of the enclosures.

4.6 Setting final specifications

Setting final specifications entails establishing ultimate specifications for concepts chosen for further advancement. This involves describing precise attributes, necessities, and benchmarks that a product needs to satisfy, to address the demands of the target market. Conclusions and decisions in this phase are derived from insights gained from organizational leadership and stakeholders during the concept testing phase. Additionally, to fulfill the objectives of the final specification phase, an inventory of materials for exploration and a cost assessment model were devised. This entailed thorough research into available material choices and the estimation of costs for each component, preceding any considerations of sponsorships or discounts.

The initial designs underwent an extensive evaluation process, involving input from leaders from the previous year's project as well as other teams involved in the project. This review aimed to pinpoint specific issues and potential challenges inherent in the designs. To tackle these concerns, the team initiated a streamlined concept development phase to refine the designs before progressing to the system-level design phase for each identified issue.

During this concept development phase, the team engaged in collaborative brainstorming sessions to generate potential solutions for the identified concerns. In addition, the team utilized software tools such as Autodesk Fusion 360 and ANSYS to model and evaluate the feasibility of these solutions. It is important to emphasize that this report will exclusively focus on the selected solution, refraining from delving into details regarding discarded options for each problem.

4.6.1 ROV

The design of the ROV frame raised several key concerns, notably addressing stability, saddle supports for the enclosures, and ensuring cable protection for the thrusters, DVL, camera, and lights. Following an assessment of various concepts, the team settled on a solution involving the installation of a cross stiffener. This design served a dual purpose: firstly, enhancing lateral stability by acting as a beam positioned between the side plates, and secondly, providing support for the saddle supports of the electronic enclosure.

The cross stiffener would be positioned at the top of the rigid box housing the battery enclosure and then connected to the saddle supports of the electronic enclosure. This approach would distribute the bearing load across multiple components, reducing strain on the clamps securing the enclosure. Moreover, the team explored the potential use of the cross stiffener as mounting points for horizontal thrusters and as gateways for cable routing. However, the specific design for thruster mounting had not been finalized at this stage. Nevertheless, the modeling process factored in the possibility of incorporating mounting points on the cross stiffener, which was taken into consideration during the concept selection phase. The cross stiffener is shown in Figure 4.1

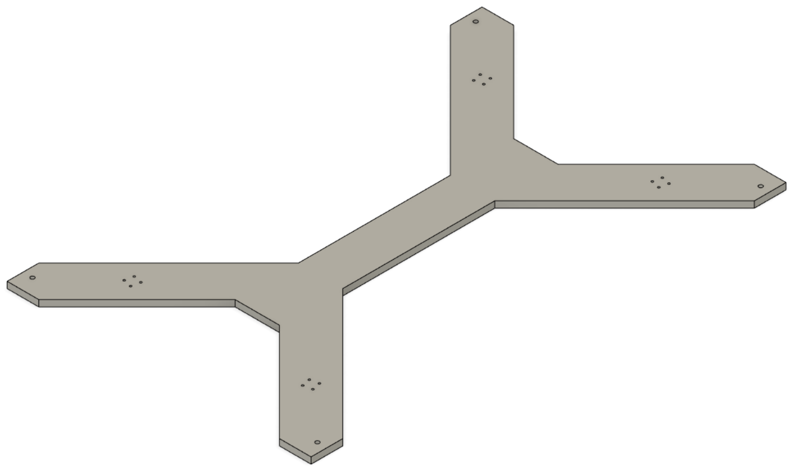


Figure 4.1: Cross-stiffener

4.6.2 Battery and electronic enclosure

The final specifications for the enclosures involved some changes in design. It was decided that the flange on the front end of both enclosures were unnecessary. The flange would create problems during the assembly and de-assembly, and the machining part would be challenging. Therefore, the original designs with the flanges was changed to flushed ends, as seen in Figure 4.2. The back ends remained the same.

There were also added a minor change to the length of the electronics enclosure, to ensure that the fitting of the internal electronics module would be unproblematic.

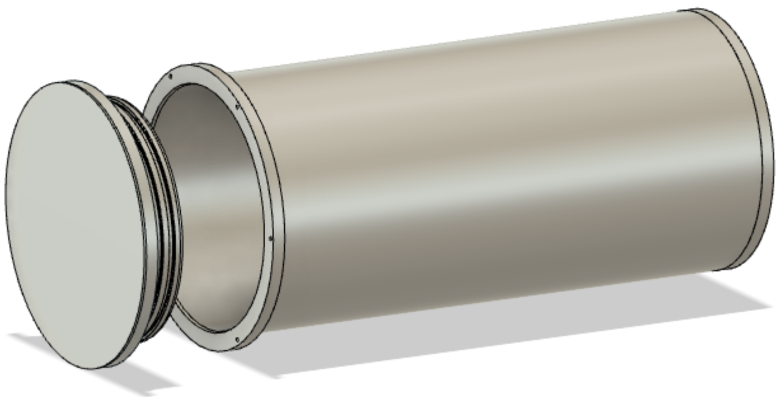


Figure 4.2: Revised electronics enclosure

4.6.3 Manipulator

The final specification phase for the manipulator project was pivotal, encompassing functional goals, performance objectives, space constraints, cost limitations, and insights from past experiences and competition requirements. This phase was crucial as it set the foundation for the subsequent system-level design phase.

Throughout the planning phase, several functional goals were established for the manipulator. These goals were organized in a matrix where each goal was evaluated based on its importance and its degree of difficulty. The primary goal for the manipulator was to handle a valve placed on the seafloor, as well as on the wall, which required a launch angle of at least 90 degrees. Additionally, considerations were made regarding the resting position of the manipulator, in other words, the position it should hold while the ROV is moving. Ensuring the arm to remain above the ROV was crucial, as it would create unnecessary drag by positioning it below the ROV. Having the manipulator in a resting position pointing outwards from the ROV was not desired either. This is due to the risk of struggling with the depth view in water, meaning that the chances of colliding with the manipulator first, increased. This resulted in having the resting position at a 60-degree angle relative to the horizontal plane, which minimized the drag from the manipulator.

A significant functional requirement emerged from the difficulty in sealing the DC motor, which was crucial for the rotational movement of the end effector. This requirement was classified as a high-importance task, as the manipulator would not possess the ability to rotate the end effector if the enclosure wasn't sealed properly.

By communicating with last year's project group, it was clarified that using PLA plastic for applications in salt water and combination with sunlight provided a brittle material over time. They experienced cracks in the structures, which eventually led to failure. This led to creating a functional goal which stated that the manipulator should be made of a material that was more suited for subsea applications.

The last two specifications were to waterproof the linear actuators and use a strong enough material for the shafts to be able to handle the forces exerted by the linear actuators. The corrosion-resistant ability of the material was also an important aspect due to the connection point between the shafts and sleeve bearings. If the shafts start to corrode, there will be additional friction in the rotational movement, which should be prevented.

The next point to be determined in this phase, was to identify the performance goals of this year's manipulator. The performance goals provide how the construction is going to complete the necessary tasks. Again, these goals were also sorted out in a matrix and graded on their difficulty and how important each task is. The most important point was the ability of the end effector to perform the rotation movement. More specifically, at least a 90-degree rotation. This would enable completing one of the valve intervention tasks on this year's TAC Challenge. A factor to consider while determining how to enable rotation of the valve, was that the motor had to be strong enough to perform a rotation while having a force to overcome.

The last two performance goals considered the gripping function and the retraction of the manipulator after extension which, based on the previous year's project group, was a challenge. Last year, these solved the gripping function with a wire connected to the end effector. To retract the wire, a motor was attached, ensuring that when it was driven, the wire would be pulled, and the end effector would perform the gripping function. The problem was with the wire getting stuck, and then the end effector ended up useless.
The problem with the retraction of the manipulator, once it had been fully extended, was a result of weak motors. These conclusions went into thorough consideration after communicating with last year's group. The conversations with people from the project last year created, along with requirements from TAC-Challenge, the foundation for the "setting final specifications" phase.

For the TAC Challenge, some weight limitations had to be dealt with as extra points could be gathered for the competition. Therefore, there was set an individual weight limitation for the manipulator. The goal was that it should not exceed 7 kg. Due to the size of the battery enclosure and the electronic enclosure, there was limited area in front for the base, resulting in space limitations as well. This established the boundaries for the base of the manipulator. There were also some limitations regarding the stroke length of the linear actuators. Due to these limitations, it was necessary to place them correctly relative to the joints, to be able to reach the desired end effector positions.

Ultimately, the final specifications are limited by the budget assigned to the group. The production of the structure itself was outsourced and sponsored for this year's project, and therefore freed up funds to spend on other necessary equipment.

4.6.4 Material exploration

Exploring and selecting the most suitable materials was a significant part of the process. Considering this year´s ROV having additional components than previous year´s, especially the battery house, weight was an important criterion. Additionally, when choosing materials for ROV´s and other subsea related installations, corrosion-resistant material is much preferred, generally those capable of resisting tough working conditions. The group drew inspiration and advice from previous year´s bachelor groups, but a deeper understanding of different materials properties was required to continue researching the most promising ones. FEA was also carried out to justify the chosen materials.

ROV Frame Critical considerations in choosing the optimal material for the ROV-frame encompassed its robustness, resilience to chlorine and saltwater conditions, lightweight nature, manufacturability, and cost efficiency.

Previous iterations of ROVs have utilized aluminum and various polymers for their frames, a practice commonly observed in the subsea sector. Specifically, Aluminum 6081 and 6082 were alloys considered for this year's ROV-frame. Moreover, high-density polyethylene (HDPE) and carbon fiber emerged as potential materials for the ROV-frame. Given the anticipated operational conditions of the ROV, low speeds in shallow waters for brief periods, all three materials were deemed suitable for the intended application.

To facilitate the decision-making process, the team devised a selection matrix to thoroughly assess and determine the most appropriate material for the ROV-frame [50] [51].

The matrix encompassed the mechanical attributes of the three potential frame materials. Furthermore, it incorporated their cost implications and environmental footprint, along with a comprehensive examination of their respective pros and cons. Table 4.15 encompass material exploration for the ROV frame, exploring respectively HDPE [51], carbon fiber [52] [53] [54] [55] and aluminum [50] as potential materials.

Table 4.15: Material exploration - ROV frame

Material exploration for ROV frame			
Material	**HDPE**	**Carbon fiber**	**Aluminium**
Density $[g/cm^3]$	0.94	1.79	2.7
Yield strength [MPa]	23	0	276
Strength-to-weight-ratio $[MPa/g/cm^3]$	8.5	3026	115
Water absorption [%]	0.01	0.8392	0
Cost [NOK/kg]	1.21	169.87	24.15
Environmental consequences	Pollution Habitat impact Microplastic generation Chemical leaching	Chemical emmisions Waste generation Non-biogradable	Extraction impact Air pollution Waste generation Corrosion concerns
Pros	Lightweight Corrosion resistance Impact resistance Cost-effectiveness Ease of fabrication Low maintenance	Strength-to-weight-ratio Fatigue resistance Customization and design Flexibility Corrosion resistance	Strength and rigidity Corrosion resistance (considering anodized aluminium) Lightweight Recyclability Cost-effectiveness
Cons	End-of-life disposal	Expensive material Repairability Delamination	Limited repairability Regulatory compliance

Carbon fiber stands out as the prime selection among the trio of materials due to its strength-to-weight ratio and remarkable yield strength. However, aluminum, known for its durability, cost-effectiveness, and resistance to corrosion, particularly when anodized, emerges as a compelling choice for the ROV-frame. Its high yield strength and exceptional durability further enhance its appeal. Nonetheless, it's worth mentioning that aluminum's manufacturing costs are relatively high, and its repair-ability options are limited [53] [54].

Conversely, HDPE presents itself as a polymer with a modest yield strength. Its characteristic of minimal water absorption renders it highly suitable for aquatic environments. Noteworthy for its corrosion resistance and high-density composition, HDPE carries minimal environmental consequences. Despite aluminum showcasing a superior strength-to-weight ratio, HDPE emerges as the preferred option owing to its cost-effectiveness in both manufacturing and material expenses [51].

Electronic enclosures For the electronic enclosures, a lightweight and corrosion resistant material was required. Thermal conductivity also needed to be considered, due to the heat generated inside the enclosures. In the exploring phase, with limited prior research, three materials was considered. Stainless steel, titanium and aluminium. All three are available as alloys suited ideally for subsea operations, with regards to strength and corrosion resistance. But after further researching, two of them were ruled out. The material exploration of the enclosures are depicted in Table 4.16.

Both stainless steel and titanium had very low thermal conductivity values, ranging from 15 to 20 W/mK. Stainless steel would also pose problems considering weight, as stainless steel has a density approximately three times that of aluminium. Titanium falls between these two in terms of density, with a density of 4.5g/cm3, but price wise far, beyond UiS Subsea´s budget. Aluminium would also give an advantage in the production process, where machining stainless steel and titanium would be time consuming because of it´s hardness [56].

Aluminium was chosen as material for the two enclosures, but the specific alloy was still up for discussion. Aluminium is generally a resistant material, due to the thin aluminium oxide protective layer formed when aluminium is exposed to oxygen. The layer also rebuilds itself if damaged, as long as there is access to oxygen. However, there are some aluminium alloys more suited to salt water environments than others. The 5000- and 6000-series alloys are used in a lot of subsea related operations. The 5083 alloy is one of them, known for an excellent resistance against salt water and several chemicals. Additionally, 5083 is one of the better choices for welding [57].

6082 is another alloy which is popular for various applications, including marine use. 6082 is highly corrosion resistant, but also used for structural purposes, due to it´s strength. 6082 also offers good formability, which makes it a versatile alloy used in many different industries. The last alloy to be explored was the 5052 class. As with the previous ones, well suited for subsea operations. Slightly weaker in terms of yield and maximum tensile strength, but that would not be of importance for this use [58] [59].

Table 4.16: Material exploration - Enclosures

Material exploration for the enclosures			
Material	**Aluminium 5083**	**Aluminium 6082**	**Aluminium 5052**
Pros	Excellent corrosion resistance Good welding characteristics Strength	Strength Thermal conductivity Corrosion resistant	Excellent corrosion resistance High fatigue strength Good welding characteristics
Cons	Machining Thermal conductivity	Lower strength in welding area Not as corrosion resistant	Not heat treatable Strength

3D-printing material The complexity of designing the clamps, supports, and DVL-mount posed production challenges for the team. Drawing on research and insights gathered from consultations with former project members, the team explored various strategies to overcome these, eventually considering 3D printing as a feasible solution.

3D printing offered several benefits, such as reduced production time, cost savings through the university's 3D printing resources, and minimized material wastage compared to traditional manufacturing methods. Furthermore, in the event of unexpected failures, relying on conventional techniques would involve using machines and cutting tools, resulting in inefficiencies and financial implications. However, despite the promise of 3D printing as a manufacturing method, ensuring its suitability for use in chlorinated and saltwater environments, while maintaining environmental sustainability, was crucial. The team had concerns regarding the environmental impact of utilizing 3D-printed plastic materials, considering the exposure of these components to chemicals and sun light, which could lead to the material dissolving.

In addressing these concerns, the team focused on identifying the most suitable material capable of safely operating the ROV in seawater conditions while minimizing its environmental footprint.

3D-printing material: Given the anticipated challenging underwater conditions and the significant weight pressures expected for these components, it was imperative to select a material renowned for its durability and longevity. The team assessed three materials suitable for 3D printing: Polyethylene terephthalate glycol (PET-G), Grey Pro Resin (Form 3) and Polylactic acid (PLA). Most of these materials were conveniently accessible in the university's 3D printing lab [60] [61] [62] [63].

The decision-making process involved analyzing the mechanical properties of the three potential 3D printing materials, alongside considering their respective costs and environmental impacts. A thorough examination was conducted to evaluate their individual strengths and weaknesses. Table 4.17 displays the material exploration for 3D printing [64] [61] [65] [66] [67].

Table 4.17: Material exploration - 3D printing

Material exploration for 3D-printing			
Material	**PLA**	**PET-G**	**Grey Pro Resin**
Density $[g/cm^3]$	1.24	1.23	1.08
Strength-to-weight-ratio $[MPa/g/cm^3]$	38.7	39.4	56.4
Water absorption [%]	0.06	0.12	0.83
Cost [NOK/kg]	10-60	20-60	2565.17
Environmental consequences	Energy consumption Limited recycling Degradation material	Non-biogradability Plastic pollution Toxic additives Marine habitat degradation Limited recycling	Non-biogradability Plastic pollution Toxic additives Marine habitat degradation Limited recycling
Pros	Mechanical strength Biogradability Lightweight Versatility Non-toxicity Reduced marine pollution Low water absorption	Mechanical strength Low water absorption Lightweight Electrical insulation	Mechanical strength Low water absorption Lightweight Electrical insulation
Cons	Limited temperature resistance Brittleness Limited recycling	Non-biogradability Plastic pollution Toxic additives Water absorption Limited recycling	Non-biogradability Plastic pollution Toxic additives Water absorption Limited recycling

PLA, widely acknowledged as a favored material for 3D printing, is notable for its minimal ecological impact. Sourced from renewable origins like cornstarch or sugar cane, it qualifies as a bio-based plastic, boasting both biodegradability and non-toxicity. Its mechanical robustness proves sufficient to endure the challenges expected by the ROV. However, it's noteworthy that PLA can degrade under UV exposure, potentially leading to brittleness over time. Nonetheless, given its low absorption rates, cost efficiency, and environmentally friendly characteristics, PLA receives strong support from the group [63] [67].

Among the materials, Grey Pro Resin stands out for its remarkable strength, providing a noteworthy strength-to-weight ratio essential for 3D printing various components. Its lightweight nature and durability further augment its appeal for this application. Nevertheless, Grey Pro Resin's environmental footprint has to be considered, given its non-biodegradable nature, posing a risk of plastic pollution and potential harm to marine ecosystems. Additionally, the inclusion of toxic additives and limited recycling capabilities supports these concerns. Similarly, PET-G showcases strength and suitability for chlorine and saltwater environments. However, its non-biodegradability and toxic additives raise the same environmental concerns.

While these materials offer desirable mechanical properties, the team faces the dilemma of their environmental impact, which contradicts the objectives for the ROV. Further discussion is necessary to balance these factors and arrive at the most appropriate material selection [61] [60] [62].

Given the array of considerations and the decision matrix at play, the process of selecting a 3D printing material for the ROV components involved various factors such as strength, environmental ramifications, and suitability for the intended usage.

4.7 Cost model

In order to secure the project's financial position, a cost analysis was crafted to measure the anticipated expenditures linked with both the advancement and manufacturing of the item. This analytical framework took into account all facets of production costs, including raw materials, workforce, operational overheads, and assorted ancillary expenses. By gaining insights to the early costs, the team was able to make careful choices concerning pricing strategies and resource allocation, thus optimizing operational efficiency.

In the early stages, there were many price factors to consider, requiring a careful review to ensure that the budget limit of 22,500kr set by the UiS Subsea organization was adhered to. This evaluation was crucial for initiating production methods, finalizing material choices, and managing discussions with sponsors. Due to uncertainty about sponsorship levels and possible discounts, the cost model was developed based on standard component prices without factoring in sponsor contributions. These prices were obtained from website information or initial quotes collected during the research stage, providing estimated costs for externally purchased components.

Table 4.18: Initial Cost Model ROV-frame

Initial cost model ROV-frame	
Parts	**Cost (NOK)**
ROV-frame	
Manufacturing plates	8 000
3D-printed components	10 000
Brackets and screws	3 000
Flotation elements	6 000
Total approximated cost - ROV-frame	**27 000**
Enclosures	
Material	5 000
Turning process	30 000
CNC - Machining	10 000
Pressure relief valves	600
O-rings	500
Clamps	2 000
Threaded rods	200
Bolts and screws	1 500
Total approximated cost - Enclosures	**49 800**
Manipulator	
Base	3 000
1. Joint	2 750
2. Joint	2 250
3. Joint	200
End effector	15
Shafts	200
Sleeve bearings	1 000
M3-Threaded inserts	350
O-rings	15
Bolts	60
Total approximated cost - Manipulator	**9 840**
Total approximated cost - Project	**86 640**

The initial cost assessment, depicted in Table 4.18, indicated that the real expenses for crafting the ROV-frame, enclosures, and manipulator surpassed the budget set by UiS Subsea. This underscored the necessity to investigate different sponsorship agreements, production techniques, and the potential for manufacturing at the UiS Workshop and UiS 3D-printing Workshop. The aim was to align the project expenses with the assigned budget.

5 PDP - System Level Design

The geometry and rough design off all components are finalized in the system level design phase. To achieve a clear understanding of the different tasks, and to divide these withing the group, the ROV is split into several subsystems. The ROV has been divided in three main categories respectively the frame, manipulator and the electronics enclosures. These are further developed in the system level design phase.

5.1 Defining architecture of concept and dividing into subsystem

The system level design phase was a milestone for the group. This meant no more major changes involving design, which was important for the development process. Given more time, there would probably be other solutions and design ideas up for discussion, however time is a scarce resource when writing a bachelor thesis. As mentioned earlier, each former main category was further divided into smaller subsystems, which laid the foundation for the system level design phase.

5.1.1 Major components and dividing into subsystem ROV-frame

The primary elements comprising the ROV-frame were highlighted. Each of these primary components necessitated specific mounting points, connections, supplementary elements, or brackets to facilitate interactions and integration, thereby fostering a well-organized system. Extensive evaluation was applied by the team to assess the interaction among the primary components, resulting in the compilation of a list of subsystems demanding design alternatives, supplemental elements, and further refinement. Table 5.1 showcasing the primary components and outlined subsystems of the ROV-frame is located below.

Table 5.1: Major components and subsystems - ROV

Major components and subsystems - ROV	
Major components	**Subsystems**
Bottom plate	Connections of the bottom plate and side plates
Left side plate	Connections of the side plates and top plates
Right side plate	Connection of the cross-stiffener
Left top plate	Connection of the electronic enclosure
Right top plate	Connection of the battery enclosure
Electronics enclosure	Connection of the battery house to the bottom plate
Electronics enclosure clamps	Connection of the battery house
Electronics enclosure saddle support	Connection of the cameras
Battery enclosure	Connection of the lights
Battery enclosure clamps	Connection of the manipulator to the bottom plate
Battery enclosure saddle support	Mounting of the electronics enclosure saddle support
Battery house left side wall	Mounting of the battery enclosure saddle support
Battery house right side wall	Mounting points for the bottom plate
Battery house roof	Mounting system for the DVL
Cross-stiffener	Mounting system for the thrusters
Thrusters	
Manipulator	
Camera	
Lights	
DVL	

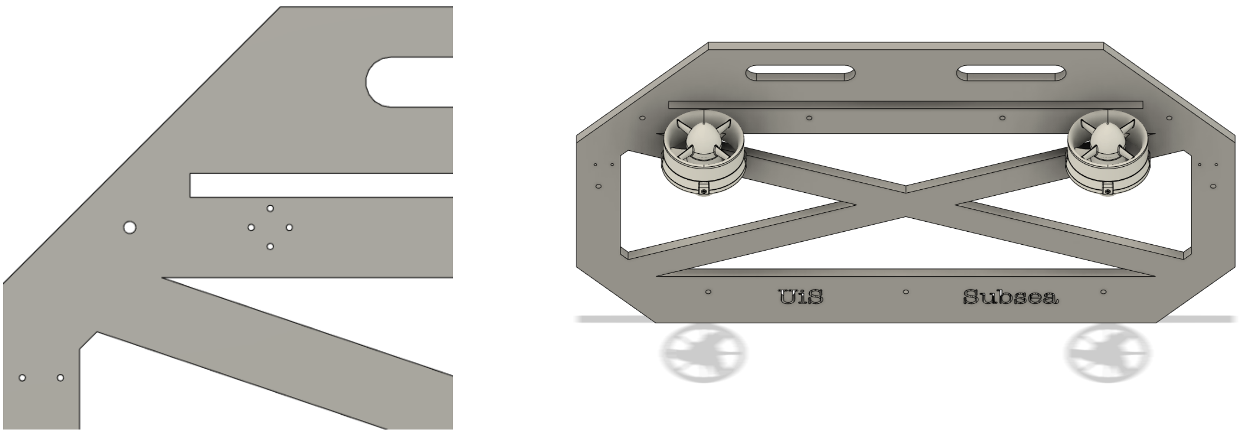
5.2 Designing, testing and evaluating subsystem ROV frame

After identifying the essential subsystems for assembly, the development and resolution process was initiated for each subsystem. Similar to concept testing, a standardized approach was used to revise each concept. A concept development procedure was carried out for each subsystem, involving collaborative brainstorming sessions to generate diverse solutions. These suggestions were then evaluated for feasibility, production possibility, and durability, with the most suitable option selected for each subsystem. The team chose to collectively discuss and assess the different options instead of pursuing individual development paths, in order to optimize time management due to project's time constraints. While some subsystems required selection matrices for comprehensive evaluation, others had clearly superior options, reducing the need for extensive analysis.

5.2.1 Thruster mounting

In order to enhance the maneuverability and ease of use of the ROV, it was determined that equipping it with eight thrusters would be advantageous. Specifically, four vertical thrusters were implemented to facilitate movement along the z-axis, as well as roll and pitch rotations. Furthermore, four horizontal thrusters were incorporated to allow for movement along the x and y axes, as well as yaw rotation. As explicated in the theoretical framework, these thrusters operate by expelling water from the front to the rear, creating a pressure differential that propels the ROV in a forward direction. Ensuring that the thrusters were mounted in a manner that constrained any excess degrees of freedom was essential. This precaution was vital in order to ensure that the force exerted on the thrusters translated effectively to the ROV, thereby maximizing its operational efficiency.

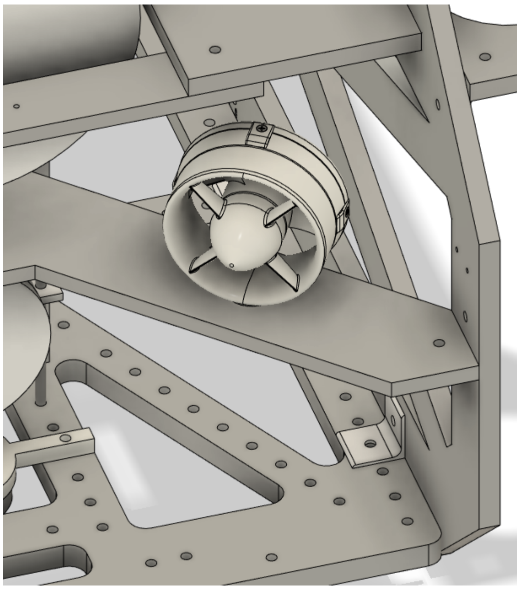
Vertical thruster mounting The vertical thrusters' mounting points, depicted in Figure 5.1, were configured at a right angle to the side plates, allowing for direct installation without the need for additional brackets. The alignment of the vertical thrusters with the top plate was prioritized for stability; however, due to the top plate's insertion into the side plate's slit, the mounting points and thrusters had to be positioned slightly above or below the level of the top plate. After discussions with organizational leaders, who were the part of the 2023 team advised the group regarding the potential challenges of submerging the ROV when the vertical thrusters were placed above the buoyancy elements, a decision was made to position the mounting points slightly below the opening in the side plate.



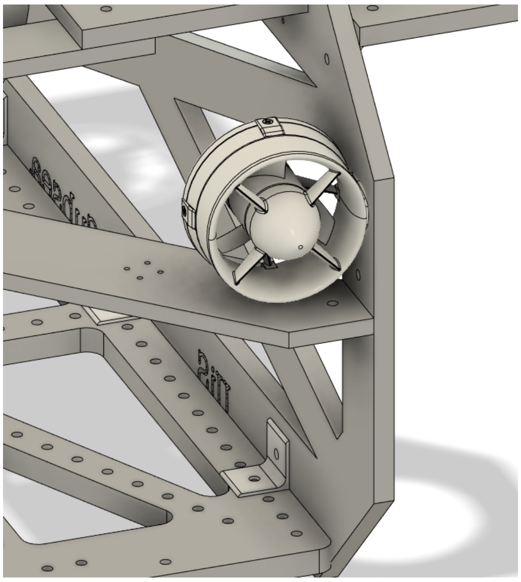
(a) Vertical thruster mounting points (b) Vertical thruster configuration

Figure 5.1: Vertical thruster mounting [18]

Horizontal thruster mounting In contrast to the vertical thrusters, the mounting points for the horizontal thrusters ran parallel to the side plate, as shown in Figure 5.2. This flexibility allowed them to be fixed to either the bottom or top plate, or an additional part could be attached to the side plate for mounting. However, positioning the thrusters too distant from the ROV's center of mass would adversely affect maneuverability, particularly in terms of yaw rotation. To reduce this issue, a decision was made to develop thruster brackets that would enable mounting the thrusters closer to the center of mass. Various potential solutions for horizontal brackets were explored to ensure that they met the ROV's requirements. Following feasibility testing of each concept, three were selected for further evaluation. Concept 1 involved mounting points directly within the cross stiffener, enabling the thrusters to be placed close to the center without additional parts. Concept 2, inspired by the previous year's ROV, entailed mounting the thrusters onto a rod, which was then fixed at each end of the side plates. This concept facilitated placing the thrusters further from the horizontal center, facilitating yaw movement and offering greater position freedom along the longitudinal axis.



(a) Horizontal thruster configuration on cross-stiffener

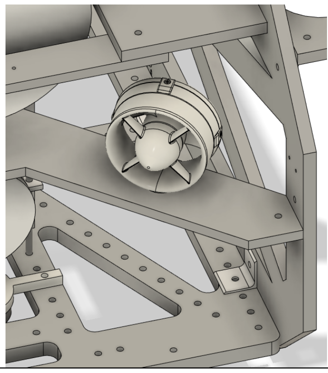
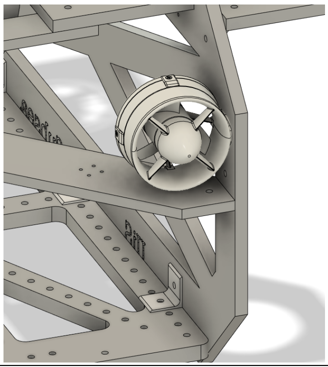


(b) Horizontal thruster configuration on side plates

Figure 5.2: Horizontal thruster configurations [18]

Following a thorough screening process, Table 5.2, concept 1 emerged as the preferred choice. This selection was primarily driven by its ability to minimize production costs, optimize weight, and effectively resolve cable transportation issues. Opting for concept 1 offered a optimized solution to several challenges with a singular component.

Table 5.2: Screening matrix - Thruster brackets [18]

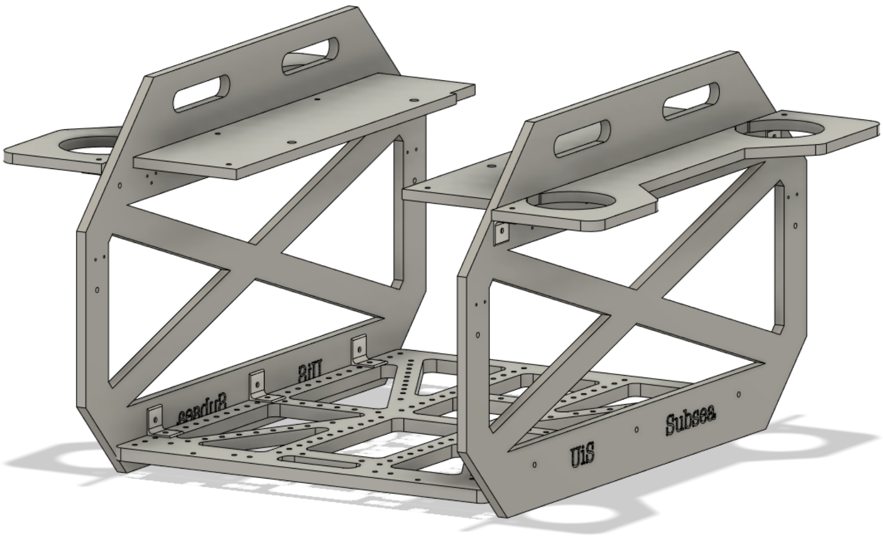
Screening matrix - Thruster brackets		
Selection criteria	A 	B 
Structural stability	+	+
Convenient access for cables	0	0
Dissassembly	+	+
Does not disrupt horizontal thruster flow	+	-
Require additional components	0	0
Injury risk parts	0	0
Within ROV's requirements	+	-
Sum +'s	4	2
Sum -'s	0	2
Sum 0's	3	3
Net score	4	0
Rank	1	2
Continue to develop	**Yes**	**No**

5.2.2 Connection of the plates

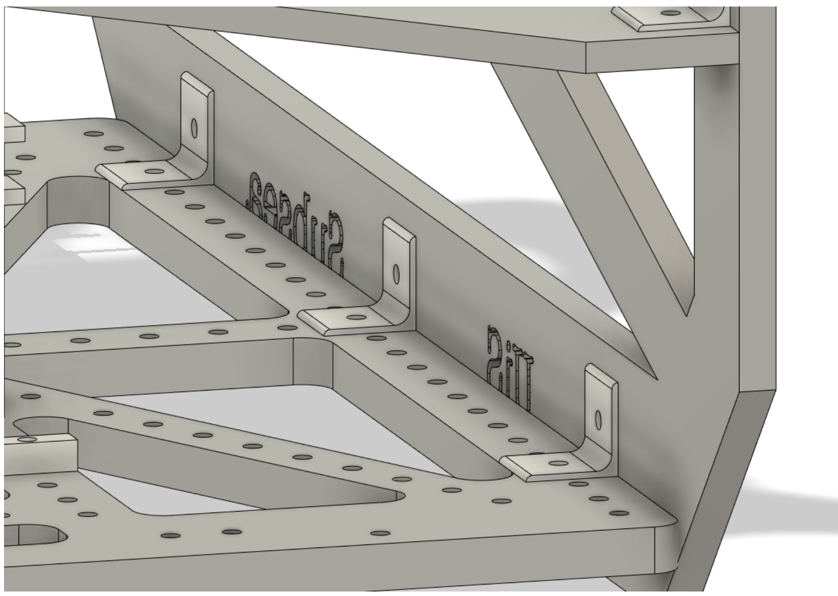
To optimize production and assembly processes, the team opted to standardize the connection method for the plates. This strategic decision aimed to enhance time management and minimize production costs. Given the symmetrical nature of the plates, standardizing this type of connection was considered practical. The design of these plate connections was carefully crafted to optimize the strength and stability of the overall structure. Gaining inspiration from the approach utilized in the 2023 ROV project, the group's decision-making process was further informed by consulting with members of the previous year's team's.

Their insight stated the viability of the approach for the current ROV project, reinforcing the team's confidence in its effectiveness and suitability.

The connection between the bottom plate and side plates, shown in Figure 5.3, consist of six brackets, divided into three brackets on each side. Similarly, the connections between the side plates and top plates, illustrated in Figure 5.4, utilize eight brackets in total, with four on each side. Insertion of the top plates into the side plates is facilitated by dedicated holes. The decision to employ identical brackets for plate connections was reached collectively, aiming to simplify manufacturing processes and minimize design variations. This approach was selected by the team to enhance the efficiency of component assembly.

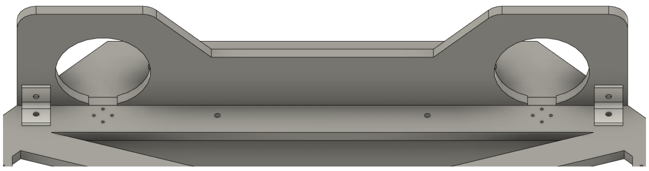


(a) Bottom plate and side plates connection

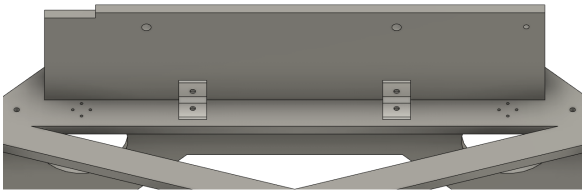


(b) Brackets configuration for the bottom plate and side plates connection

Figure 5.3: Mounting system of the bottom plate and side plates



(a) Brackets configuration for the side plates and top plates connection



(b) Brackets configuration for the side plates and top plates connection

Figure 5.4: Mounting system of the side plates and top plates

The brackets utilized for plate connections, depicted in Figure 5.5, were uniform in design, all crafted by the team. These brackets served multiple connection purposes across various components of the ROV. Aluminum was chosen as the material for these brackets to reduce weight, a critical consideration given the numerous brackets employed for component-frame connections. Opting for aluminum not only contributed to weight savings, but also aligned with budget constraints, facilitated by the university workshop's provision of available materials. Furthermore, seeking insights from former project participants regarding the durability of aluminum, it was noted that previous team members stated its capacity to securely support the components.

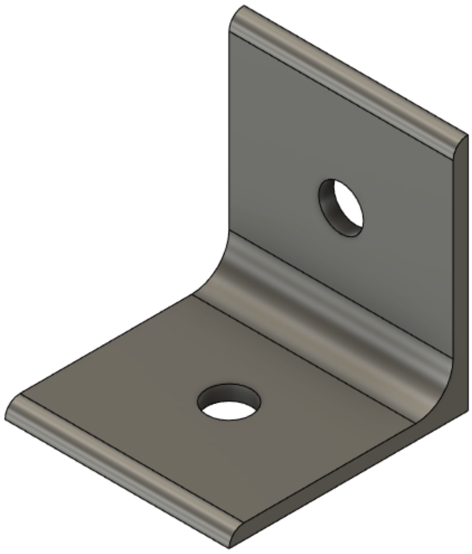


Figure 5.5: Bracket used for several connection system

5.2.3 Connection of the cross-stiffener

Regarding the connections of the cross-stiffener, Figure 5.6, the approach closely resembled the connecting method used for the plates. Considering the symmetric design of the cross-stiffener, it made practical sense for the team to employ the same connection method as for the plates. This consistent approach proved beneficial for the group, enabling efficient time management and cost minimization in the production of the cross-stiffener connections.

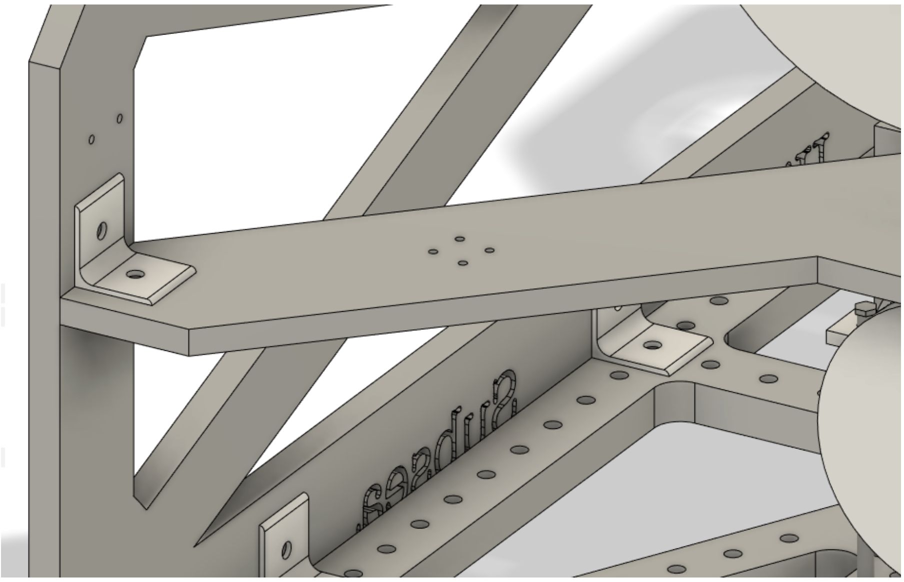


Figure 5.6: Brackets configuration for the cross-stiffener and side plates connection

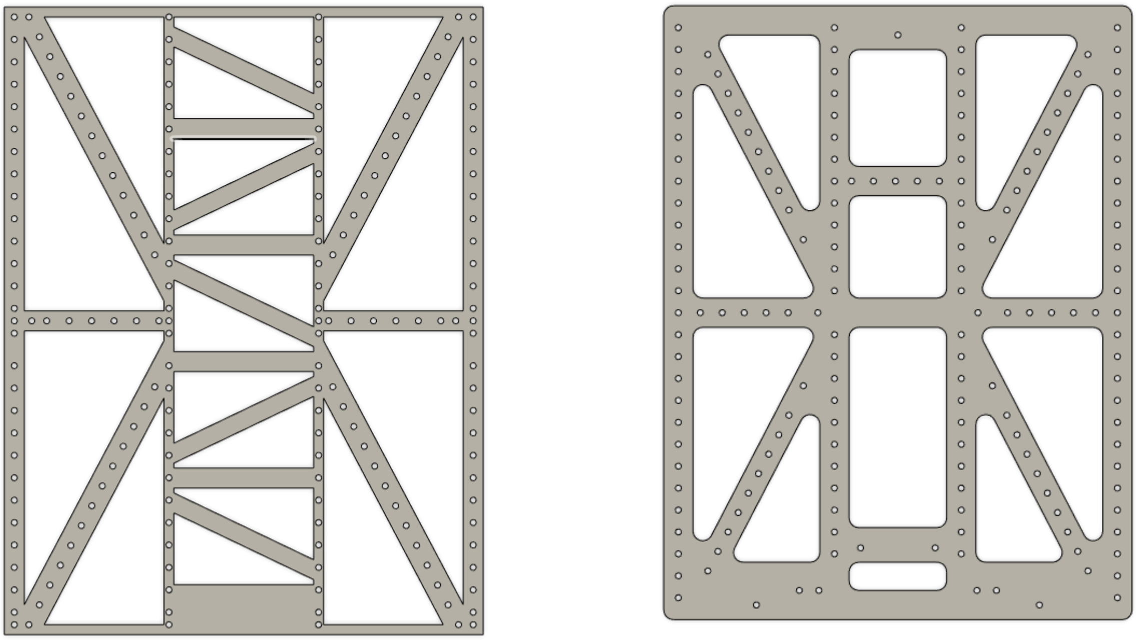
The cross-stiffener is connected to the side plates using four brackets. There are no connections in the middle of the cross-stiffener, as the group determined it unnecessary. Given that the electronics enclosure will be supported on top of the cross-stiffener, the team considered this arrangement sufficient to secure its placement. Furthermore, the brackets used for the cross-stiffener connection are identical to those used for the plates, chosen for their practicality and ability to ensure the stability and placement of the cross-stiffener.

5.2.4 Mounting points of the bottom plate and connection of the manipulator

During the design phase of the bottom plate, the team developed two conceptual designs. This allowed to assess which design could effectively withstand the forces exerted by the components placed on the bottom plate. Additionally, the team aimed to optimize the bottom plate for material and weight efficiency to reduce costs and production time, as the manufacturing process would be outsourced to an external company. The team's philosophy regarding the design of the bottom plate was centered on simplicity for efficiency. To ensure structural integrity, ANSYS Workbench was utilized to analyze the bottom plate's design.

Concept 1's design, depicted in Figure 5.7, features a zigzag pattern for the joints located in the middle of the bottom plate. This design choice was made to enhance the structure's integrity and stability. Additionally, Concept 1 includes a skeletal design to minimize excess material. Four angled joints originating from the exterior structure further enhance the bottom plate's sturdiness. Moreover, Concept 1 incorporates numerous mounting points, enabling various components to be attached to the bottom plate.

The design strategy utilized in Concept 2, shown in Figure 5.7, is similar to that of Concept 1, with a notable divergence being the exclusion of zigzag joints in the center of the structure. Instead, Concept 2 opts for three straight joints in the middle, aiming to simplify the overall design by reducing complexity. Consistent with Concept 1, Concept 2 integrates four angled joints stemming from the exterior structure. Furthermore, the team widened the joints to improve structural integrity.



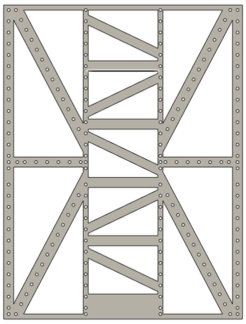
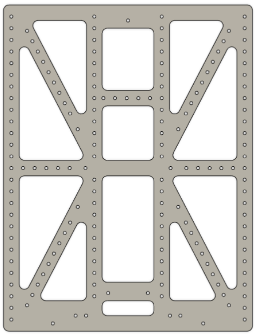
(a) Bottom plate concept 1

(b) Bottom plate concept 2

Figure 5.7: Bottom plate concepts

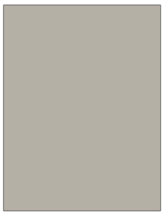
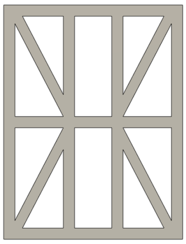
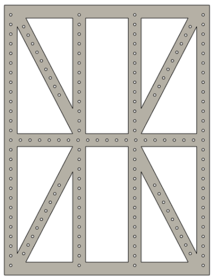
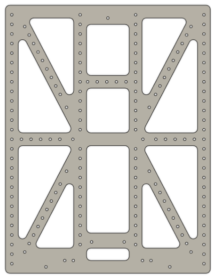
Following a screening process, Concept 2 was selected for advancement, as illustrated in Table 5.3. ANSYS Workbench simulations demonstrated that Concept 2 exhibited superior structural integrity, durability, and a lack of failure compared to Concept 1. Additionally, Concept 2 includes mounting points for all attached components.

Table 5.3: Screening matrix - Bottom plate mounting

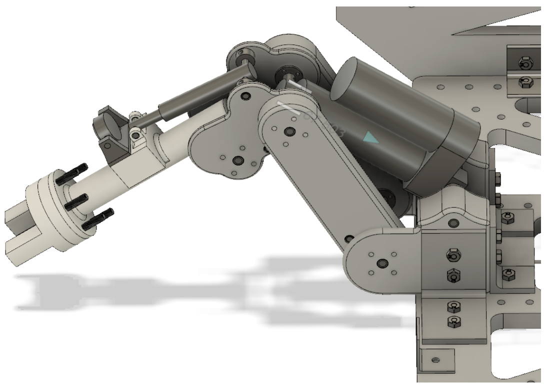
Screening matrix - Bottom plate mounting		
Selection criteria	A 	B 
Stability	-	+
Durability	-	+
Optimal material usage	+	+
Mounting points for lights	0	0
Mounting points for camera	0	0
Mounting points for manipulator	-	+
Mounting points for DVL	0	0
Mounting points for ballast	0	0
Connection points for sideplates	-	+
Within ROV's specifications	0	0
Sum +'s	1	5
Sum -'s	4	0
Sum 0's	5	5
Net score	-3	5
Rank	2	1
Continue to develop	**No**	**Yes**

Initially, Concept 2's design comprised a single plate. However, the team determined that optimizing material and weight usage could be achieved by cutting out sections of the plate. This approach involved designing the plate in a skeletal manner, removing excess material while preserving its strength and stability. Subsequently, mounting locations were incorporated for the components to be attached to the bottom plate. The team aimed to maximize the number of mounting locations to accommodate multiple components and potential ballast attachments. Concerns arose regarding the potential impact on structural integrity, yet ANSYS Workbench simulations provided reassurance that the bottom plate would withstand the added weight. To further enhance the structural strength and prevent failure, the team implemented three joints in the middle of the bottom plate and applied fillets to its corners. The mounting development of the bottom plate is illustrated in Table 5.4.

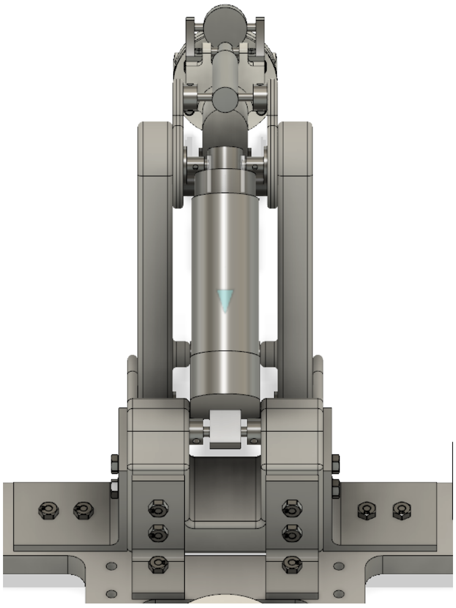
Table 5.4: Mounting development - Bottom plate

Bottom plate mounting development			
Initial design	**Material and weight reduction**	**Inserting mounting locations**	**Strength optimization**
			

The attachment of the manipulator to the bottom plate, depicted in Figure 5.8, is achieved through four brackets, each with a unique configuration. One pair of brackets located on the sides, and one at the rear end of the manipulator. The decision to utilize two bolts for the side brackets was driven by the team's concern regarding the potential detachment of the manipulator during underwater rotation of the ROV. In contrast, the rear brackets were considered sufficient with a single bolt each. Additionally, since the manipulator primarily serves a rotational function rather than bearing significant weight, the team determined that a single bolt for the rear brackets would properly secure the manipulator during underwater operations.



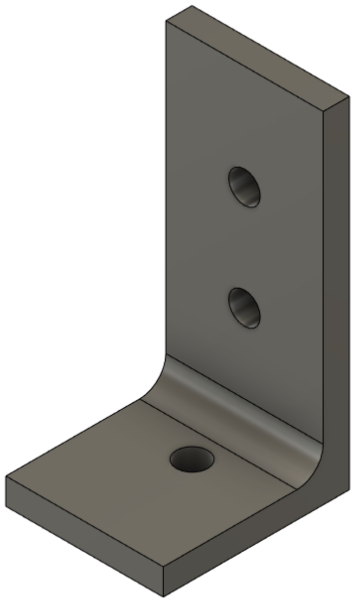
(a) Brackets configuration for the manipulator's side connection



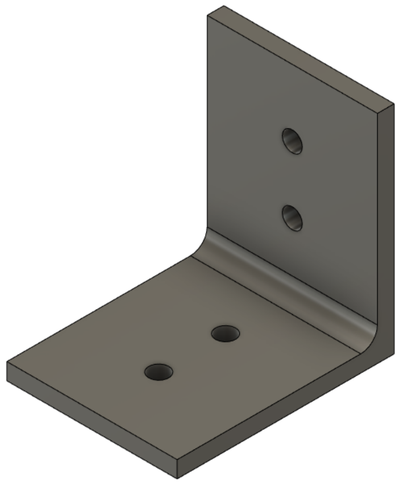
(b) Brackets configuration for the manipulator's rear connection

Figure 5.8: Mounting system of the manipulator

Figure 5.9 illustrating the brackets employed to link the manipulator with the bottom plate were manufactured differently from those utilized for other component-to-frame connections. This decision stemmed from considerations regarding the manipulator's size and stability. With the manipulator featuring two inserts, the standard brackets, equipped with only one hole both vertically and horizontally, did not meet the required specifications. Consequently, brackets with two vertical holes were utilized to accommodate the inserts. Furthermore, ensuring the manipulator's stability was important, prompting the team to design brackets specifically to maintain its robustness. Aluminum remained the material of choice.



(a) Bracket used for manipulator's rear connection

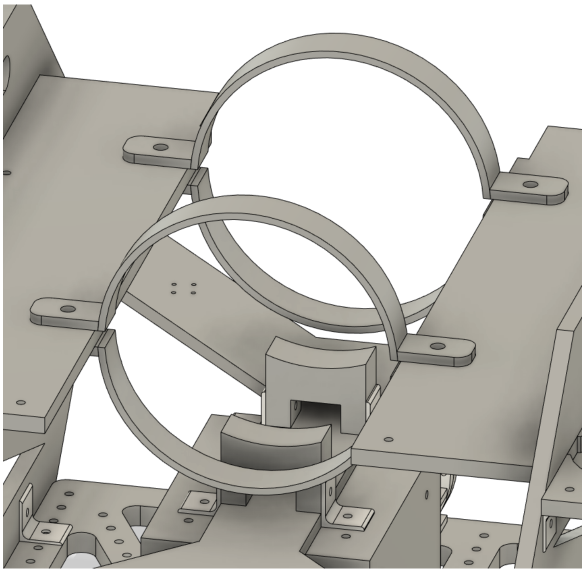


(b) Bracket used for manipulator's side connection

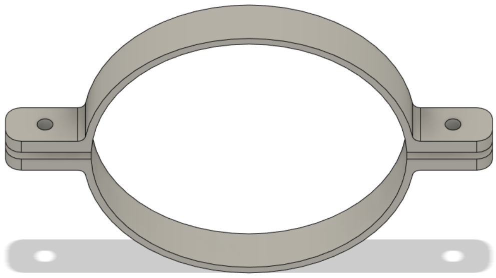
Figure 5.9: Brackets for the mounting system of manipulator

5.2.5 Connection of the Electronics enclosure

Securing the electronics enclosure to the frame presented a significant challenge for the team. This connection needed to ensure robustness without compromising the structural integrity of the frame, while also withstanding the forces exerted by the electronics enclosure. Furthermore, efficient placement was crucial due to limited space within the ROV frame. Through extensive research and consultation with former team members responsible for similar tasks the group developed a solution for attaching the electronics enclosure.



(a) Connection of the electronics enclosure clamps and top plates



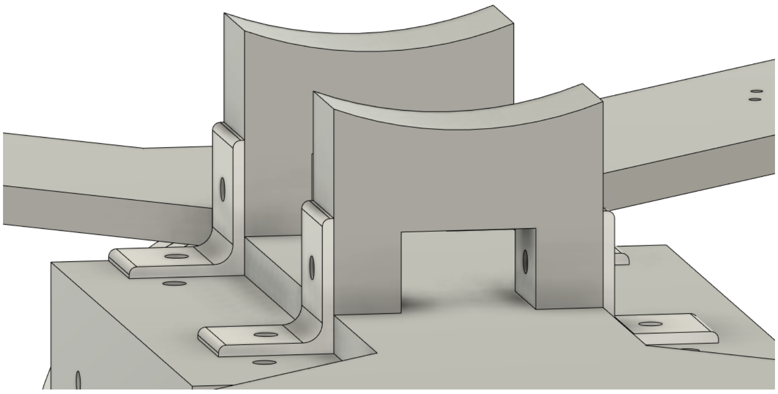
(b) Clamps for the electronics enclosure

Figure 5.10: Mounting system of the electronics enclosure

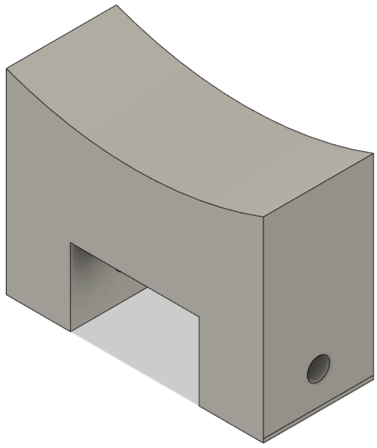
The method chosen to develop the enclosure clamps mirrored that of pipe clamps, illustrated in Figure 5.10. This decision stemmed from the resemblance between the electronics enclosure and a cylindrical metal pipe. The team delved into the functionality of pipe clamps and adapted their design for the enclosure clamps. Confident in the feasibility of this approach, the team conducted a simulation using ANSYS Workbench, demonstrating the clamps' ability to withstand the enclosure's force. The proposed design comprises four clamps, with two allocated to both the front and rear of the enclosure. These clamps are fixed to the frame's top plates using bolts, secured with washers and nuts.

Utilizing 3D printing technology was deemed a favorable approach. This method offers cost-effectiveness and efficiency, aligning well with the team's objectives. PLA was the chosen material for 3D printing the clamps for the electronics enclosure. Its selection was based on its ability to withstand the weight imposed by the enclosure, cost-effectiveness and its availability at the 3D printing workshop. To ensure the suitability of 3D printing for enduring the forces exerted by the electronics enclosure, a comprehensive analysis was conducted. Following a thorough examination of the results, the team confidently opted to proceed with 3D printing for the production of the electronics enclosure clamps.

Even though the clamps provided sufficient security for the positioning of the electronics enclosure, due to stability concerns, the team opted to support the enclosure with a pair of saddle supports. They were printed in PLA as well. Upon simulating the connection in ANSYS Workbench, it was found that the FEA yielded improved results with these supports. The connection's strength was enhanced, and there were no indications of failure.



(a) Connection of the saddle supports to the battery housing



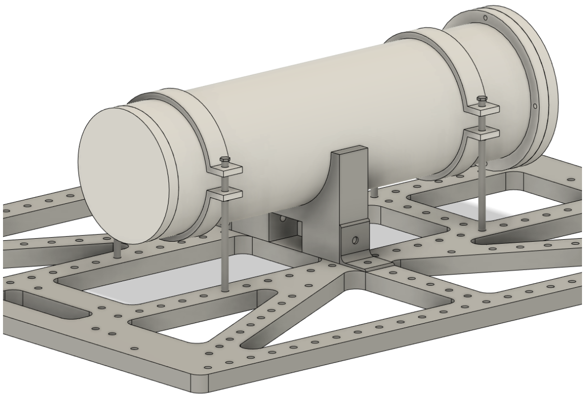
(b) Saddle support for electronics enclosure

Figure 5.11: Support for the electronics enclosure

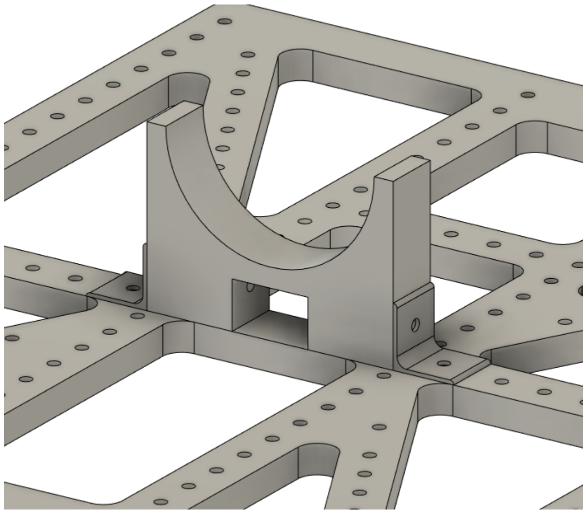
The brackets will secure the support firmly in position, as shown in Figure 5.11. These brackets, identical to those utilized for plate and cross-stiffener connection, will each be fastened with two bolts, one linking to the support and the other to the roof of the battery house. Additionally, the supports play a vital role in anchoring the cross-stiffener in place, as the supports rest on top of it.

5.2.6 Connection of the Battery enclosure

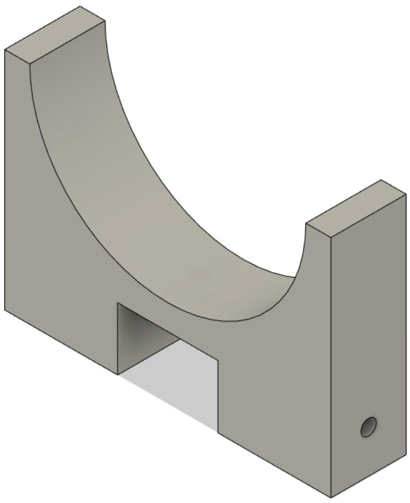
The team faced a challenge in installing the battery enclosure onto the bottom plate due to limited space. Securing the cylindrical battery enclosure posed further difficulty in finding a suitable connection method. Addressing this concern and maintaining cost efficiency became the primary focus for the group. The group opted for a mount design similar to the clamps manufactured for the electronic enclosure. The pipe clamps, positioned at the front and rear, feature two threaded bolts on each side, secured by four nuts, enhancing the interference between the enclosure and clamps, depicted in Figure 5.12. A U-shaped saddle support, installed at the enclosure's midpoint, supporting its weight and matching its outer diameter.



(a) Installation of the battery enclosure



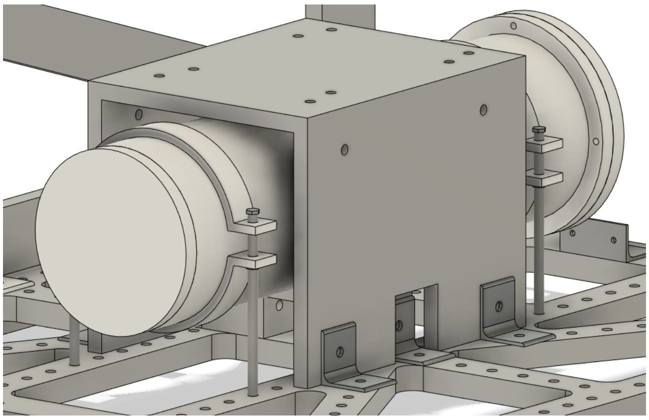
(b) Connection of the support to the bottom plate



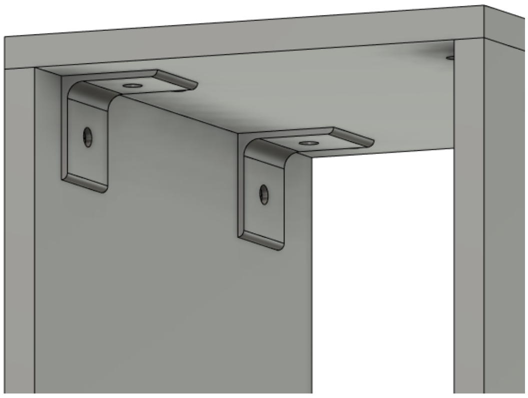
(c) Support for the battery enclosure

Figure 5.12: Mounting system of the battery enclosure

The attachment of the battery enclosure to the bottom plate led the team to create a battery housing structure, illustrated in Figure 5.13. This housing serves the two functions: providing support for the cross-stiffener and the saddle supports, shown in Figure 5.11. Recognizing the uneven surface of the battery enclosure, the team considered it necessary to create a flat platform to accommodate other components of the ROV frame. The battery housing is secured to the bottom plate using four brackets fastened with bolts and nuts.



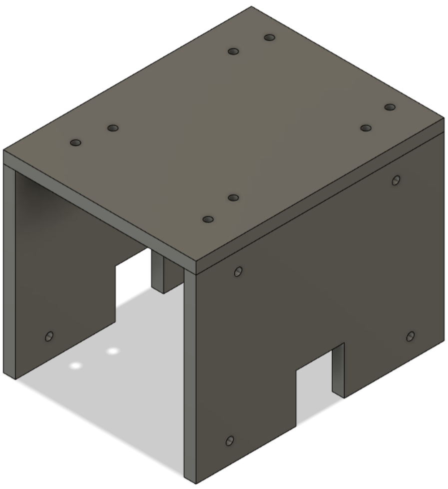
(a) Battery house



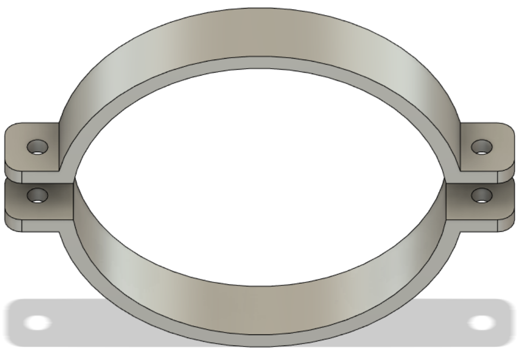
(b) Connection of the battery house's roof and walls

Figure 5.13: Mounting system of the battery house

Similar to the clamps for the electronic enclosure, PLA was selected for the battery clamps. The battery housing material was HDPE, as illustrated in Figure 5.14a. HDPE as selected due to its strength, ensuring it can support other attached components. Utilizing FEA in ANSYS Workbench, the team assessed the housing's, clamp's and saddle support's ability to withstand weight forces. Based on thorough simulation analysis, HDPE and PLA emerged as valid material choices.



(a) Roof and walls of the battery house

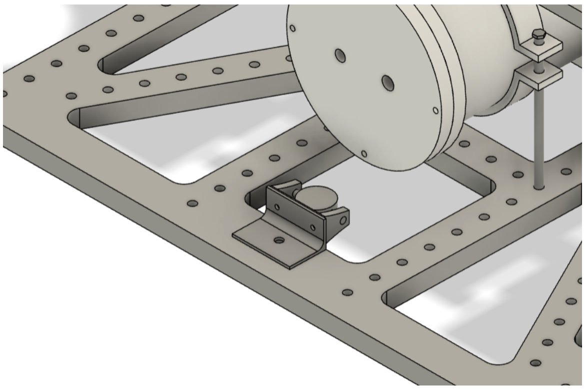


(b) Clamps for the battery enclosure

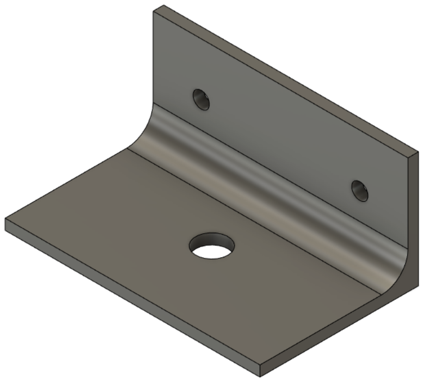
Figure 5.14: Battery house and clamps

5.2.7 Connection of the cameras

Three cameras were assigned to the ROV, one with a downward view and the other two facing forward, depicted in Figure 5.15. The group was responsible for providing support for these cameras. Positioned at the rear of the ROV, is the downward-facing camera. The camera is mounted onto a bracket custom-designed by the team. The team determined that utilizing a bracket for camera attachment was preferable to designing a hole in the bottom plate. Aluminum was the material selected for the camera brackets, mirroring the choice made for the other brackets utilized on the frame.



(a) Installation of the downward-looking camera



(b) Bracket for the downward-looking camera

Figure 5.15: Mounting system of the downward-looking camera

The forward-facing camera is fixed to the front of the ROV, mounted on the bridge secured by the top plates. shown in Figure 5.16. Key challenges in determining the placement of the forward-looking camera was ensuring an unobstructed view, maintaining its position in the center of the ROV and protection. This positioning solved the issues, as it elevates the camera sufficiently to prevent obstruction by the manipulator, and making sure the camera was not the outermost point on the ROV. Moreover, the bridge contributes to enhancing the stability of the structure with its linkage between the top plates. The camera, with its bracket, were bolted to the bridge. Unlike the downward-facing camera, no additional bracket was necessary for the forward-facing camera.

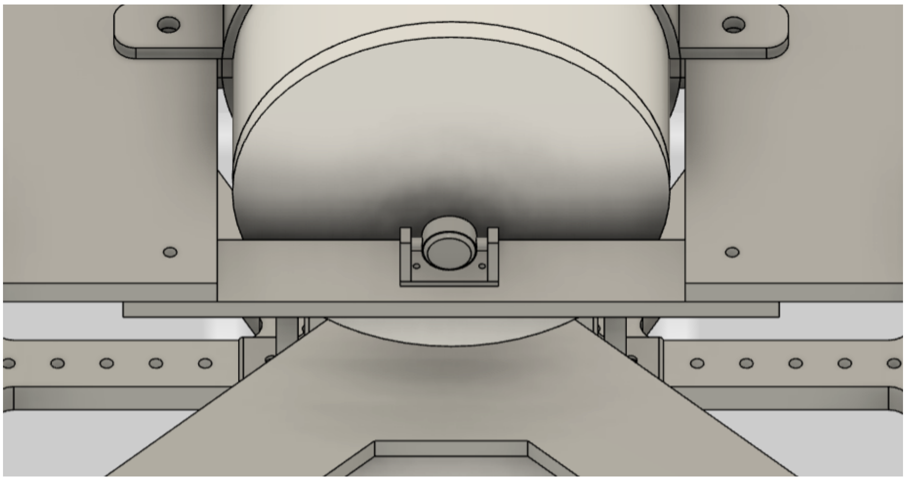


Figure 5.16: The forward-facing camera mounted on the bridge

The secondary forward-facing camera is securely positioned on the manipulator, depicted in Figure 5.17. Its primary function is to provide a perspective aligned with the manipulator's grasp. Given the manipulator's vertical mobility, integrating a camera allows for comprehensive upward and downward visibility of the ROV. This setup facilitates anticipation of surface encounters and enhances vision during manipulator operation.

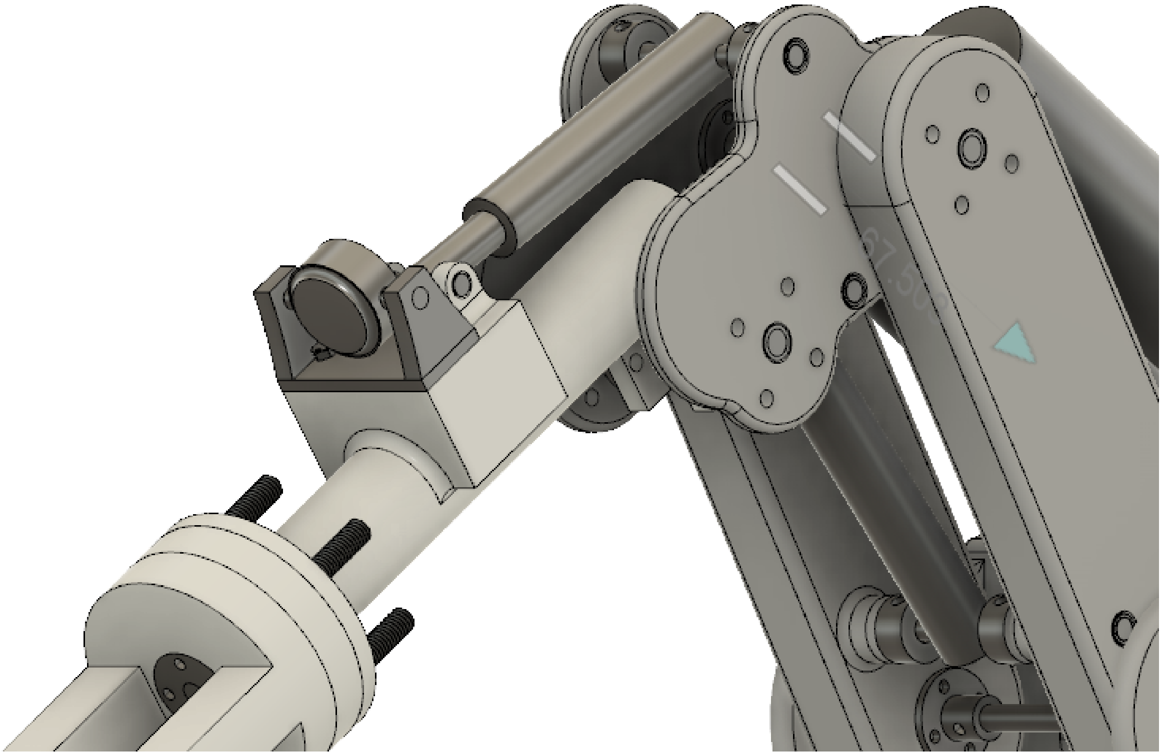


Figure 5.17: The forward-facing camera mounted on the manipulator

5.2.8 Connection of the lights

The ROV features a total of four lights strategically placed for optimal visibility during its operations. Two of these lights are positioned horizontally to effectively enlighten the forward view. In contrast, the remaining two lights are mounted vertically, facing down, to illuminate the area beneath the ROV. To simplify this arrangement, the vertically positioned lights are fixed to a specially designed bracket manufactured by the team.

The horizontally mounted lights are directly screwed into the side plates, illustrated in Figure 5.18. One challenge encountered was avoiding interference with the camera's vision. Installing the lights too close to the camera could potentially blind the camera. This issue was avoided by positioning the two lights on the side plates.

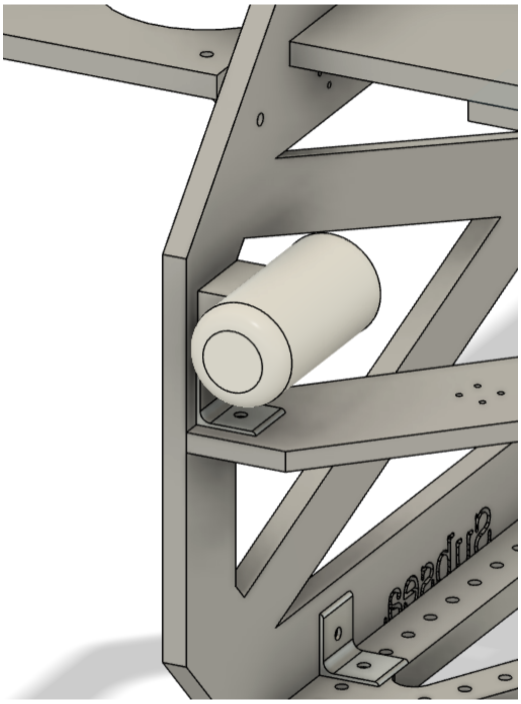
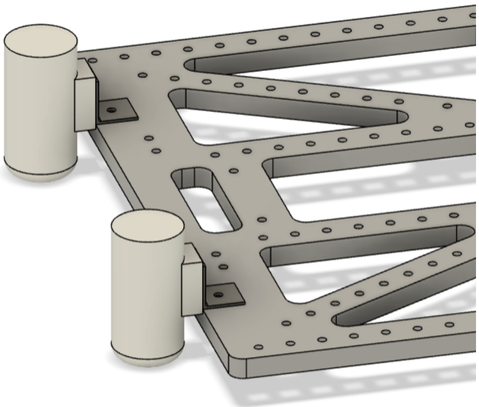
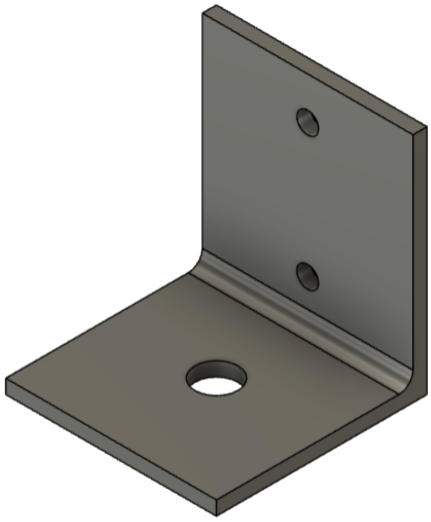


Figure 5.18: The horizontally mounted lights

The vertically mounted lights, shown in Figure 5.19, are secured to custom-designed brackets designed for their attachment. Initially, attempts were made to fix the lights directly to the bottom plate, but this posed a problem as the lights would have interfered with the ground, being the lowest point of the ROV. The brackets are connected to the bottom plate using bolts, each bolt fastened with nuts and washers. These brackets were manufactured in aluminum.



(a) Installation of the vertically mounted lights



(b) Bracket for the vertically mounted lights

Figure 5.19: Mounting system of the vertically mounted lights

5.2.9 Connection of the DVL

Ensuring the secure positioning of the DVL sensor is a critical task given its importance and high cost. The team's primary concern was to install the DVL in a location that is both safe and non-obstructive to its functionality, avoiding interference with the ground and ensuring an unobstructed view for the sensor. Positioning the DVL at the center of the ROV was not feasible due to the presence of the puck to be attached to the bottom plate in the TAC challenge. Initially, the team explored placements further back on the ROV, but found it impracticable due to interference with the back plate of the battery enclosure. Subsequently, the team attempted front installation, where a suitable mounting possibility was identified.

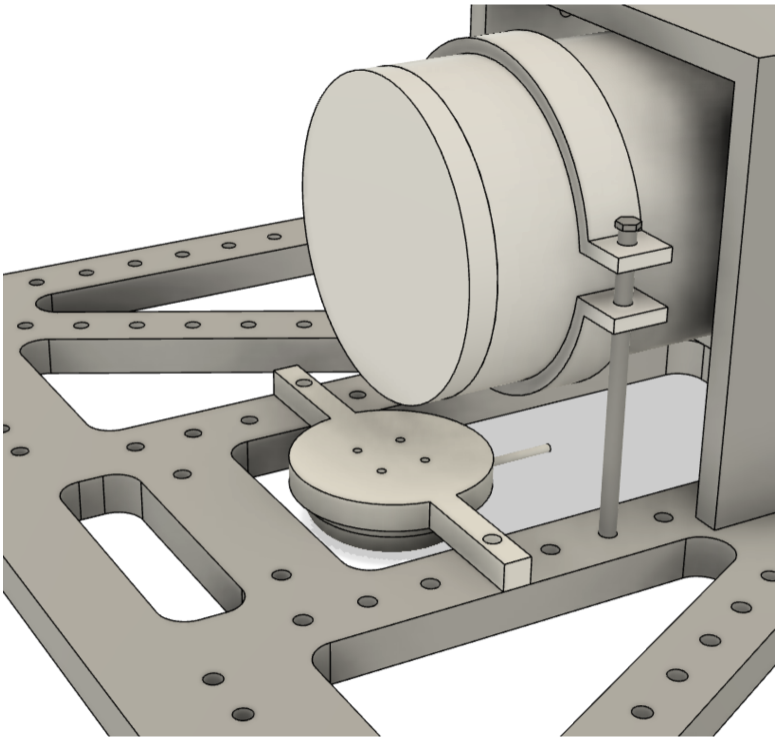


Figure 5.20: Mounting system of the DVL

The DVL is fixed to a specifically manufactured mounting bracket, depicted in Figure 5.20, to ensure its connection without causing any interference. Moreover, the mount's design guarantees that it won't obstruct the DVL sensors' field of vision. It's secured to the bottom plate using bolts. The DVL is then fastened onto the mount. PLA was selected as the material for 3D printing the mount for the DVL, shown in Figure 5.21. To verify its strength and stability and prevent any potential buckling, the team conducted FEA analysis. The results confirmed that the mount could withstand the weight and forces exerted by the DVL.

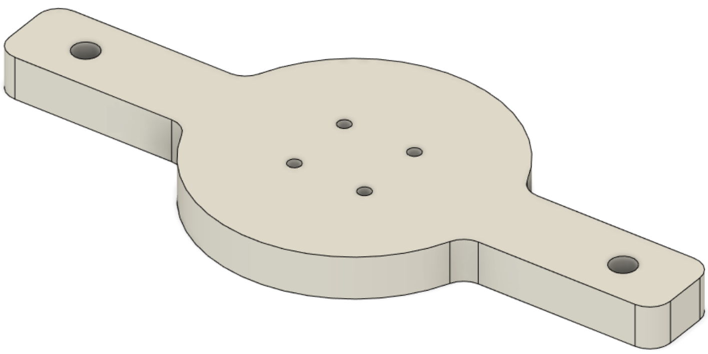


Figure 5.21: Mounting component for the DVL

5.3 Designing, testing and evaluating electronic enclosures

The electronic enclosures stood out as the pivotal element within the ROV setup. This placed a significant weight on the shoulders of the engineering team, tasked with creating a waterproof solution while ensuring seamless collaboration with all departments dependent on the housing. The enclosure was segmented into four key subsystems: the front cap, end cap, main enclosure, and the internal electronics module. Moreover, the team needed to design a mounting concept that allowed for swift and effortless disassembly.

5.3.1 Front cap to enclosure

Following the concept development stage, the team explored several approaches for mounting the front cap to the enclosure, with three proposals incorporating o-rings. One suggestion involved welding, a departure from the previous year's approach. This year's design excluded the need for a transparent dome to house the internal camera, as waterproof external cameras were chosen instead. Additionally, there was no requirement to detach the front cap from the enclosure, making welding a feasible option. However, after conducting research on aluminum welds, the team opted not to pursue this concept any further.

When exposed to air, aluminum undergoes oxidation, forming aluminum oxide. While this oxide layer acts as a protective barrier for the metal, it also poses challenges during the welding process. Aluminum oxide has a significantly higher melting point than aluminum itself, raising the risk of the weld penetrating through the metal once the oxide layer is breached, potentially damaging the enclosure. Additionally, welding aluminum presents issues such as porosity in the weld and challenges in temperature control due to aluminum's high conductivity[68]. Given that none of the team members possessed specific welding expertise beyond what was demonstrated in workshops, and considering the inherent difficulty of welding aluminum, alternative options were considered.

Another approach involved securing the front cap to the enclosure using bolts, which initially seemed to be the primary solution for waterproofing. The front cap would feature a flange to accommodate bolt holes. To facilitate a watertight connection it was also needed to use o-rings. However, after thorough consideration, it was concluded that utilizing bolts at the front was unnecessary since disassembly was not required. This decision also simplified the machining process, eliminating the need of the front flange during lathe operations.

The team also explored the option of vacuum sealing. This method involves removing air from the enclosures, creating a low-pressure environment inside the cylinders. The vacuum would assist in securing the end caps for a waterproof seal. While this sealing solution seemed effective, the main concern was the maintenance of the internal electronics module, which necessitated disassembling the enclosure.

The last solution involved examining press and shrink fit connections, ultimately settling on press fitting for the front cap. Press fitting involves joining two parts with differing diameters, with the larger part being pressed into the smaller one [69]. In this instance, the front cap, with the larger diameter, was press fitted into the enclosure. Achieving the required precise machining with high dimensional accuracy. The shrink fit connection method entails subjecting one of the workpieces to heat treatment, causing it to expand. Subsequently, the pieces are joined, and upon cooling to room temperature, contraction occurs, completing the connection. While the machining process for shrink fit is similar to that of press fit, implementing shrink fit would necessitate heat treatment for the enclosures. In the interest of efficiency and resource, the decision was made to opt for the press fit connection. [70].

5.3.2 End cap to enclosure

The approach for the end cap differed from that of the front cap. It had to be designed allowing for disassembly, eliminating some of the previously mentioned methods. The team debated between bolting the back end to the enclosure or utilizing vacuum sealing. With vacuum sealing already dismissed, bolted connections emerged as the final choice, offering advantages in assembly. Consequently, a flange was required at the back of the enclosure. Mounting the internal electronics module to the back end became the responsibility of the communication group. Although the use of threaded rods was considered, the solution depicted in Figure 5.22 was selected. The frame securing the electronics in place would be fastened to the back end using four M3 screws.

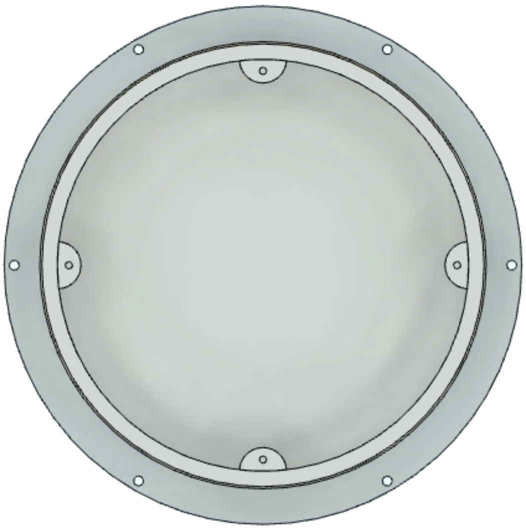


Figure 5.22: Mounting points for internal electronics module

The machining aspect turned out to be less challenging than initially anticipated. The workshop staff provided assistance in machining the back and front ends of each enclosure, and offered thorough guidance on operating the lathe and pillar bore. The material chosen for the electronics enclosure remained consistent with that of the previous year. While the cylinder's diameter exceeded the necessary dimensions both internally and externally, the group determined that it would be more economically and environmentally friendly to utilize the already ordered cylinder, rather than purchasing a new.

5.3.3 Hole placements end cap

The positioning of holes on the end cap underwent extensive discussion both internally within the group and in collaboration with other bachelor groups. The machine group initiated an Excel sheet where other groups specified the types of connectors each team required. The end cap ended up with some additional holes compared to the previous year, although this decision fell outside the jurisdiction of the machine group. The layout itself drew inspiration from last year's configuration, prioritizing the placement of the largest and most powerful plugs in the center. Additionally, there was a specific request from the regulation group, responsible for the thruster, to position them on either side of the back end for convenient access to the thrusters. The battery group sought to have their plug positioned as low as possible, considering the placement of the battery house just below the electronics enclosure. The placement of plugs for cameras and lights was also determined based on their locations on the ROV. The hole placements are shown in Figure 5.23

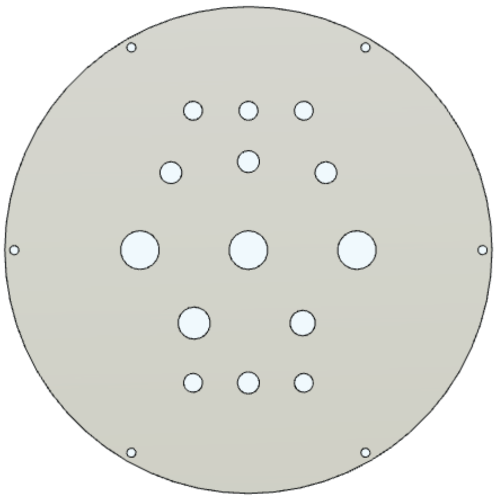


Figure 5.23: Hole placements end cap

5.4 Designing, testing and evaluating battery enclosure

Following multiple rounds of discussion and collaboration with the battery group, it was determined that the design process for the battery enclosure should mirror that of the electronics enclosure. Similar methods for waterproofing were explored for both enclosures. Since neither the electronics nor the battery house necessitated disassembly of the front cap, press fitting was decided as a suitable solution. However, disassembly was required for the back end, prompting the adoption of the same solution as with the electronics enclosure, bolts through a flange. Additionally, the back end required plugs, one pressure relief valve and one specified by the battery group. To mount the internal battery and circuit cards, two holes were drilled and threaded, with threaded rods subsequently installed, as illustrated in Figure 5.24. The battery group designed the internal module in a manner that allowed them to fit it onto the rods.

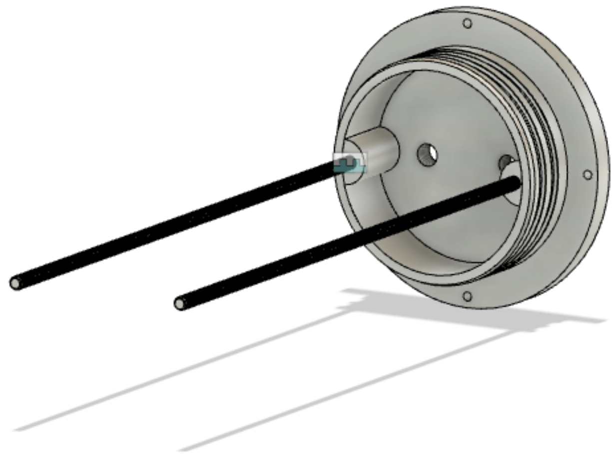


Figure 5.24: Back end battery

The machining process for the battery enclosure would resemble that of the electronic enclosure, on a smaller scale. The workshop at UiS handled the machining of the back and front caps, and the dimensions for the battery house cylinder were carefully selected to minimize the amount of turning necessary, thereby reducing material waste as much as possible.

5.5 Designing, testing and evaluating subsystem manipulator

The system-level design phase for the manipulator commenced with the identification and determination of its major components, which included the manipulator base, the various joints, and the end effector of the structure. Subsequently, the focus shifted towards identifying the subsystems of the manipulator. These subsystems involved connection points between the base and the ROV frame, as well as components such as rotating shafts and sleeve bearings. The major components and subsystems is arranged in Table 5.5.

The system-level design phase for the manipulator involved the creation of rough models to visualize the final assembly. These models were heavily influenced by the requirements of both responsible groups namely the electro-engineering group and mechanical engineering group, as well as those related to the TAC Challenge. These considerations collectively led to the final specifications for the model. The objective for this phase was to develop multiple models based on the finalized requirements.

Several alternatives were considered for the tilting function, including hydraulic linear actuators, electric linear actuators, and stepper motors. However, stepper motors presented challenges as these required a waterproof housing, leading to additional weight and potentially create bending moments throughout the arm. This would in turn have propagated into larger structural dimensions and the need for stronger motors. In addition, last year's project experienced challenges with the strength, exerted by the stepper motor, being to small. Therefore, it was concluded that the stepper motor wasn't a good choice to proceed with.

The hydraulic linear actuators were initially of interest, however limited experience with hydraulic systems and concerns about potential leaks led to reconsideration of this choice. Ultimately, electric linear actuators were chosen to avoid the complex hydraulic system and risk of oil leaks. This choice proved to be the preferred option for this year's manipulator, providing sufficient strength while also enabling it to reach the desired positions for the project.

The system-level design process is iterative, often leading to the need for different components as concepts evolve. Initially, a BLDC motor was considered for rotational movement. However, after a discussion with the electro-engineering group, led to not go through with this choice as it presented challenges regarding holding torque. Ultimately, it was decided to go through with a DC motor. This motor fulfilled both the functional- and performance goals related to the rotational movement.

The last critical component evaluated during this phase was the choice of material for the structure. There were several factors to consider especially due to the water application. Salt water in combination with sunlight can be highly detrimental for some plastic materials. The arm will also be subjected to some forces, meaning that the material strength is highly relevant as it could lead to failure.

Throughout the project, the approach heavily relied on iterative modeling and prototyping. The process was initiated by exploring various concepts using the modeling software Fusion360. This phase demanded extensive communication not only within the team, but also with external stakeholders. Close collaboration with the electro- engineering group, as well as with the students from last year's project, was paramount. Their insights and requirements, particularly regarding the third joint, shaped the design direction. The work towards designing a third joint represented one of the largest changes during the iterative process. This was a requirement from the electro-engineering group.

Another important aspect was the frequent interaction with Energy X, a machining company located at Ålgård. These discussions offered fresh perspectives and prompted reevaluation of challenges from different angles. Their expertise inspired and guided the project towards innovative solutions, creating the path to the final product. This sums up the importance of open communication and collaboration. Enabling to navigate challenges effectively, and ultimately achieve the project goal.

From a system-level perspective, there are areas for enhancement in future projects. One such area involves addressing the end effector's ability to perform the gripping function. Additionally, when it's determined that the production will be outsourced, early communication of the estimated timeline is important. Providing a clear and realistic timeframe from the project's outset allow for better planning and coordination with external partners. By prioritizing these aspects in future projects, the project teams can continuously develop into a more efficient organization.

Table 5.5: Major components and subsystems - Manipulator

Major components and subsystems - Manipulator	
Major components	**Subsystems**
Base	Brackets
1. joint	Shafts
2. joint	Sleeve bearings
3. joint	Couplings
End effector	

6 PDP - Detail Design

In the detail design phase, all designs and blueprints were finalized and prepared for production. For the general product development process, this meant no further changes in design and drawings after finishing this phase, unless anything unexpected arose during the testing and refinement phase. Similar to the system-level design, this point served as a milestone for the group. After this phase the group could start focusing more on production and writing, as the designs were now set.

The detail design phase represented a pivotal milestone within the product development journey, where the initial product concepts underwent a comprehensive transformation into a finely detailed design. Throughout this phase, an exhaustive blueprint was manufactured, addressing the product's functionality, specifications, material selection, cost analysis, and manufacturing methods. Moreover, the design considerations included elegance, performance optimization, material efficiency, weight reduction strategies, and the enhancement of overall user engagement. The important objective of the detail design phase was ensuring that the product design followed all requirements, optimizing the manufacturing process. By inspecting every aspect of the design, potential manufacturing hurdles were removed, and thereby increasing the likelihood of realizing a functional ROV, meeting all objectives.

6.1 Final product design ROV-frame

The project placed huge importance on excelling in both the TAC challenge and environmental considerations. Hence, the design underwent optimization effort aimed at realizing material and weight efficiencies. Recognizing the insufficiency of manual computations in determining the thickness for each part, Finite Element Analysis (FEA) emerged as the preferred tool for material optimization.

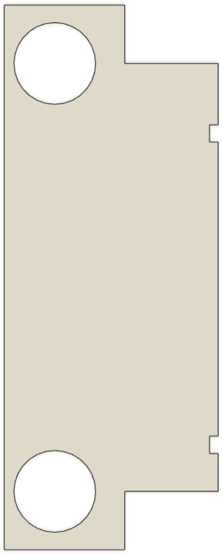
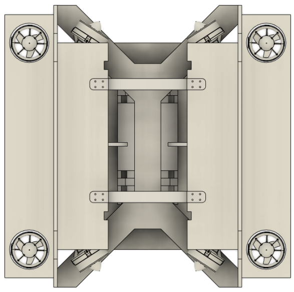
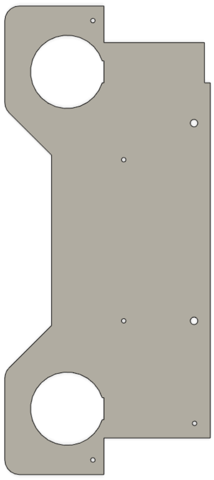
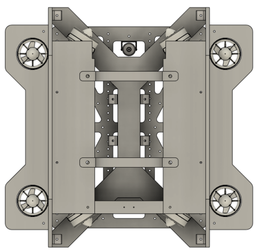
6.1.1 Detail changes to the design

Throughout the refinement phase of the design process, evaluation was conducted on each element comprising the ROV-frame. While certain parts demanded no additional modifications, or only minor adjustments, others underwent more extensive alterations.

Top plates In the detail design phase, the team noticed that the top plate of the ROV exhibited excessive dimensions, notably in the extrusions designated for thruster protection. Moreover, adjustments were made to the plate design to facilitate efficient connection between the top and side plates. The team attempted to optimize the design of the top plates to ensure structural integrity and effective thruster protection.

In response to these concerns, efforts were made to minimize material from the top plate, while maintaining protection for the thrusters, shown in Table 6.1. Additionally, adjustments were implemented by removing portions of the rear section of the top plates to accommodate for the flange of the electronics enclosure. Notably, this modification was not required for the front portion of the top plates, as the front plate of the electronics enclosure fitted smoothly. Furthermore, strategically positioned holes were integrated into the front, back, and middle sections of the top plates to serve as attachment points for the clamps of the electronics enclosure and the ROV's plates.

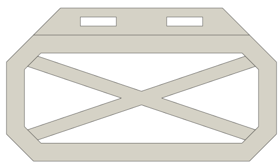
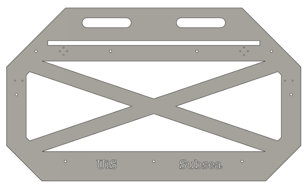
Table 6.1: Top plate - ROV frame [18]

Top plate - ROV frame		
	Model	**Assembly**
Original		
Modified		

Side plates During the detail design phase concerning the side plates, the team observed a notable absence of mounting points for various components such as the top plates, bottom plate, cross-stiffener, lights, and thrusters. Essentially, the initial design of the side plates lacked functional utility for the ROV. Additionally, adjustments were made to slightly increase the height of the ROV, allowing for the mounting of components on the bottom plate without ground interference. Moreover, the team recognized the absence of elegance in the side plates, which appeared rather plain. Consequently, efforts were directed towards incorporating aesthetic enhancements to create the side plates visually appealing.

The team undertook modifications to refine the initial design (Table 6.2). Mounting points for several components were incorporated into the design. Moreover, the lower section of the side walls was heightened slightly to prevent interactions with the ground. This adjustment was particularly crucial considering the mounting of the DVL to the bottom plate, given its high cost. Additionally, decorative enhancements were made by engraving the "UiS Subsea" design onto the lower section of the side plates. Furthermore, sections beneath the handles were removed to facilitate the insertion of the top plates. These modifications were crafted to ensure optimal integration between the plates and components without compromising the structural integrity of the system.

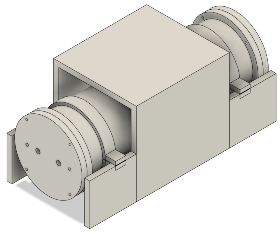
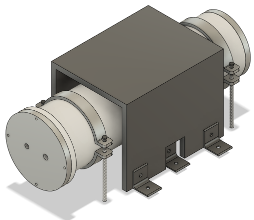
Table 6.2: Side plates - ROV frame

Side plates - ROV frame	
	Model
Original	
Modified	

Battery house Throughout the detail design phase of the battery housing, Figure 6.3, the team encountered various considerations regarding its connection to the bottom plate and the establishment of a mounting system for both the battery enclosure and the saddle supports, positioned on top of the battery housing. Additionally, uncertainties arose regarding the battery housing's capability to support the clamps of the battery enclosure. These connections and mounting points held significance as they dictated the positioning of the battery housing and saddle supports for the electronics enclosure. They also facilitated the attachment of the side walls and roof of the battery housing, and ensured the secure placement of the battery enclosure.

To address these issues and improve the functionality, several modifications were implemented. Multiple mounting points were introduced to secure the battery housing to the bottom plate. Mounting points for connecting the saddle supports of the electronics enclosure were also incorporated onto the roof. Furthermore, a decision was made to eliminate the supporting wall for the clamps. Sections of the side walls for the battery housing was cut, to accommodate the installation of a central bracket for connecting the battery enclosure's saddle support to the bottom plate. The team opted for threaded rods to support the clamps of the battery enclosure.

Table 6.3: Battery box - ROV frame

Battery box - ROV frame	
	Model
Original	
Modified	

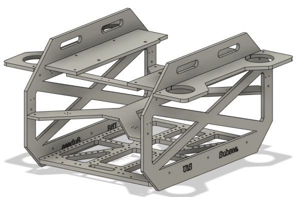
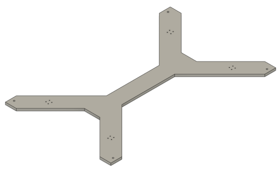
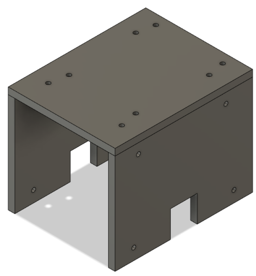
6.1.2 Material Choice and Manufacturing Method

Upon the completion of the design phase for each component, the subsequent stage entailed the exploration, assessment, and selection of suitable materials and manufacturing techniques for their fabrication. Considering the project's constrained budget and the cost projections established during the concept development stage, indicating potential expenses surpassing the allocated budget, efforts were directed towards securing sponsorships and exploring various production methods. Furthermore, environmental considerations were important, with a particular focus on reducing waste material. Whenever viable, 3D-printing were prioritized over machining manufacturing due to the environmental sustainability. The objective was to discover manufacturing methods that balanced cost-effectiveness with environmental responsibility.

Plates, Cross-stiffener and Battery house During the initial phases of the project, the team sought advice from individuals involved in the previous year's project regarding the fabrication of the plates, cross-stiffener, and battery enclosure for the ROV. Feedback from former project members indicated their choice of HDPE as the material for the plates, which were then manufactured by a IKM Industrigravøren. This input was taken into consideration alongside other options during the analysis phase. Ultimately, the team opted to utilize HDPE. Companies specializing in HDPE production and manufacturing were contacted to gather information on pricing, fabrication techniques, and lead times. Following thorough research and evaluation of various options, the team collaborated with IKM Industrigravøren regarding the manufacturing process, as illustrated in Table 6.4. Their recommended method, water jet cutting, was considered optimal for precision cutting across various materials. This technique avoids heat generation, particularly suited polymers like HDPE or Carbon Fiber. Opting for aluminum alloy and water cutting could have resulted in unnecessary weight due to its high density properties. Moreover, water jet cutting stood out as an environmentally friendly option. Despite its advantages, water jet cutting presented limitations such as restricted thickness and rough edges. Fortunately, these setbacks were inconsequential for the components, given their slimness. Cost was a concern for the team, however IKM Industrigravøren's sponsored the manufacturing, reducing financial worries.

As mentioned, the team utilized HDPE for the plates, cross-stiffener, and battery housing due to its cost-effectiveness and suitability for water jet cutting manufacturing. HDPE presents mechanical properties capable of withstanding diverse environmental conditions encountered by the ROV. Moreover, its corrosion resistance and minimal environmental impact further underscore its appeal. While Carbon Fiber offers superior mechanical properties ideal for the components, its utilization was decided impractical due to cost. Despite being compatible with water cutting, the expense exceeded the project's budgetary constraints. Similarly, aluminum was weighed as an alternative material, however, its heavier weight and higher cost, coupled with longer manufacturing lead times, made it less favorable compared to HDPE.

Table 6.4: Manufactured parts by IKM Industrigravøren

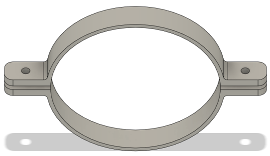
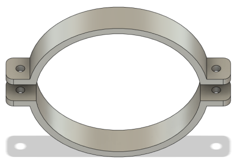
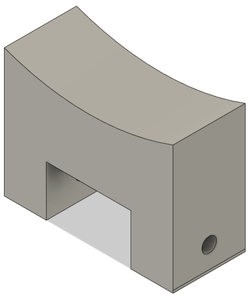
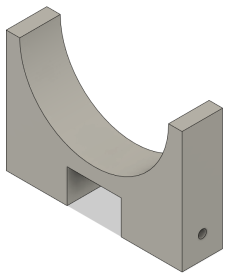
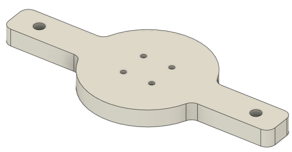
Manufactured parts by IKM Industrigravøren			
	Plates	**Cross-stiffener**	**Battery house**
Manufactured parts			

Clamps, supports and DVL-mount Given the design requirements for the electronics and battery enclosure clamps, as well as the DVL-mount, the team encountered challenges with the traditional machining manufacturing method. Consequently, the team opted for 3D printing to produce these components, as depicted in Table 6.5. Machining would have resulted in significant material waste and necessitated the use of cooling liquids. Fortunately, the 3D printer lab provided the project with unlimited access to the lab, which enabled cost-free 3D printing of the clamps, supports, and DVL-mount, while offering rapid production of spare parts. It's important to acknowledge that these 3D-printed components may offer lower lateral stability in the ROV's top plate, compared to metal counterparts.

The electronics enclosure clamps and battery enclosure clamps were designed to be fixed to the top plates and on threaded rods, respectively. The supports are connected in a similar fashion. Additionally, the decision to 3D print the DVL-mount was driven by the need for expedited manufacturing, cost savings, and the lightweight nature of the DVL, making it an optimal choice.

The team examined PLA as a potential material, valued for its biodegradability, low toxicity, and ease of manufacturing. Moreover, PLA's availability in the university's 3D printing lab facilitated convenient production of spare parts in case of unexpected failures, enhancing both cost-effectiveness and time efficiency. PLA's design flexibility was another advantage, allowing for easy shaping into complex geometries and configurations, aligning well with the project's requirements.

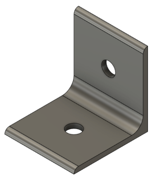
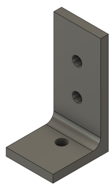
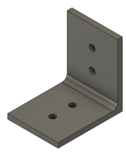
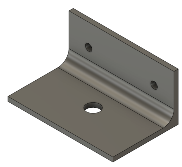
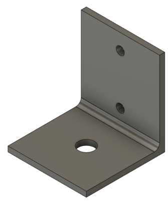
Table 6.5: Manufactured parts by 3D printing

Manufactured parts by 3D printing			
Manufactured parts	**Electronic enclosure**	**Battery enclosure**	**DVL**
Clamps			N/A
Supports			N/A
Mount	N/A	N/A	

Brackets To enhance rigidity and strength, the group chose aluminum brackets for pivotal connection points among various components, including plates, cross-stiffeners, manipulator, battery housing, supports, and others. The different brackets are depicted in Table 6.6. Despite the potential for increased time, environmental impact, and cost associated with fabricating these brackets locally in the university workshop as opposed to purchasing standard ones, the team found value in this approach. The group reasoned that despite the additional resources required, it would simplify the overall process, particularly considering the limited time for the design phase. Furthermore, the marginal increase in time, cost, and environmental impact was decided insignificant in the context of the project's objectives.

Through a selection process, aluminum emerged as the preferred material for the brackets. Recognized for its lightweight, high resistance to corrosion, and excellent strength-to-weight ratio. Additionally, its relative ease of fabrication proved advantageous for the team.

Table 6.6: Manufactured at UiS workshop

Manufactured at UiS workshop				
	Frame	**Manipulator**	**Camera**	**Lights**
Brackets		 		

6.1.3 Material saving of ROV-frame

Following the completion of component design and material selection, the next step was to figure out the optimal thickness while preserving an adequate safety margin. This was accomplished through FEA using the software ANSYS Workbench. Through consulting experts and conducting thorough research, the team was able to ensure precise inputs and definitions of forces and supports to calculate the ideal thickness for each components.

Plates During the evaluation of plate thickness, several options were considered and tested for the plates, including 7mm, 10mm, 12mm and 15mm thickness. The FEA was based on estimated forces from each bolt and the force generated by the manipulator, during transport of the ROV. Given uncertainties regarding precise forces and weights, a overestimation approach was used, intentionally over-dimensioning with a safety factor exceeding standard requirements.

Bottom Plate: In order to ensure the structural integrity of the bottom plate, it was essential to consider the weight imposed by the manipulator, electronics, and battery enclosure. Thus, a substantial safety margin was deemed necessary as a precautionary measurement. The inclusion of a safety factor was prioritized to uphold the strength and stability of the bottom plate, which plays a critical role in bearing the weight and distributing the load of the various components.

Following an evaluation of the bottom plate, illustrated in Table 6.7, it was observed that the 10mm thickness led to high stress levels with a safety factor of 2.6. Oppositely, the 12mm thickness had a reduced stress levels and increased the level of safety factor to 3.4. The stress level difference between the 12mm and 15mm thickness was significant with also an increased safety factor to 6.2. Based on these findings, the 15mm thickness exhibited the most promising characteristics for the thickness selection of the bottom plate. Consequently, the team determined that a 15mm thickness was the optimal choice due to its minimal stress levels and highest safety factor. Furthermore, the cost and weight differences compared to the 12mm thickness were deemed insignificant.

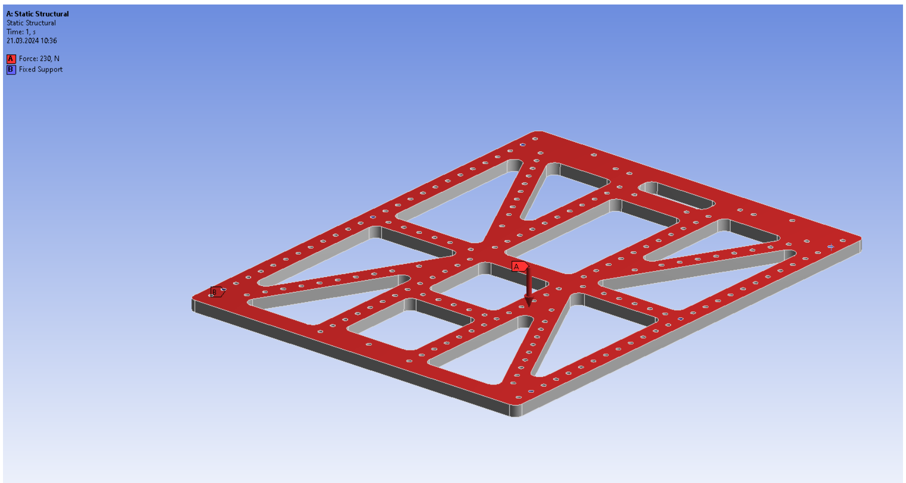
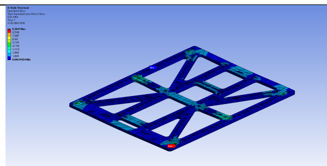
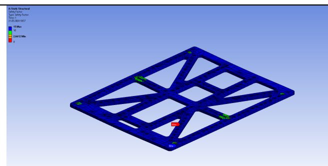
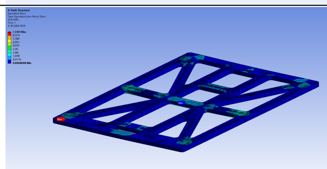
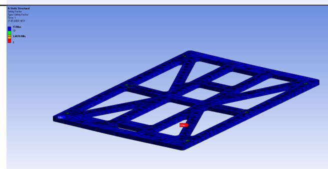
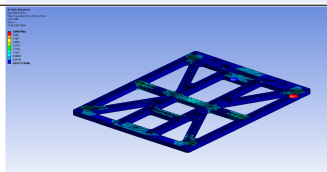
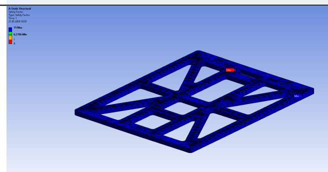


Figure 6.1: Forces and supports input set on bottom plate in ANSYS

Table 6.7: Material saving - Bottom plate

Material saving - Bottom plate		
Thickness	**Equivalent stress**	**Safety factor**
10mm		
12mm		
15mm		

Side plates: The examination of Table 6.8 showed that a 7mm thickness caused high stress levels with a safety factor of 15. On the other hand, the 10mm thickness had a lower stress levels acting on the side plates, but had a similar safety factor of 15 as the 7mm thickness. The variance regarding the stress levels between the 10mm and 12mm thickness was insignificant. The 12mm thickness also had a safety factor of 15. Despite the fact that each thickness had a safety factor of 15, the group decided that a 12mm thickness was the best option because it had the lowest stress levels. Additionally, the cost and weight between the 10mm and 12mm thickness for the side plates was quite identical.

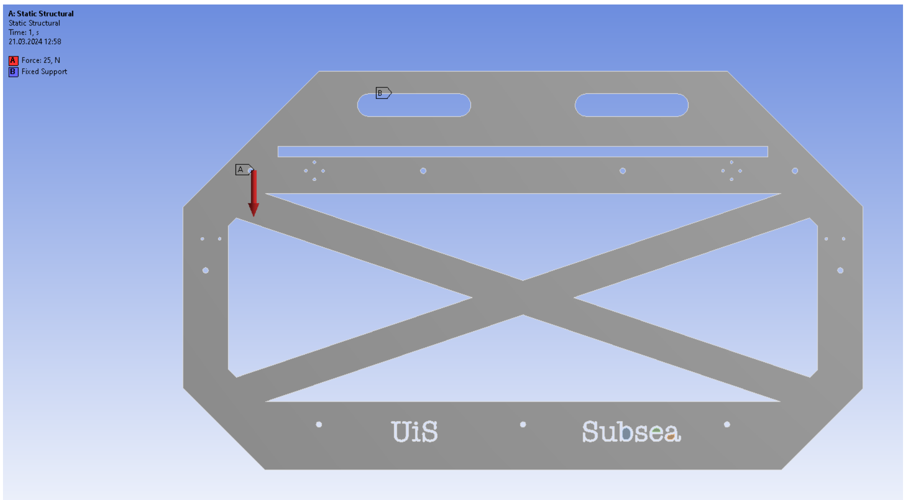
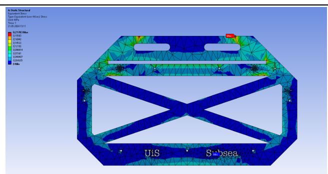
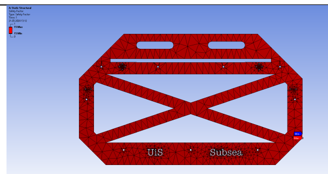
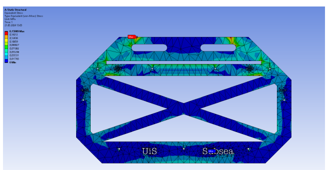
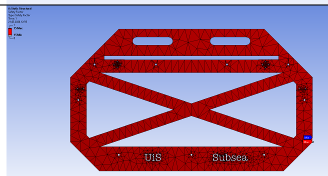
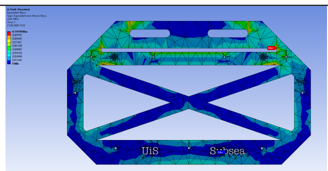
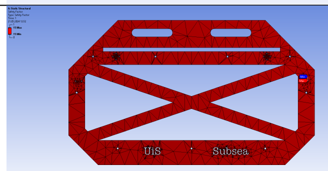


Figure 6.2: Forces and supports input set on side plates in ANSYS

Table 6.8: Material saving - Side plate

Material saving - Side plate		
Thickness	**Equivalent stress**	**Safety factor**
7mm		
10mm		
12mm		

Top plates: After evaluating Table 6.9, regarding the top plates, it was observed that a 7mm thickness led to high stress levels with a safety factor of 5.7. In contrast to a 10mm thickness, diminished the stress levels acting on the top plates and increased the level of safety factor to 9.2. Although the difference between the 10mm and 12mm thickness was negligible, the 12mm had a higher safety factor. Despite the fact that each thickness had a high safety factor, the team decided to choose the 12mm thickness for the top plates due to its lower stress levels. Additionally, the cost and weight comparison between the 10mm and 12mm thickness options for the side plates were found to be nearly identical.

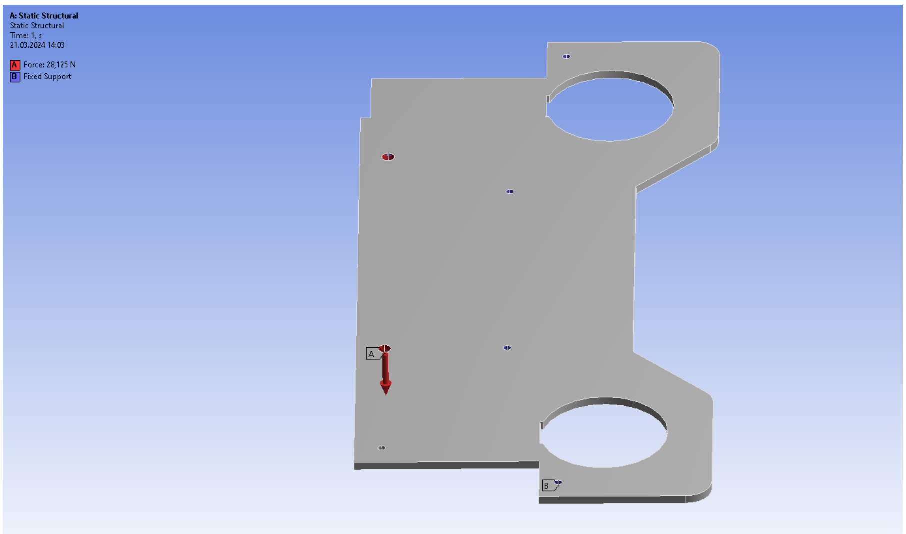
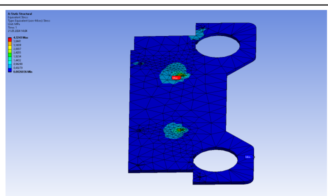
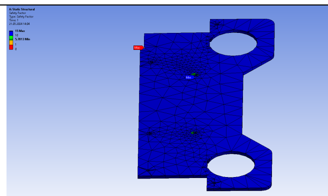
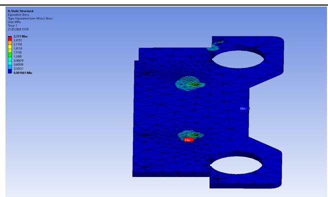
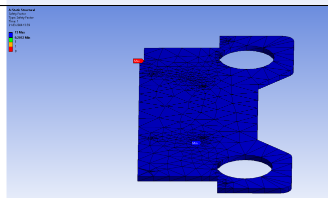
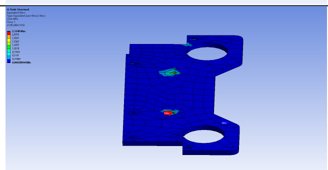
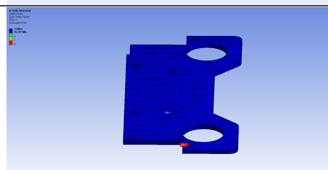


Figure 6.3: Forces and support input set on top plates in ANSYS

Table 6.9: Material saving - Top plate

Material saving - Top plate		
Thickness	**Equivalent stress**	**Safety factor**
7mm		
10mm		
12mm		

6.2 Final product design electronic enclosures

After choosing which connections to use for waterproofing in the system level design phase, a more detailed look was required. Additionally, all measurements and tolerances had to be specified on millimeter precision, for optimal results in the production phase.

For the electronics enclosure the material was the same as last year´s enclosure. This meant some additional hours in the workshop due to the size of the pipe, however this was the right thing to do from both an economic and environmentally view. This year, both the body and end caps were produced in aluminium 6082. Aluminium 6082 were also used for the battery end caps and enclosure.

6.2.1 Detailed design electronics enclosure

During the detail design phase, several adjustments were made concerning the electronics enclosure. The length was determined in accordance with specifications provided by the communications group, which oversaw the internal electronics module, a simple yet crucial step to simplify the assembly processes. While the inner diameter was established relatively early in the project to facilitate circuit board production and ordering, the outer diameter was finalized during the detail design phase. The inner diameter was fixed at 190mm. To determine the optimal outer diameter, a buckling equation was employed, which is originally solved for the critical pressure given a long pipe, but rearranging the formula offered the team a benchmark for minimum wall thickness. Additionally, Ansys served as a supplementary tool to validate the calculated thickness. The final electronic enclosure design is shown in Figure 6.4.

As illustrated below, the critical thickness, was computed at 2.96mm. However, the decision was made to reduce the outer diameter to 200mm, resulting in a wall thickness of 5mm. This choice was motivated by several factors. Firstly, considering the likelihood that the electronics housing will play a diminished role in next year's bachelor project, the upcoming machine group may inherit a fully machined electronics housing from a previous year, allowing for minor adjustments rather than fabricating a new one. This influenced the decision to opt for a 5mm thickness, affording flexibility for the next group to adjust thickness if needed, without requiring new material, or to utilize the 5mm thickness for operations exceeding depths of 200 meters. Another practical rationale for increasing the wall thickness was for the machining process. Given the dimensions of the component, further reduction after reaching 200mm diameter was deemed impractical. During turning, a plug was inserted at the end of the enclosure, to reduce pressure on the walls.

The formula for calculating the critical wall thickness is given as: [71]

$$t_{\text{critical}} = r \times \sqrt[3]{\frac{4(1-v^2)\times \ P_{\text{critical}}}{E}} \tag{39}$$

$$t_{\text{crit}} = 2.96 \text{ mm}$$

The critical pressure in the formula was implemented as the pressure at 50 meters depth, the Poisson ratio as 0.33 and the elasticity modulus as 69 GPa [72]. The radius is denoted as r.

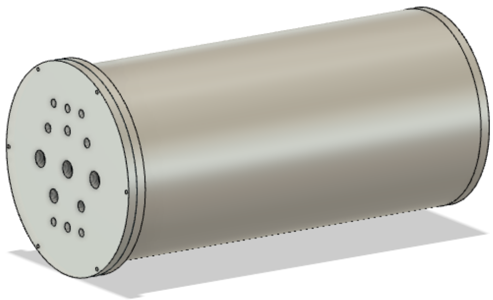


Figure 6.4: Final design electronic enclosure

6.2.2 Detailed design end cap

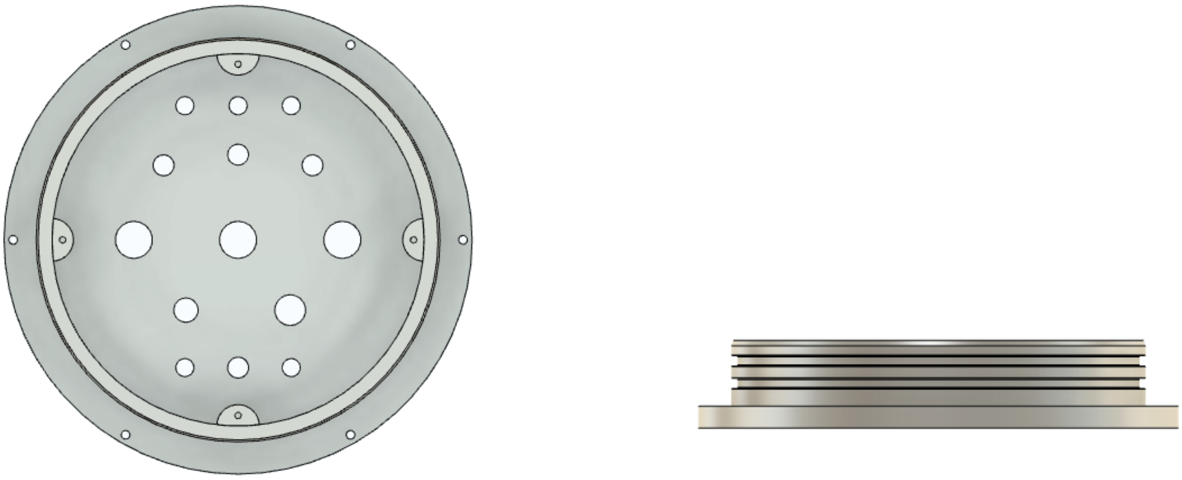
During the detailed design phase, the group deliberated over the configuration of the o-ring grooves for the end cap. Two alternatives were considered: male or female o-ring glands. From the positive experience of the previous year's utilization of male o-ring glands and the practicality in terms of manufacturing, the group opted to maintain the same approach. The distinction lies in the placement of the o-ring grooves on the components. Had female o-ring glands been chosen, the grooves would have been integrated into the electronics housing rather than into the front and end caps.

The grooves were crafted in accordance with SealEngineering's o-ring specifications, which can be seen in Table 6.5. Considering a cross-section of 3.53mm, both the depth and width of the grooves were adjusted accordingly. The choice of 3.53mm stemmed from its status as a standard o-ring cross-section, available in various diameters and materials, while also deviating from the measurements utilized by the previous year's group.

Installation recommendations for rectangular groove									
Cross section	Radial installation						Axial installation		Radius
	Groove depth		Groove width				Groove depth	Groove width	
	Static	Dynamic	No backup	1 backup	2 backups	Backup ring			
d_2	$t + 0.05$	$t_1 + 0.05$	$b_1 + 0.2$	$b_2 + 0.2$	$b_3 + 0.3$	height h_1/h_2	$h + 0.05$	$b_4 + 0.2$	r (max)
1.5	1.10	1.25	2.00	3.00	4.00	1.10/1.00	1.10	2.10	0.30
1.6	1.20	1.30	2.10	3.10	4.10	1.10/1.00	1.20	2.20	0.30
1.78	1.30	1.45	2.40	3.80	5.20	1.50/1.40	1.30	2.50	0.30
1.90	1.40	1.55	2.60	4.00	5.40	1.50/1.40	1.40	2.70	0.30
2.00	1.50	1.65	2.70	4.10	5.50	1.60/1.40	1.50	2.80	0.30
2.40	1.80	2.05	3.20	4.60	6.00	1.60/1.40	1.80	3.30	0.30
2.50	1.85	2.15	3.30	4.70	6.10	1.60/1.40	1.85	3.40	0.30
2.62	2.00	2.25	3.60	5.00	6.40	1.60/1.40	2.00	3.70	0.60
3.00	2.30	2.60	4.00	5.40	6.80	1.70/1.40	2.30	4.10	0.60
3.10	2.40	2.70	4.10	5.50	6.90	1.70/1.40	2.40	4.20	0.60
3.53	2.70	3.10	4.80	6.20	7.60	1.70/1.40	2.70	4.90	0.60
4.00	3.10	3.50	5.20	6.90	8.60	2.10/1.70	3.10	5.30	0.60
4.50	3.50	4.00	5.80	7.50	9.20	2.10/1.70	3.50	5.90	0.60
5.00	4.00	4.40	6.60	8.30	10.00	2.20/1.70	4.00	6.70	0.60
5.33	4.30	4.70	7.10	8.80	10.50	2.20/1.70	4.30	7.30	0.60
5.50	4.50	4.80	7.10	8.80	10.50	2.20/1.70	4.50	7.30	0.60
5.70	4.60	5.00	7.20	8.90	10.60	2.30/1.70	4.60	7.40	0.60
6.00	4.90	5.30	7.40	9.10	10.80	2.30/1.70	4.90	7.60	0.60
6.50	5.40	5.70	8.00	9.70	11.40	2.30/1.70	5.40	8.20	1.00
6.99	5.80	6.10	8.60	11.10	13.60	3.20/2.50	5.80	9.70	1.00
7.50	6.30	6.60	9.10	11.60	14.10	3.20/2.50	6.30	9.90	1.00
8.00	6.70	7.10	9.80	12.30	14.80	3.20/2.50	6.70	10.00	1.00
8.40	7.10	7.50	10.00	12.50	15.00	3.40/2.50	7.10	10.30	1.00
9.00	7.70	8.10	10.60	13.10	15.60	3.40/2.50	7.70	10.90	1.50
10.00	8.60	9.10	11.60	14.10	16.60	3.60/2.50	8.60	12.00	2.00
12.00	10.60	11.00	13.50	16.00	18.50	3.80/2.50	10.60	14.00	2.00

Figure 6.5: SealEngineering´s catalog [73]

The specific material of the o-ring held little significance, given the absence of extreme pressure or temperature conditions. Therefore, the group opted for the standard nitrile-butadiene rubber. An essential measure to ensure the longevity of the o-ring involved designing small chamfers and fillets on all sharp edges. A notable departure from last year's design pertained to the reduction from 3 to 2 o-ring grooves. It was indicated that 3 grooves were excessive, with one likely being sufficient. Hence, the group settled with 2 grooves, receiving no objections during the inspection of the drawings by SealEngineering. The final design for the end cap can be seen in Figure 6.6



(a) End cap top-view

(b) End cap side-view

Figure 6.6: Final design end cap

6.2.3 Detailed design front cap

During the detailed design phase, the tolerances and o-ring groove for the front piece were established. As previously outlined in the system-level design phase, the front piece was intended for a press-fit connection. The dimensions of the o-ring grooves mirrored those of the rear component, ensuring consistency. Meanwhile, the press fit tolerance was set at H8/r7, representing an interference fit achievable without the need for heat treatment. While various tolerance combinations exist for such interference fits, including H7/p6, P7/h6, R7/h6, and others, the group opted for H8/r7 in line with the European standard EN 20286. [74]. The final front cap is shown in Figure 6.7.

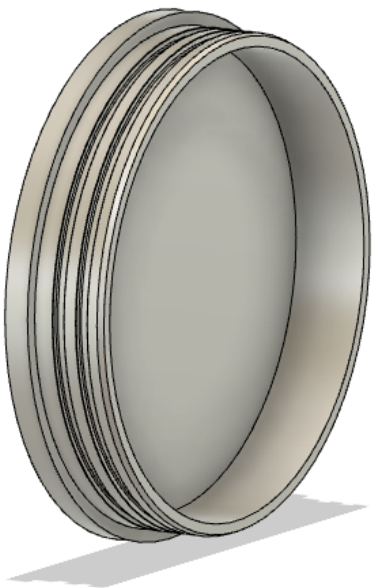


Figure 6.7: Front cap

6.3 Final design battery enclosure

The final battery enclosure design, shown in Figure 6.8, resulted from following the same procedure as with the electronics enclosure. Aluminium 6082 was the chosen material, and the o-ring grooves had the same dimensions. The critical wall thickness was calculated as 1.63 mm, using the buckling equation for a long pipe. The final machined wall thickness was 5 mm, but the same arguments applied. This would make room for flexibility regarding next year´s battery group.

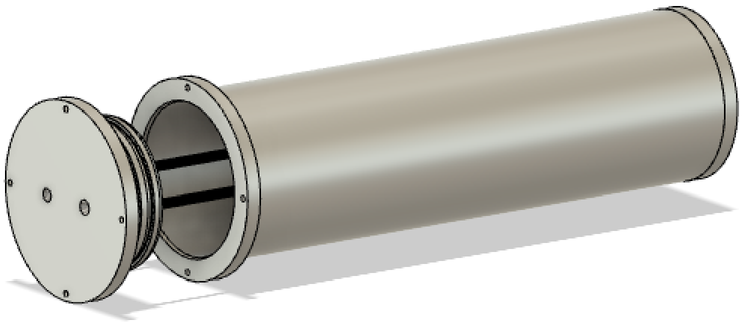


Figure 6.8: Final design battery enclosure

6.4 Material saving Electronics enclosure and Battery enclosure

After finalizing the design and selecting materials for the enclosures, the team proceeded to determine the optimal thickness with a focus on safety. Utilizing FEA via ANSYS Workbench, the team analyzed various parameters to achieve a balance between structural integrity and efficiency. Drawing on insights from industry specialists and extensive research, the team calibrated inputs and defined forces and supports to derive the most suitable thickness for the enclosures.

Enclosures In the exploration of enclosure thickness, a variety of options underwent thorough examination and experimentation. Thicknesses of 3mm, 5mm, and 7mm were deliberated as potential candidates for the enclosures. The FEA analysis focused on approximating the forces induced by the enclosures' front plates underwater, accounting for the pressures at depths of 50 meters, and considering the fixed supports at the rear of both electronic- and battery enclosures. Given the uncertainties surrounding precise force measurements, water pressures, and weights, a conservative approach was adopted.

Electronics Enclosure: Upon inspecting Table 6.10, of the electronics enclosure, it became evident that a 3mm thickness resulted in elevated stress levels, maintaining a safety factor of 15. Conversely, opting for a 5mm thickness, substantially relieved stress on the enclosure while still upholding the same safety factor. Although the disparity between 5mm and 7mm thicknesses was minimal, the latter exhibited lower stress levels. Despite maintaining the safety factor across all thicknesses, the team favored the 5mm option due to its significant stress reduction compared to 3mm. Moreover, considering the cost and weight implications, the 5mm thickness emerged as the most wise choice, aligning with the project's budgetary and material efficiency goals.

The batter enclosure followed the same procedure. Wall thickness of 3 mm led to heightened stress levels, while maintaining a safety factor of 15. Conversely, opting for a 5mm thickness notably minimized stress on the battery enclosure, while keeping the same safety factor. 7 mm wall thickness was also explored. Despite maintaining consistent safety factors across all thicknesses, the team favored the 5mm option due to its stress reduction compared to the 3mm thickness.

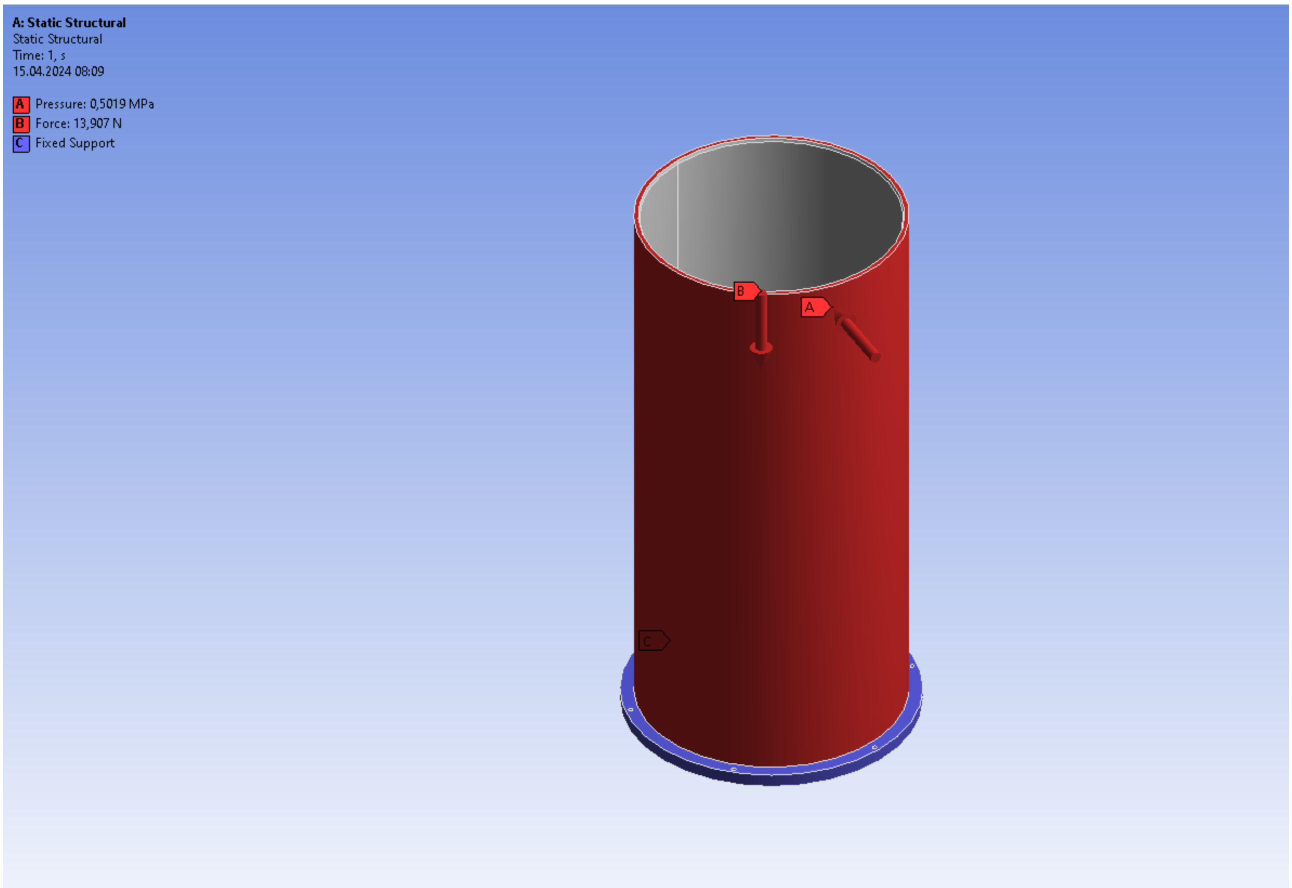
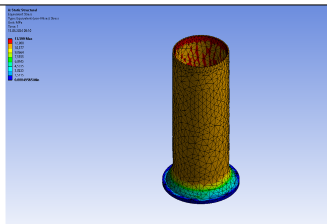
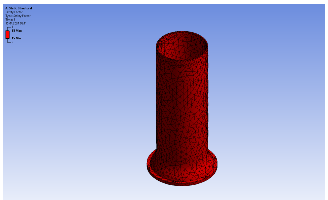
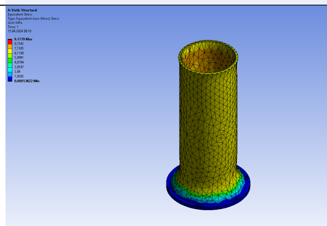
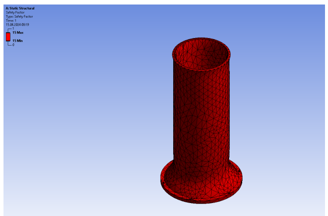
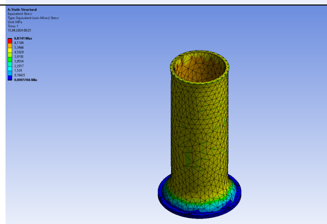
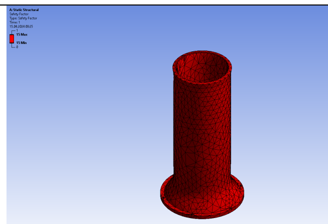


Figure 6.9: Forces and supports input set on Electronics Enclosure in ANSYS

Table 6.10: Material saving - Electronic enclosure

Material saving - Electronic enclosure		
Thickness	**Equivalent stress**	**Safety factor**
3mm		
5mm		
7mm		

Battery Enclosure: The battery enclosure followed the same procedure, depicted in Table 6.11. Wall thickness of 3 mm led to heightened stress levels, while maintaining a safety factor of 15. Conversely, opting for a 5mm thickness notably minimized stress on the battery enclosure, while keeping the same safety factor. 7 mm wall thickness was also explored. Despite maintaining consistent safety factors across all thicknesses, the team favored the 5mm option due to its stress reduction compared to the 3mm thickness.

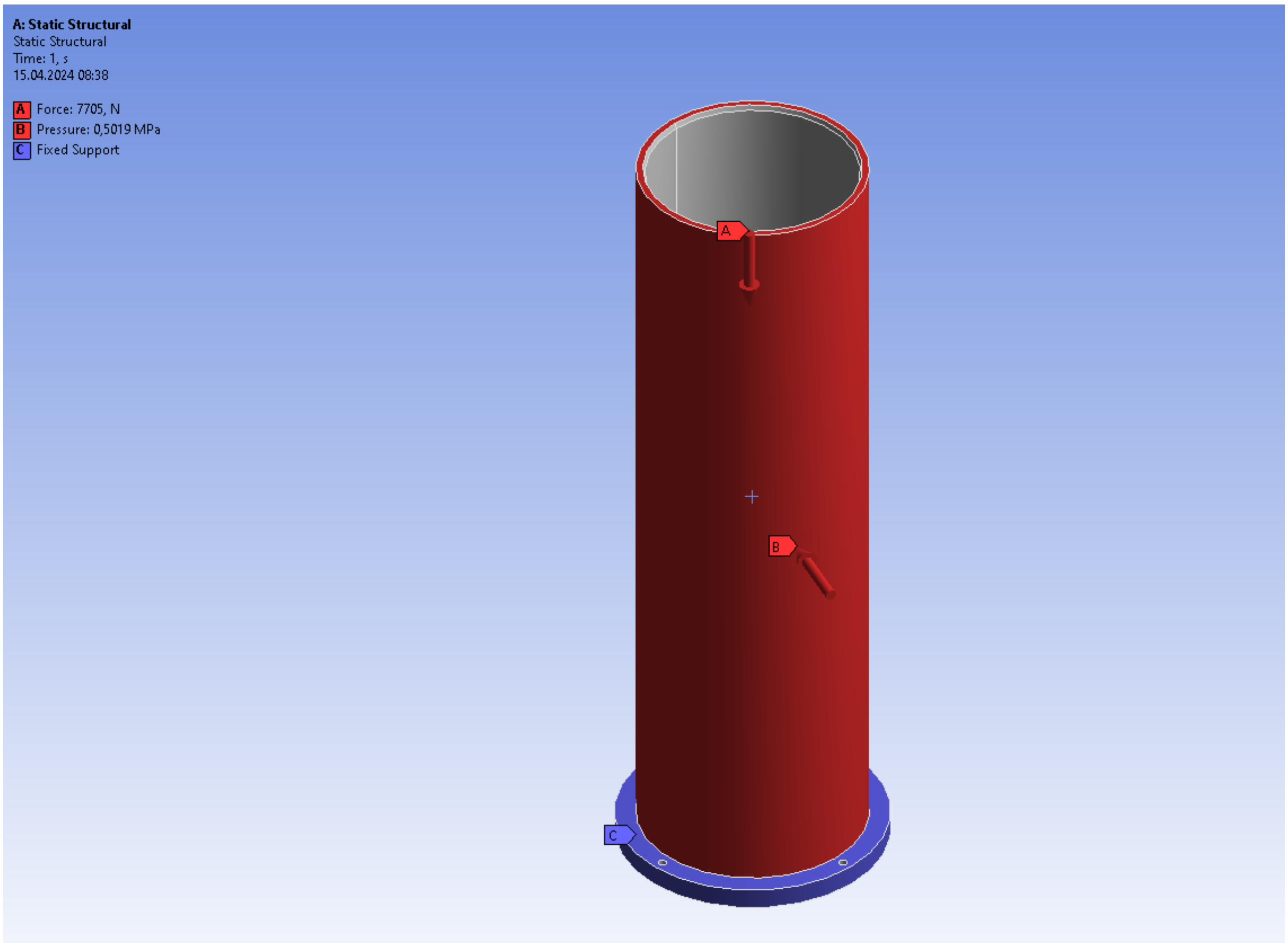
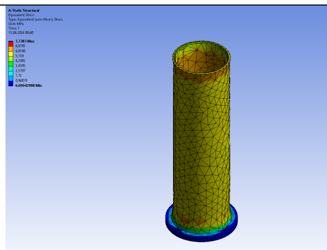
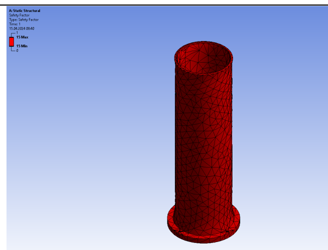
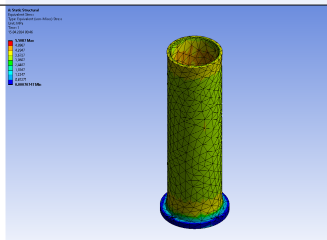
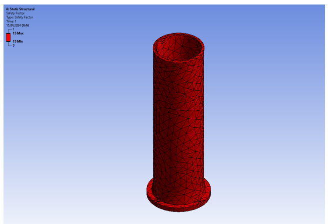
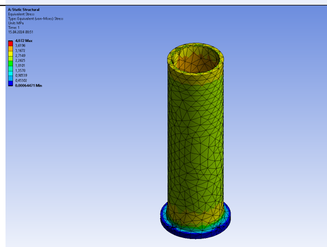
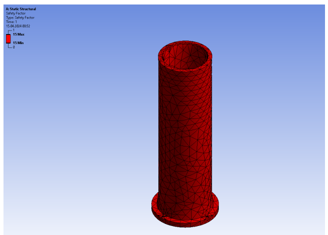


Figure 6.10: Forces and support input set on Battery Enclosure in ANSYS

Table 6.11: Material saving - Battery enclosure

Material saving - Battery enclosure		
Thickness	**Equivalent stress**	**Safety factor**
3mm		
5mm		
7mm		

6.5 Final product design Manipulator

The detailed design phase of the manipulator involved careful consideration of materials, dimensions, and various components to ensure optimal performance. This year's manipulator consists of multiple components making it possible for the manipulator to execute the desired tasks, with every single component selected for a specific purpose. A notable difference from previous projects was the decision to utilize electrical linear actuators for the arm's tilting function. Last year's project had significant challenges raising the arm in water. Due to the water resistance, the stepper motors were simply not strong enough. Thus, opting for linear actuators seemed a logical solution. However, as mentioned earlier, an issue occurred with the linear actuators not being waterproof, requiring the need to seal them. While waterproof actuators were available, budget constraints made it difficult. During this phase, a significant decision was made to abandon the plans for a gripping function for the manipulator. This decision was prompted by challenges encountered in sealing the enclosures designed to accommodate the intentional DC and BLDC motor. The rectangular housing that was supposed to hold the two motors posed difficulties in achieving effective sealing and occupied considerable space, in addition to extra weight causing substantial moments away from the support structure. Additionally, the valve intervention task on the TAC Challenge didn't require the gripping function. These arguments in addition to both limited time and resources led to a conclusion that the gripping function for this year's manipulator was to be scrapped.

The positioning of each linear actuator emerged as a crucial aspect for enabling the arm to achieve the desired angles. With each actuator possessing a limited stroke length, careful consideration was required in determining their positioning along the arm's structure to optimize functionality. For the first actuator, it was established a "resting" position for the arm at a 60-degree angle from the horizontal plane. Initial calculations and formulas provided rough estimates for the actuator's support placement, which were further refined through trigonometric analysis and iterative modeling in Fusion360. However, the second linear actuator posed a unique challenge due to the requirement for the entire second joint to rotate by 90 degrees. As a result, adjustments were made to accommodate this range of motion. Following the establishment of functional requirements for joint 2, the design process proceeded in the same manner as for the first joint. Lastly, the position of the third joint was determined by a compact linear actuator featuring a 30mm stroke length. The functional objective of this joint was to enhance the manipulator's maneuverability by introducing additional freedom in terms of positioning. Collaborative discussions with the electro-engineering group led to the joint decision that the last joint should be able to tilt at least +/- 15 degrees, thereby expanding the manipulator's operational range.

The selection of bearings for the manipulator was a crucial aspect of the design process. The primary contenders were ball bearings and sleeve bearings, each offering distinct advantages and considerations. A significant concern with the ball bearings is the risk of corrosion by utilizing them in salt water. While specialized ball bearings designed for subsea applications exist, their need was questioned given the specific application. Additionally, the requirement for high rotational speeds typically mandates the use of ball bearings. However, this is not the case for this application as the joints in the structure are not subjected to such high speeds. Therefore, it was decided to go through with a more cost-effective alternative, the sleeve bearing.

The decision to opt for sleeve bearings was reinforced by a recommendation from Energy X, which had successfully employed sleeve bearings in their designs. This justification provided additional confidence in the bearing selection process. One of the primary motivations for choosing sleeve bearings was to eliminate the risk of failure due to corrosion. The sleeve bearings considered were made of plastic, supporting this objective. However, plastic also has its downside as it may be prone to cracks. Nevertheless, it was concluded that for this project's application involved rather small forces and was therefore sufficient. Initially, based on the dry test platform, proceeding by not using bearings at all was a possibility. However, upon consultation with the electro-engineering group, it became apparent that this approach would lead to unnecessary wear of the structure. Additionally, the electro-engineering group specified a requirement involving that the shafts had to rotate in conjunction with the joints, to enable constant monitoring of joint positions. Given these considerations, it was evident that utilizing sleeve bearings was necessary to ensure the longevity and proper functioning of the manipulator.

A critical aspect addressed during this phase was the determination of tolerances, particularly for the sleeve bearing housings and the shaft ends that interfere with the bearings. The precise tolerances for the bearing housings were crucial to ensure optimal performance and longevity of the manipulator. For the sleeve bearing housings, achieving the correct tolerances was important as the bearings required a press fit to remain securely in place. After communicating with the producer of the sleeve bearings it was found that the housing tolerance given by the producer of the parts could not be used for this application. The reason for this was that the sleeve bearing producer assumed that the sleeve bearings was to be installed into a steel material, which differed significantly from the intended use of plastic material for this project. The importance of accurate tolerances for the housing cannot be overstated, as any clearance could lead to movement of the bearing, compromising its functionality. Conversely, the tolerance cannot be too tight as the bearing could be damaged during assembly. Utilizing a steel material would have met the requirements to proceeded with the tolerances provided by the manufacturer, which would have ensured a proper fit for the bearing.

Another critical aspect to consider was the use of o-rings and the nitrile rubber seal to prevent water intrusion along the rotating shaft, crucial for maintaining the integrity of the manipulator's components. O-rings played a vital role in sealing the lid attached to the enclosure that protects the DC motor. Two key tolerances were considered for achieving a proper o-ring seal for axial installation: one tolerance for the depth of the o-ring groove and one tolerance for the groove width. For an o-ring with a cross-sectional diameter of 3.53mm, the tolerance for the groove depth was set at +0.05mm, while the tolerance for the groove width was +0.2mm. Following these tolerances for the groove design, ensured the creation of an effective seal, theoretically preventing water intrusion. In addition to o-rings, nitrile rubber seals were utilized to seal the rotating shaft, enabling the rotation of the end effector. The tolerance for a 15mm outer diameter rubber seal housing was set at +0.027/-0.000mm, while the Ø6mm shaft tolerance was set at 0/-0.075mm. Ensuring a robust connection between the DC motor and the end effector was crucial to achieve the desired rotational movement as outlined in the performance goals. This connection was facilitated by a shaft, linked to a DC motor by a Ø6mm shaft coupler. The coupler equipped with four screws, exerted sufficient pressure on the attached shafts leading to maximum moment transfer from the DC motor and onto the shaft.

The waterproofing of the third joint emerged as a significant point of discussion, driven by the decision to utilize the DC motor as the driving force for the rotational movement. Initially, aluminum was considered as a material for manufacturing the joint. However, the option presented drawbacks, including increased weight due to aluminum's material density. Even though aluminum is a considered a lightweight material, it presents considerable weight addition when compared to plastics. There were also challenges posed by the complex geometry of the model. The complex geometry was a result of actuator supports, a pivoting point, and a surface where a camera could be supported properly. If aluminum material had been chosen, it would require the structure to be manufactured in multiple parts due to the complexity of the design. While welding could have been considered to merge parts, the complexity of aluminum welding prompted the exploration of alternative production methods. Recognizing the effectiveness of 3D modeling in manufacturing complex geometries, it was explored as a potential manufacturing method. However, ensuring precise tolerances was critical, and concerns arose regarding the suitability of certain plastics for water application. After discussions with lab personnel at the 3D printer lab at the University of Stavanger, it was decided to proceed into the testing phase with a similar geometry made of resin material namely, grey pro resin. The printer used for resin prints was also a high-quality printer enabling to achieve fine tolerances for the application of o-rings and the nitrile rubber seal. A crucial consideration in the use of o-rings was ensuring sufficient pressure on the o-ring from the opposite surface. To achieve this, bolted connections were employed, utilizing M4 screws with nuts and washers. The washer was necessary as the plastic material is relatively soft, ensuring even distribution of pressure and preventing damage to the material. Similarly, for the proper functioning of the nitrile rubber seal, a press fit was essential during installation. The housing was designed with a 15mm diameter, matching the outer diameter of the nitrile rubber seal bearing. However, attempting to press the seal into this hole directly, would risk damaging the seal due to the sharp edges. To facilitate easier assembly and prevent damage, a lead-in chamfer was designed. This approach was also utilized for the corresponding holes for the sleeve bearings. Given the weight, and possible external forces exerted on the manipulator, led to the conclusion of a sufficient connection with the ROV frame deemed necessary. The last factor addressed during the detail phase was minimizing the stress concentrations in the manipulator's structure. Specifically, all edges where two surfaces met were rounded. This modification led to reduced stress concentrations, enhancing the overall robustness of the manipulator.

The final design of this year's manipulator project is depicted in Figure 6.11.

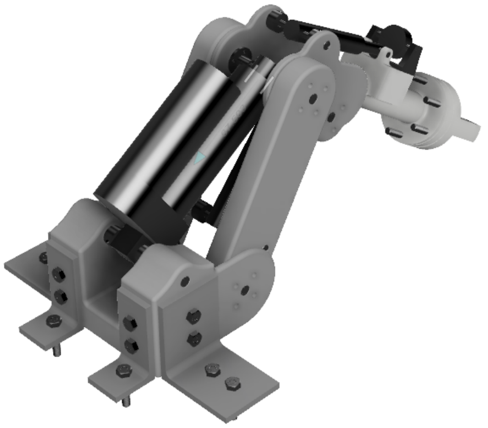


Figure 6.11: Manipulator final design

6.6 Buoyancy and stability

From the theory section, it is evident that a positive net buoyancy would cause a component to float to the water surface. The reason for this is due to the buoyant force exerted on the component is greater than its weight force.

Both the electronic- and the battery enclosure included hollow sections, which theoretically can contribute to buoyancy. The electronic enclosure, characterized by its large volume and relatively low weight, created a large net buoyancy for the ROV. For this year's project, it was also necessary to consider the battery enclosure, unlike previous projects. The battery enclosure possesses a smaller volume compared to the electronics enclosure, and due to the relatively high weight of the battery stack, resulting in a negative net buoyancy as depicted in Table 6.12.

The manipulator also exhibited a negative net buoyancy on the ROV. The first linear actuator, extending from the base to the first joint, provides a relatively large net buoyancy due to its weight. In addition, the manipulator structure is constructed of a plastic material which also contributes to a negative net buoyancy. In contrast, the ROV frame, which is made of HDPE, contributes to a positive net buoyancy.

As indicated in Table 6.12, the ROV is exerting a negative net buoyancy of approximately 8 N, meaning that the ROV would sink when submerged in water. This implied the necessity of considering floating elements to achieve the objective of a positive net buoyancy of approximately 1 N. This goal ensures that in the event of unforeseen incidents, and the ROV has to shut down, the vehicle will float to the water's surface due to the buoyant force.

Another aspect to consider was to determine the orientation of the ROV in the water. Would it be front-heavy or rear-heavy? This assessment was essential to determine the need to utilize ballast to counteract the imbalances. After realizing that the vehicle was front-heavy from the CAD model supported by a buoyancy test, it was necessary to counteract the weight force exerted in the front, with a ballast position further back on the ROV. The bottom plate for the vehicle is designed with a large number of holes, allowing positioning ballast at multiple points, and in this way enabling correction of imbalances. In addition, it was possible to make small adjustments to the enclosures in the horizontal direction, which would affect the positions of COM and COB.

As mentioned, the distance between COM and COB was crucial to determine the maneuverability of the ROV. A smaller distance between the two points would cause an unstable ROV. A strong desire for this year's project was to manufacture a stable ROV, capable of executing the intended tasks.

Table 6.12 and Table 6.13 provides a detailed description of the values utilized to compute the total mass and net buoyancy of the ROV and manipulator respectively.

Table 6.12: Buoyancy calculations - ROV

Component	**Quantity**	**Volume $[cm^3]$**	**Net buoyancy [N]**
Sidewall	2	4370	2.455
Thruster	8	1560	-17.610
Brackets	33	114.594	-3.734
Cross stiffner	1	1076	0.391
Electronic enclosure	1	14424	48.1
Clamps - electronic enclosure	4	553.2	3.964
Top plate - frame	2	3100	1.666
Bottom plate - frame	1	2237	0.976
DVL	1	69.361	-2,833
Casing - DVL	1	46.642	0.064
Camera	2	59.151	-1.913
Battery enclosure	1	3956.9	-11.419
Support - battery enclosure	1	139.8	0.447
Clamps - battery enclosure	4	77.418	0.258
Cover - battery enclosure	1	911	0.316
Bolts, nuts and washers	134	139.096	-13.098
Support - electronic enclosure	2	159.994	0.527
Bridge - frame	1	119.3	0.050
Lights	2	65.849	-1.592
Manipulator	1	1476.047	-13.835
Threaded rod - battery enclosure	4	12.92	-1.168
Total		**34668.272**	**-7.988**

Table 6.13: Buoyancy calculations - Manipulator

Component	Quantity	Volume cm^3	Net buoyancy [N]
Sidewall - Joint 1	2	360.2	-0.584
Base	1	404.8	-0.589
Sidewall - Joint 2	2	68.918	-0.130
Joint 3	1	131.8	0.600
End effector	1	48.912	0.194
Shaft coupling	1	6.786	-0.404
Camera	1	29.575	-0.956
Shafts	7	17.546	-1.045
Couplings	8	8.662	0.006
Flange couplings	7	7.846	-0.541
50mm linear actuator - Joint 1	1	300.4	-5.123
50mm linear actuator - Joint 2	1	18.977	-1.119
30mm linear actuator - Joint 3	1	8.119	-0.539
Faulhaber DC motor	1	37.077	-1.432
Bolts, nuts and washers	22	24.053	-2.139
Sleeve bearings	18	2.375	-0.035
Total		**1476.046**	**-13.836**

The coordinates from Table 6.14 supports what happened during the water test. The y coordinate displays the longitudinal direction of the ROV. Negative y direction is oriented towards the manipulator, which is considered as the front of the ROV. Therefore, a negative y coordinate means that both the COM and COB is located towards the manipulator, supporting the statement of a front-heavy ROV.

Table 6.14: Coordinates for COM and COB

Coordinates	COM	COB	Δ
X	-0,001	-4,85E-06	9,95E-04
Y	-20,45	-7,221	13,229
Z	41,182	68,125	26,943

7 PDP - Testing and Refinement

After several months of designing, theory and simply understanding the process behind developing a fully functional ROV, it was time to enter the testing and refinement phase. This phase also included manufacturing any remaining parts. All parts underwent testing, some multiple times, whether it was to asses strength, waterproofing or as being part of the full assembly. The group had early begun exploring alternative solutions or improvements, if parts in the testing phase were to break or leakages would occur.

7.1 Construction and manufacturing

As mentioned earlier, the group had responsibility of manufacturing most parts itself, with assistance from the UiS workshop. This included the two enclosures, brackets, clamps and other 3D-printed components. The front caps and back-ends for both enclosures were manufactured by the workshop personal, as were the threading of holes.

7.1.1 ROV-frame

The manufacturing of the ROV frame were mostly performed and sponsored by IKM Industrigravøren at Bryne. The project would have looked completely different without their contribution, as the parts were machined by water cutting, which is not available at UiS. The supports for the two enclosures were 3D-printed at UiS, as well as the DVL-bracket. As the components were all printed in PLA, this made for an economic and environment friendly process. The fully assembled frame can be seen in Figure 7.1.

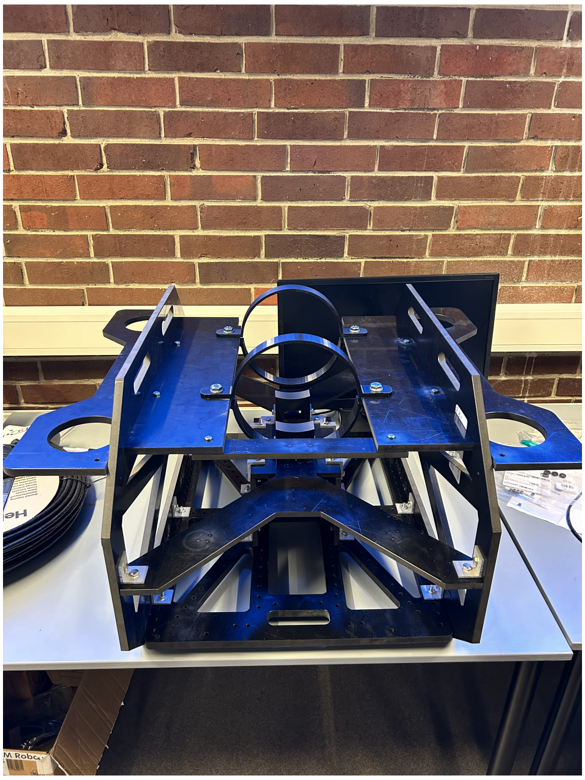
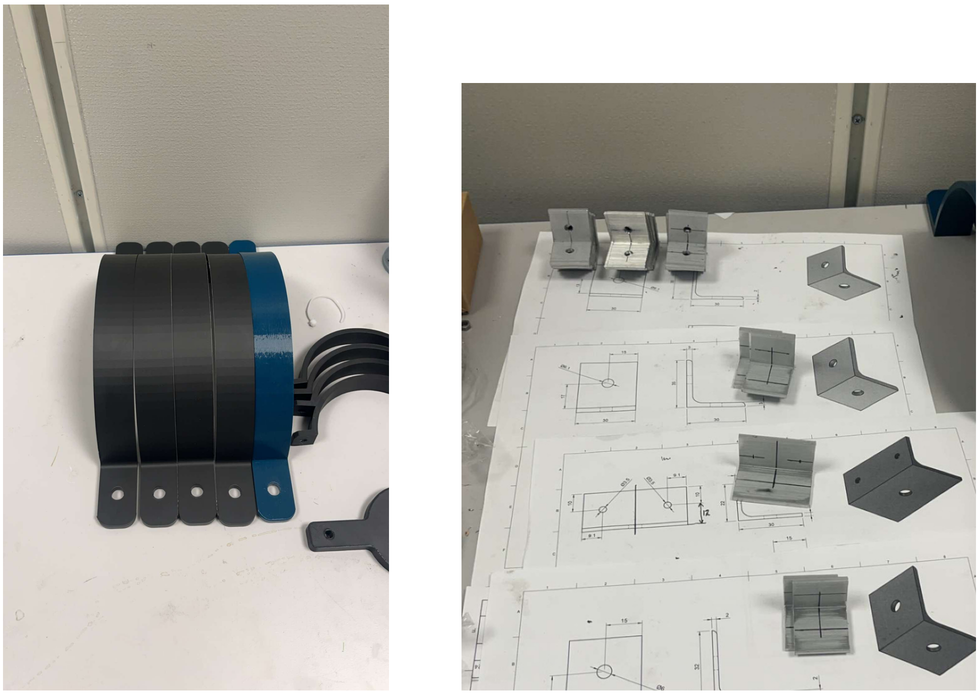


Figure 7.1: Manufactured ROV-frame

7.1.2 Brackets and clamps

The frame was connected by the use of angled brackets. The manipulator also required brackets for mounting, as well as the supports for the enclosures. The manufacturing was quite time consuming, with various types of brackets required. The first step involved cutting all pieces to the correct lengths. Then followed marking the holes from each inner corner of the brackets, as well as drilling holes. For the clmamps, a fillet was implemented on the inner edges, to increase strength and reduce the chances of breaking when tightening the bolts. The manufactured brackets and clamps can be seen in Figure 7.2.



(a) Clamps (b) Brackets

Figure 7.2: Manufactured clamps and brackets

7.1.3 Electronic Enclosure

The group found themselves tasked with managing the machining process independently. Initially, the intention was to seek assistance and collaboration from local machining companies. However, high production demands, particularly in the Rogaland region, posed challenges in meeting deadlines. Previous discussions with the school workshop had primarily revolved around material selection and design solutions rather than production. Nevertheless, the workshop demonstrated a keen willingness to assist the production phase. As mentioned previously, the group received assistance in machining the various back and top caps, while keeping the responsibility for fabricating the two electronics enclosures.

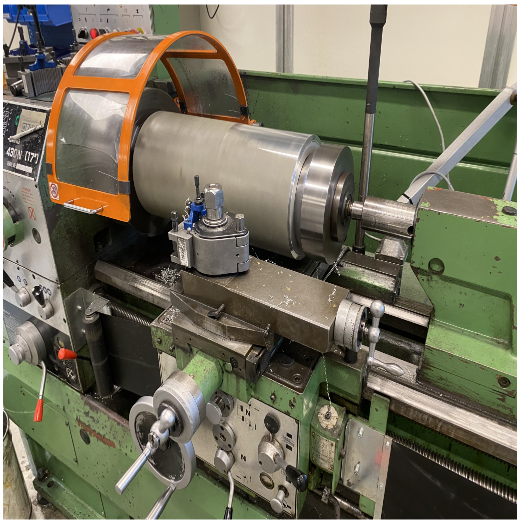
The machining process commenced with a thorough analysis of safety procedures for the machinery involved. Initially, the electronics housing was trimmed to the correct length, leaving sufficient clearance on each side. The internal turning process was prioritized, recognizing it as the most time-consuming aspect. The process is visualised in Figure 7.3. An additional support tool was required to secure the housing in place. Given the dimensions of the pipe, safety precautions took on heightened significance for the group when operating the lathe. As a substantial portion of the material needed to be removed, the group dedicated weekends and Easter holidays to meet various deadlines. With multiple teams depending on waterproof containers for testing circuit boards and other components, the electronics housing was of great importance for the machine group's full assembly and water testing. The enclosures were also required for mounting and adjusting floating elements.

During solo sessions in the student lab, it was important to keep at least two group members present, at all times. Continuous supervision was also necessary throughout the turning process. To prevent overheating, a combination of coolant and cutting oil was employed. The coolant was sprayed directly onto the piece, between the cutting steel and the enclosure, while the oil was applied to the area where the enclosure had contact with the support tool. As the cuts grew larger, the material heated up and expanded. Consequently, it became essential to adjust the support tool accordingly, to prevent the enclosure from being compressed and potentially damaged. Additionally, wearing safety glasses was of utmost importance, particularly during the larger cuts, as aluminum splints dispersed in various directions.

Following the turning process, the piece was refined to meet precise dimensions within the specified tolerances. Subsequently, thorough adjustments were made to ensure the correct length, accompanied by the smoothing down of scratches and sharp edges. The final task was drilling holes for the bolts.

(a) Trimming

(b) Internal turning



(c) External turning

Figure 7.3: Manufacturing of the electronics enclosure

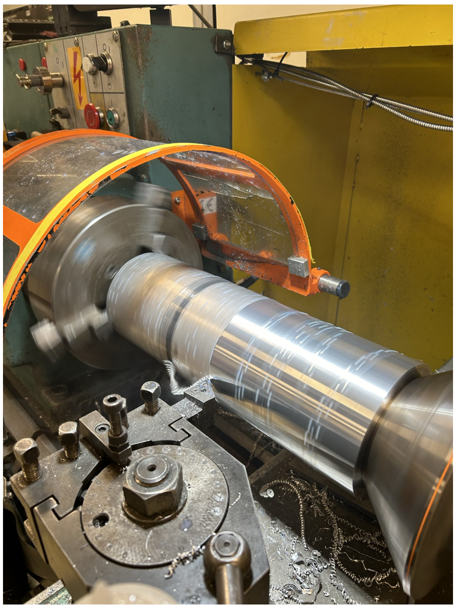
7.1.4 Battery Enclosure

The machining of the battery housing, shown in Figure 7.4, followed a similar procedure. Despite the aluminum tube's delayed arrival due to various factors, it did not pose any issues regarding project deadlines. An advantage with the battery housing was its initial dimensions, which required less turning compared to the electronics housing. With the tube initially measuring 120mm on the outside and 90mm on the inside, only 10mm of the outer and inner diameter required turning. Furthermore, the size of the tube proved advantageous, as it was more manageable on the lathe. Being shorter and in smaller diameter, the group could execute larger cuts both internally and externally. The group had gathered valuable experience from working on the more challenging electronics housing, which ensured a quick and easy process with the battery enclosure.

(a) Trimming the battery enclosure

(b) Internal turning process

(c) Internal tolerance turning process



(d) External turning process

Figure 7.4: Manufacturing of the battery enclosure

The workshop staff handled the machining of both the front and rear parts. Leveraging CNC machines offered a distinct advantage, as the lab engineers operated based on the 3D models designed by the group. Consequently, the resulting products closely mirrored the specifications of the original models, ensuring a high level of precision.

7.1.5 Manipulator

During the concept development phase, each component of the manipulator was 3D printed – a critical step to assess its ability to meet the specified functional requirements. At this stage in the product development process, sleeve bearings were not integrated. Therefore, the shafts were directly inserted into their respective holes, which resulted in stainless steel shafts coming into contact with the 3D-printed PLA plastic. This configuration, if chosen for the final product, would present an increased risk of wear in the holes. While wear resistance was not a primary concern during this phase, it remained a consideration for the final product. The parts used for the concept model were produced using the standard PRUSA printers and PLA plastic. A 15% infill percentage was utilized, meaning that 15% of the inner volume consisted of plastic, while the remaining 85% was void. This printing configuration was chosen for efficiency, as strength at this stage was not a primary requirement.

The primary components of the manipulator, namely the base, the first joint, and the second joint, were produced by Djuvik Machining, located in Sauda. During the start of the collaboration, discussions revolved around potential plastic materials, suitable for this application, primarily considering PEHD 500 plastic and PA6 plastic. For underwater applications, PEHD500 emerged as a favorable option due to its low absorption rate. However, its softer nature posed challenges for press-fitting sleeve bearings into the structure. Because of the press fit, the material would tend to yield under pressure, meaning that it wasn't possible to obtain the necessary pressure from the housing onto the sleeve bearing. This justification in addition to a tight deadline, led to the decision to proceed with the PA6 plastic material for this year's manipulator, despite being aware that this was not the optimal choice. The tight deadline stemmed from a miscommunication with a company that was supposed to produce the part for the manipulator. Due to the absence of a specified completion date, they did not have time to produce the parts within the desired timeline. With the water test for this year's project scheduled to be executed on the 10th of April, forcing the group to seek alternative solutions after declining the offer from the original manufacturer. A backup solution that the group collectively agreed on was to 3D print the entire manipulator. However, due to past challenges from last year's project, the aim was to avoid using this production technique. As the project progressed, Djuvik Machining was contacted for assistance, a machining company based in Sauda. The same day, a TEAMS meeting was arranged to chart the course of action. Given the water test scheduled for April 10th, the goal was to have the manipulator completed before April 9th. In the following days, there was frequent communication with the CNC-operator tasked with producing the manipulator parts. Machining tolerances and specifications for relevant holes were determined, and at this point, production could start. Remarkably, by March 22nd, the first part had already been manufactured. Through effective communication and excellent work performed by Djuvik machining, all parts were successfully manufactured during the Easter holidays.

Following the Easter break, the focus shifted towards manufacturing the shafts supporting the manipulator structure. Given the subsea operating environment, opting for AISI 316L stainless steel for its corrosion resistance properties. However, significant challenges were encountered due to the length and diameter requirements. The UiS workshop only had Ø8mm shafts made of the correct material in stock, meaning the shafts required turning to Ø6 mm and Ø5 mm, respectively. The protrusion from the attachment point on the lathe proved too long, relative to the diameter of the shaft. Consequently, the shafts began to vibrate when the cutting tool contacted the material. Therefore, the surface of the shaft became uneven, rendering the shafts unsuitable for these requirements. In pursuit of smoother cuts, it was experimented with adding supports to the shafts to minimize vibrations. However, still encountering vibrations in the shafts, prompting to explore one last method. At this point, the shaft was divided into smaller segments. The idea was to turn down each segment individually, hoping for better results. However, even with the shafts protruding approximately 20-30 mm from the lathe, the same results occurred. Considering the time limitations of the project, it was decided to stop the process of manufacturing the shafts in-house. Instead, the supplier utilized by the workshop at UiS was contacted. The supplier had the required h9 tolerance in stock, resulting in ordering shaft in both Ø6 and Ø5 sizes, ensuring a timely resolution for this particular challenge.

Given the complex structure of the third joint of this year's manipulator, various production methods were considered to ensure its waterproofing capability. As mentioned earlier, the risk of water intrusion was evaluated with certain plastics. The process of choosing the production method proceeded by internally discussing the pros and cons of different production methods. Initially, machining the components from aluminum emerged as a possible production method. This choice of material was due to the relative lightweight of aluminum. Precision machining of the components would enable the requirement regarding tolerances to ensure a waterproof structure. However, the downside of this production method was that some of the components were small, posing challenges during manufacturing. Additionally, the need of welding the parts together for assembly, which presented potential difficulties, led to considering other methods. The development process proceeded with a solution that involved a combination of a 3D-printed part and a machined part. The part of the third joint that had the complex geometry was 3D-printed, while the other part of the joint, which was supposed to ensure a proper seal, was machined. Opting to machine the waterproof component, aimed to achieve precise tolerances for both the o-ring and the shaft seal. However, this method also had its downside. The transition between the 3D printed part and the machined part would pose a potential weak point, enhancing the risk of water intrusion. As the production method selection proceeded, the solution of 3D printing the entire third joint was discussed. After consultations with lab personnel, it was decided to enter a testing phase, to test different 3D printing approaches. The conclusion from the testing phase, was to manufacture the third joint by using the SLA 3D printing method. This method offered not only a waterproof enclosure but also satisfied the complex structure required for the joint. However, the progress encountered a setback as the SLA printer broke down indefinitely during the testing phase. Fortunately, by recommendation from Energy X, Quest Innovate was contacted for assistance with 3D printing the enclosure with a similar setup as tested with the FORMLABS FORM 3B+ printer at the UiS 3D printing workshop. Later on, the lab personnel at the 3D printing workshop fixed the SLA printer, enabling to print another third joint enclosure. The final manufactured manipulator can be seen in Figure 7.5

Figure 7.5: Manufactured manipulator

7.2 Final cost model

After the manufacturing phase, the team proceeded to formulate the definitive cost model for the project. Remarkably, sponsorship agreements were secured with IKM Industrigravøren, Djuvik Maskinering, and Seal Engineering, reducing the financial burden associated with the majority of high-value components. The other components were either fabricated locally by laboratory engineers at the University of Stavanger or manufactured by the team. The design of 3D-printed parts was customized to ensure compatibility with the university's 3D printers, thereby eliminating any additional expenses. The final cost model of the ROV, enclosures, and manipulator are shown in the table below, Table 7.1, 7.2, and 7.2.

Table 7.1: Final cost model - ROV

ROV-frame		
Parts	**Initial Cost(NOK)**	**Final Cost (NOK)**
Manufacturing plates	8 000	0 - Sponsored by IKM Industrigravøren
3D-printed components	10 000	0 - Sponsored by UiS 3D-printing Workshop
Brackets and screws	3 000	0 - Sponsored by UiS Workshop
Floatation elements	6 000	0 - Used previous year's components
Total cost - ROV-frame	**27 000**	**0**

Table 7.2: Final cost model - Enclosures

Enclosures		
Parts	**Initial Cost (NOK)**	**Final Cost (NOK)**
Material	5 000	0 - Sponsored by UiS Workshop and used previous year's component
Turning process	30 000	0 - Manufactured by team
CNC - Machining	10 000	0 - Sponsored by UiS Workshop
Pressure relief valves	600	710
O-rings	500	0 - Sponsored by SealEngineering
Clamps	2 000	0 - Sponsored by UiS 3D-printing Workshop
Threaded rods	200	69
Bolts and screws	1 500	0 - Sponsored by UiS Workshop
Total cost - Enclosures	**49 800**	**1 188**

Table 7.3: Final cost model - Manipulator

Manipulator		
Parts	**Initial Cost (NOK)**	**Final Cost (NOK)**
Base	3 000	0 - Sponsored by Djuvik Maskinering
1. Joint	2 750	0 - Sponsored by Djuvik Maskinering
2. Joint	2 250	0 - Sponsored by Djuvik Maskinering
3. Joint	200	0 - Sponsored by UiS 3D-printing Workshop
End effector	15	0 - Sponsored by UiS 3D-printing Workshop
Shafts	200	0 - Sponsored by UiS Workshop
Sleeve bearings	1 000	1 000
M3-Threaded inserts	350	350
O-rings	15	0 - Sponsored by SealEngineering
Bolts	60	0 - Sponsored by UiS Workshop
Total cost - Manipulator	**9 840**	**1 350**
Total cost - Project	**86 640**	**2 538**

According to the final cost assessment, the project successfully remained below its initial budget allocation of 22,500 NOK, stipulated by UiS Subsea. This accomplishment can be ascribed to various contributing factors, including the team's early evaluation of initial expenses, securing sponsorship agreements with diverse suppliers, and a focus on designs for efficient manufacturing. This facilitated the in-house production of components at the UiS Workshop and UiS 3D-printing Workshop, proving to be a streamlined, cost-effective measure. The close collaboration between UiS Subsea organization and the university's lab engineers played a pivotal role, particularly in instances where specific machinery, beyond the team's authorization, was required. Moreover, their guidance and support throughout the manufacturing processes conducted by the team were invaluable. The cost model attests to the project's triumph in achieving a cost-effective product development trajectory. Additionally, the accrued savings provided supplementary resources for other project stakeholders, potentially expanding opportunities for groups that may not have explored sponsorship avenues to the same extent.

7.3 Testing

The tests were conducted on the three main systems on the ROV; the enclosures, the frame and the manipulator. The waterproofing tests were the most crucial, as the entire bachelor project depended on sealed enclosures. It was important to conduct tests on all components before full assembly and the first water test, to avoid wasting time at the pool. The testing and refinement phase was also an important step towards TAC challenge, where everything would need to be in order to achieve the highest possible score in the various challenges.

7.3.1 ROV frame

Testing regarding the ROV frame mostly occured after assembly, and focused on stability, making sure all components fit as planned and maintaining the overall structural integrity. After tightening bolts and mounting the cross-stiffener, the ROV proved to be incredibly stable, which was one of the early goals during the bachelor planning phase. There were concerns regarding the strength of the 3D-printed clamps, and how tightly they could be secured before breaking. Since the two enclosures had no connections to the frame, apart from the clamps, it was crucial that the clamps would prevent the enclosures from moving. To check the clamps, the M10 bolts were tightened, and the results were surprisingly good, even without the fillets. However, as an improvement, the fillets were implemented and rubber bands were placed between the enclosures and clamps to ensure these stayed in place. To verify the overall structural integrity, the frame was lifted, tilted and shaken, and external forces were applied at appropriate locations on the ROV.

7.3.2 Enclosures

Testing the two enclosures were a significant part of the testing and refinement phase. Without sealed enclosures, there would be no ROV and no participation in this year´s TAC challenge. Several tests were conducted before mounting the internal electronics module in both enclosures, as a leakage would probably damage the internal electronics module. Two main tests were performed on each enclosure; a vacuum test and a water-vacuum test.

Vacuum test After fitting the o-rings, applying o-ring grease and mounting the front-caps, the enclosures were submerged with the front in water for approximately an hour, to rule out any early leaks. There were no signs of water inside, as expected, as the front caps had both o-rings and the press fit connections. The same procedure was used on the end caps, where the connectors also had to be mounted. There were some misunderstandings during the ordering of plugs, resulting in one of them not fitting the threaded hole in the back end of the electronics enclosure. However, this was solved by casting using epoxy. Eventually the epoxy solidified, and the enclosures was ready for vacuum testing.

The vacuum tests involved pumping air out of the enclosures, using a vacuum pump and connecting it to the pressure relief valve, shown in Figure 7.6. The components would be deemed waterproof if the enclosures were able to keep the vacuum, preventing air from entering. During TAC challenge, the ROV wont be submerged much deeper than four to five meters. However, as the enclosures were such critical components, a vacuum corresponding to a depth of 10 meters was created, which is approximately 1 bar. The vacuum was held for an hour, with no drop in pressure, which was a good indicator for waterproof enclosures. A soap test was also considered, as this is an easy way to locate potential leaks, but as the pressure held constant, this was deemed unnecessary.

Figure 7.6: Vacuum test of the enclosures

Water-vacuum test The next sealing test was the water-vacuum test. This made for a more realistic test, as the enclosure were submerged in a container with room-temperature water, while remaining the same vacuum as with the previous test. The test was crucial for determining if the electronics module could finally be fitted inside the enclosure, which would take the group one step closer to the overall functional water test. After one hour in water, the results were the same as with the vacuum test, no drop in pressure. The enclosures were then deemed waterproof, but before every water test, the enclosures would need to go trough the vacuum test again.

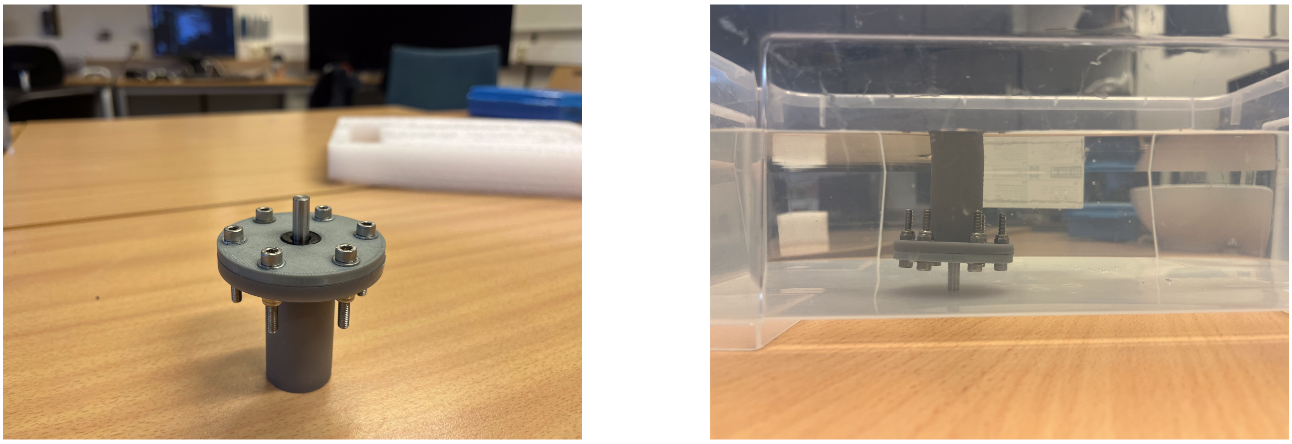
7.3.3 Manipulator

The initial test aimed at ensuring the proper sealing of the first linear actuator, which fell under the responsibility of the electro-engineering group. The electro-engineering group sealed the actuator by opening the actuator house and filling it with grease. The same process is commonly employed for wire protection in, for example, boats. Additionally, silicone was applied along the joint edges, to enhance the seal. Following the completion of the sealing process, the actuator underwent two tests to assess its performance. For a second test, salt was added to the water to simulate conditions closer to those encountered for this project's application. Throughout the test, the actuator piston was cycled in and out, simulation operational conditions. This sealing test was a success as there were no signs of water intrusion in the motor housing.

The second test involved a "dry test" to assess the end effector's capability to reach the desired angles that were established during the planning phase. At this point, there were no requirements attached to the material's water suitability. The entire model was 3D printed at the UiS 3D printing workshop, and the three linear actuators were put in their respective locations. The electro-engineering facilitated the engagement of the linear actuators. During the test, three design flaws became apparent. Firstly, the rubber lining attached to the drive shaft of the first linear actuator interfered with joint 2, preventing the first actuator from fully retracting. This problem was solved by creating the second joint 2 cm wider. Secondly, collisions occurred between the first and second linear actuators in certain positions. Communicating with the electro-engineering group led to a solution for avoiding these critical positions by programming. However, another challenge arose regarding the rotational movement of the end effector. When the drive shaft of the DC motor rotated to manipulate an object, the entire motor would rotate inside its enclosure. This meant a support for the motor was necessary, to prevent the motor from rotating when the drive shaft is manipulating an object. A permanent solution was implemented by casting the motor in place within its enclosure. Although this wasn't ideal, it was decided to go through with this solution as this method also effectively sealed the attached motor cables.

Following the completion of the first part by Djuvik Machining, the decision was made not to proceed with producing the remaining parts immediately. Instead, prioritizing conducting tests on the complete part, to ensure that it was possible to press-fit the sleeve bearings into the structure, while also inserting a h9 tolerance shaft, which was able to freely rotate. Performing this test before manufacturing the rest of the parts was crucial as this would eliminate the risk of reproducing the parts over again. Initially, the sleeve bearings were delivered with installing specifications. However, it was tied uncertainty to the installation specifications as the group were unsure if these specifications were designed for steel housing. This concern was resolved by contacting the distributor of the sleeve bearings. The sleeve bearings were originally designed for bearing housings made of steel, leading to their installation tolerances being based on this material. This was also the reasoning behind the fact that a tighter fit was desired when installing the bearing into the structure. However, some concerns arose whether the fit would be too tight or not, and therefore not being able to assemble the sleeve bearings. With a too-tight fit, the bearing would experience too much pressure from the housing, and therefore either break or deform the bearing. Both cases would make the requirement of rotating shafts difficult or even impossible. A simple test was conducted at Djuvik Maskinering's workshop. Fortunately, the test demonstrated the ability of assembling the bearings, allowing the shaft to rotate freely.

The manufacturing of the intended third joint´s waterproof enclosure involved a lot of testing. The initial test entailed printing two components, a simplified version of the third joint and its lid, depicted in Figure 7.7, using the FORMLABS FORM 3B+ printer. These components were sealed with an o-ring and fastened together with bolts and washers. The material chosen for this operation was "Grey Pro Resin". SLA FORMLABS printer were utilized, aiming to achieve a sealed enclosure. This step was crucial in the work towards identifying a setup that would provide the waterproof enclosure which the project depended on. To detect potential water intrusion, paper sheets were placed inside the structure. The print was not entirely successful, leading to doubts about its waterproofing capabilities. The o-ring groove had flaws that potentially compromised the sealing ability of the o-ring. To assess its performance, three tests were conducted, gradually increasing the minutes spent in water. The first test performed lasted for 1 hour, and the model exhibited minor bubbling when submerged. This stopped after approximately 1-2 minutes. However, this test proved that even though some factors could have led to water intrusion, the o-ring together with the bolted connection provided sufficient sealing. The second test was conducted just after concluding the first test. During assembly of the lid for the second test, a small crack in the lid occurred. The model was now tested for 2 hours in water. Again, the test showed that the o-rings effectively maintained their job and kept the enclosure sealed. The final test conducted for the lid enclosure involved keeping the enclosure in water overnight, lasting approximately 14 hours. Once again, the results demonstrated zero water intrusion. Based on these three successful tests, it was concluded that the first sealing test for joint 3 was a success.



(a) Simplified model of joint 3

(b) Joint 3 submerged in water

Figure 7.7: Test setup - joint 3

The next step was to produce a new lid for the structure. The lid would now consist of a hole in the middle designed for the shaft seal. However, as the 3D printing proceeded, an unexpected issue occurred. The FORMLABS FORM 3B+ printer malfunctioned while printing the new lid, and the printer was now out of service indefinitely. Consequently, an alternative plan for producing the lid had to be developed. It was decided to go through with an FDM print of the lid, and by recommendation from the lab personnel, the test proceeded with a lid created by PET-G material. Utilizing FDM printing for the lid posed challenges, as the layer-by-layer printing method was not optimal for parts intended to be used for waterproof structures. The lid was printed with the finest attainable resolution, to meet the requirements of the o-ring groove. As this test was successful, the test phase moved on to focus on a proper seal around the shaft that would perform the rotational movement. While o-rings were still utilized for sealing the lid properly, a nitrile rubber seal was required for the shaft seal. The test was performed in two phases. The first phase lasted for about 3 hours and the shaft was rotated after approximately 1 hour in water to assess the effectiveness of the shaft seal. The test indicated that both the housing seal and the shaft seal performed effectively as there was no water identified inside the enclosure. The second interval was an overnight test and lasted for 16 hours. The shaft was rotated before leaving for the day and also right before opening the enclosure. Once more, the test proved that the enclosure met the requirements. This marked the conclusion of the testing phase of the front end for the third joint of the manipulator.

Due to the broken SLA printer, alternative methods were explored. Without the capability to produce the third joint in the SLA printer, turning to experiment with FDM printing. The first test was completed by using the PRUSA MK4 printer with a layer height of 0.15mm. O-rings were assembled, and the lid was bolted together. However, the results of this first test, lasting approximately 10 minutes, were not positive. Before immersing the structure in water, paper towels were placed inside the chamber to detect potential water intrusion. Unfortunately, the paper towels from this test revealed water intrusion. The other test object was printed by using the Stratasys Fortus 450mc, a printer able to produce parts with high geometrical accuracy. This printer can produce parts within an accuracy of +- 0.127mm or +- 0.0015mm, meaning that it was possible to achieve the required tolerances for o-ring application. The model printed by the Stratasys Fortus 450mc printer was printed with a layer height of 0.25mm. Similar to the first test, the o-ring was assembled, the lid was bolted together, and tested for 10 minutes submerged in water. Again, the outcome from this test indicated water intrusion. Therefore, it was concluded that layer-by-layer printing was unsuitable for waterproofing structures, as the water would penetrate between the layers of the printed object.

During the test regarding casting the motor in its surrounding enclosure, an unforeseen incident occurred. As the epoxy was poured into the enclosure, it penetrated the motor and entered the motor system, leading to motor failure. However, as a result of this, it wasn't possible to execute the planned test for rotational movement of the end effector. A new motor was ordered right away, however it couldn't be delivered within the deadline of this thesis. Therefore, this test is scheduled to be executed by end of May.

The last test regarding the waterproof third joint was to ensure a proper seal around the motor cables. This was completed by utilizing epoxy to cast the motor cables, as seen in Figure 7.8. As the DC motor had broke down, it wasn't possible to perform a sealing test with the motor cables through the enclosure. Therefore, it was decided to perform a test which would reveal if the epoxy casting would provide sufficient sealing, filling all gaps where water could potentially intrude.

(a) Setup for casting the enclosures

(b) Joint 3 with water inside

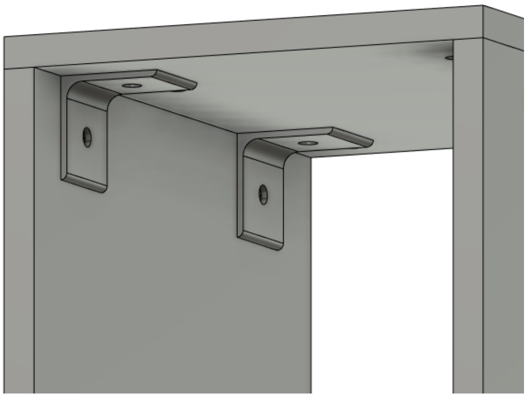
Figure 7.8: Test setup - Casting joint 3

7.4 Refinements

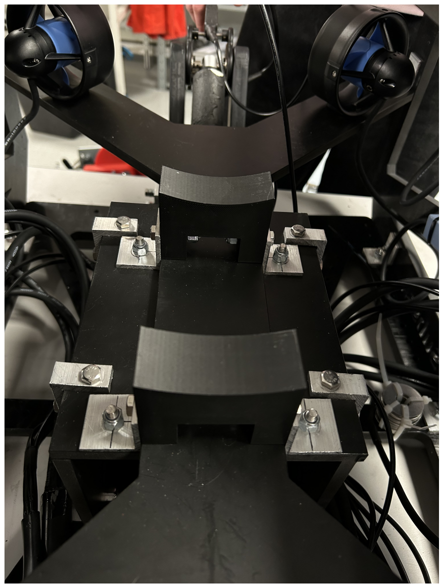
Following the testing of each component, adjustments were implemented to repair any shortcomings or faults identified. This was done to align every component with the requirements and expectations of stakeholders, while also guaranteeing the optimal performance of the ROV.

7.4.1 ROV frame

In the initial blueprint, the plan for the battery house involved internally connecting the roof and sideplates using brackets, primarily for aesthetic reasons. However, this aesthetic-driven approach compromised the efficiency of the connections. Mounting the brackets internally proved challenging and time-consuming. In response, the team opted to enhance the connection design by relocating the brackets to the exterior of the battery house, depicted in Figure 7.9d. This adjustment yielded significant improvements. External placement of the connections did not disrupt other components, and attaching the brackets to the roof and sideplates became notably easier and more efficient. The team prioritized functionality over aesthetics to optimize the battery house connections.



(c) Intial design of the connections



(d) Refined design of the connections

Figure 7.9: Refinement of the connections

7.4.2 Enclosures

Originally, the locking mechanism of the electronics and battery enclosure featured several threaded holes secured with bolts. However, this design proved inefficient, as screwing the bolts into place was time-consuming. By eliminating the threads, the water sealing integrity of the enclosures remained unaffected. This modification resulted in seamless bolt fastening.

7.4.3 Manipulator

As detailed in the testing section, several issues were encountered while performing the "dry test", affecting the overall functionality of the manipulator. The problems included restricted movement range of the first linear actuator, collision between the first and second linear actuator, and non-restricted rotational movement of the DC motor in joint 3. The limited stroke length of the first actuator stemmed from the narrow distance between the walls of joint 2. The rubber lining of the first actuator collided with the walls of joint 2, preventing the actuator from fully retracting its piston. This also obstructed the idea of placing the entire manipulator in an operating position as the operating position required the first linear actuator to fully retract. This problem was resolved by enhancing the distance between the walls of joint 2. The distance was expanded by 2 cm, enabling the actuator to fully retract, and enabling the manipulator to its intended operating position. To resolve the second issue, cooperation between the mechanical- and the electro engineering group was initiated. There was a strong desire for not moving the positions of the linear actuators, from a mechanical point of view, as this could disrupt many other factors of the manipulator. The electro-engineering group proposed an idea that these could prevent collision between the linear actuators, by programming. As for the issue concerning sealing of the motor cables which will go through the back of the third joint, a solution quickly appeared. The idea regarding this issue was proposed as a permanent solution, which involved casting the motor cables. Despite acknowledging this solution not being ideal, it was decided to proceed, as the solution offered the added benefit of effectively sealing the motor cables as well. The solution was not ideal because the motor would be located permanently in the enclosure. Therefore, a solution for a sealed third joint for future projects could involve manufacturing a third joint with the possibility of disassembly.

7.4.4 Underwater Testing

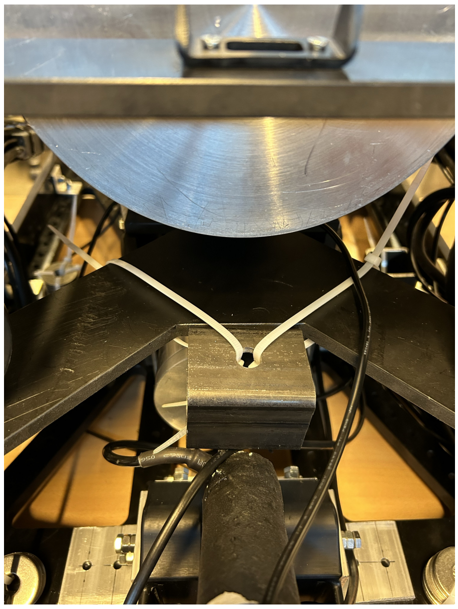
Following comprehensive testing and adjustments to vital elements and components, the fully assembled ROV, illustrated in Figure 7.10, was ready for underwater testing. The tests were conducted to ascertain the performance of the systems and sub-components crafted by the various teams within UiS Subsea. Throughout the first underwater test, the team focused on the watertight integrity of both the buoyancy elements, and the enclosures. The buoyancy elements also had to be adjusted during the testing, to remain a net positive buoyancy and stability.

Initially the goal was to have the ROV ready for water testing by April 10th. This plan was crafted to give each team time for adjustments ahead of the TAC Challenge in June. However,this was an optimistic goal, and it became apparent that following this timeline posed significant challenges. Most other teams within UiS Subsea were also not ready for water testing at this time. Consequently, a decision was made to push the test date to May 10th. Unfortunately, the functional underwater test had to be further postponed due to technical issues.

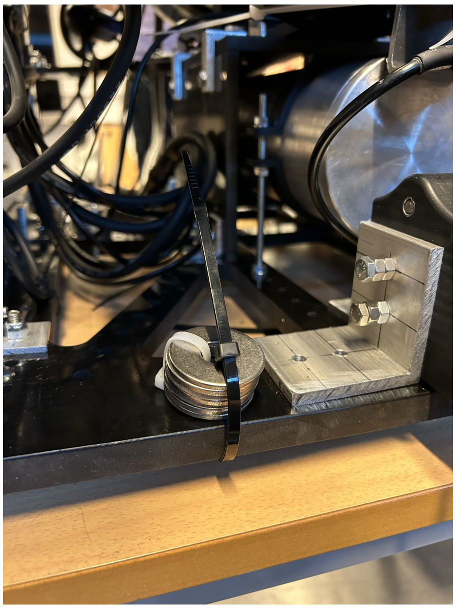
Figure 7.10: ROV-assembly for underwater test

Underwater testing the ROV The machine group performed an early water test, illustrated in Figure 7.11 and Figure 7.12, which took place on May 6th. Key components such as the internal electronics module, cameras, lights, and DVL were not yet prepared nor installed. The team focused on evaluating buoyancy and stabilization by applying equivalent weights to the frame. Prior to submerging the ROV in the pool, the team conducted a vacuum test on both enclosures, ensuring its waterproofing integrity. After 20 minutes in the pool, the ROV was retrieved for inspection, revealing no indications of leakage from either the electronics or battery enclosure. A noteworthy outcome.

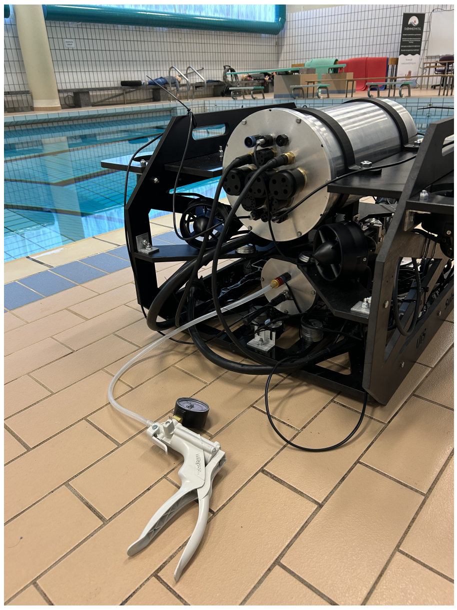
(a) Ballast installation on the rear end



(b) Ballast installation on the front end



(c) Ballast installation on the front end



(d) Vacuum test of battery enclosure before underwater test

Figure 7.11: Preparations for underwater test

During this water testing session, the team also assessed the buoyancy, stability, and maneuvering capabilities of the ROV. Surprisingly, despite expectations that the rear end of the ROV would be heavier, it was found that the front end carried more weight, with the ROV weighing in at 36kg. To evaluate maneuverability and stability, the team focused on correctly positioning the ballast and flotation elements to align with the horizontal and vertical axes of CB_y and CG_y, and CB_z and CG_z. The ROV showcased movement across all six degrees of freedom and proved easy to navigate.

Overall, the ROV demonstrated commendable stability across roll, pitch, yaw, heave, sway, and surge axes, showcasing positive maneuvering capabilities for the functional water test at May 10th. Despite experiencing sinking during testing, the team successfully addressed the issue by optimizing the buoyancy elements to attain positive buoyancy without reliance on thrusters.

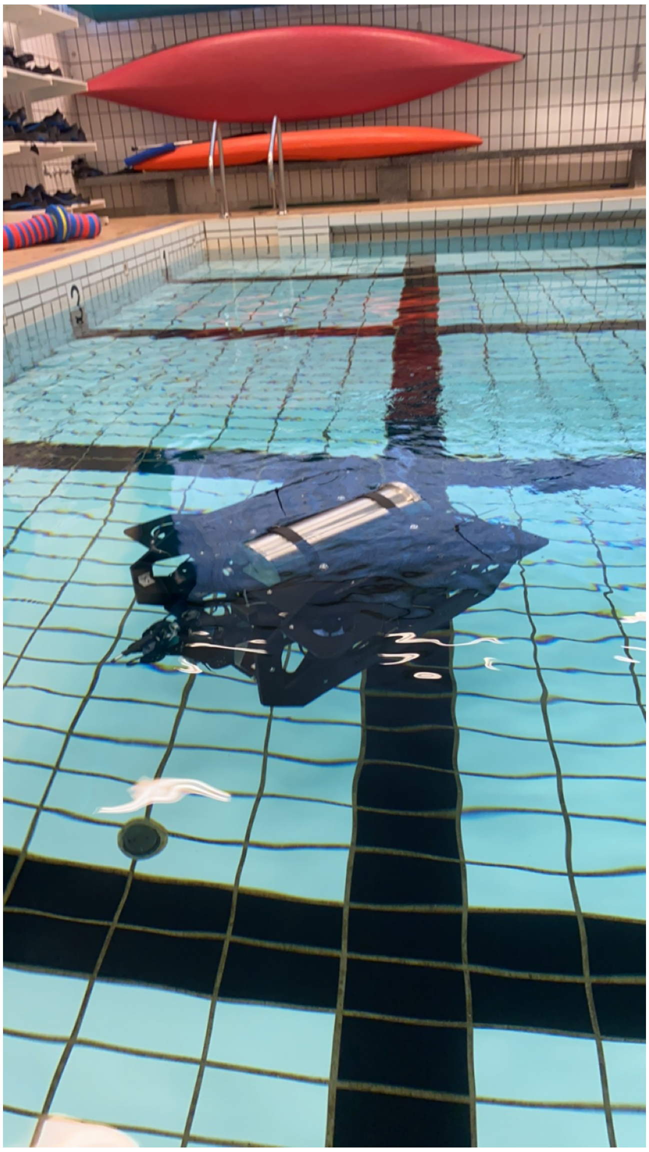


Figure 7.12: Underwater test of the ROV

8 Project Evaluation

The team's initial objectives for the project involved developing a ROV-frame, electronic enclosures, and manipulator capable of executing the tasks given at the TAC Challenge 2024. Highlighting durability, stability, and compatibility were pivotal in framing our design goals. Durability is critical for the frame, considering its exposure to various conditions like chlorine and saltwater, as well as potentially challenging environment subsea. Ensuring the frame remains stable considering these challenges is equally crucial. Our aim was to obtain a balance between stability, weight, and cost to adhere to the TAC Challenge's constraints. Furthermore, the frame was engineered to integrate various components seamlessly. The design of the electronics and battery enclosure prioritizes waterproofing and resilience against hydrostatic pressure. Given the depths that the ROV is designed for, preventing water intrusion and withstanding pressure are crucial to prevent malfunctions. The manipulator design focuses on operational efficiency and robustness for the TAC Challenge demands. Its primary function is to rotate a valve, requiring resilience against underwater forces during operation.

At the beginning of the semester, the team defined the scope evaluation. Establishing the needs matrix, specifications, Gantt Chart, and Long Lead items constituted the team's primary objectives. Initially, the team crafted a needs matrix to understand the requirements of various components, seeking establishment of precise specifications for the ROV-frame, enclosures, and manipulator. This step was critical for designing components that are both efficient and functional. Subsequently, the team created a Gantt Chart to map out schedule milestones involving planning, development, manufacturing, and testing phases of these components. The chart facilitated a visual representation of the project's timeline, supporting efficient time management and maximizing productivity. Moreover, a long lead items list was created to catalog items with significant delivery time. Given the project's time constraints, this list played a critical role for avoiding unnecessary delays and ensuring consistency regarding scheduled milestones.

The team mapped out the timeframes for planning, development, manufacturing, and testing of these components to gain a comprehensive understanding of the project's trajectory. Resource allocation emerged as a crucial aspect, considering the team's responsibility for designing and manufacturing four pivotal ROV components. However, the execution of the plan deviated slightly from the initial projections. The development phase consumed more time than anticipated due to several design challenges. However, the manufacturing process progressed faster than expected, compensating for the time lost during development. Despite the expedited manufacturing phase, testing was postponed. This delay stemmed from other project groups not completing their manufacturing tasks within the scheduled timeframe for testing.

UiS Subsea has a diverse group of sponsors, including industry leaders like Subsea 7, Oceaneering, DOF Subsea, Tekna, OceanInstaller, AkerBP, IXYS, RTS, ShearWater, Exail Technologies, Stinger Technology, UTEC, Ashtead Technology, INNOVA, KYSTDESIGN Subsea Technology, ENERGY X, FFU, REACH Subsea, Djuvik Maskinering, QUEST INNOVATE and Blue Logic. The collaboration with these sponsors played a pivotal role in shaping the design, manufacturing process, and overall budget of the project. Engaging with these sponsors proved invaluable, as their expertise and insights were important in refining specific designs to optimize performance. Moreover, the sponsors made substantial contributions to the manufacturing process, producing several components of the ROV. Furthermore, the involvement of professionals in the manufacturing ensured precision and quality in the production of these components.

In efforts to minimize risks, the team conducted extensive Finite Element Analysis (FEA) of the components, sought insights from former project members, and conducted thorough literature reviews. During the concept development phase, the team had some uncertainties regarding the functionality of the concepts. The FEA analysis enabled the team to pinpoint concepts with the highest potential for success and reduce the risk of failure. Furthermore, leveraging the experiences of past project members and studying relevant literature played a significant role in avoiding design failures and ensuring the functionality of the ROV. Moreover, the vacuum testing conducted on the electronics and battery enclosures played a pivotal role in verifying proper sealing before the water test. Subsequent to this vacuum test, the ROV underwent water testing to confirm the actual water sealing efficiency of the enclosures. These combined efforts were crucial in reducing risks, thereby minimizing the likelihood of failures and project delays.

Budget and resource management were integral aspects of the project's execution. With a team comprising three members, each individual was assigned specific responsibilities pertaining to the ROV-Frame, Enclosure, and Manipulator. The team meticulously analyzed the objectives associated with these components and allocated them accordingly among the members. One team member focused on developing and designing the manipulator, while the other two collaborated on the development and design of the enclosures and ROV-Frame. This approach facilitated efficient resource allocation, eliminating redundant tasks and ensuring effective workload distribution across the project. Furthermore, the team adhered to the Gantt chart to monitor the timeline of their respective responsibilities, thereby striving to meet the project's scheduled milestones and preempt any potential delays. Regarding the team's fiscal management, they successfully secured sponsorships and negotiated discounts for various components. This enabled significant savings in both monetary and temporal resources, while also ensuring efficient allocation of resources. However, there remains room for improvement in ensuring accurate component procurement to avoid any discrepancies or inefficiencies in the purchasing process.

During the detail design phase, the team dedicated efforts to finalize the selection of materials and manufacturing methods for the project components. Various elements of the ROV-Frame, such as the top plates, side plates, and battery house, underwent revisions to optimize their design for functionality. Subsequently, the team evaluated different material options to meet the specific specifications of the ROV and withstand diverse environmental conditions. Based on insights gained from past project members and extensive literature reviews, the team formulated ideas and considerations for material selection. Additionally, input from sponsors provided valuable guidance on suitable manufacturing methods for these components. The refinement stage of the ROV was important to ensure its operational functionality. This efficient approach allowed the team to maximize time utilization during this phase of the project.

The team encountered numerous obstacles in the development process of their product. Designing the ROV-frame presented challenges regarding the mounting of the electronics- and battery enclosure. Overcoming these obstacles demanded more time and effort than initially anticipated. Similarly, ensuring the waterproof integrity of the enclosures and manipulator proved to be a time-consuming task. Particular attention was paid to the design and manufacturing of these components to guarantee waterproofing. The team gained valuable insights into the significance of both design and manufacturing processes in project development, understanding that the right approach and method are essential for ensuring the functionality of the ROV.

Overall, the team successfully designed and produced the parts. Despite unexpected challenges, the group managed to stay on track with the schedule. The manufacturing of the ROV-Frame proceeded smoothly with the assistance of IKM Industrigravøren, ensuring all components fit together correctly and the structure remained stable both on land and in testing conditions. The vacuum testing for the enclosures yielded positive results, indicating no air leakage and thus minimizing the risk of water leakage. The manipulator components were also waterproof, showing no signs of water intrusion, and the structure proved to be stable during testing. Although testing was delayed by a few weeks due to other groups' manufacturing delays, overall, the team was pleased with the project's outcomes and their contributions to the component development.

Participating in the project team offered valuable insight into project execution. One of the most significant lessons gained was the importance of maintaining a clear plan moving forward. Almost every meeting were concluded with a summary of tasks assigned to each group before the next meeting. A checklist were made, making each group responsible for their task, providing clarity for everyone involved.

Another experience gained regarded the academic background of the project leader. Appointing a mechanical engineer student to this role posed challenges in comprehending the problems that the other two engineering disciplines encountered, as the mechanical students are not familiar with the terminology. The lack of understanding led to difficulties in providing sufficient guidance. Therefore, it was concluded that assigning the project leader role to an electro-engineering student, who understands the terms of the data groups as well, would be preferable. It would also be easier for them to comprehend the mechanical aspect of the project.

9 Conclusion

The initial goal for this bachelor thesis was to develop a fully functional ROV for participation in TAC challenge later this year. The development included three main parts: Designing, manufacturing and testing of almost all of the ROV´s components. The development was based on the general product development process, which served as the guiding principle for the structural framework of this thesis. The economic and environment friendly perspective was also central in the development of the ROV.

The official start of the project was on January 3rd this year, however the project management team had already begun planning in October last year. During the early pre-project planning phase, discussions revolved around needs, goals and preferences regarding this year´s ROV. Specifications such as the type of ROV, how many and basic physical requirements were outlined. As two of the group members also were members of the project management team, the overall planning and delegation of responsibility were determined early. This proved valuable. The task seemed quite overwhelming in the beginning, but following last year´s plans, and the product development process, led to an efficient working environment being established.

It was a natural choice to adopt the product development process as a guide for the project. All group members had previously participated in a course here at the University of Stavanger called product development and 3D-modelling, covering both the general development process and valuable experience within computer aided design software. The product development process was also highly recommended by the groups thesis adviser and last year´s mechanical group. In the previous year, the same tasks were divided among five students, with one bachelor group focusing on the ROV development and the other on the manipulator. As these tasks were combined in this year´s bachelor project, due to the lack of machine students, it became even more important to maintain a structured and organized approach, which the product development process ensured. The combining led to the group dividing responsibility, where one member focused mainly on the manipulator and the other two on the ROV. Delegation was essential to meet project deadlines, and did not cause any problems or harm the groups communication. This was likely due to a shared common understanding of what, and when things needed to be done. In summary, the product development process was important for keeping the project running efficiently and in an organized way, given limited room for errors.

The early goals and requirements, as well as the target specifications, were mainly based on the TAC challenge participation. Fundamental requirements were set regarding weight, size, buoyancy and the manipulator's movement. The weight was a concern in the beginning of the project. The battery thesis was new of this year, and the enclosure turned out to be bigger and heavier than expected. Due to it´s size, the group also struggled finding a suitable placement and mounting method. The frame was also affected by the battery house in terms of weight and size, which again had a combined impact on the buoyancy. However, the weight did not turn out to be a problem, with the final weight being around 36kg. Instead the ROV became incredibly stable, both on land and in water. As mentioned earlier, the project management team set an optimistic goal on 25 kg, but keeping it under 50 kg would suffice. This was due to the weight requirements from TAC challenge, where ROV´s under 25 and 50 kg would be granted additional points.

In terms of environmental impact, the group achieved all early goals and targets within it´s control. As mentioned in the system level and detail design chapters, the aluminum pipe used for the production of the electronics enclosure resulted in some material waste, due to it´s size. However, the group concluded, from both an environmentally and economic perspective, that utilizing material from last year would be advantageous instead of purchasing new. As there were no bachelor thesis regarding the battery on last year´s ROV project, the group also needed an aluminium pipe for the battery enclosure. However, the previous material issue with material waste was taken into consideration, and the group ordered a pipe with the dimensions that would minimize material waste.

Economically, the group completed the project with good a margin, thanks to support from local firms and UiS Subsea´s sponsors. As seen in the final cost table, the group spend only 2 538 kr of the initial budget of 22 500 kr.

The work towards manufacturing a functional manipulator proved to be a challenging task. Multiple tests were performed to confirm that the manipulator met the requirements for subsea application as well as the requirements for the TAC Challenge. As mentioned previously, due to the unforeseen incident with the DC motor, the group were unable to perform the rotational test for the end effector, which should have proved, or disproved its ability to turn a valve 90 degrees. However, the group were satisfied with the results from multiple sealing tests, proving that it was possible to seal a 3D printed enclosure. Even though the task was challenging, it provided a lot of learning regarding both the technical part, but also collaboration across engineering disciplines.

In terms of the final assembly of the ROV, there were room for improvements, particulary regarding the weight. From a material strength perspective, both plate thicknesses and the enclosure walls could be reduced a couple millimeters, which would reduce the overall weight. However, having designed one of the bigger ROV´s in UiS Subsea´s history, which was necessary because of the additional battery enclosure, this would most likely have a negative impact on the ROV´s stability. Other less significant optimizations would be not threading the holes for the bolts connecting the back ends to the enclosures, and increasing the diameter of the holes. The threading part was a waste of both machining and assembly time, as it served no functional purpose. Regarding the hole diameter, it was originally set 0.1 mm bigger than the bolt diameter, but this should have been increased for ease of assembly. There is always room for improvements in projects like this, with no group members having experience from the Subsea industry, meanwhile facing a strict time limit. However, the primary goal of the bachelor project was achieved: to develop a fully functional ROV, including the new and improved manipulator.

In conclusion, writing a bachelor thesis for UiS Subsea has been a demanding, yet exciting experience. To be part of a larger project, involving almost 30 engineering students, has granted the group both educational and personal growth opportunities. It has been such a wide specter of challenges. From the early meetings, discussing ideas and plans with the other groups, to generating concepts and designs using CAD software, and eventually ending up working 8 hour shifts turning in the lathe machine. However, it is the diversity of challenges that has provided the group with the most valuable experience. As mentioned earlier, the group completed it´s early goal of developing a fully functional ROV. The next item on the agenda is participating in TAC challenge on June 10th, where the ROV hopefully makes it´s way to the podium, if not all the way up.

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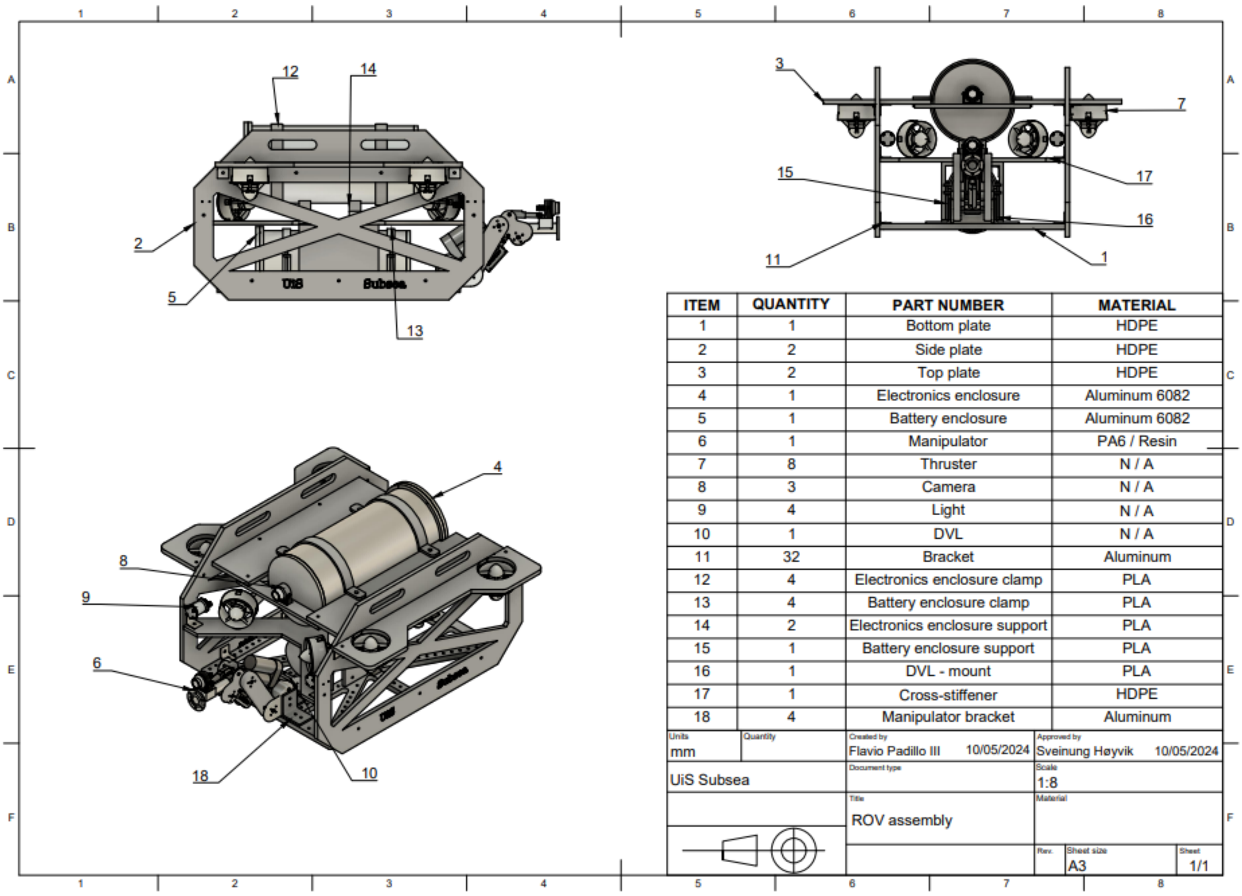
A Appendix - Technical Drawings ROV Frame



ITEM	QUANTITY	PART NUMBER	MATERIAL
1	1	Bottom plate	HDPE
2	2	Side plate	HDPE
3	2	Top plate	HDPE
4	1	Electronics enclosure	Aluminum 6082
5	1	Battery enclosure	Aluminum 6082
6	1	Manipulator	PA6 / Resin
7	8	Thruster	N / A
8	3	Camera	N / A
9	4	Light	N / A
10	1	DVL	N / A
11	32	Bracket	Aluminum
12	4	Electronics enclosure clamp	PLA
13	4	Battery enclosure clamp	PLA
14	2	Electronics enclosure support	PLA
15	1	Battery enclosure support	PLA
16	1	DVL - mount	PLA
17	1	Cross-stiffener	HDPE
18	4	Manipulator bracket	Aluminum

Figure A.1: Technical drawing of the assembled ROV

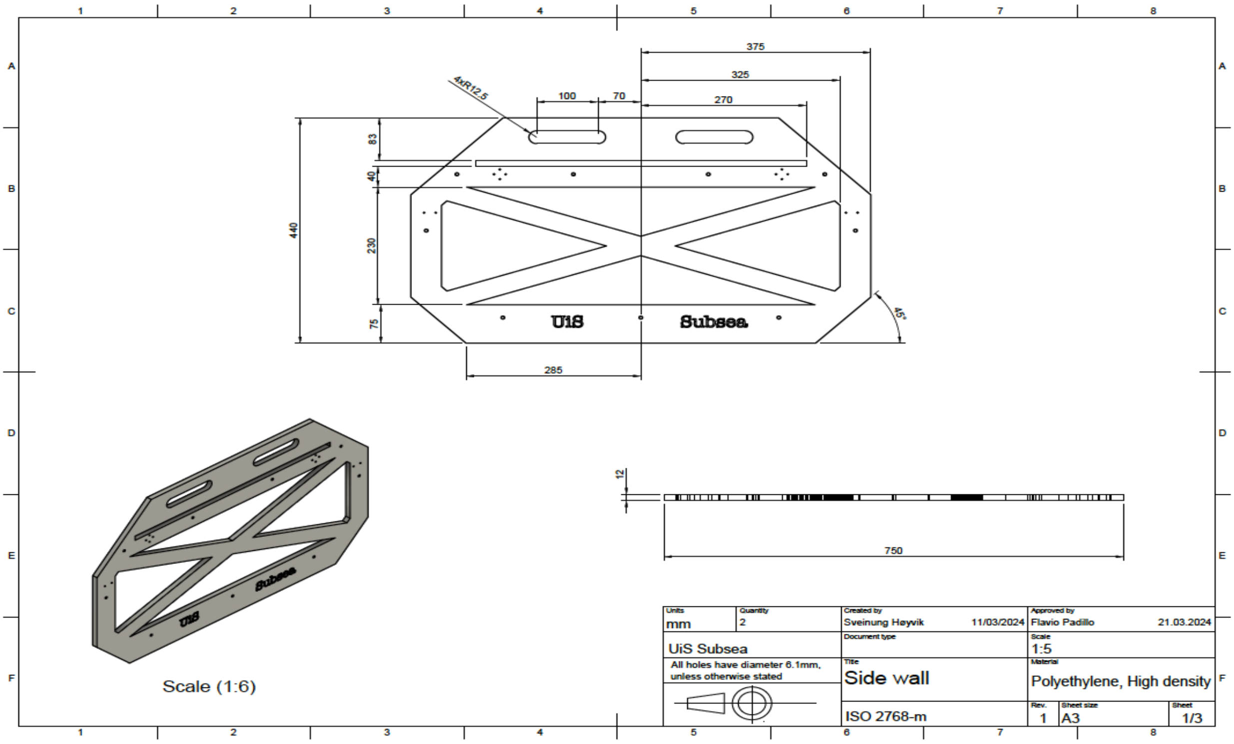


Figure A.2: Technical drawing side wall 1:3

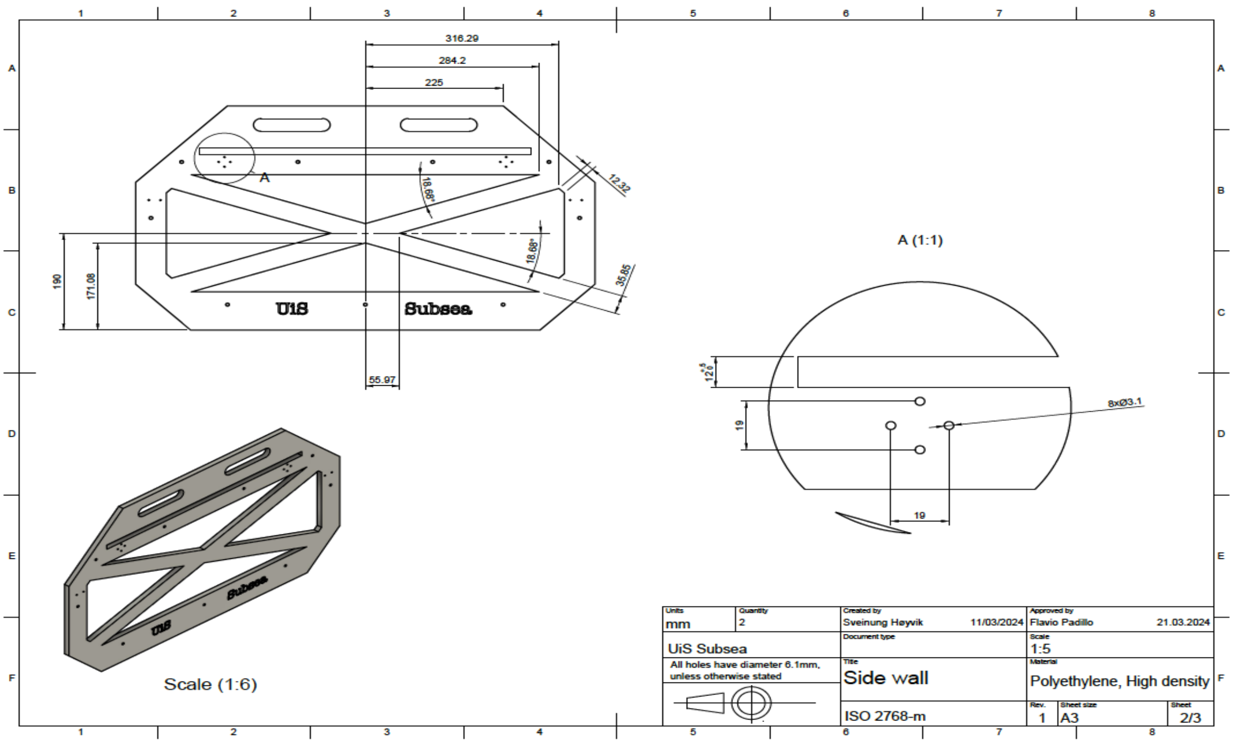


Figure A.3: Technical drawing side wall 2:3

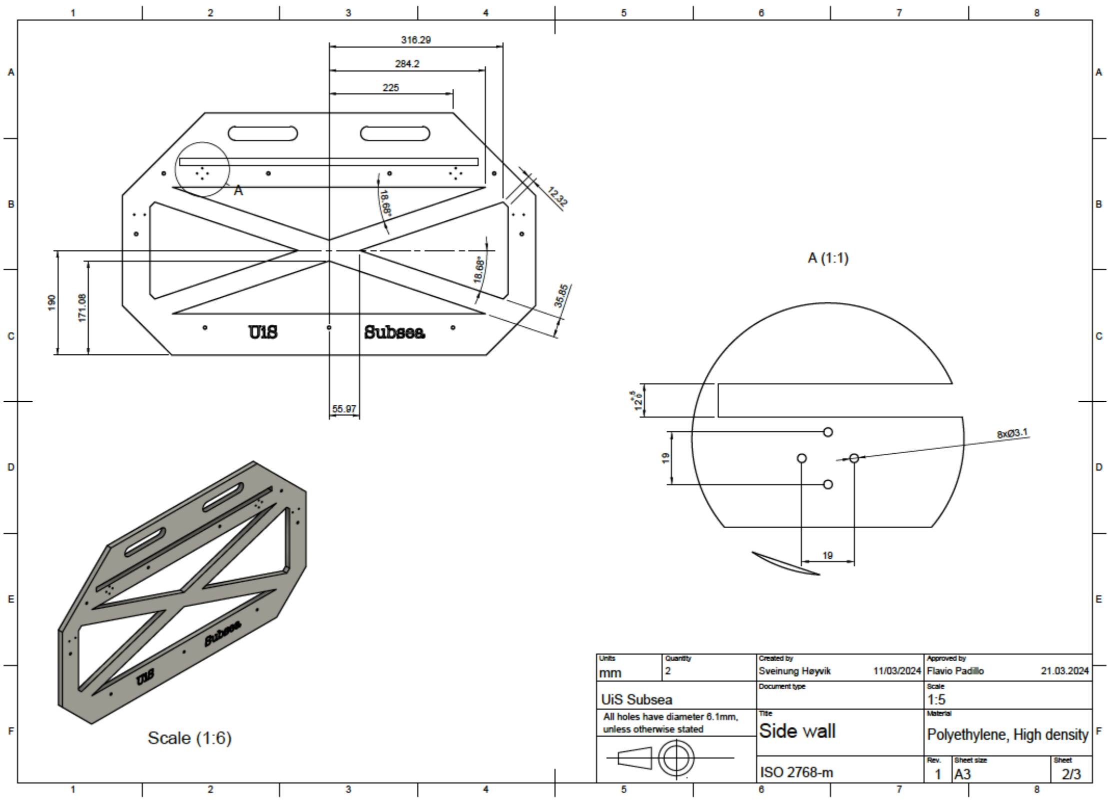


Figure A.4: Technical drawing side wall 3:3

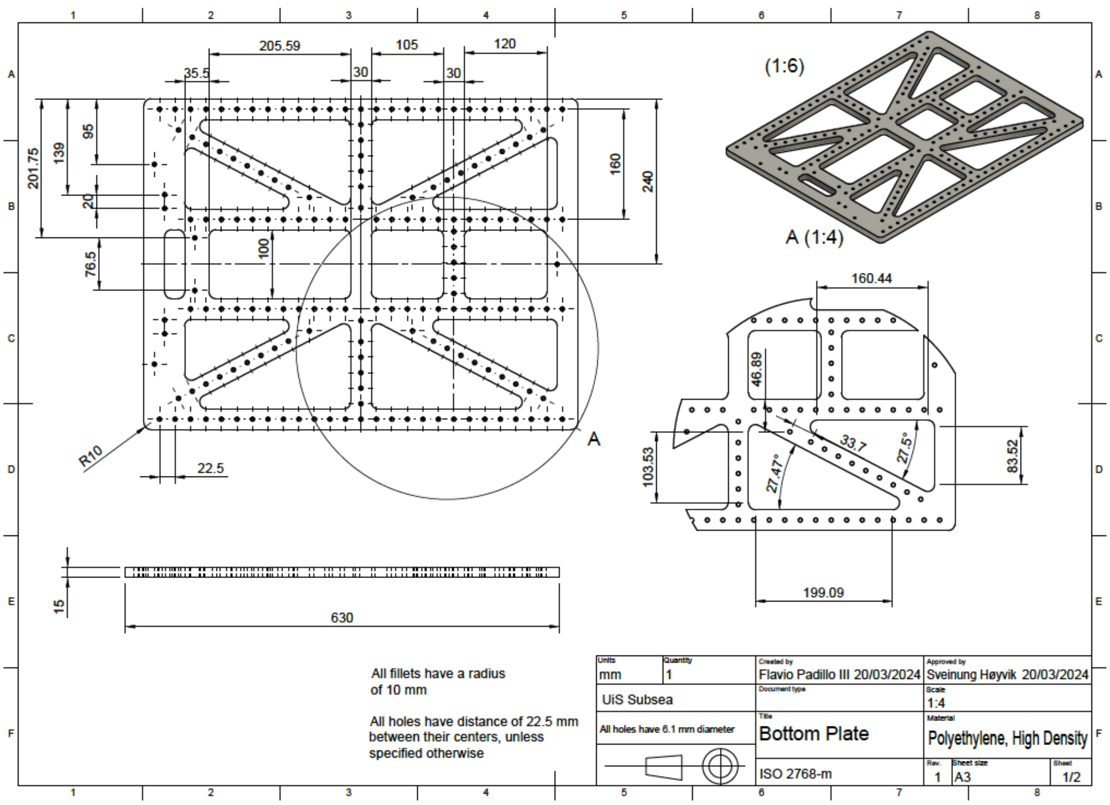


Figure A.5: Technical drawing bottom plate 1:2

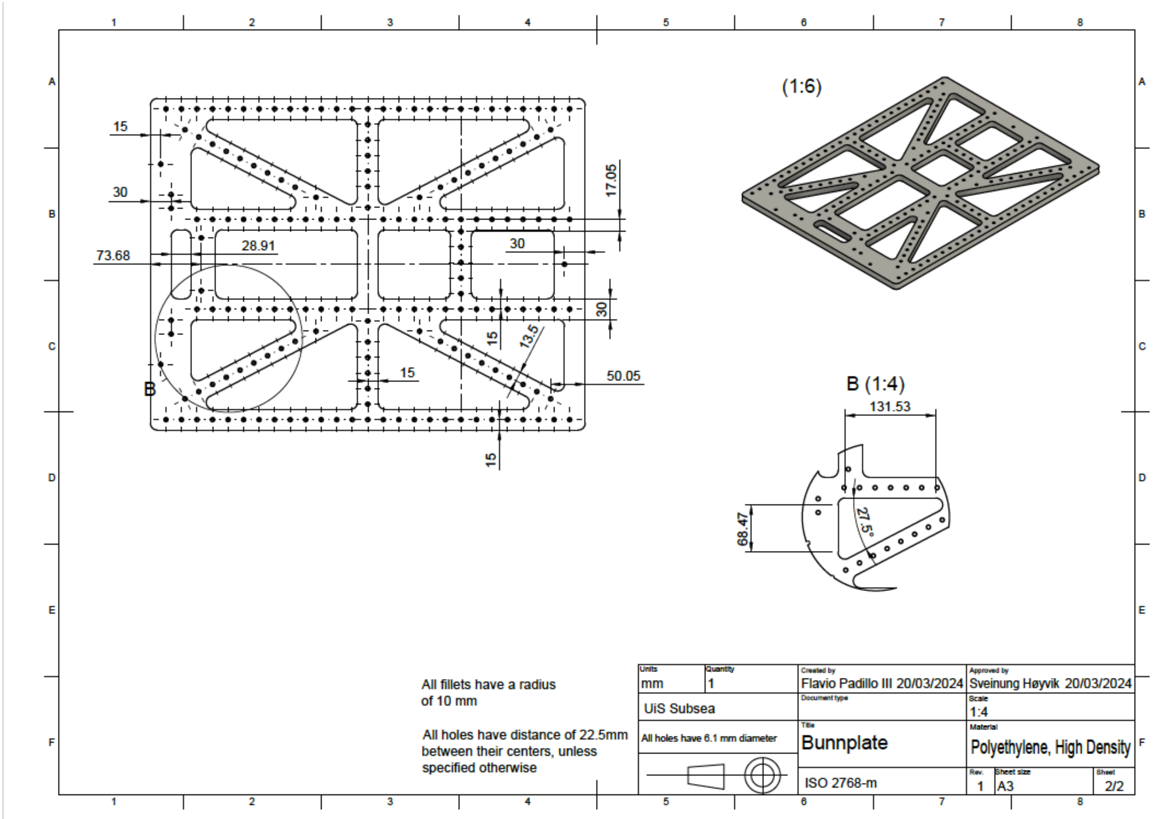


Figure A.6: Technical drawing bottom plate 2:2

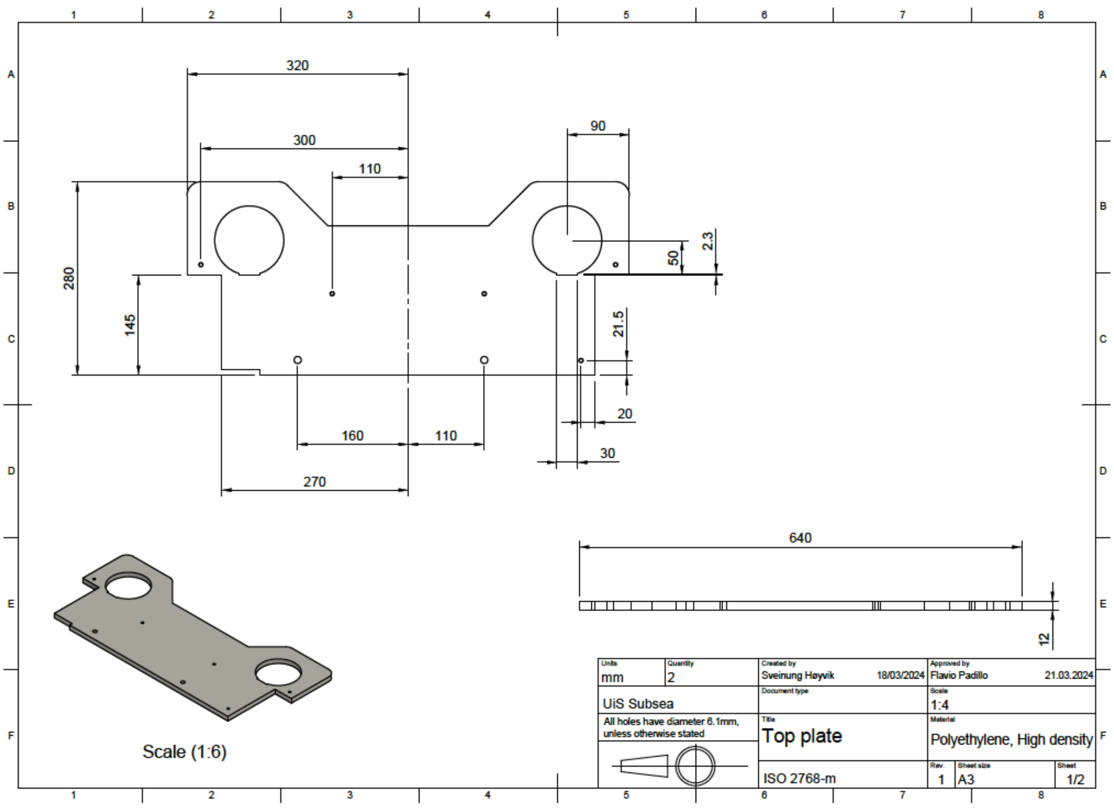


Figure A.7: Technical drawing top plate 1:2

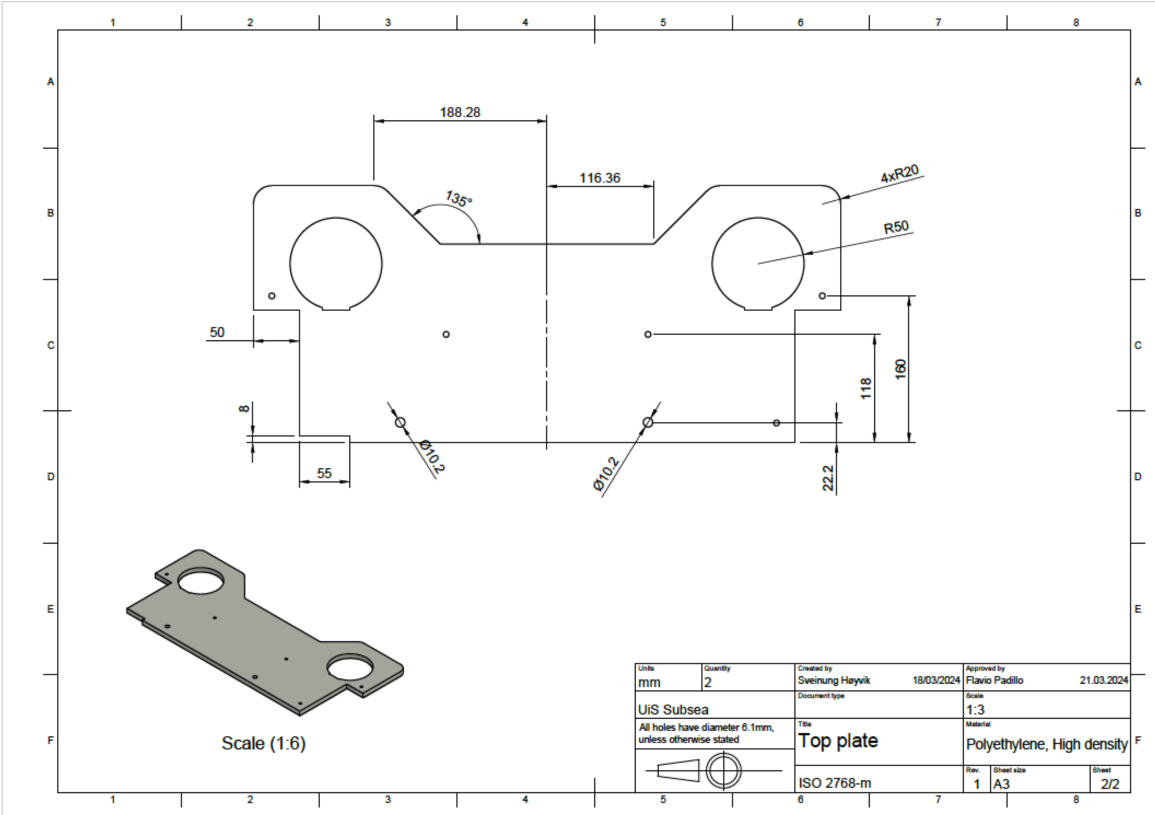


Figure A.8: Technical drawing top plate 2:2

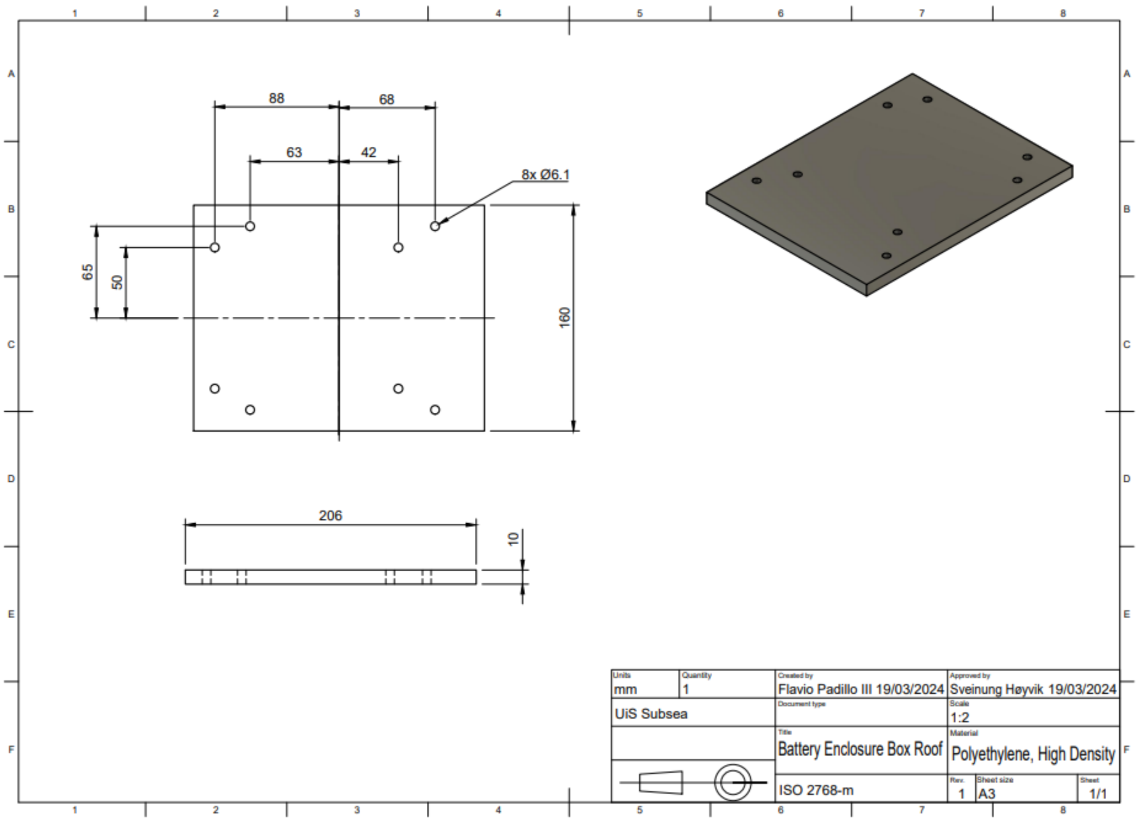


Figure A.9: Technical drawing of the battery house's roof

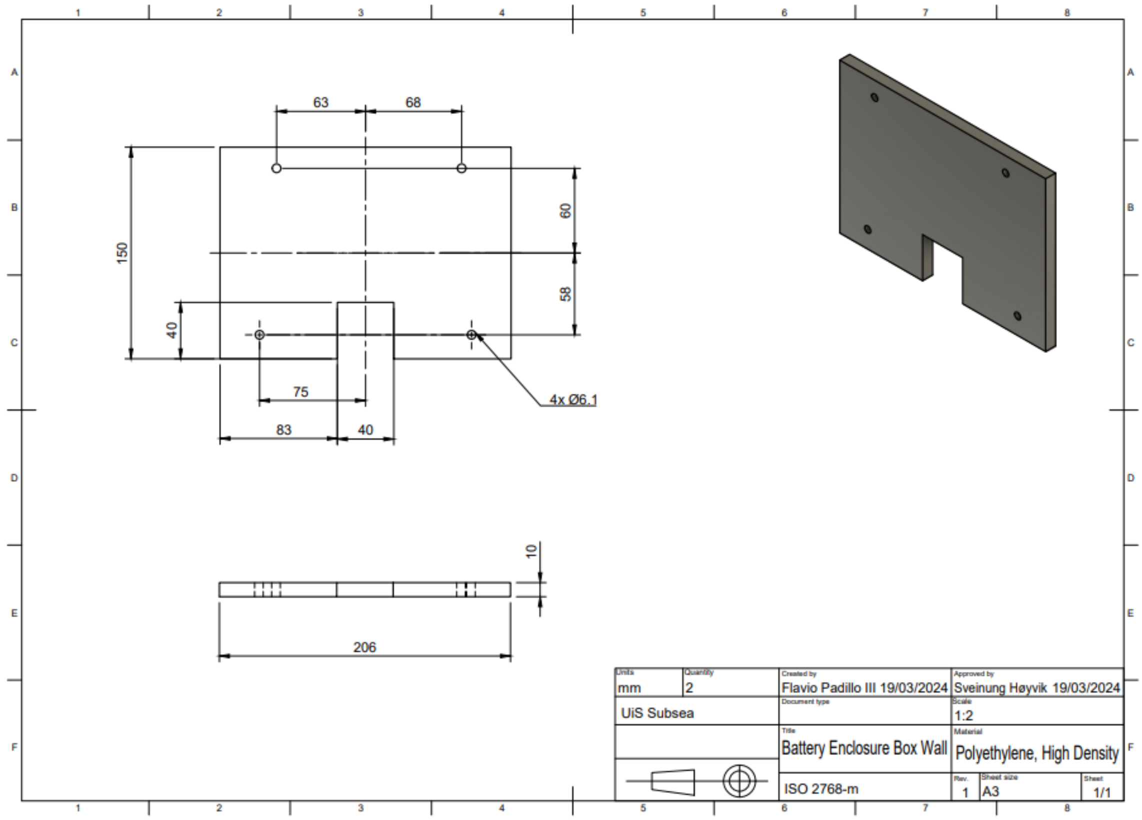


Figure A.10: Technical drawing of the battery house's wall

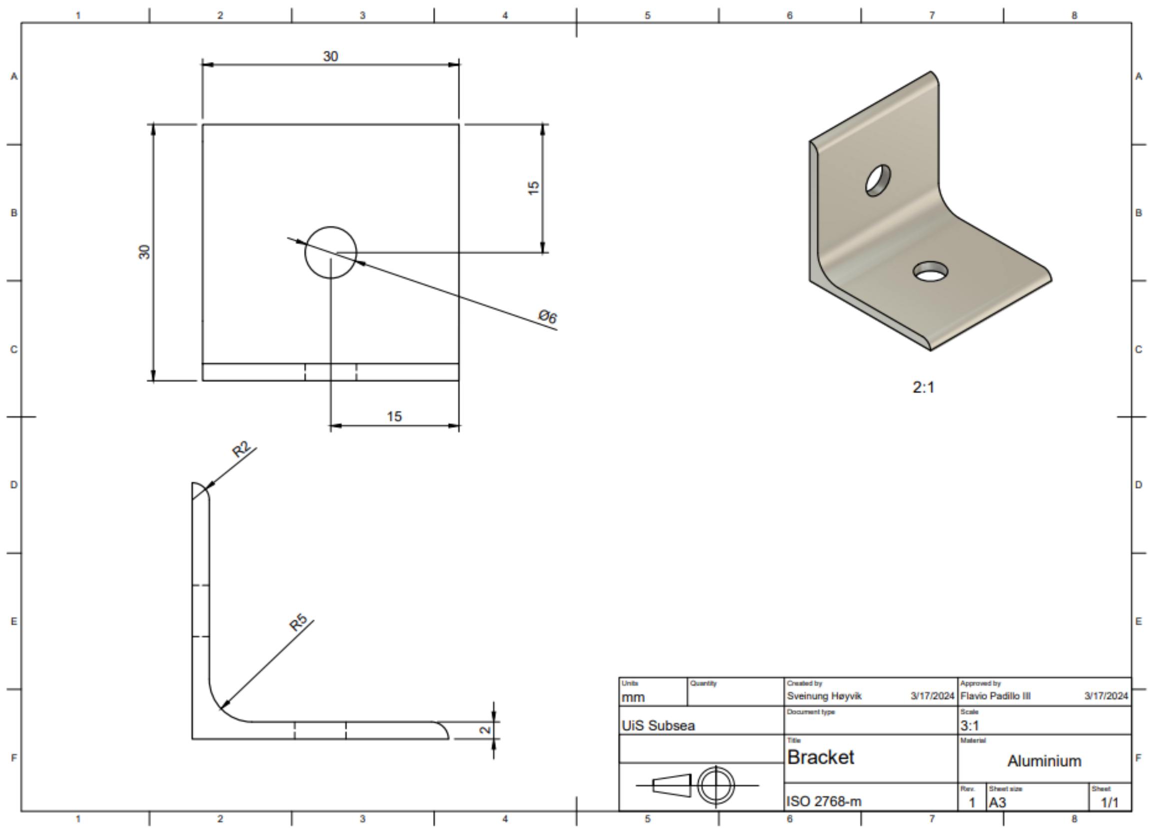


Figure A.11: Technical drawing of the bracket

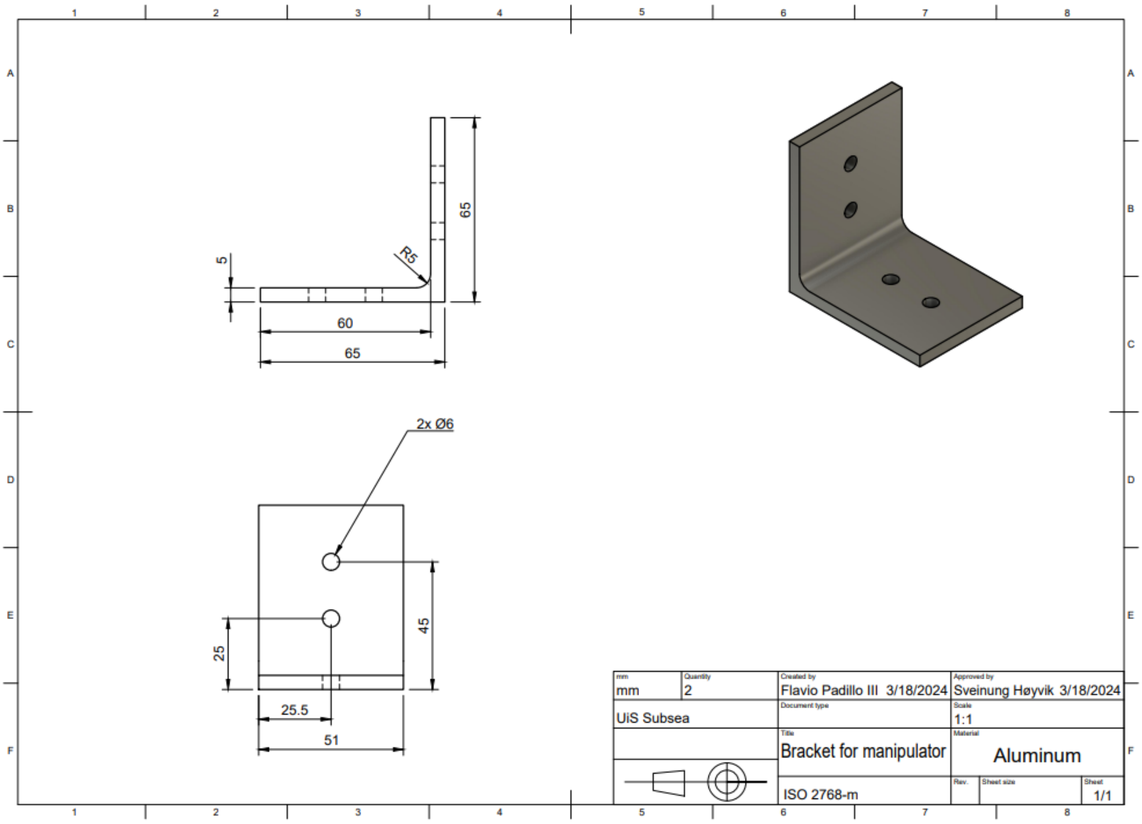


Figure A.12: Technical drawing of the bracket for manipulator 1:2

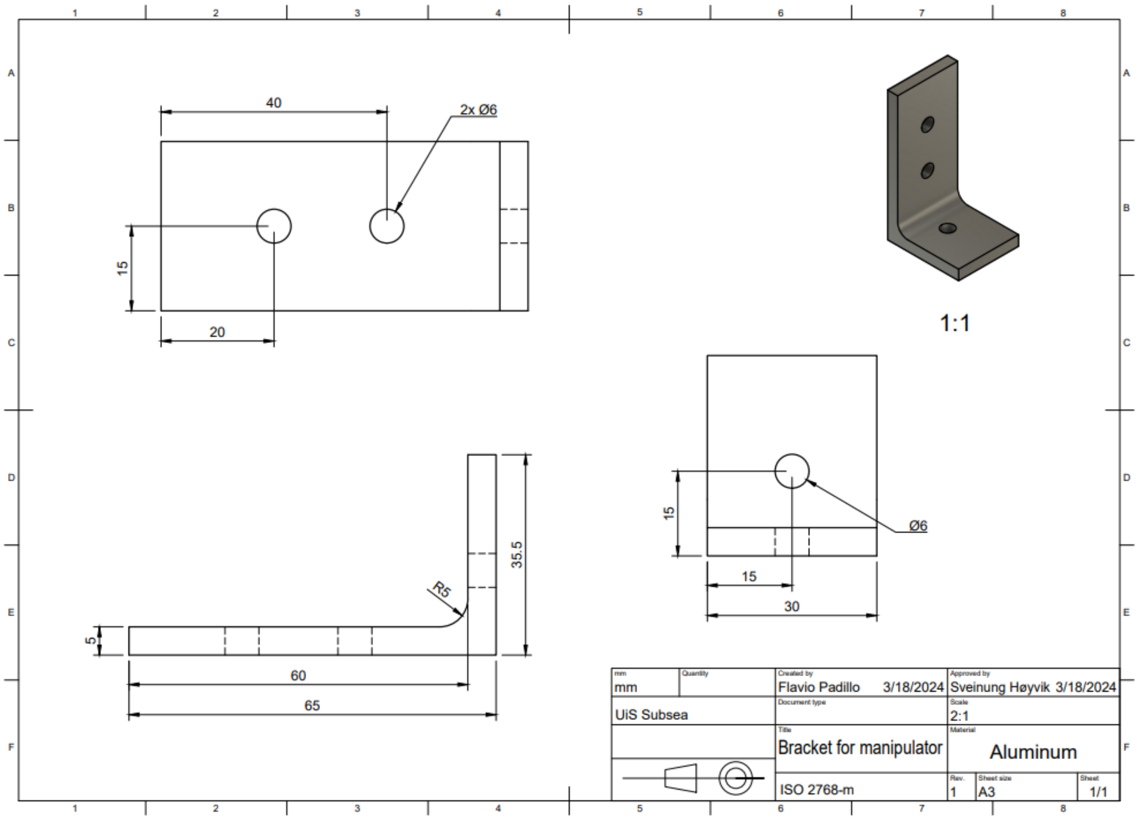


Figure A.13: Technical drawing of the bracket for manipulator 2:2

B Appendix: Technical Drawings Electronics Enclosure

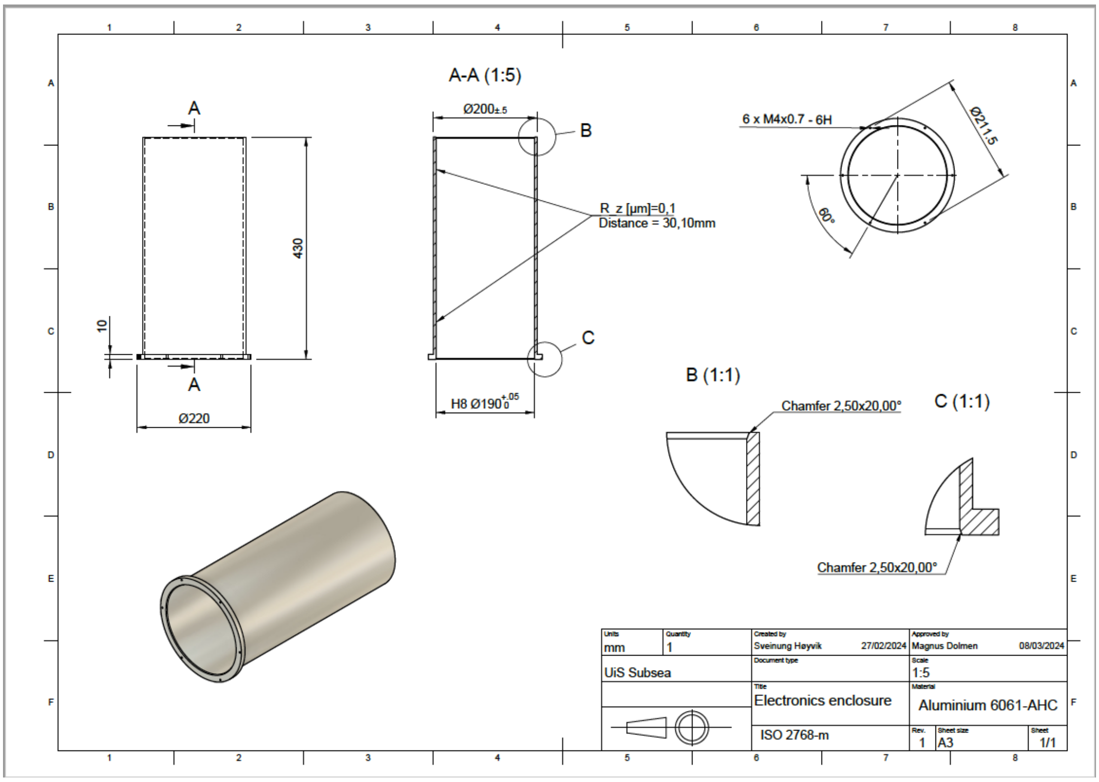
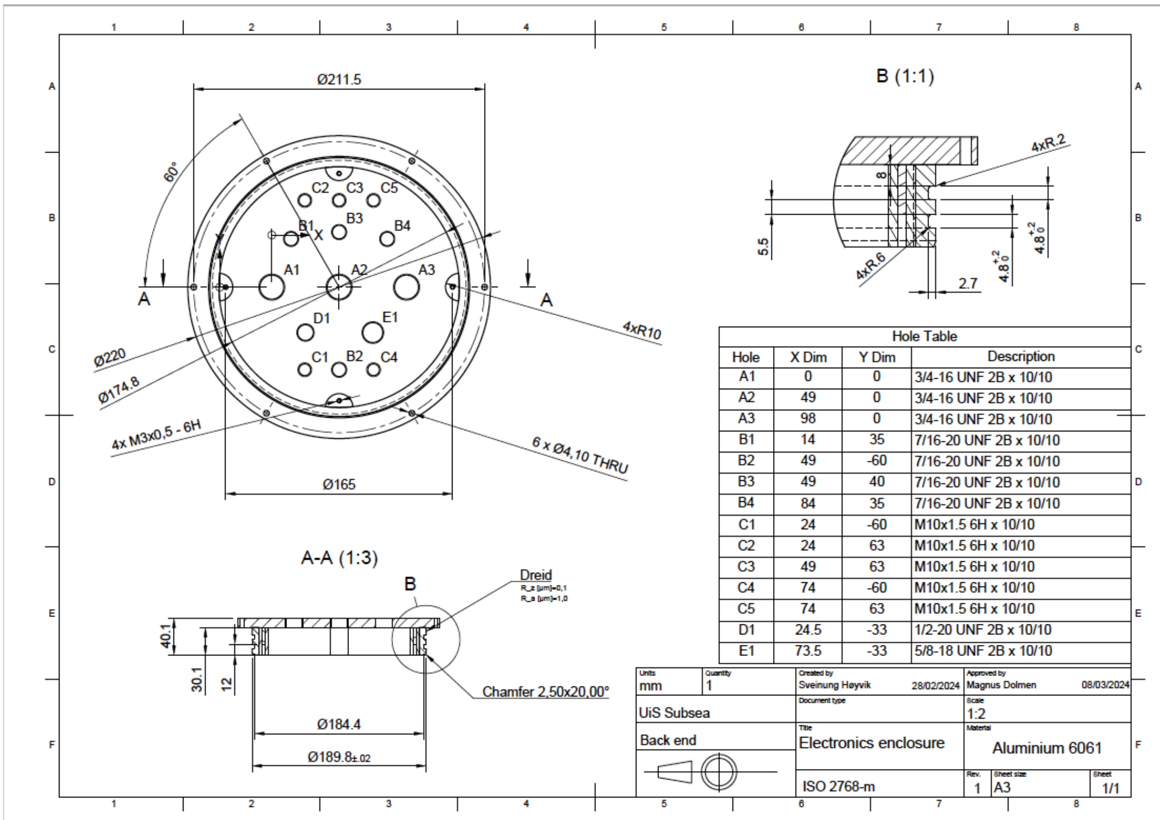


Figure B.1: Technical drawing of the electronics enclosure



Hole Table

Hole	X Dim	Y Dim	Description
A1	0	0	3/4-16 UNF 2B x 10/10
A2	49	0	3/4-16 UNF 2B x 10/10
A3	98	0	3/4-16 UNF 2B x 10/10
B1	14	35	7/16-20 UNF 2B x 10/10
B2	49	-60	7/16-20 UNF 2B x 10/10
B3	49	40	7/16-20 UNF 2B x 10/10
B4	84	35	7/16-20 UNF 2B x 10/10
C1	24	-60	M10x1.5 6H x 10/10
C2	24	63	M10x1.5 6H x 10/10
C3	49	63	M10x1.5 6H x 10/10
C4	74	-60	M10x1.5 6H x 10/10
C5	74	63	M10x1.5 6H x 10/10
D1	24.5	-33	1/2-20 UNF 2B x 10/10
E1	73.5	-33	5/8-18 UNF 2B x 10/10

Figure B.2: Technical drawing of the electronics enclosure's rear cap

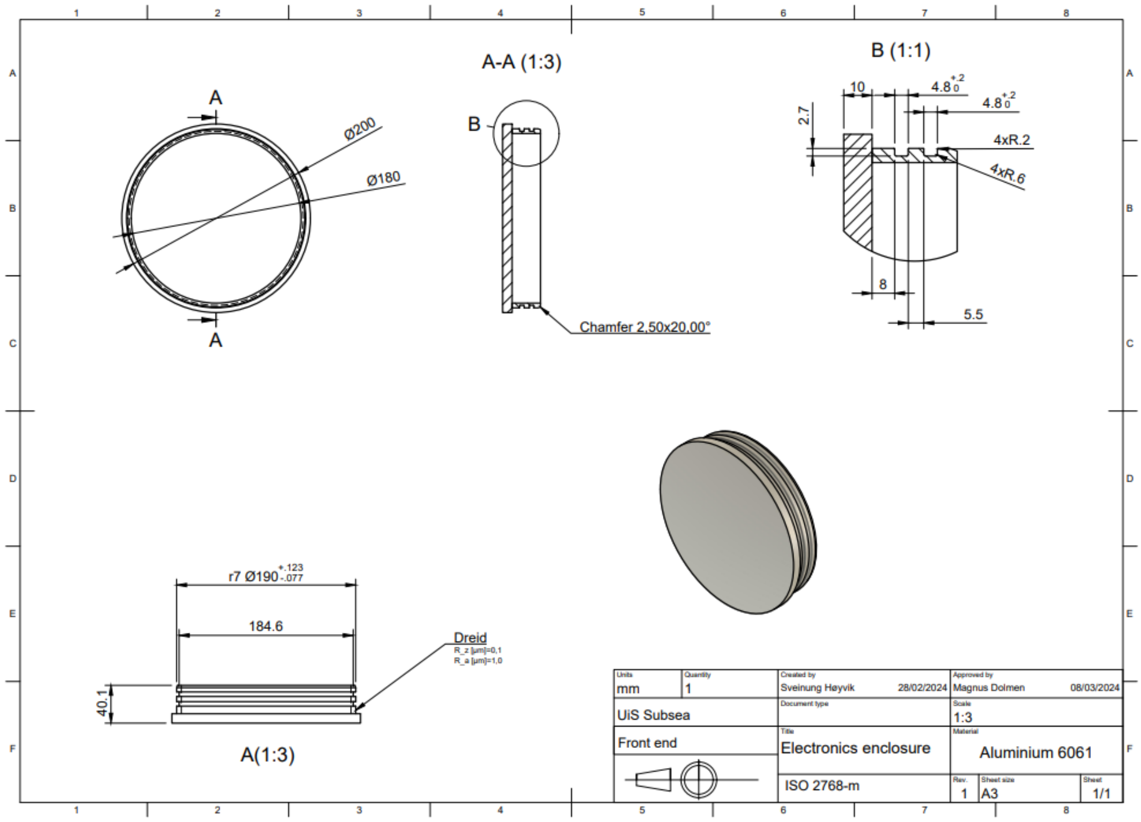


Figure B.3: Technical drawing of the electronics enclosure's front cap

C Appendix: Technical Drawings Battery Enclosure

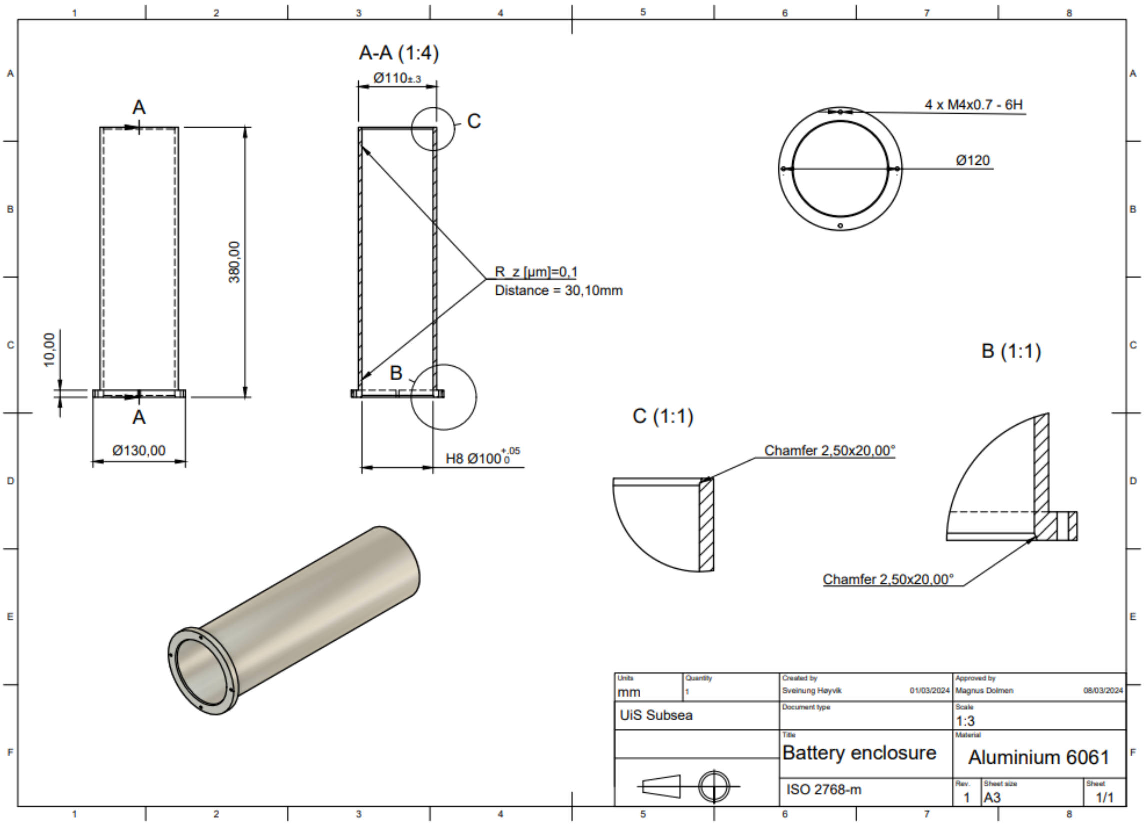


Figure C.1: Technical drawing of the battery enclosure

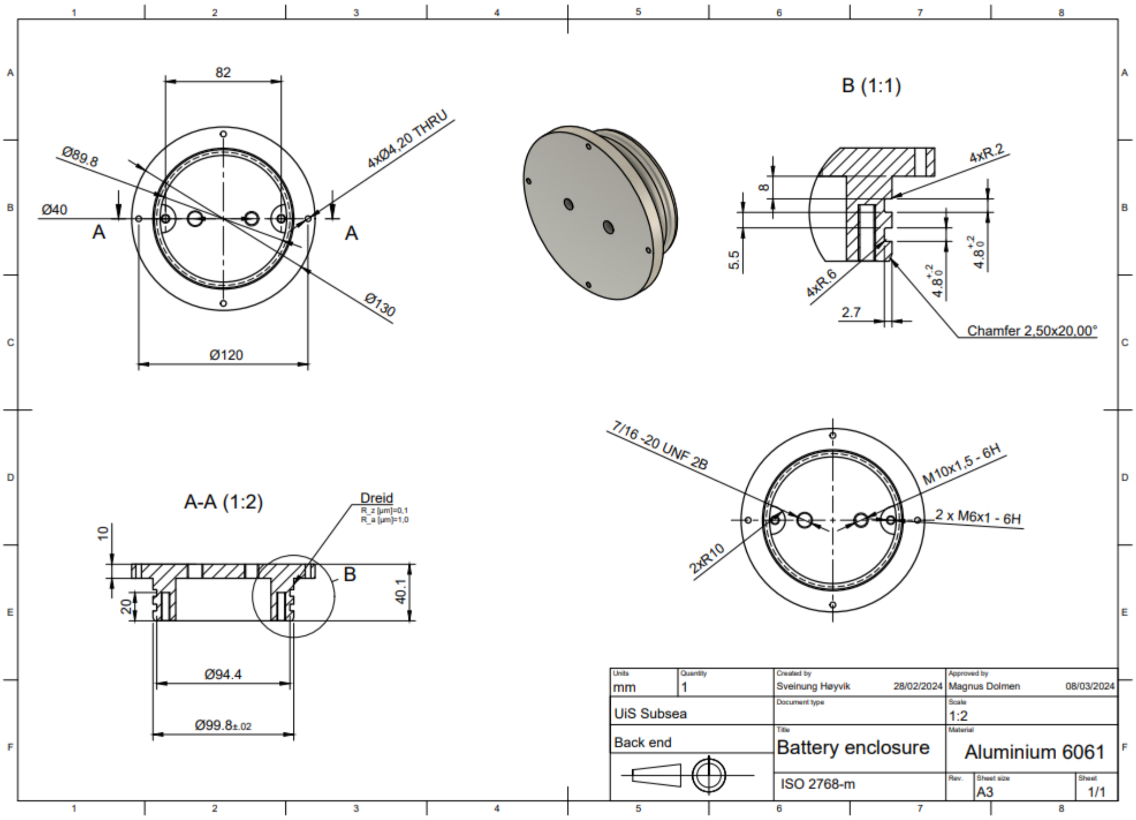


Figure C.2: Technical drawing of the battery enclosure's rear cap

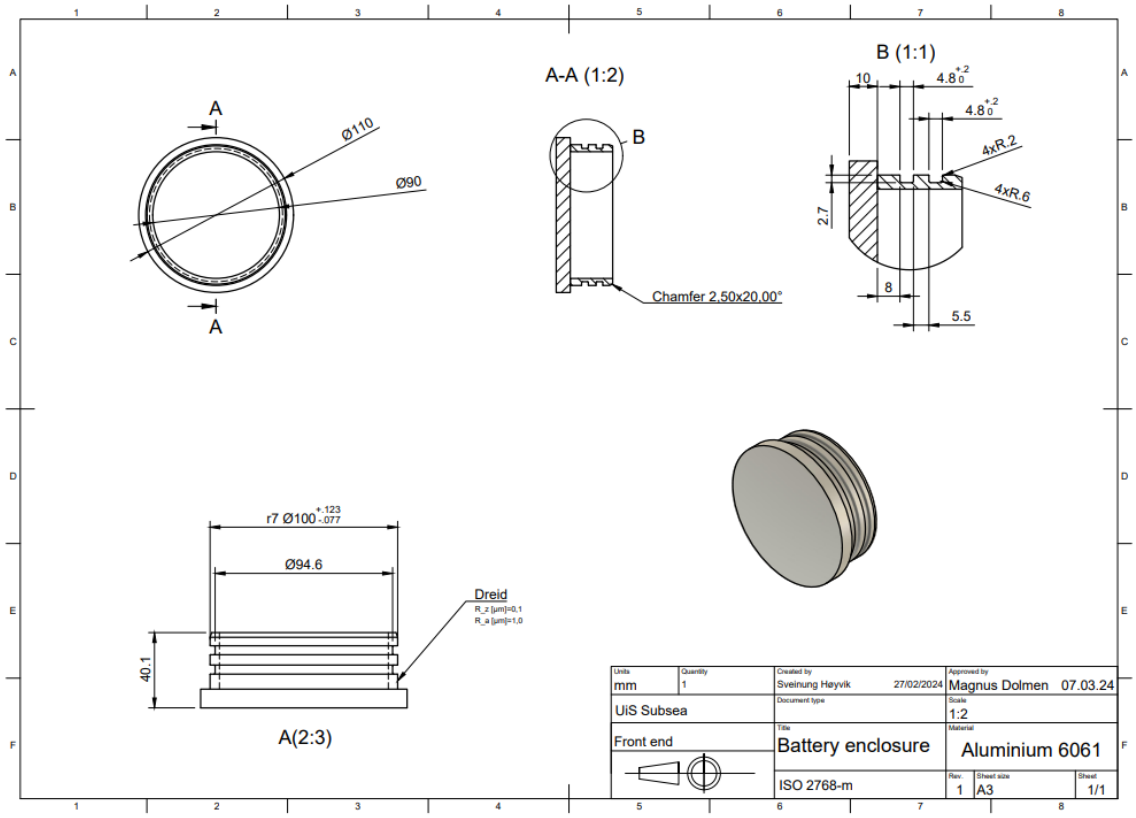
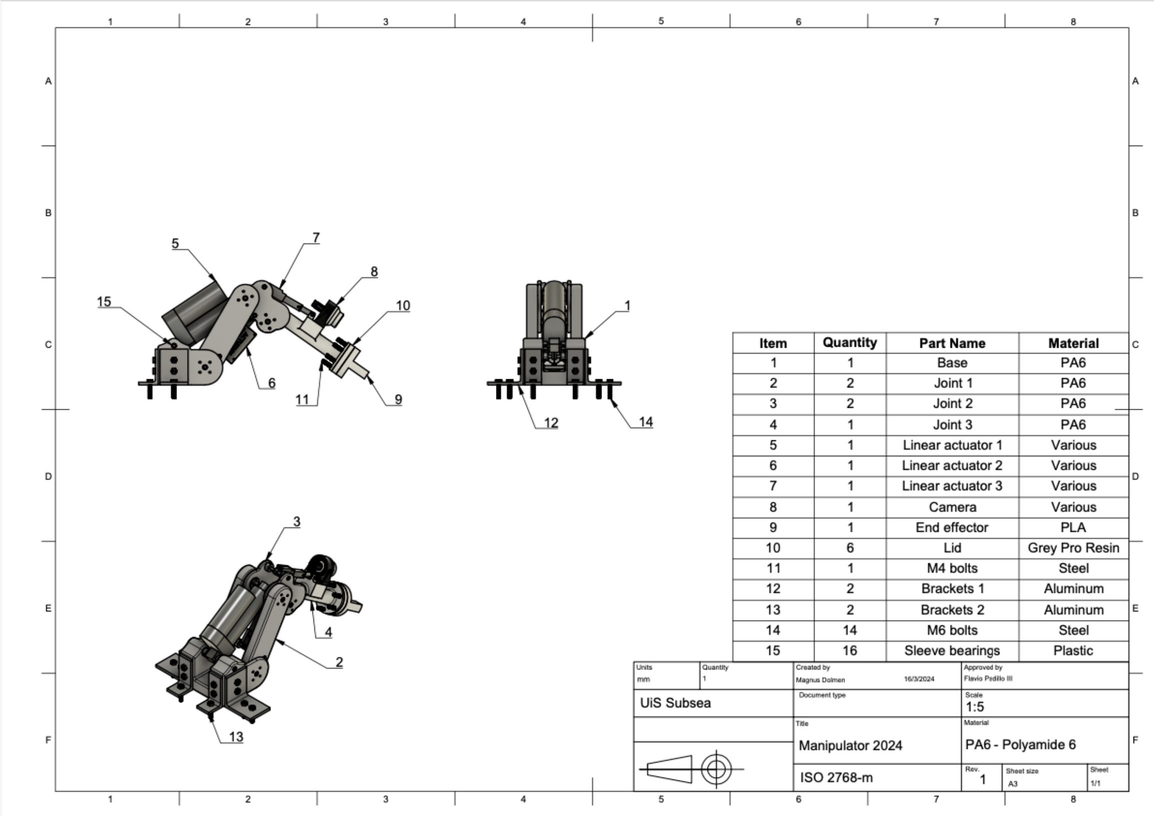


Figure C.3: Technical drawing of the battery enclosure's front cap

D Appendix: Technical Drawings Manipulator



Item	Quantity	Part Name	Material
1	1	Base	PA6
2	2	Joint 1	PA6
3	2	Joint 2	PA6
4	1	Joint 3	PA6
5	1	Linear actuator 1	Various
6	1	Linear actuator 2	Various
7	1	Linear actuator 3	Various
8	1	Camera	Various
9	1	End effector	PLA
10	6	Lid	Grey Pro Resin
11	1	M4 bolts	Steel
12	2	Brackets 1	Aluminum
13	2	Brackets 2	Aluminum
14	14	M6 bolts	Steel
15	16	Sleeve bearings	Plastic

Figure D.1: Technical drawing of the assembled manipulator

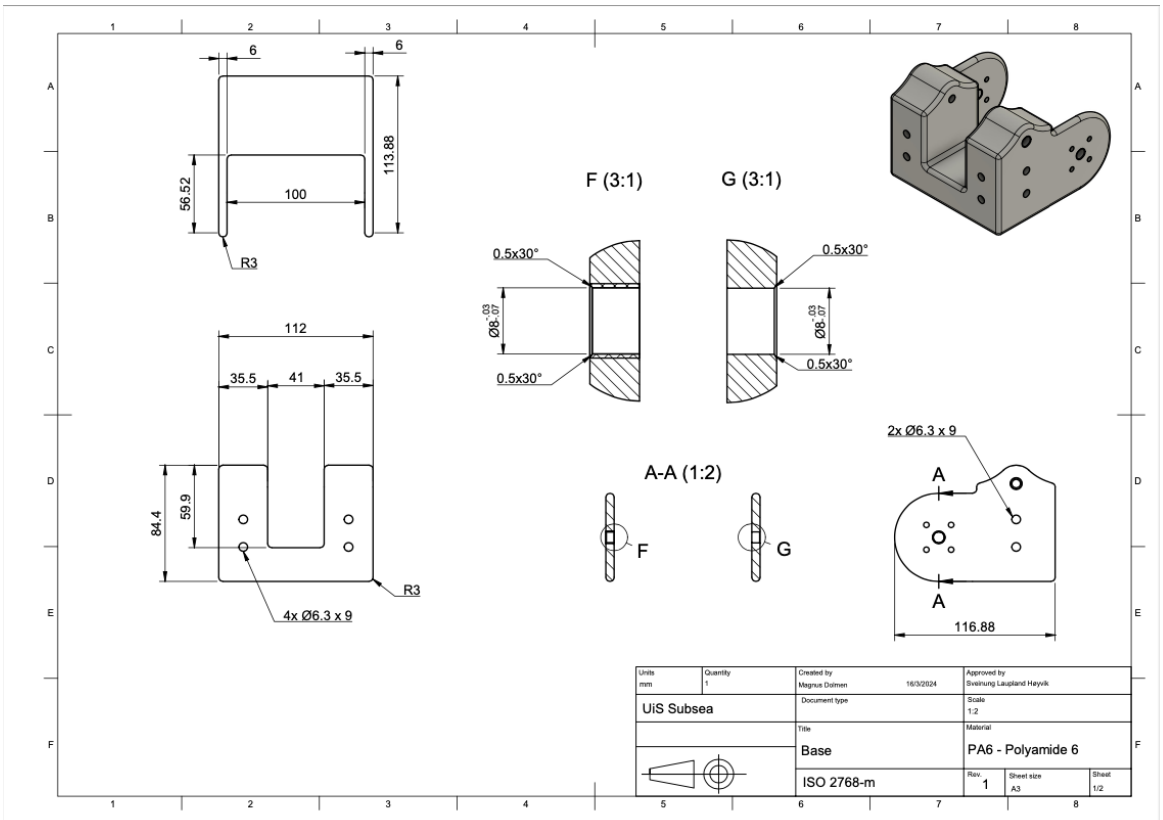


Figure D.2: Technical drawing of the manipulator base

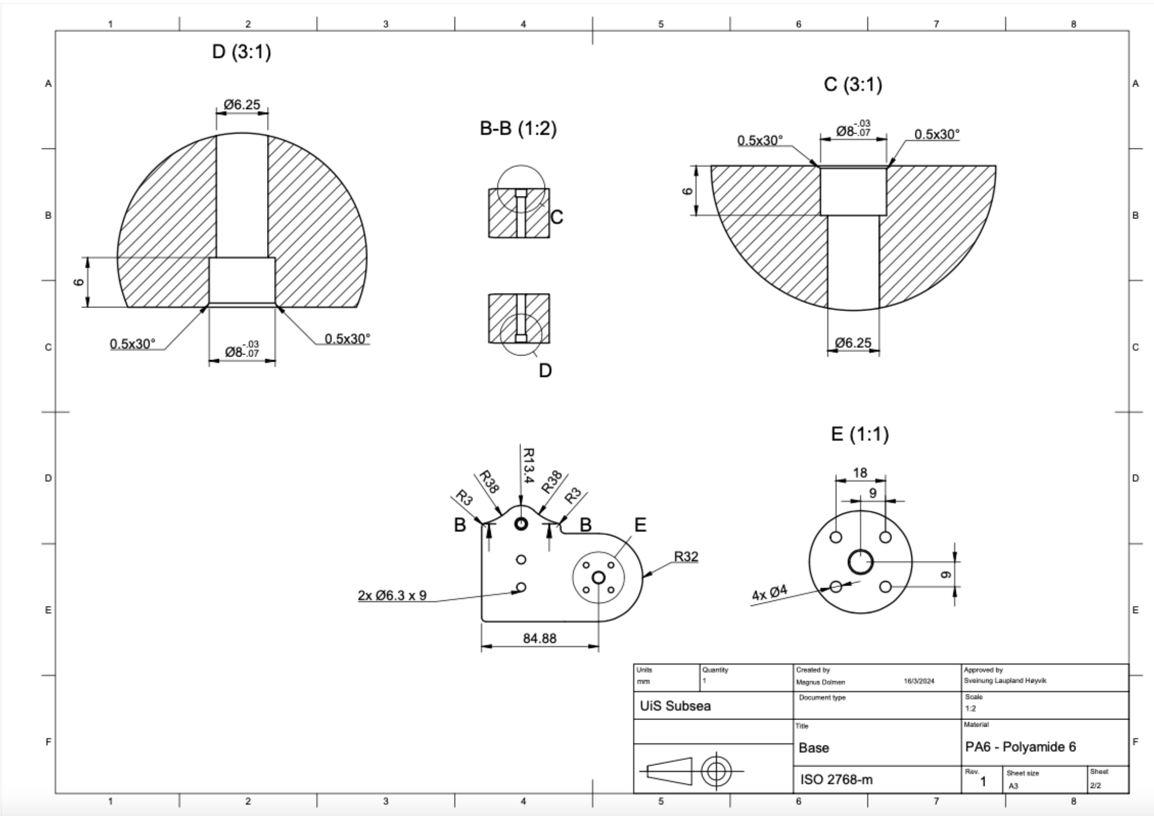


Figure D.3: Technical drawing of the manipulator base holes

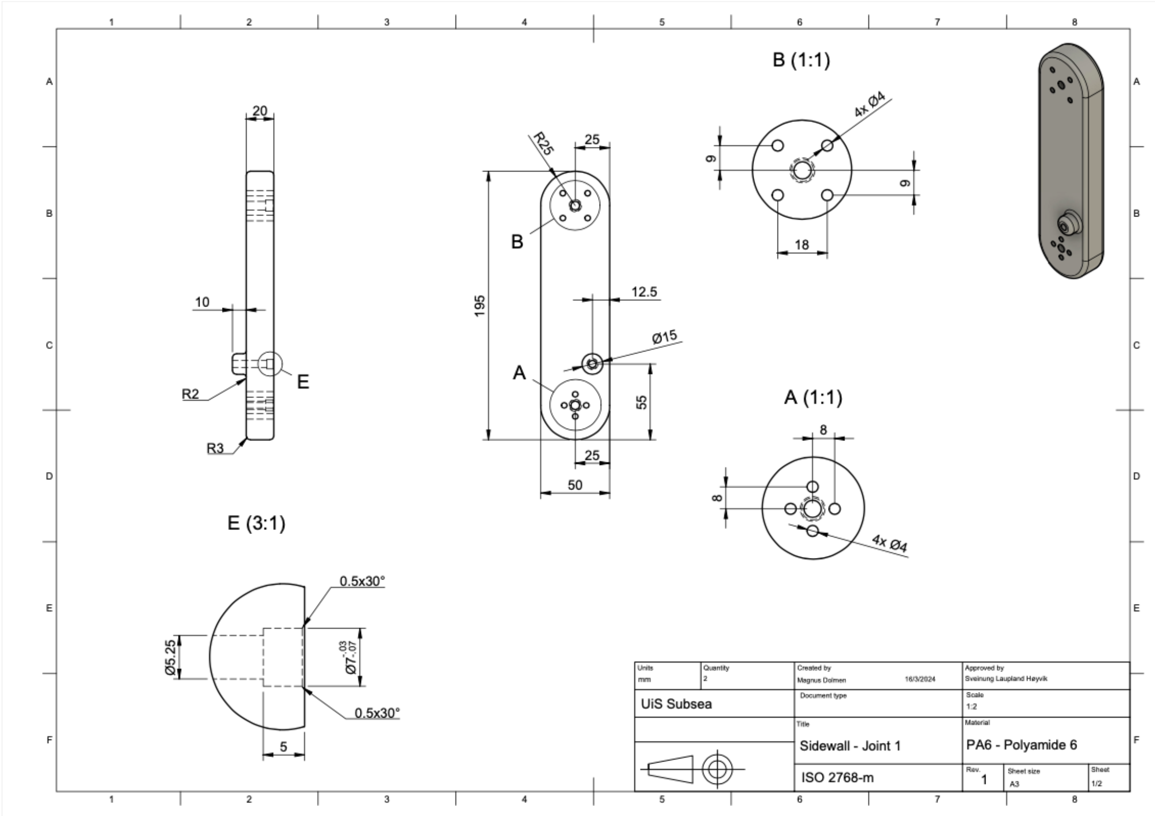


Figure D.4: Technical drawing of the manupulator 1. joint

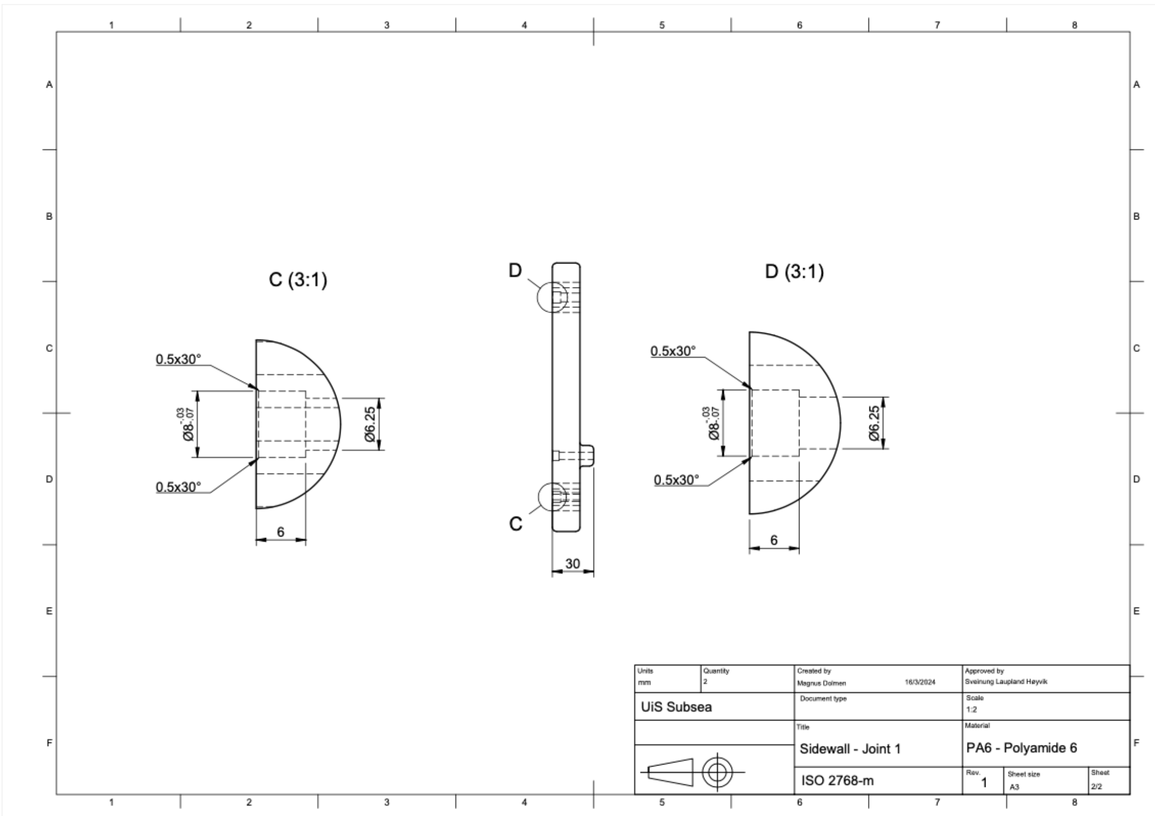


Figure D.5: Technical drawing of the manupulator 1. joint holes

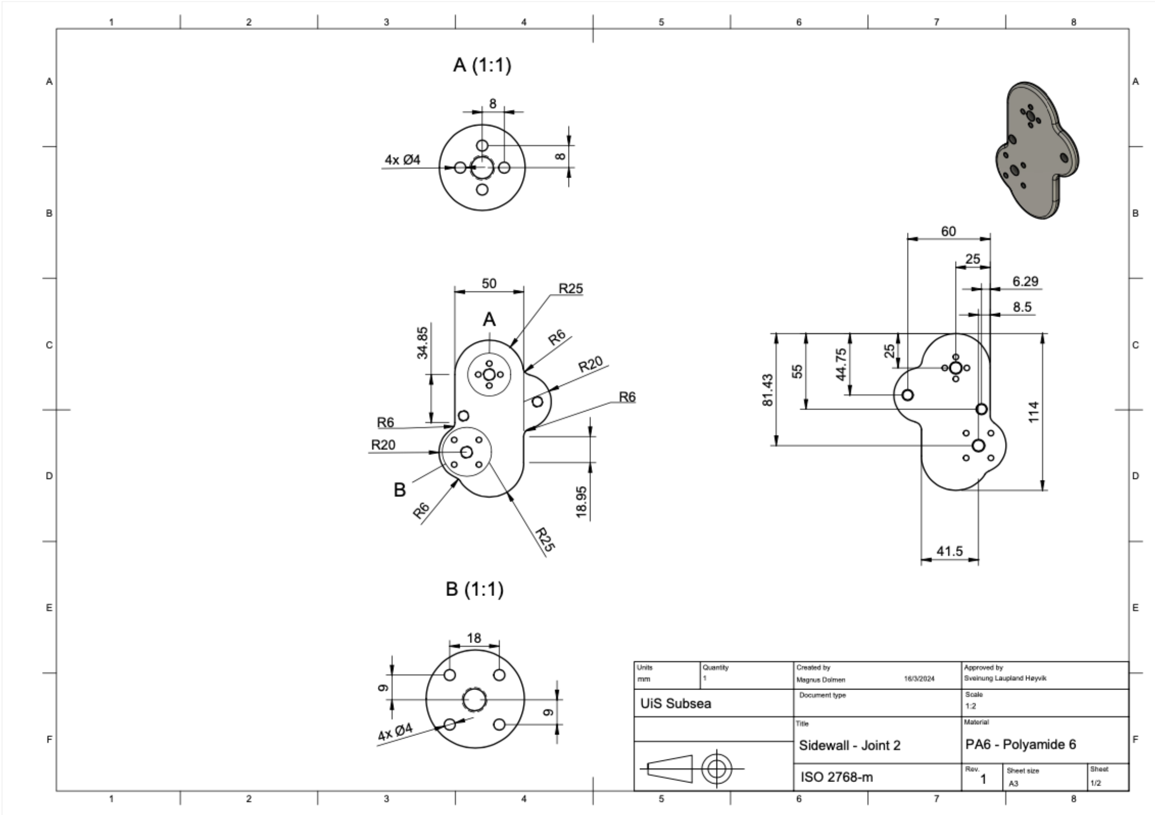


Figure D.6: Technical drawing of the manupulator 2. joint

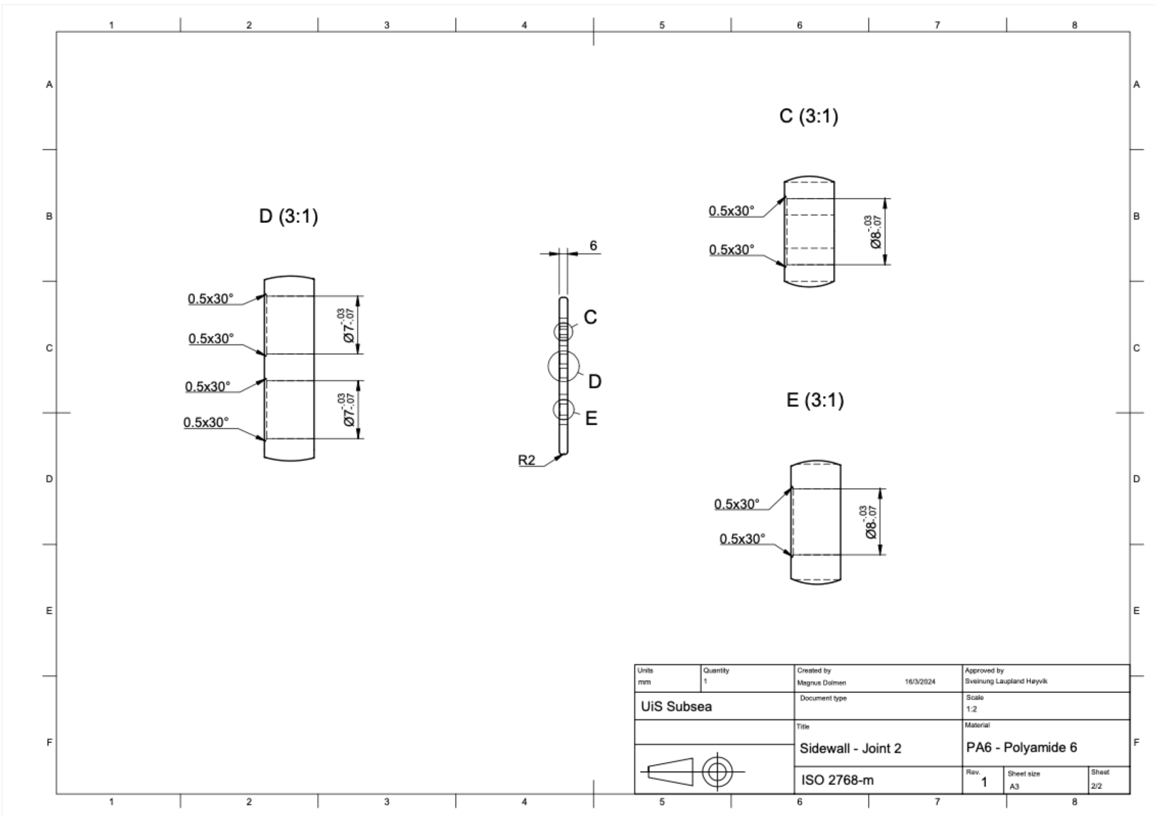
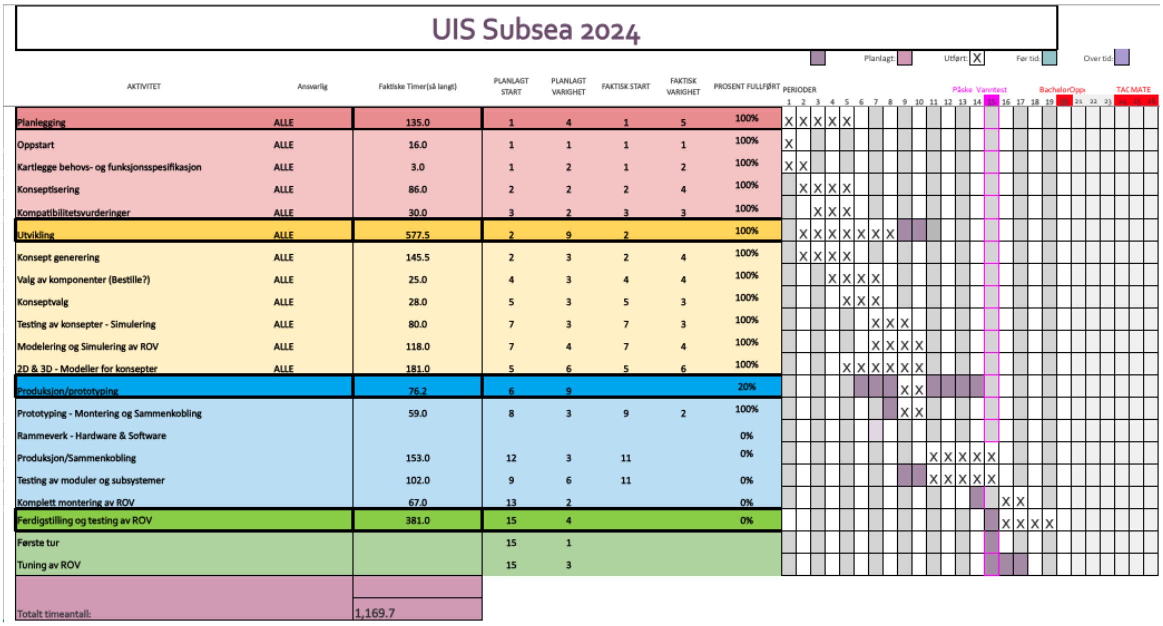


Figure D.7: Technical drawing of the manupulator 2. joint holes

E Appendix: Individual GANTT Chart



AKTIVITET	Ansvarlig	Faktiske Timer(så langt)	PLANLAGT START	PLANLAGT VARIGHET	FAKTISK START	FAKTISK VARIGHET	PROSENT FULLFØRT
Planlegging	ALLE	135.0	1	4	1	5	100%
Oppstart	ALLE	16.0	1	1	1	1	100%
Kartlegge behovs- og funksjonsspesifikasjon	ALLE	3.0	1	2	1	2	100%
Konseptisering	ALLE	86.0	2	2	2	4	100%
Kompatibilitetsvurderinger	ALLE	30.0	3	2	3	3	100%
Utvikling	ALLE	577.5	2	9	2		100%
Konsept generering	ALLE	145.5	2	3	2	4	100%
Valg av komponenter (Bestille?)	ALLE	25.0	4	3	4	4	100%
Konseptvalg	ALLE	28.0	5	3	5	3	100%
Testing av konsepter - Simulering	ALLE	80.0	7	3	7	3	100%
Modelering og Simulering av ROV	ALLE	118.0	7	4	7	4	100%
2D & 3D - Modeller for konsepter	ALLE	181.0	5	6	5	6	100%
Produksjon/prototyping		76.2	6	9			20%
Prototyping - Montering og Sammenkobling		59.0	8	3	9	2	100%
Rammeverk - Hardware & Software							0%
Produksjon/Sammenkobling		153.0	12	3	11		0%
Testing av moduler og subsystemer		102.0	9	6	11		0%
Komplett montering av ROV		67.0	13	2			0%
Ferdigstilling og testing av ROV		381.0	15	4			0%
Første tur			15	1			
Tuning av ROV			15	3			
Totalt timeantall:		1,169.7					

Figure E.1: Technical drawing of the assembled manipulator