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PRACA DYPLOMOWA INŻYNIERSKA

Opracowanie projektu i prototypu pojazdu podwodnego do celów badawczo-poszukiwawczych.

Development of the design and prototype of an underwater vehicle for research and exploration purposes.

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1. ABSTRACT

This engineering thesis presents a comprehensive development of a submersible vehicle for research and exploration purposes, focusing on both mechanical and electronic solutions.

The main objective of this thesis is to create an initial concept and design of a functional prototype of the underwater vehicle. Due to time constraints and budget limitations, creating a fully functional prototype within the designated timeframe proved unfeasible. Nevertheless, this concept is currently in an advanced stage and will be utilized in the near future to develop the first physical prototype.

The mechanical part involves designing and creating a prototype capable of withstanding operational depths, ensuring structural integrity, and enabling precise control and maneuverability.

Key mechanical innovations include the incorporation of a dry hull (pressure hull) housing critical electronic components, such as the Raspberry Pi, ESP32, water pump, batteries, electric motor, and servomotors, ensuring watertight integrity. The wet hull, dedicated to structural support and steering capabilities, remains continuously filled with water to maintain overall buoyancy. The pressure hull, a critical component, employs precision machining and specially designed seals to counteract high pressures, facilitating rotational and linear movements, and enabling the transfer of power from the motor to the propeller. The propulsion system is further optimized with the inclusion of a diffuser, enhancing hydrodynamic efficiency, reducing turbulent flow, and minimizing drag for improved energy consumption.

The electronic framework includes a power distribution system, data collection infrastructure, communication network, and collaborative efforts between the ESP32 and Raspberry Pi controllers.

The ESP32 serves as the central controller, efficiently managing mechanical components and interfacing with a variety of internal and external sensors. External sensors, including pressure, temperature, conductivity, and O2 sensors, provide real-time environmental data, while internal sensors focus on structural integrity and health monitoring. A sophisticated leakage sensor, positioned strategically, enhances safety by detecting and alerting to water penetration which promptly resurfaces the submarine before any further damage occurs.

The Raspberry Pi complements the ESP32 with advanced sensors such as cameras and sonar, contributing to data analysis and establishing real-time communication with the surface. Both controllers work collaboratively, with the ESP32 handling execution functionalities and the Raspberry Pi utilizing its processing power for data analysis and decision-making.

A Battery Management System (BMS) ensures optimal battery performance, preventing overcharging and over-discharging.

Overall, this submersible vehicle's electronic architecture reflects a sophisticated, collaborative, and adaptable system, poised to contribute to the evolving field of underwater exploration and research. The system's modularity allows for the incorporation of many more biological and scientific sensors to enhance exploration capabilities.

2. INTRODUCTION

In the ever-evolving landscape of marine exploration and research, Autonomous Underwater Vehicles (AUVs) have emerged as revolutionary tools, pushing the boundaries of underwater knowledge and technological capabilities. AUVs, designed to operate autonomously without direct human intervention, have become indispensable assets in scientific research, defense applications, and commercial ventures.

The purpose of this introduction is to delve into the current state of advancement in AUV technology, and its place in marine exploration, and address the position of this thesis within this framework.

Kongsberg [1], a global leader in maritime technology and solutions, has significantly contributed to the AUV landscape with its cutting-edge Hugin series. Renowned for their precision, versatility, and reliability, Hugin AUVs have played a pivotal role in advancing our understanding of the underwater world. These vehicles are equipped with sophisticated sensors, navigation systems, and communication tools, allowing them to execute complex missions with a high degree of autonomy.

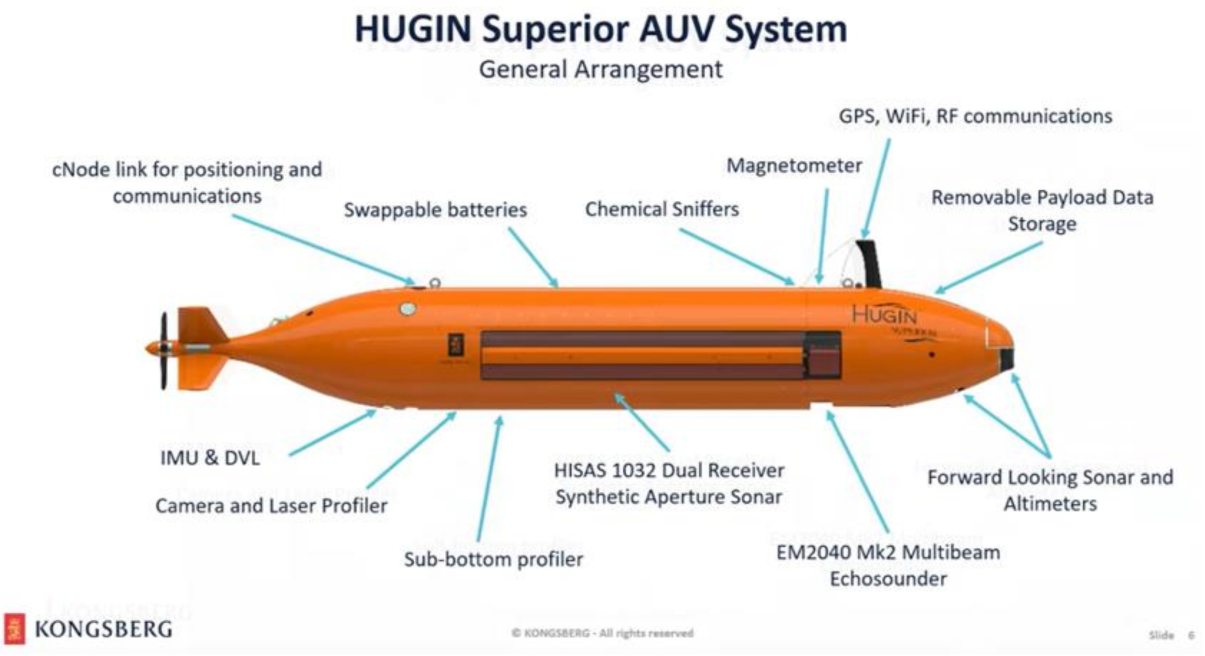


Figure 2.1 Kongsberg's Hugin Endurance - leading AUV in the marine industry. [1].

AUVs serve a myriad of purposes, including marine biology research, environmental monitoring, and defense applications. Their ability to navigate challenging underwater environments autonomously allows for efficient data collection, enhancing maritime security by performing tasks such as mine detection, underwater surveillance, and infrastructure inspection, reducing the risks associated with human divers in hazardous conditions.

Bathymetry, the measurement of underwater depth and topography, stands as one of the primary applications of AUVs. The Hugin models, for instance, are equipped with advanced sonar and LIDAR systems capable of mapping the seafloor with unprecedented detail. This capability is instrumental in charting unexplored regions, studying geological features, and identifying potential hazards. The precision and efficiency of Hugin AUVs in bathymetric surveys have made them invaluable tools for scientific research institutions, environmental monitoring agencies, and industries involved in offshore activities.

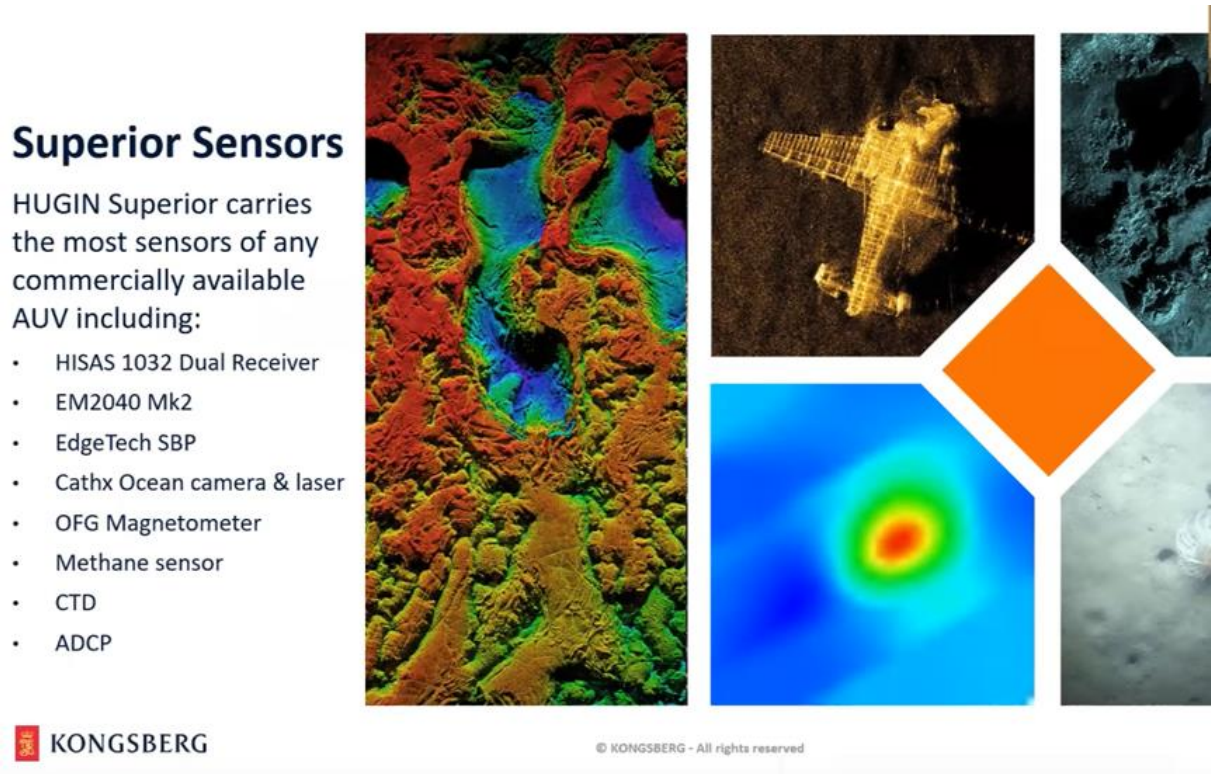


Figure 2.2 Kongsberg's Hugin Superior AUV - onboard sensors and ocean-mapping capabilities. [1]

In the dynamic field of autonomous underwater vehicles, Kongsberg faces competition from a cadre of innovative companies that have collectively propelled the industry forward. Notable rivals such as Bluefin Robotics, Teledyne Gavia, and Saab Seaeye have significantly contributed to the diversification and advancement of AUV technology in the past decade. Each of these companies brings its unique expertise and technological prowess to the table.

Bluefin Robotics [2], a subsidiary of General Dynamics Mission Systems, has established itself as a prominent player in the AUV arena. Renowned for its Bluefin-9 and Bluefin-21 models, the company has focused on modularity and adaptability, allowing for efficient customization to meet specific mission requirements. Their Bluefin®-21 has a gimbaled, ducted thruster for propulsion and control.

Their propulsion system (shown on the Figure 2.3) is completely different than the one of Kongsberg's Hugin which incorporates two propellers turning in opposite directions and uses X-type rudder system (Figure 4.16) for enhanced control and maneuverability (more about this later in 4.4. Rudder System section).

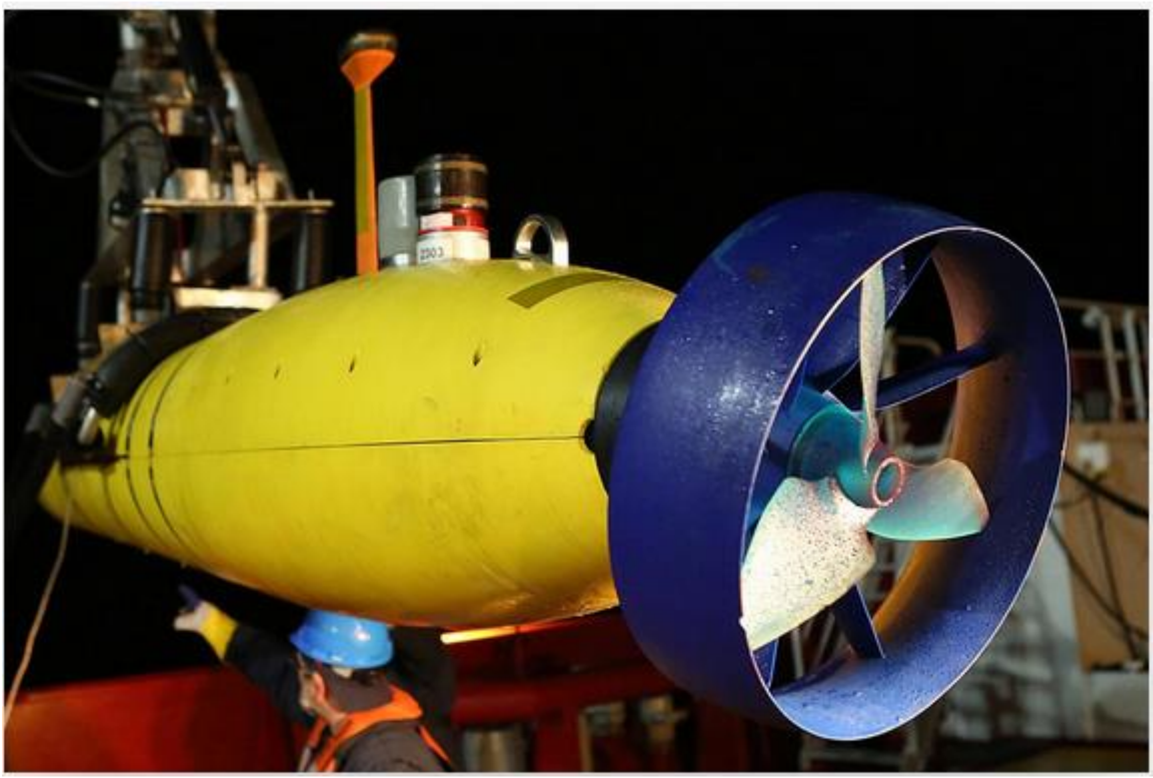


Figure 2.3 General Dynamics Bluefin-21 Unmanned Underwater Vehicle (UUV)[2]

Teledyne Gavia [3], part of the Teledyne Marine Group, has made significant strides in the mini AUV segment. Their Gavia AUVs are known for their compact design and versatility, making them suitable for a wide range of applications, from hydrography and environmental monitoring to mine countermeasures. Teledyne Gavia's AUVs are known for their modularity to make reconfigurations easy.

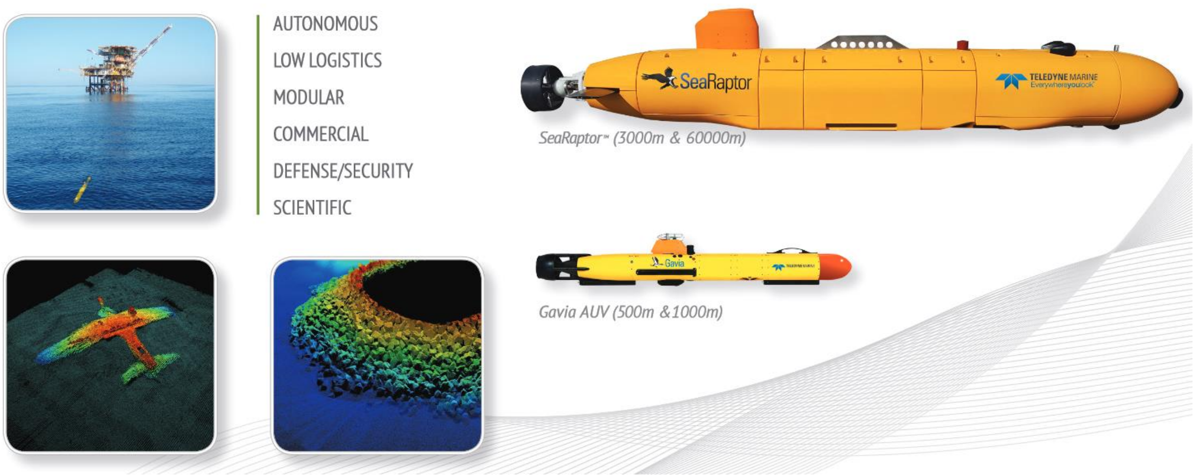


Figure 2.4 Teledyne Autonomous Underwater Vehicle offer – Gavia and SeaRaptor.[3]

This thesis is focused on the development of a new type of AUV. This type will be much smaller than huge marine underwater vehicles currently used in the marine industry. Its main purpose will be to offer incredible flexibility and compatibility while ensuring a broad range of applications.

Mission: The goal of this project is to introduce a new type of underwater vehicle that transcends the limitations of conventional AUVs. By focusing on the development of smaller, highly flexible AUVs, the project aims to establish these AUVs as indispensable tools across diverse sectors, from maritime safety to scientific research. All this combines mechanical solutions with electronics and advanced computer algorithms.

Technical Overview: The proposed AUVs are characterized by their compact size, ensuring agility and adaptability in various underwater environments. Engineered to function collaboratively in groups, they leverage collective intelligence to perform intricate tasks with remarkable efficiency. The integration of advanced sensors and communication systems empowers these AUVs to swiftly locate and pinpoint the positions of individuals in distress, offering a revolutionary solution to emergency response scenarios.

Safety Applications: One of the primary applications of our innovative AUVs lies in enhancing safety measures on ships and near bodies of water, where drowning incidents pose significant risks. Traditional methods of rescue operations involving professional scuba divers can be time-consuming and limited in certain conditions. The proposed AUV design eliminates these constraints, providing a rapid and reliable means of locating victims and assisting first-response teams during rescue operations.

Search and Rescue Capabilities: The compact size of our AUVs makes them ideally suited for search and rescue missions in challenging environments, such as caves and shipwrecks. Their maneuverability and adaptability enable efficient exploration of confined spaces, offering unprecedented access to areas that were previously difficult or impossible to reach.

Scientific Exploration: Beyond safety applications, our AUVs open new frontiers in scientific exploration. Equipped with advanced scientific instruments, these vehicles enable scientists to conduct research in remote and inaccessible locations. This new concept of small underwater vehicles provides a cost-effective and versatile solution for scientific missions, overcoming the limitations of larger AUVs that require transportation by ships.

3. OBJECTIVES AND SCOPE OF THE THESIS

Given the intricate nature of this project, the author of this thesis anticipated encountering numerous engineering challenges and obstacles during various stages of development. Thus, it was imperative to establish clear objectives.

The main objective of this engineering thesis is to develop a “**Submersible Vehicle for Research and Exploration Purposes**" as stated in the topic.
After developing an initial concept, a prototype should be built to stress-test the entire system which will not be in the scope of this thesis.

This prototype will be designed to withstand the pressures found at operational depths, maintain the vehicle's structural integrity, particularly in areas housing sensors, propulsion system, and control mechanisms, and enable precise control and maneuvering, including the implementation of steering and stabilizing systems. In addition, the thesis will focus on developing a concept of an electronic system to efficiently distribute power from the vehicle's batteries, collect both internal and external data (such as leak detection and temperature monitoring internally, and pressure and temperature measurement externally), and facilitate communication between the on-board computer and the user while transmitting data from various onboard sensors.

I organized my objectives into two distinct categories: mechanical and electronic, to enhance clarity.

- **Mechanical Solutions:**

→ Designing and creating a prototype of a submersible vehicle capable of withstanding the pressures encountered at the operational depths.
→ Ensuring the integrity and sealing of the entire vehicle, particularly in areas where sensors, as well as the main propulsion and control mechanisms, are located.
→ Enabling precise control and maneuverability, including the implementation of steering and stabilizing systems as well as ballast tanks system.

- **Electronic Solutions:**

→ Establishing a robust power distribution system from the vehicle's batteries to all its components.
→ Implementing data collection capabilities inside the vehicle (e.g., detecting leaks, monitoring internal temperature) and outside the vehicle (e.g., measuring pressure and temperature).
→ Enabling communication between the onboard computer, the user, and the transmission of sensor-derived data.

This thesis aims to address the fundamental engineering challenges associated with the development of a submersible vehicle for research and exploration, emphasizing both mechanical and electronic solutions to ensure the vehicle's structural integrity, operability, and data acquisition capabilities.

Celem pracy jest opracowanie projektu i prototypu pojazdu podwodnego do celów badawczo-poszukiwawczych:
W zakresie rozwiązań mechanicznych, które m.in.:
- zapewnią odporność/wytrzymałość na ciśnienie panujące na głębokościach w których operować będzie pojazd,
- zapewnią szczelność całego pojazdu, przede wszystkim w rejonach gdzie wyprowadzone będą czujniki, oraz napęd główny i sterujący pojazdem,
- zapewnią możliwość sterowania i wykonywania odpowiednich manewrów (ster, stabilizatory)

W zakresie rozwiązań elektronicznych:
- zapewnią dystrybucję energii z akumulatorów do wszystkich podzespołów,
- zapewnią możliwość gromadzenia danych wewnątrz pojazdu (wystąpienie przecieków, temperatura pracy wew. itp) jak i na zewnątrz (ciśnienie, temperatura itp)
- pozwolą na komunikację między głównym sterownikiem, a użytkownikiem oraz przesyłanie danych pomiarowych zbieranych za pomocą czujników.

Zadania do wykonania:
1. Opracowanie wymogów jakie musi spełniać pojazd, aby sprostać wymaganiom związanym z panującymi pod wodą warunkami,
2. Zdefiniowanie podstawowych problemów, które należy rozwiązać, aby pojazd spełniał postawione mu wymagania
3. Opracowanie modelu 3d pojazdu, który będzie mógł poruszać się pod wodą i spełniał postawione wymagania,
4. Opracowanie układu elektronicznego wraz z rozwiązaniem kwestii sterowania pojazdem,
5. Spisanie wniosków z przebiegu pracy, które posłużą w dalszych etapach pracy.

4. MECHANICAL PART

Following the development and assessment of various mechanical concepts to determine the most effective and efficient solution, the submersible vehicle below was created.

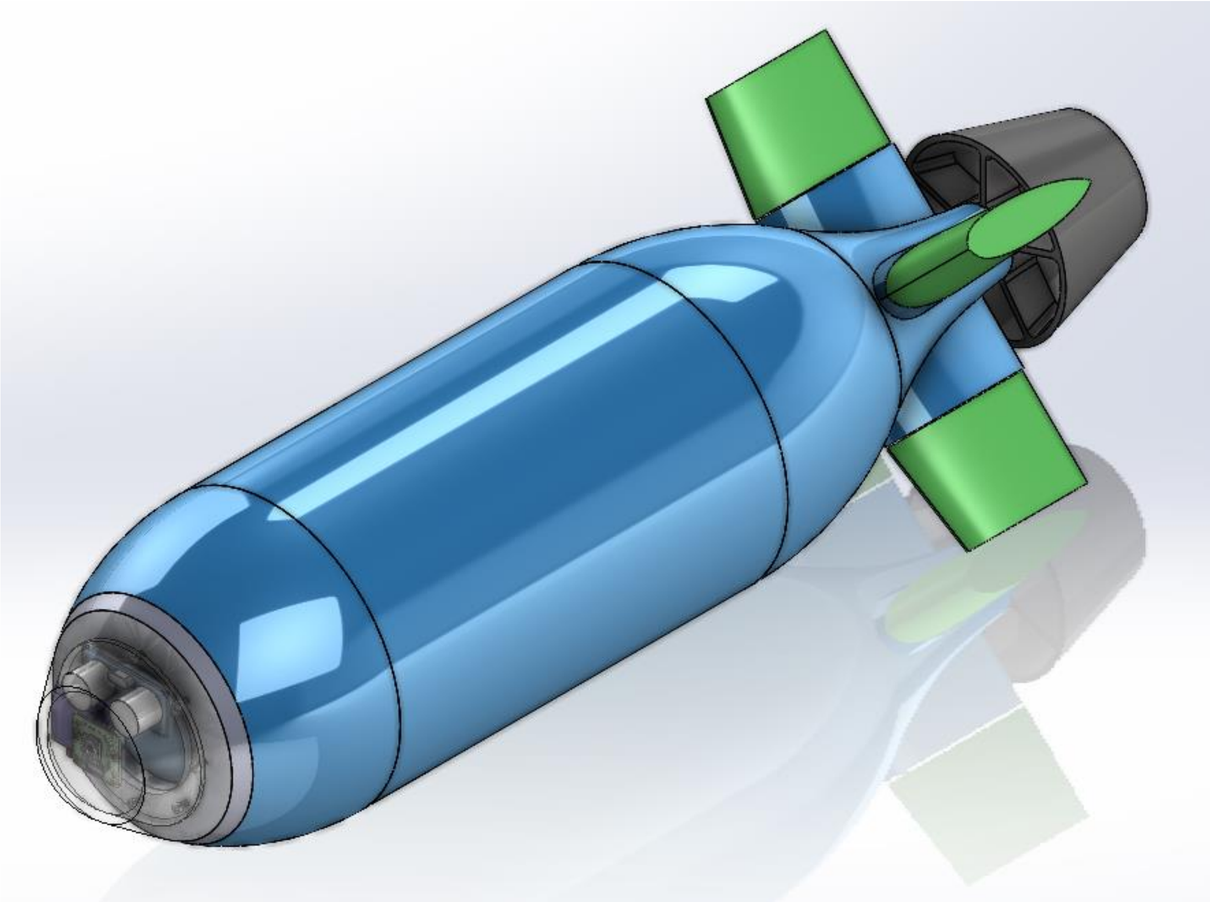


Figure 4.1. Isometric view of the "Underwater Vehicle for Research and Exploration Purposes"

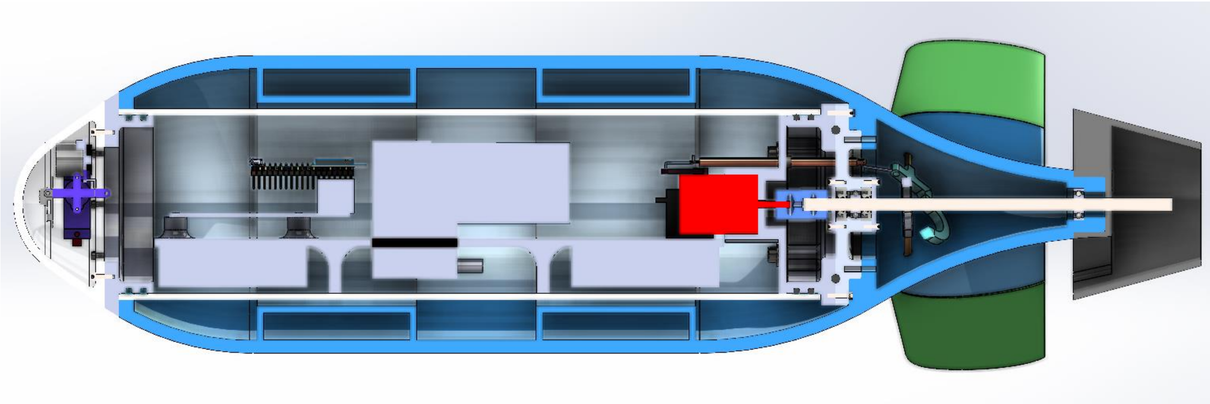


Figure 4.2. Section view of the entire submarine.

The submersible vehicle consists of two distinct hulls (see Figure 4.2): one designated as the dry hull, and the other as the wet hull, each serving unique purposes and possessing specific features.

4.1. WET HULL

The wet hull primarily serves a structural role, having hydrodynamic properties and enabling steering capabilities for the vessel. It remains continuously filled with water and supports the overall buoyancy of the vehicle.

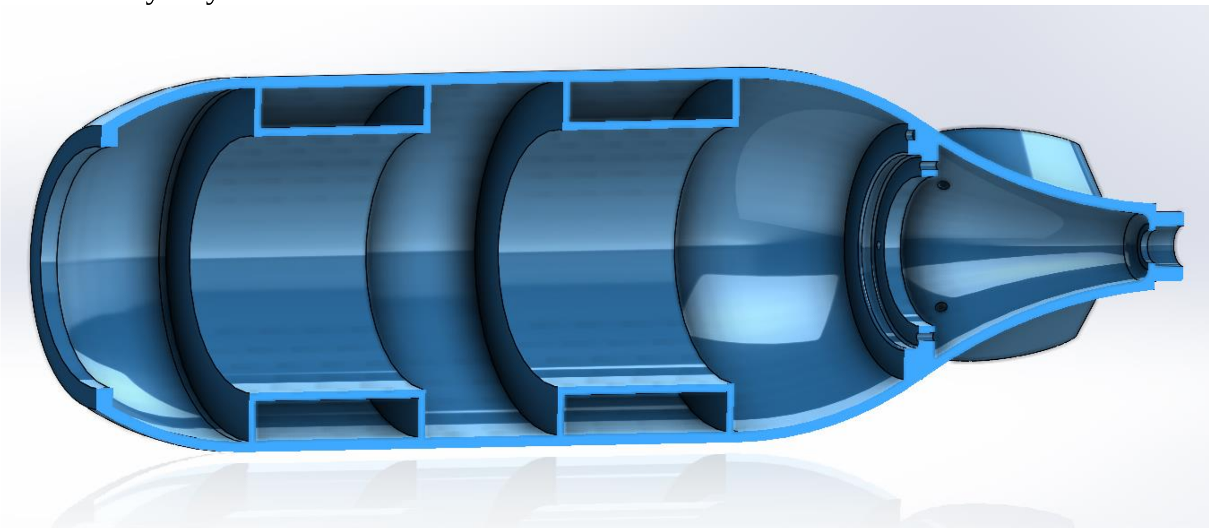


Figure 4.3. Wet Hull cross-sectional view.

Since the pressure inside the wet hull is the same as the outside pressure, this structure doesn't have to be very resistant since it is not exposed to enormous pressure at the operational depths.

4.2. PRESSURE HULL (DRY HULL)

It is the most important part of the vessel since it houses essential electronic components, including the Raspberry Pi, ESP32, water pump, batteries, electric motor, and servo motors. This compartment remains watertight and functions as a protective enclosure for sensitive electronics.
It is the most vital part of the submersible, ensuring complete watertight integrity and resistance to high pressures, thus in this section, I will describe different components and mechanisms that ensure water tightness and resistance to high pressure, while allowing rotational movements (main power shaft), linear movements (servomotors and linkages) as well as the connection between on-board computer and different sensors located on the outside of the hull.
The pressure hull consists of an acrylic tube that is hermetically sealed with tightly fitted flanges and end caps (see Figure 4.4).

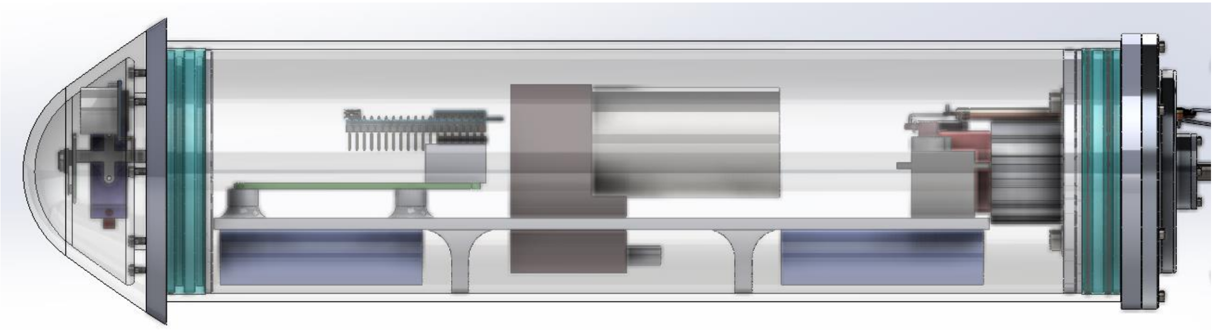


Figure 4.4. Pressure Hull left side view.

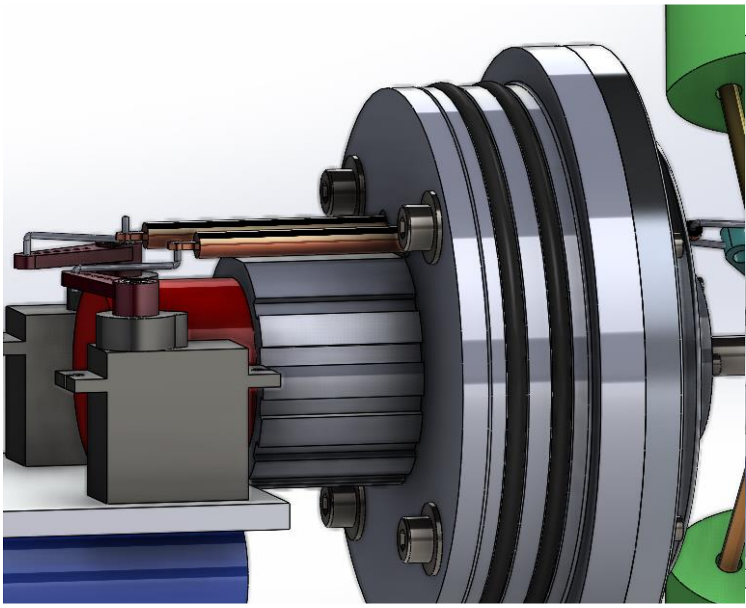
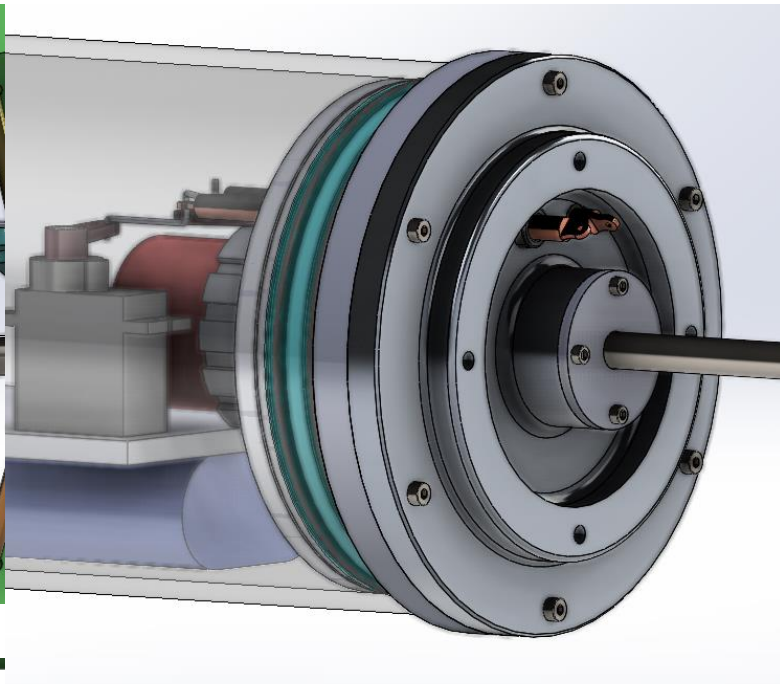


Figure 4.5 O-rings places in grooves of the flange



To prevent any leakage between the flange and the wall of the acrylic tube a static sealing solution was applied. It is done by using two o-rings tightly positioned in special grooves on the circumference of the flange (Figure 4.5). There is also one o-ring between the front face of the end cap and the flange that is squeezed using screws connecting these two parts (see Figure 4.6 Section view of the sealing solution).
I decided to precision-machine the end parts of the acrylic tube (the walls around the circumference) to ensure a perfect fit for the seals and to achieve a smooth surface with minimal roughness.

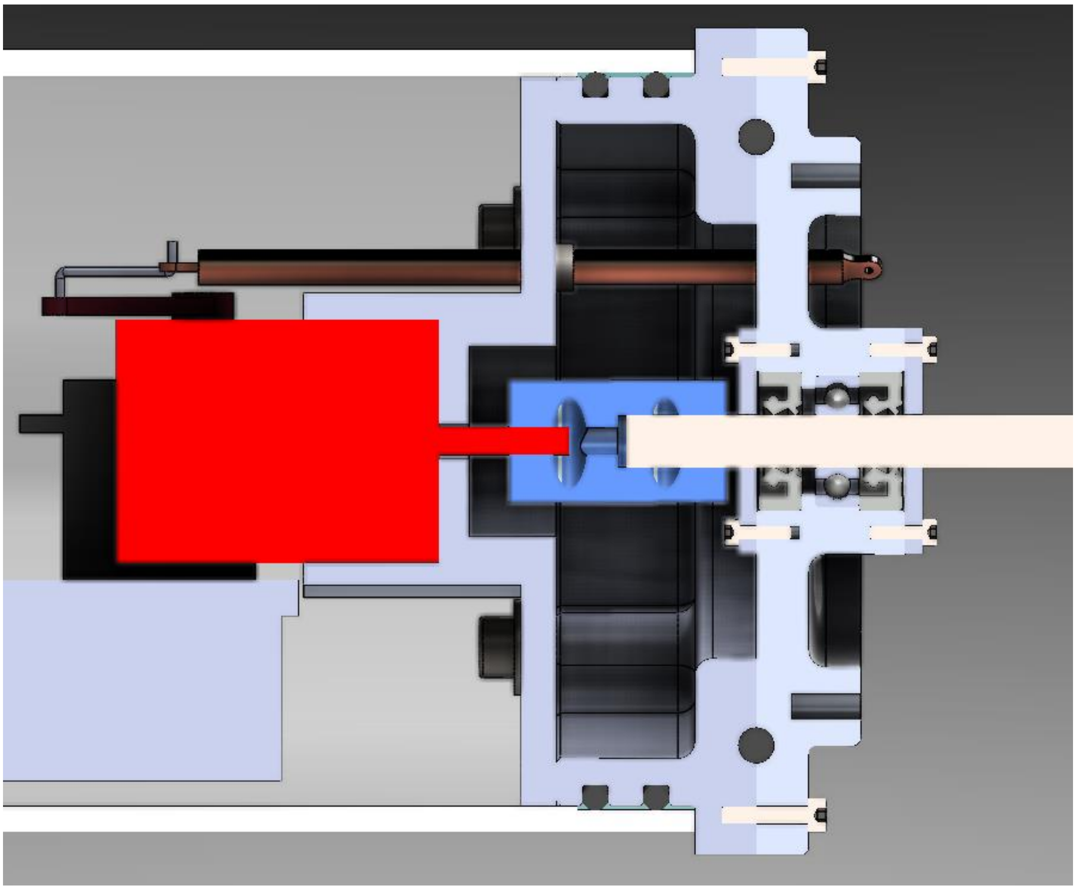
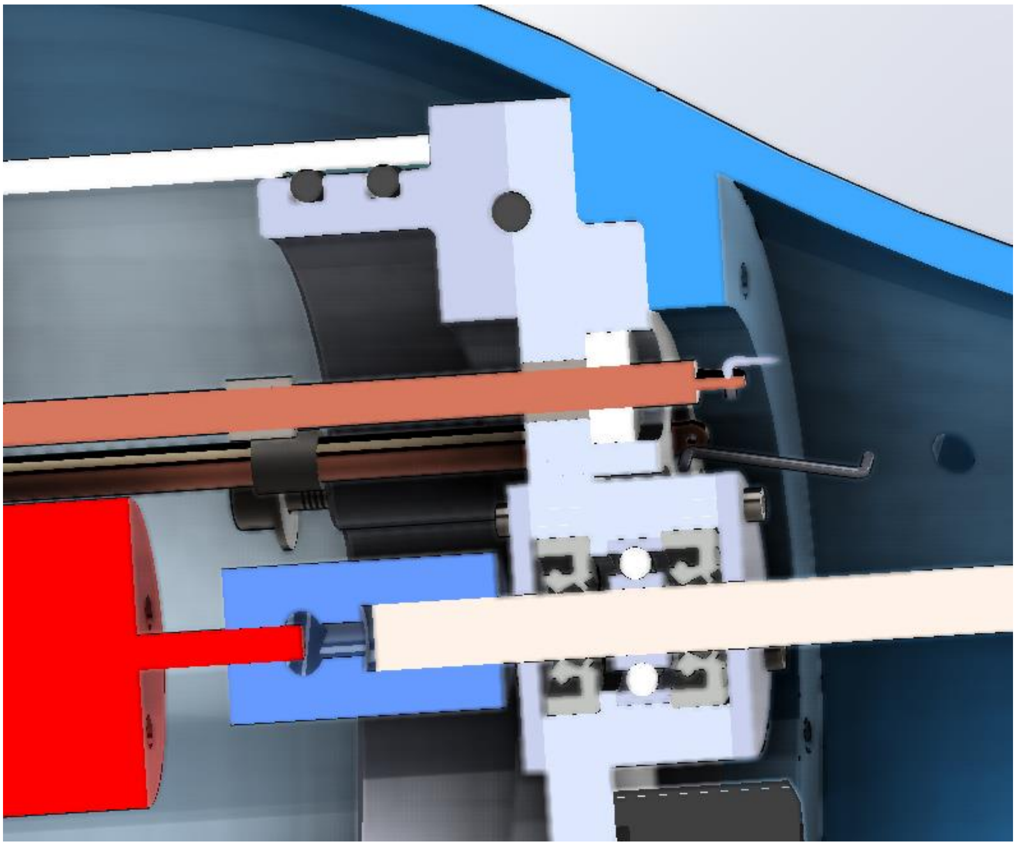


Figure 4.6 Section view of the sealing solution

To ensure complete water tightness of the rotating shaft that transfers power from the motor (installed inside the pressure tube) to the propeller(that is outside the tube), I decided to use specially designed ‘radial shaft seals’. A complete guide to how to use them effectively can be found here: [4]

The linkage system operated by servomotors for rudder control will be moved linearly. Thus a special rod seal is used [5]. The same seals are used in hydraulic systems.

To minimize friction, a sliding bushing is utilized, which contains an internal sliding layer made of PTFE with embedded lead within a porous bronze layer.



All the seals were strategically positioned to accommodate the substantial pressures exerted inwards, towards the pressure hull. This strategic placement ensures that the seals effectively counteract the high pressure acting in the direction of the hull, guaranteeing the submersible's integrity and overall functionality.

This is particularly important as the seals are prone to slight deformation called “extrusion” into any minor gaps due to the pressure. I had to carefully consider this aspect while designing the grooves to securely position the seals within them.

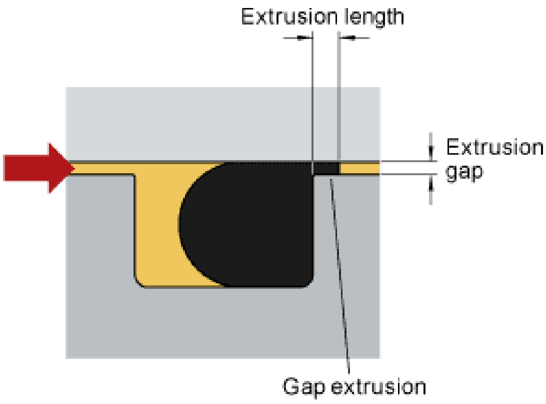


Figure 4.7. Gap extrusion phenomena (source: SKF)

On the other side of the pressure tube, the flange was designed to have the same curve as the wet hull (blue).

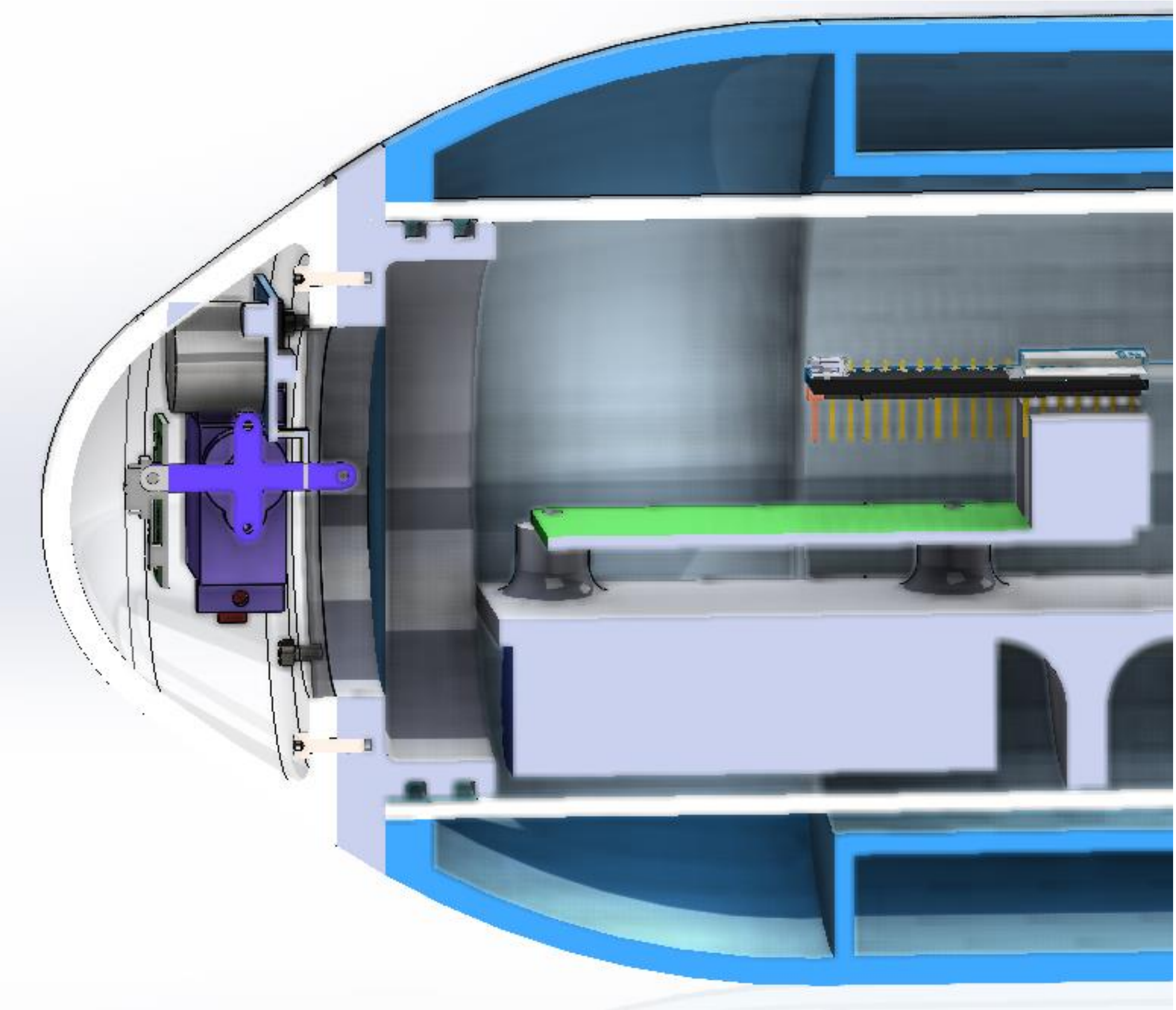


Figure 4.8. Front side of the submarine - flange and end cap shape matches the same curve as the wet hull

The end cap here is replaced with an acrylic dome (as shown on the Figure 4.8), specially shaped to maintain the continuity and hydrodynamic characteristics of the outer hull.
The acrylic dome due to its shape will most likely be manufactured using casting. A 3D-printed mold will be prepared for use with liquid acrylic, which, after the curing process, will take on the desired shape as intended.

4.3. INITIAL MECHANICAL CALCULATIONS

In the early stages of conceptualizing this underwater vehicle, I performed various fundamental calculations while designing the basic mechanical components of this project to ensure that what I designed aligned with proper physical parameters, thereby preventing any failures during operations in harsh underwater conditions.

These calculations encompassed essential parameters such as volume and displacement forces, evaluation of axial and radial forces acting on the shaft (to determine the necessity of employing angular ball bearings versus simple deep groove ball bearings), drag and thrust assessments, and numerous other factors. These calculations were crucial in guiding decisions related to motor power, bearing selection, overall vehicle dimensions, and many other factors.

Accurate estimation of the diverse forces exerted on the body in the fluid domain demands advanced numerical calculations, such as the Computational Fluid Dynamics (CFD) method. Therefore, the initial calculations serve as preliminary approximations, laying the groundwork for subsequent, more precise analyses in the future.

$$\mathbf{D = 0.5 \cdot Cd \cdot \rho \cdot A \cdot V2}$$

Equation 4.1 Drag calculations

Where:
D is the drag force,
Cd is the drag coefficient (dimensionless),
ρ is the fluid density (in this case water),
A is the reference area (cross-sectional area perpendicular to the flow direction),
V is the velocity of the object relative to the fluid.

The drag coefficient (Cd) is a dimensionless parameter that depends on the shape of the object and the flow conditions. Different shapes and surface conditions result in different drag coefficients. To account for the worst-case scenario I decided to use drag coefficient for a bullet-like shape.

Nasa has a great graphic regarding drag coefficients for different shapes (Figure 4.9).

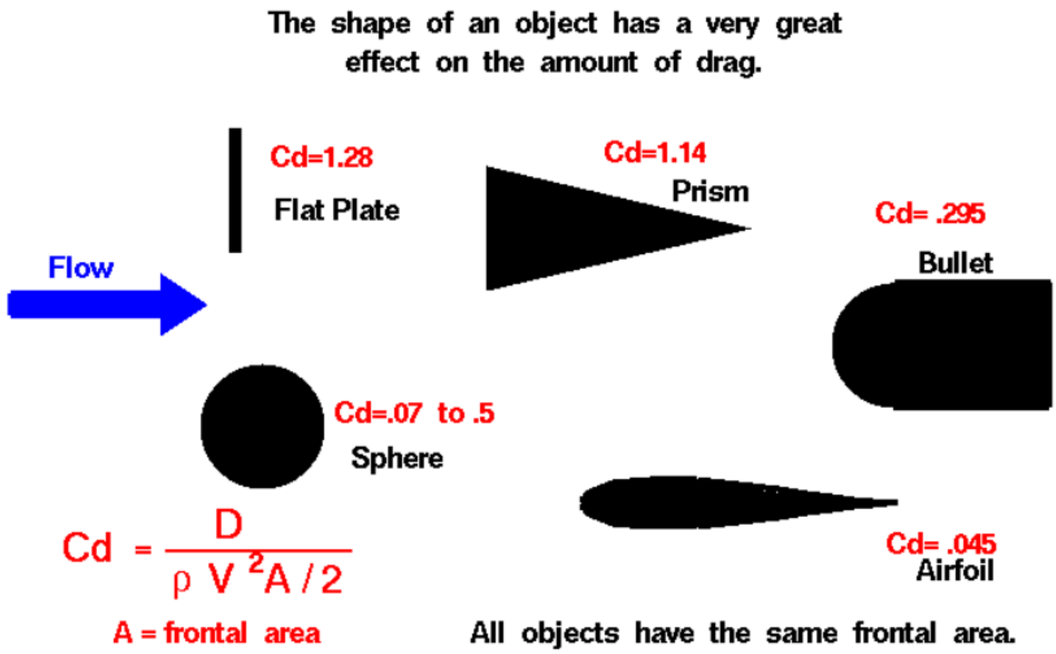


Figure 4.9. Drag coefficient changes for different object's shape (source: NASA)

To calculate drag force, which will be used later to calculate the axial force acting on the shaft, as well as total motor power, I had to make some simplified assumptions. First I decided that the vehicle's top speed would be approx. 2 m/s. Secondly, the cross-sectional area will be a circle with a diameter of 140mm (Figure 4.10)

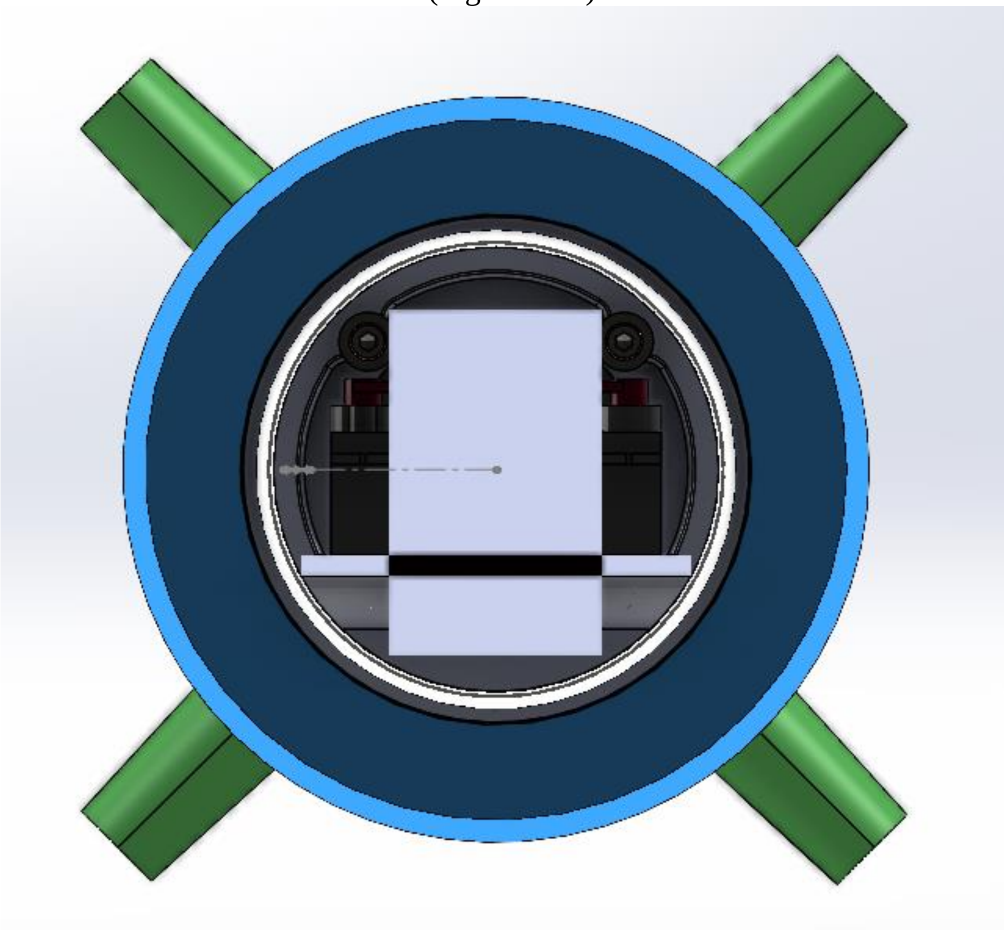


Figure 4.10 Cross-section considered in drag calculations

In total, the drag force equaled $\mathbf{D_{force} = 9N}$.

One of the critical calculations I undertook was determining the total displacement force resulting from the buoyancy of the vessel's hull.
After completing this analysis, I realized that what I anticipated which was the need to trim down weight or opt for lightweight components was wrong Surprisingly, the issue was the opposite—the vessel turned out to be too light.
The initial concept was too large compared to its weight, making it positively buoyant. To balance it, I'd have to add an extra 5kg in the form of permanent ballast, an impractical solution due to space constraints and overall sustainability issues. Consequently, I realized I had to not only keep the overall size of the vehicle minimal but also maximize the weight of individual components. This led to the decision to utilize aluminum for most parts instead of 3D printing them all with PETg (plastic).

In the case of submarine operations, buoyancy is a critical factor governing the vessel's ability to dive and surface. Submarines achieve different buoyancy states—neutral, positive, or negative—by adjusting their overall density.
Neutral buoyancy is the desired state for maintaining a constant depth. In this condition, the submarine's weight is precisely balanced by the buoyant force, allowing it to remain suspended at a specific depth (called operational depth) without sinking or rising.
Positive buoyancy occurs when the buoyant force exceeds the submarine's weight, causing it to float or rise towards the surface. This state is desirable for ascending or surfacing. Conversely, negative buoyancy results from the submarine being denser than the surrounding water, causing it to sink.
Achieving neutral buoyancy is crucial during underwater operations, as it allows for precise control of the submarine's depth. This control is typically achieved by adjusting the volume of water in ballast tanks or by using control surfaces like dive planes to alter the vessel's angle, effectively controlling its ascent or descent in the water column.
I decided to use both dive planes along the ballast tank systems to achieve a fast, responsive, and precise depth control system.

Before delving into additional calculations, it is crucial to highlight a significant aspect of submarine design related to stability.
To ensure the submarine won’t roll over, especially while staying on the surface, it is of paramount importance to maintain the center of buoyancy of a submerged submarine always above the center of gravity (explained here: [6]).

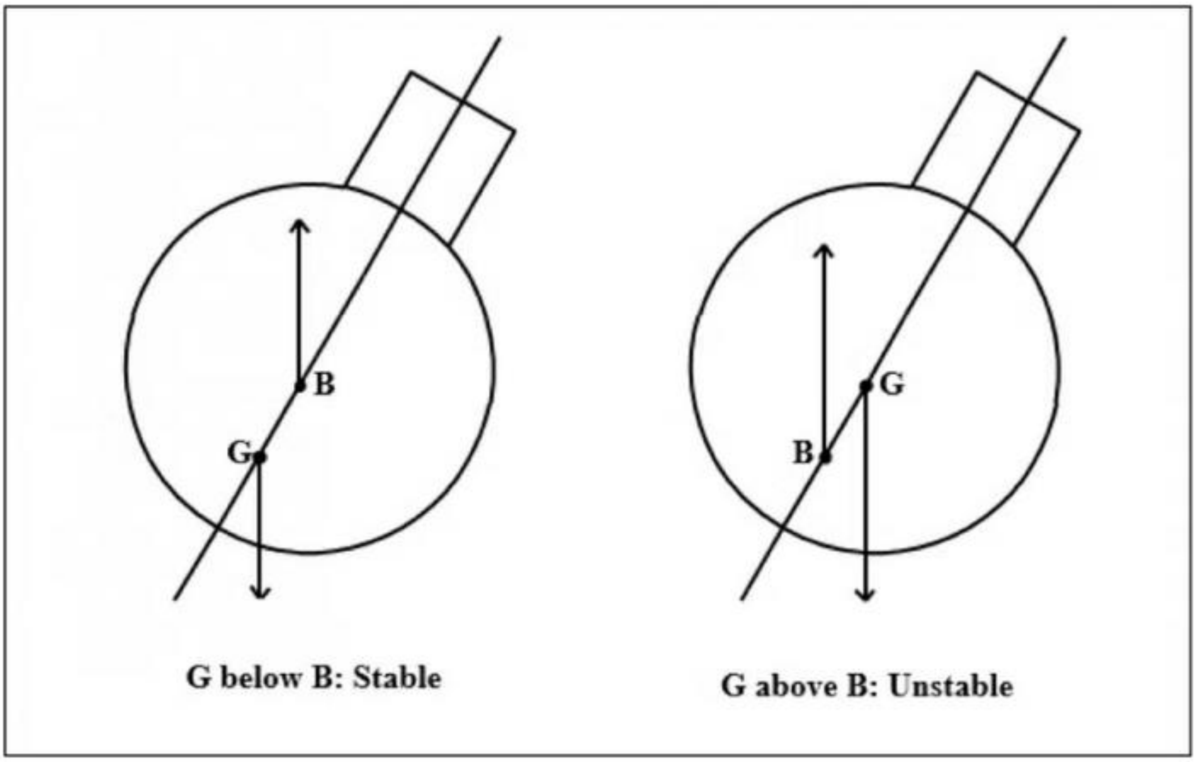


Figure 4.11. Submarine stability aspect - buoyancy and gravitational force distribution (source: www.marineinsight.com)

This configuration ensures the submarine's stability, as the weight of the vessel acts as a stabilizing force. When the CG (center of gravity) is below the CB (center of buoyancy), any tilting or rolling motion prompts a restoring moment that counteracts the inclination, helping the submarine maintain an upright position.
Conversely, if the CG were positioned above the CB, the submarine would be prone to instability. In this scenario, any tilt or roll would generate a destabilizing moment, exacerbating the inclination and potentially leading to the submarine rolling over.
Therefore, the strategic placement of the center of gravity below the center of buoyancy is a fundamental design consideration to prevent rolling and maintain stability during underwater operations.
That is why I strategically planned to position all the batteries and heavier components in the lowest section of the pressure hull.

Having said that the calculation of the displacement force of my vessel is as follows:

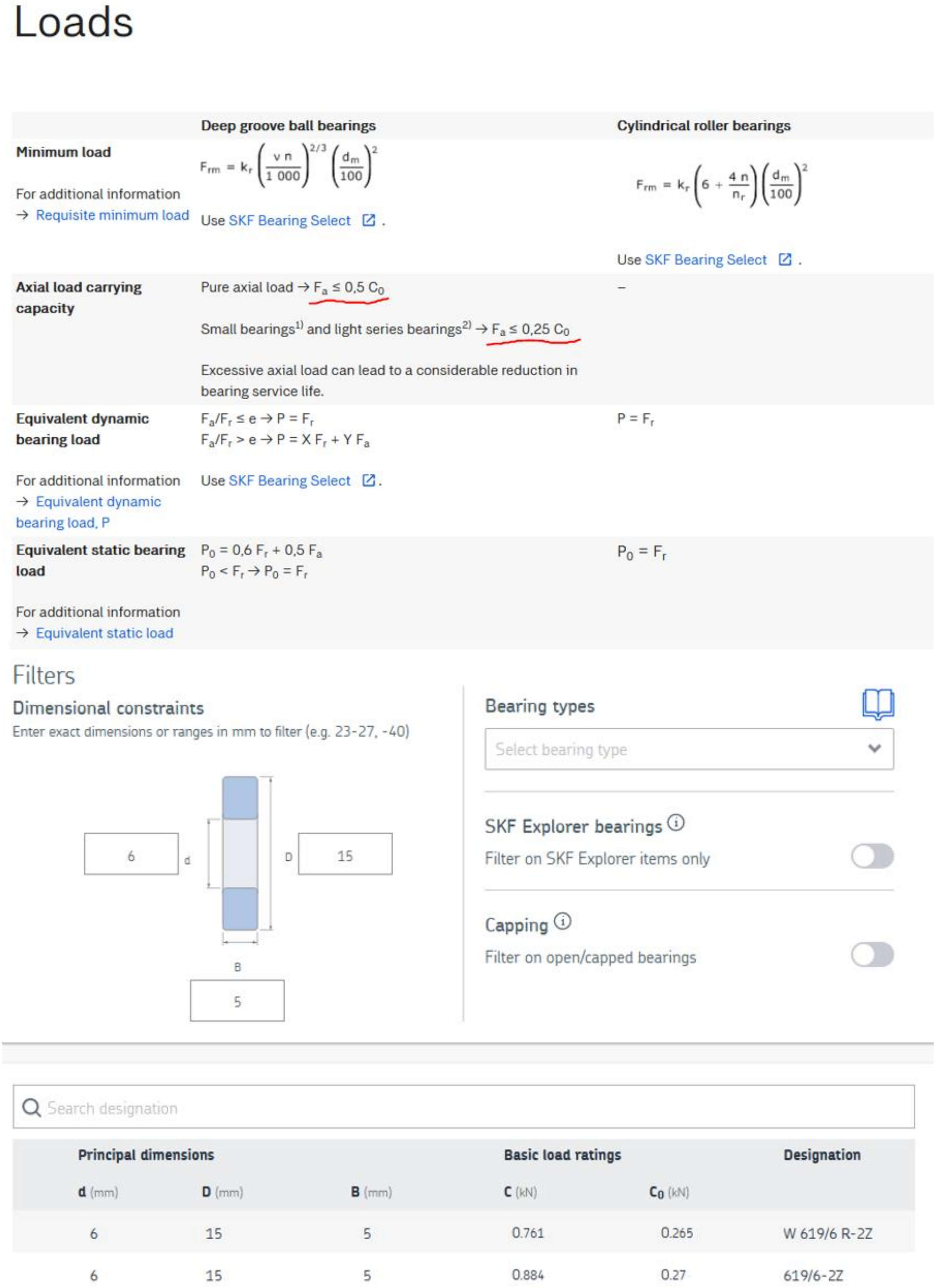
$$\mathbf{Fbuoyancy = \rho fluid \cdot g \cdot Vdisplaced}$$

Equation 4.2. The equation used to calculate the buoyancy force of the submarine.

In my scenario, the submarine's overall volume measures approximately 5.42 liters (I use liters for quick comparisons with the additional weight required to achieve neutral buoyancy). This volume was automatically computed by my 3D software (SolidWorks).
Consequently, the total displacement force, denoted as $F_{Buoyancy}$, amounts to **53.17 N**.
This implies that the entire **weight of my vessel needs to be approximately 5kg**.
To regulate buoyancy, both negatively and positively, I must incorporate ballast tanks to introduce extra weight (water) as needed.
Striking the right balance is crucial because having too little 'permanent' weight would necessitate disproportionately large ballast tanks, an impractical solution due to space constraints.

Furthermore, after evaluating axial forces by the propeller (that generates thrust), hydrodynamic drag, buoyancy force, and other parameters that can only be precisely calculated using CFD methods I concluded that axial forces in the worst-case scenario will not exceed **60N**.
It is crucial not to underestimate the axial forces acting on the main shaft, due to the limitations of regular ball bearings in carrying axial loads. Excessive force could lead to the destruction of standard ball bearings, necessitating the adoption of more costly angular ball bearings.

I compared that to the technical parameters of deep groove ball bearings which are shown below:



Loads

	Deep groove ball bearings	Cylindrical roller bearings
Minimum load For additional information → Requisite minimum load	$F_{rm} = k_r \left(\frac{\nu\, n}{1\,000}\right)^{2/3} \left(\frac{d_m}{100}\right)^2$ Use SKF Bearing Select .	$F_{rm} = k_r \left(6 + \frac{4\,n}{n_r}\right) \left(\frac{d_m}{100}\right)^2$ Use SKF Bearing Select .
Axial load carrying capacity	Pure axial load → $F_a \leq 0{,}5\ C_0$ Small bearings[1] and light series bearings[2] → $F_a \leq 0{,}25\ C_0$ Excessive axial load can lead to a considerable reduction in bearing service life.	–
Equivalent dynamic bearing load For additional information → Equivalent dynamic bearing load, P	$F_a/F_r \leq e \rightarrow P = F_r$ $F_a/F_r > e \rightarrow P = X\,F_r + Y\,F_a$ Use SKF Bearing Select .	$P = F_r$
Equivalent static bearing load For additional information → Equivalent static load	$P_0 = 0{,}6\ F_r + 0{,}5\ F_a$ $P_0 < F_r \rightarrow P_0 = F_r$	$P_0 = F_r$

Filters

Dimensional constraints

Enter exact dimensions or ranges in mm to filter (e.g. 23-27, -40)

d 6, D 15, B 5

Bearing types

Select bearing type

SKF Explorer bearings

Filter on SKF Explorer items only

Capping

Filter on open/capped bearings

Search designation

Principal dimensions			Basic load ratings		Designation
d (mm)	**D** (mm)	**B** (mm)	**C** (kN)	**C_0** (kN)	
6	15	5	0.761	0.265	W 619/6 R-2Z
6	15	5	0.884	0.27	619/6-2Z

Figure 4.12. The axial load carrying capacity of an SKF ball bearing 619/6-2Z used in my design (source: SKF Ball Bearings)

The ball bearings that I chose are 619/6-2Z with C_0 = 0.27 kN and axial load Fa < 0.25 C_0 . This gives us a maximum axial load of 67.5 N,
Consequently, I determined that angular ball bearings, while potentially more suitable for my shaft diameter, would incur a cost over ten times greater than the chosen bearings. This makes the current selection sufficient for the initial prototype.
However, with subsequent iterations and the development of larger-scale versions of the vehicle, I expect a shift towards angular bearings. These bearings align better with the increasing size, speed, and capabilities of the boat, effectively handling the heightened axial forces exerted by the propeller and evolving hydrodynamic characteristics. This evolution aims to ensure a more efficient and reliable power transmission system as the vehicle progresses.
When it comes to choosing the right motor I calculated the power that I needed using the formula below:

$$\mathbf{P} = \frac{\boldsymbol{F} \cdot \mathbf{v}}{\boldsymbol{\eta}}$$

Equation 4.3. The formula used to estimate motor power.

Where:
F is the total force (i.e. drag) in my case equals to around 65N
V is the velocity of the object relative to the fluid, in my case is 2 m/s
$\boldsymbol{\eta}$ is the motor efficiency, in the worst case scenario equals 0.75

That gives the result of **173 Watts**.

Having these rough estimates, I was able to choose the motor that would have sufficient power but also be energy-efficient. The motor and all of the electronics needed for its operation were purchased in the HobbyKing online store ([7]).
I decided to go with the inrunner BLDC motor. Generally, outrunners have more torque and lower kV due to their design specification. When it comes to powering submarine propellers it is better to have high torque and low revolution per minute.
However, inrunners are more efficient, especially due to their heat transfer capabilities. Their coil windings touch the outer case (the rotor is inside and the outer metal housing doesn't rotate which is the opposite for outrunners), which greatly helps with heat dissipation, improving efficiency, but also making it easier to install such motors in tight spaces such as in the submarine. Though BLDC motors are generally waterproofed (their windings are isolated) working in salty water with lots of organic debris would greatly reduce the motor's lifetime.
Thus I decided to place an inrunner BLDC motor inside the pressure hull. I just made sure that the motor I chose had the lowest possible kV which states the number of revolutions per applied voltage, and thus the highest torque in low RPM.

I chose Turnigy XK3674-2200KV 1750w Brushless Inrunner which is a BLDC sensorless motor with much more power than I need. However, it was the only motor with very low kVs and enough power with relatively low power consumption. Its high power capacity has the advantage of being suitable for future upgrades to this project, meaning it can be used with much bigger and more advanced future versions of the underwater vehicle.

Figure 4.13. Turnigy XK3674-2200KV 1750w BLDC Inrunner Motor (source: hobbyking.com)

To control this motor I had to purchase a speed controller (ESC). It is crucial to choose the one that can facilitate maximum continuous current of more amperage than the motor can consume, which in this case is around 70A. Moreover, it is important to choose ESC that can work with multiple battery packages, not only with regard to their cell configuration (2S-6S) and thus their voltage but also the type of batteries (Li-Ion, Li-Pol, NiMh, etc).

I chose the YEP 120A LV (2-6S) Brushless Speed Controller (Figure 4.14).

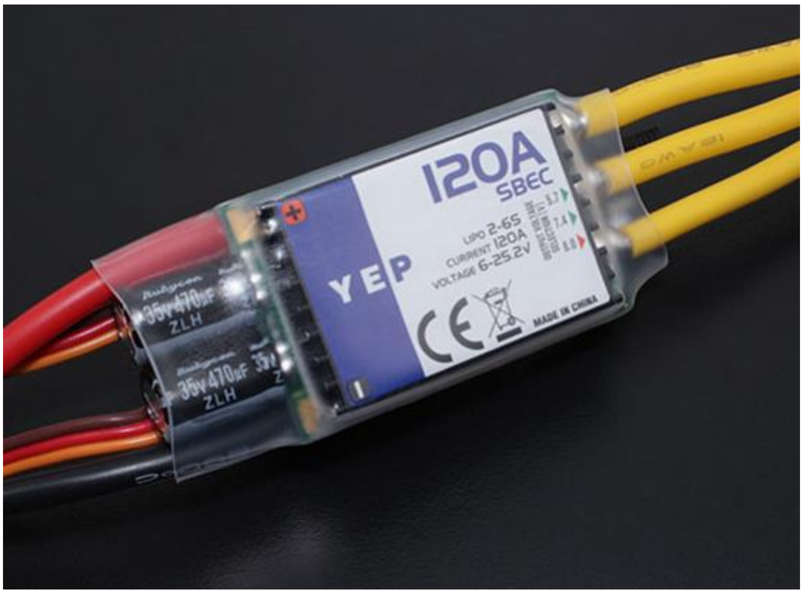


Figure 4.14 YEP 120A LV (2-6S) Brushless Speed Controller

4.4. RUDDER SYSTEM

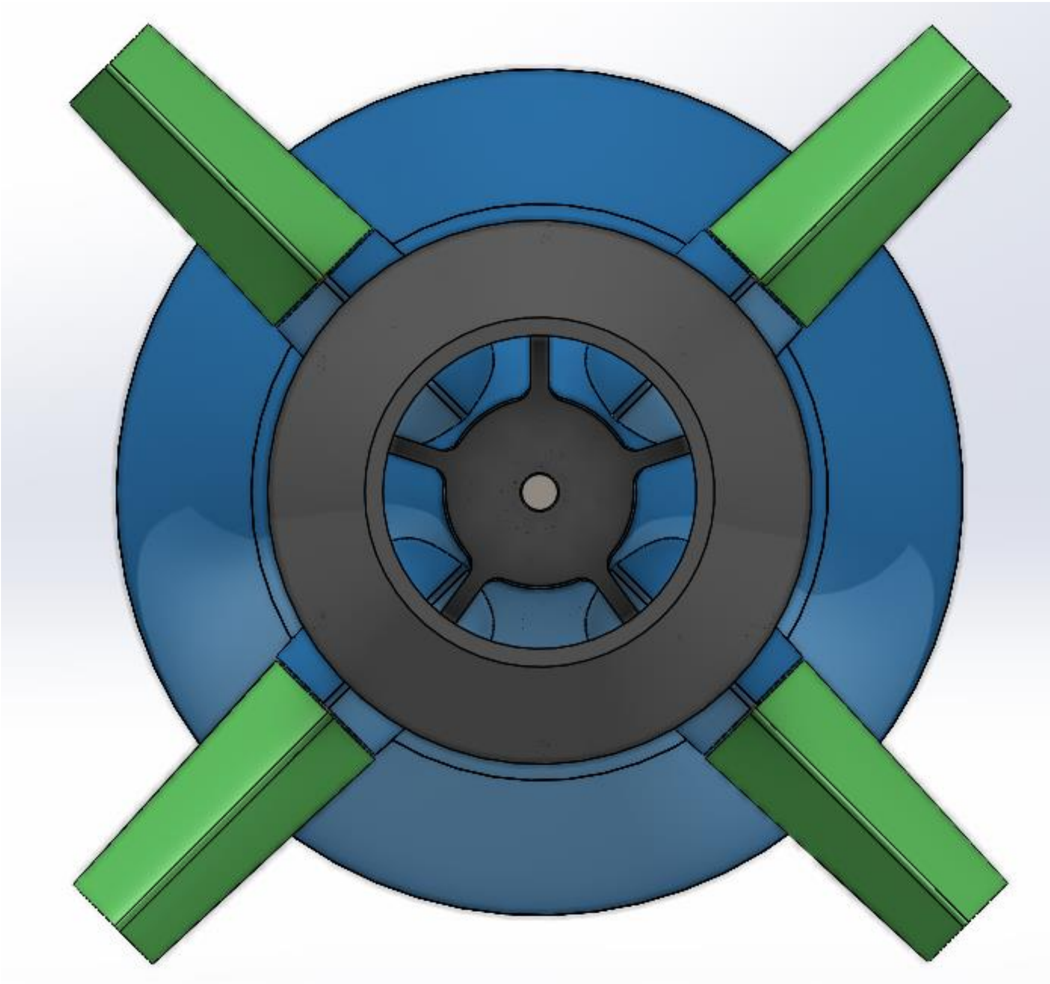


Figure 4.15 Rear view of the submarine demonstrating the rudder configuration.

There are two main types of rudder configuration:cross-plane and x-plane rudder systems [8].

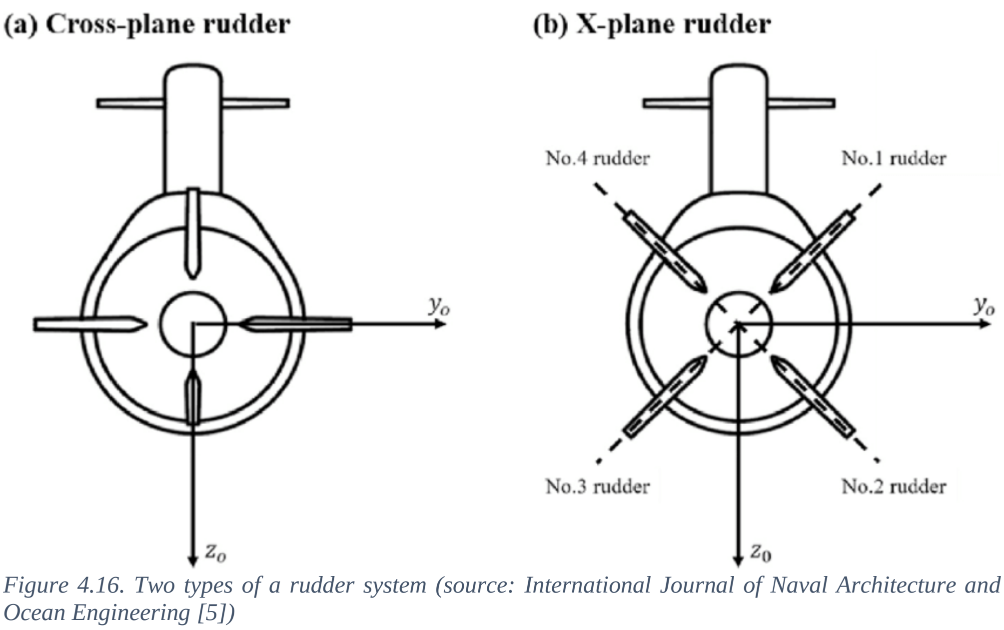
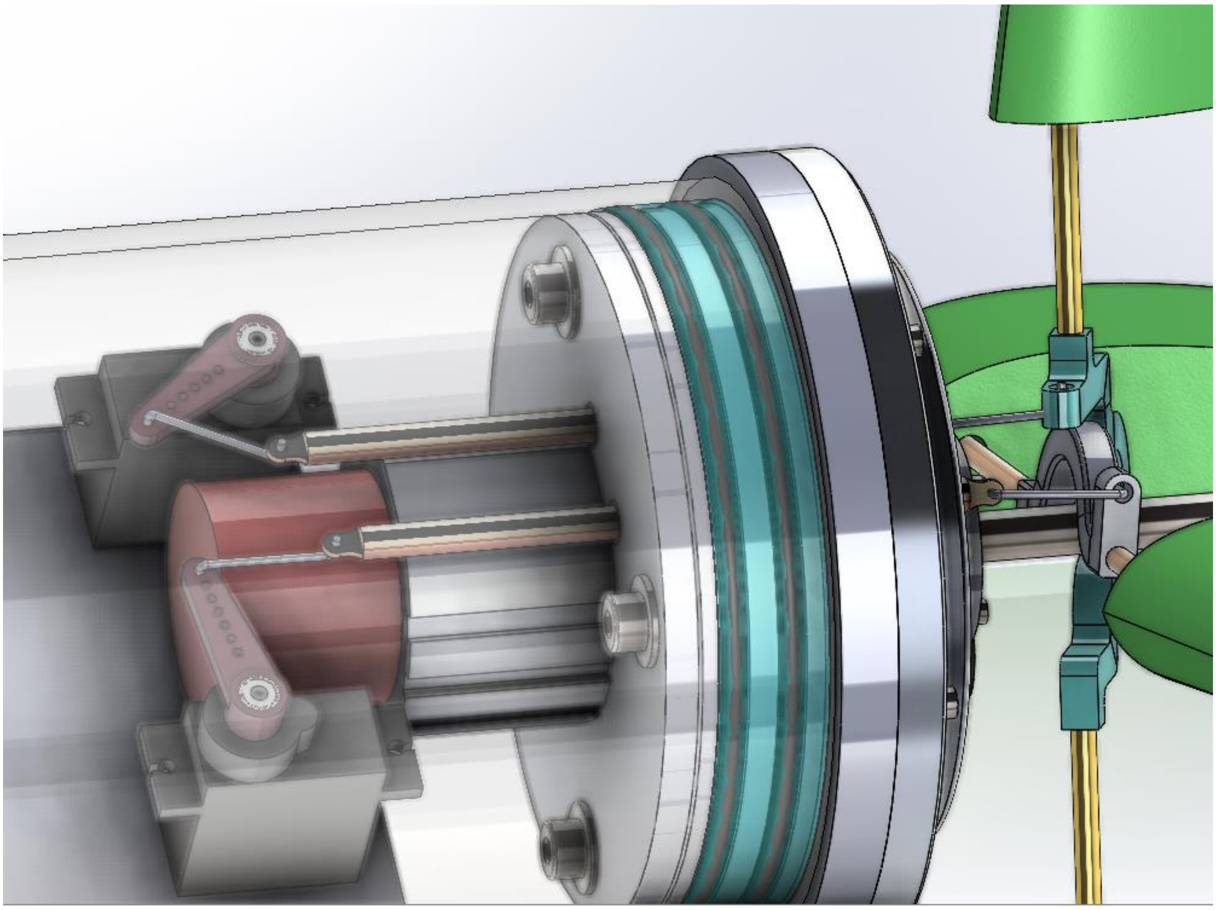


Figure 4.16. Two types of a rudder system (source: International Journal of Naval Architecture and Ocean Engineering [5])

Both have their advantages and disadvantages, but for this project x-type system was chosen. The x-type configuration utilizes all four rudders during maneuvers, which translates to increased control and maneuverability in comparison to the cross-plane system. This expanded surface area of rudders allows for more precise adjustments in various directions, enhancing the submersible's ability to navigate challenging underwater environments.
Furthermore, the x-plane rudder system is known for its improved hydrodynamics, resulting in reduced drag and enhanced overall efficiency. This design feature complements the project's aim to create an agile and responsive submersible while maximizing energy efficiency.



I use two servomotors to control both pairs of rudders, each of which has its axis of rotation

Figure 4.17 Isometric view showing two servomotors inside the transparent, acrylic tube (pressure hull).

inclined at a 45-degree angle (Figure 4.17).
To maintain linear motion for the main linkage due to the requirements of the sealing method, it was necessary to incorporate auxiliary linkages that effectively translate the rotational movements of the servos into the desired linear motions required for controlling the rudders.

Both pairs of linkages are connected to rotational braces, which in turn are connected to the rudder ends/tips to facilitate the translation of servo movements into the desired rudder adjustments. The shapes of these components (shown in Figure 4.18) are carefully designed to prevent any potential collisions with the main shaft and the second rudder brace during their rotational motion.

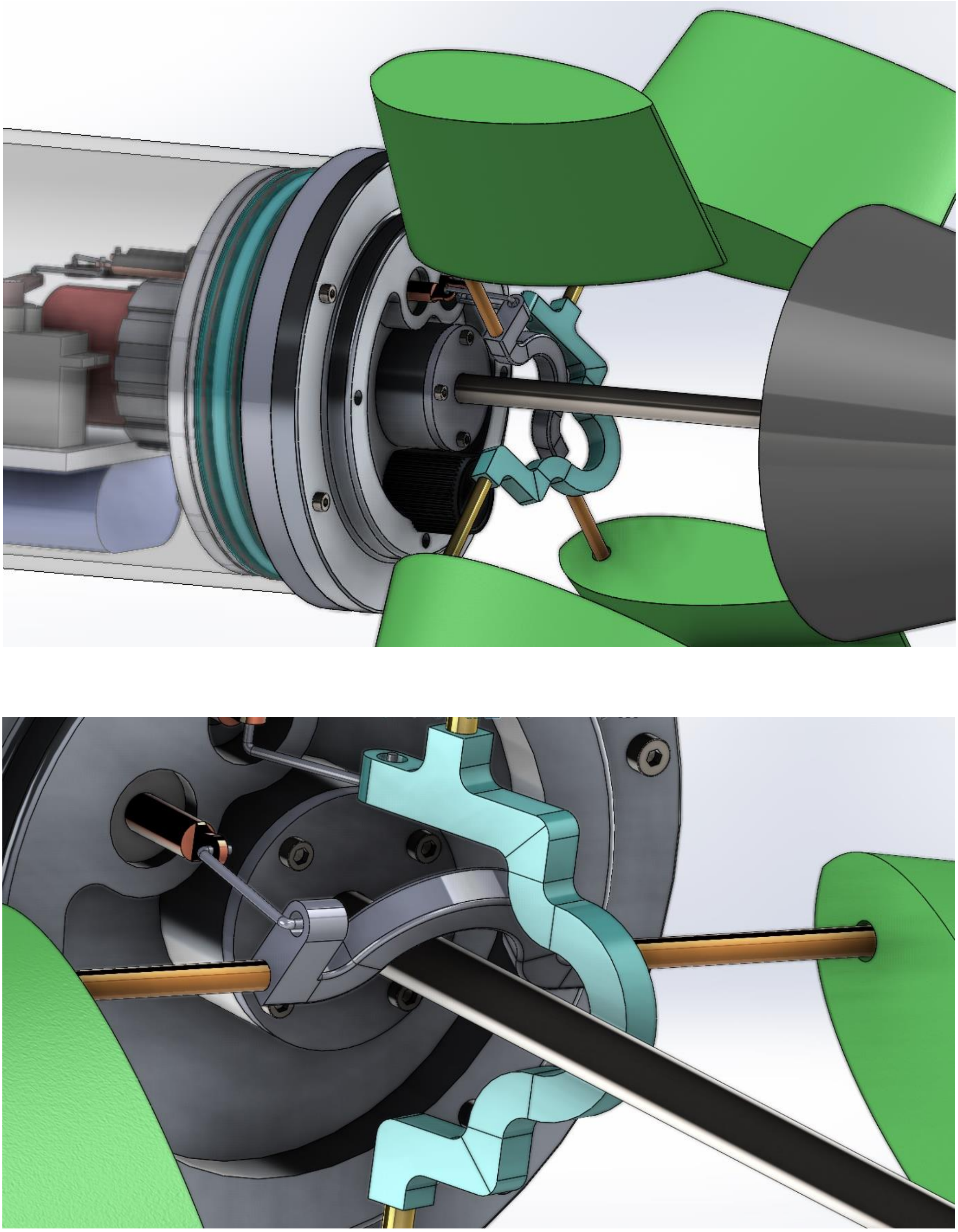


Figure 4.18 Isometric views showing the rudder braces connected to the rudder tips using brass rods.

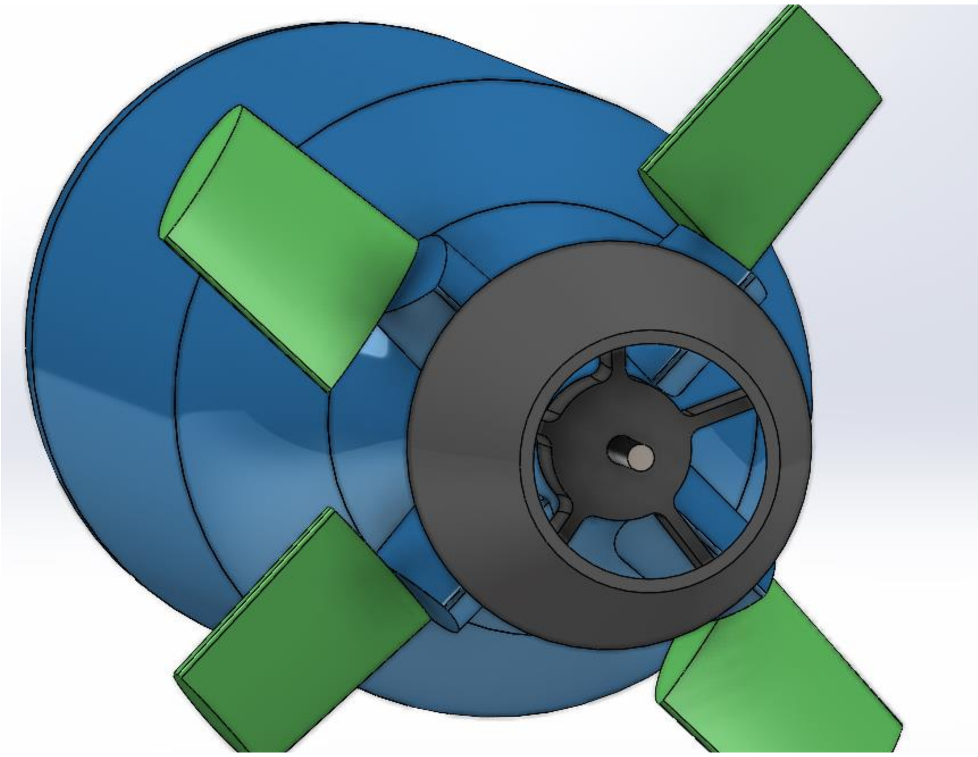


Figure 4.19 Maximum rotation (30 degrees) of the rudder tips.

The rudder tips have a maximum rotation capability of 30 degrees from the neutral position (Figure 4.19). This limit is set to ensure the preservation of maneuverability and the prevention of drift which otherwise could lead to a loss of control over the vessel's trajectory.

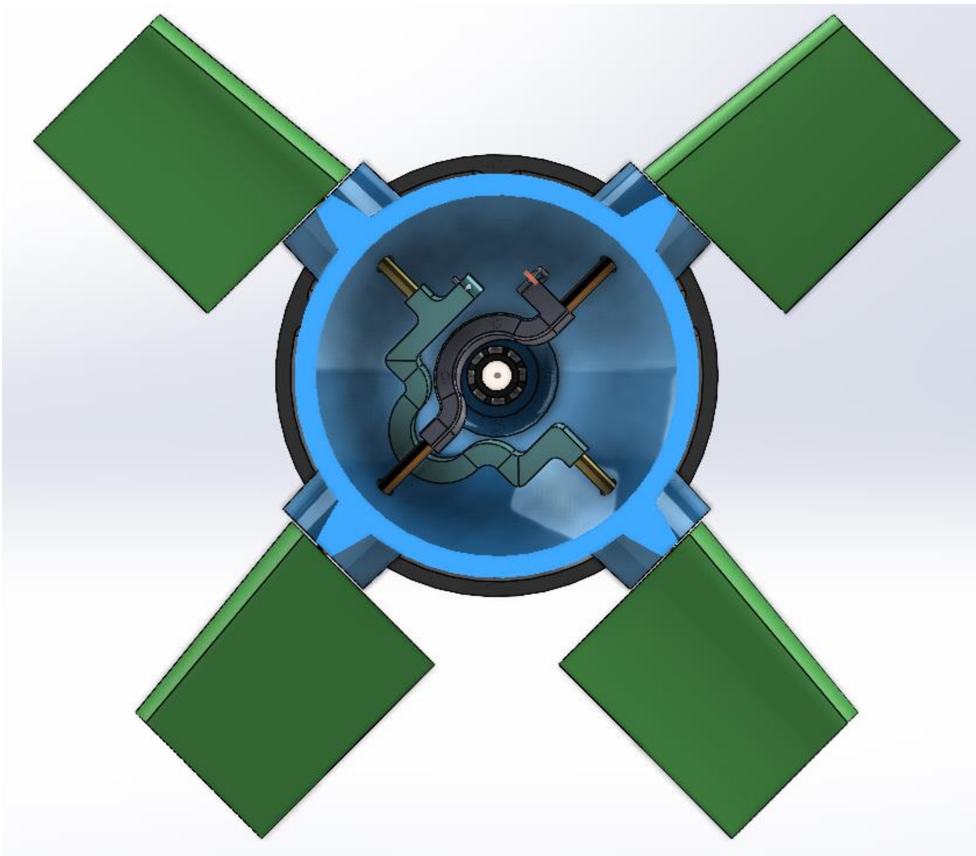


Figure 4.20 Rear cross-sectional view of the rudder configuration with its 30-degree limits.

When it comes to the propulsion system, I decided to incorporate a diffuser along the propeller which significantly impacts the vehicle's performance and efficiency underwater.

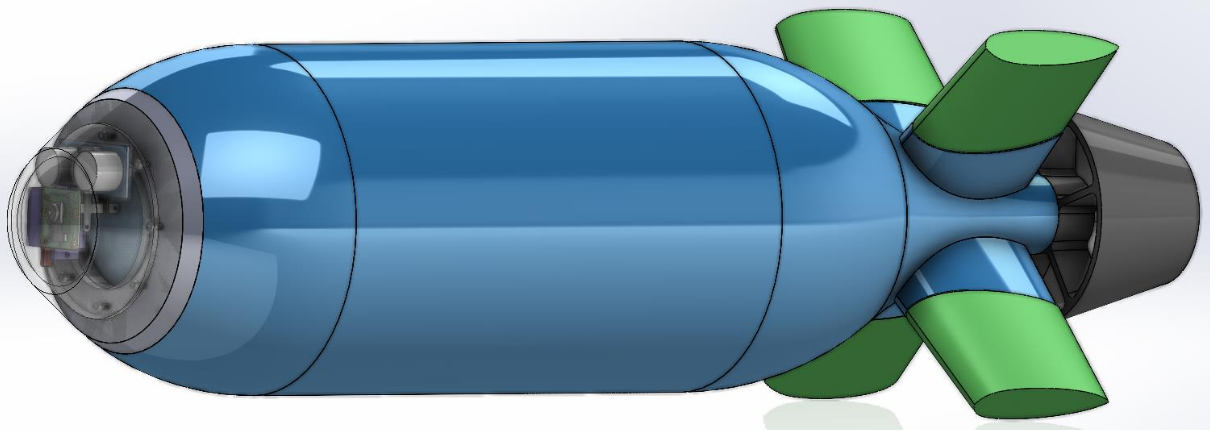


Figure 4.21 Isometric view showing the diffuser (black) behind the rudder.

The incorporation of a diffuser into the propulsion system serves several critical functions. First and foremost, it enhances hydrodynamic efficiency by streamlining water flow, reducing turbulence, and minimizing drag. This efficiency improvement results in reduced energy consumption, and thus extended operational capability.

Furthermore, the diffuser plays a significant role in noise reduction. It works by reducing turbulent water flow and minimizing cavitation, making the submarine less acoustically detectable, which is vital for underwater research and military operations. Additionally, the diffuser prevents the propeller's blades from being damaged.

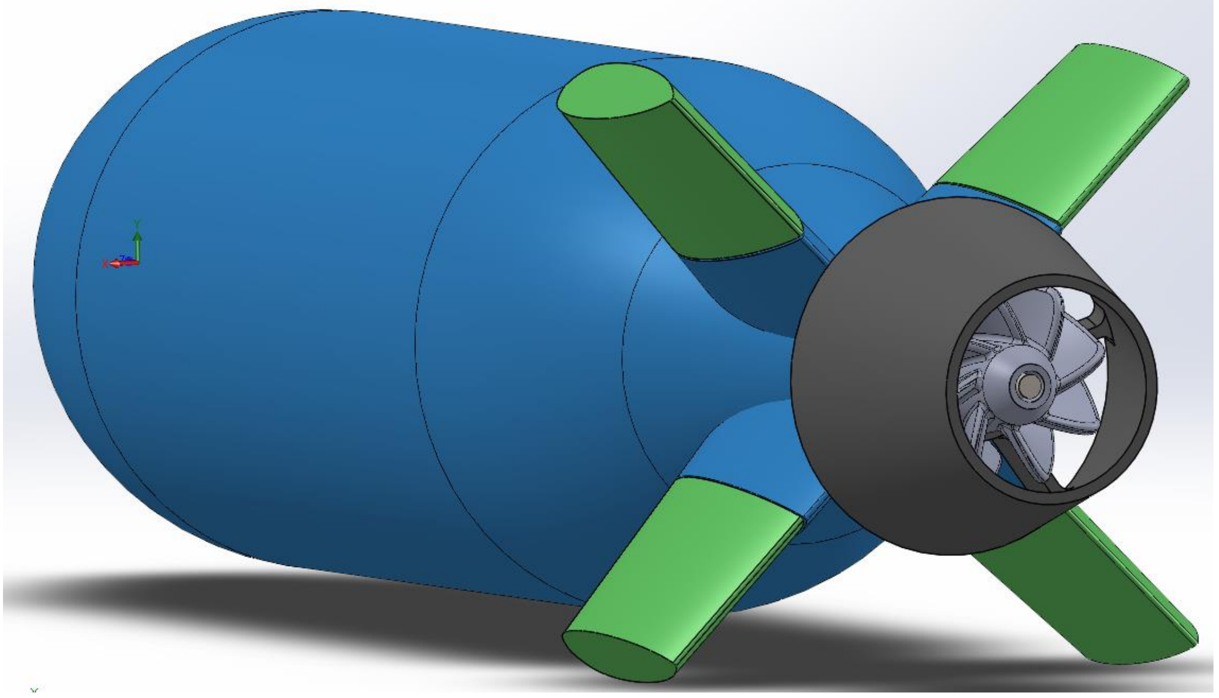


Figure 4.22 Rear isometric view showing the propeller inside the diffuser.

4.5. BALLAST TANK SYSTEM

The design and functionality of a ballast tank system play a pivotal role in the operational capabilities and stability of a submarine. These systems are integral to controlling the submarine's buoyancy, allowing it to submerge, surface, and maintain desired depths during underwater maneuvers. The biggest advantage of this system is best seen when compared to ROVs which are Remote Operated Vehicles. These vehicles use thrusters (often 6) to control their depth and steering capabilities. To maintain the desired operational depth for a prolonged period of time, they need to constantly use their thrusters to make adjustments due to the buoyancy effect. Thus it is a very inefficient system that requires a lot of power.
That is why in my vehicle I decided to work on a ballast system that would ensure the overall efficiency and effectiveness of underwater operations.

Exploration of Ballast Tank Systems:
Various options and designs exist for ballast tank systems in submarines, each with its own set of advantages and disadvantages (see [9] for more detailed information). Among them are piston tanks, compressed gas ballast systems, vented low-pressure systems, water pump systems, and compressed air systems.

- **Piston Tanks:**

This is the most common system in RC submarines for submarine enthusiasts. It offers precise control over buoyancy by using stepper motors to adjust the volume of water inside the tank. They are fairly simple and reliable.
However, they require a lot of space to accommodate pistons and rods. Moreover, their operational mechanism, involving water suction at one end of the piston rather than evenly across the cylinder's entire space, impacts weight distribution. This non-uniform filling, with the weight of water concentrated at the front before reaching full capacity, results in uneven diving and surfacing. The nose becomes heavier than the rest, influencing stability and surfacing performance. To address this problem, piston tanks often incorporate two separate pistons, although this solution introduces additional spatial constraints, which generally is not an option in most advanced underwater vehicles.

- **Compressed Gas Ballast System:**

Compressed gas systems, often utilizing air or another inert gas, provide quick response times for buoyancy adjustments. They are relatively simple in design and are widely used in many submarine models. However, the biggest drawback of this system is the need for refueling with liquid air. This requirement is caused by the limited air volume that can be compressed into the storage tank. Each time the submarine intends to resurface or make slight adjustments to its operational depth, it must expel water from a ballast tank using compressed air. After a few cycles, the storage runs out of its air supply, making the entire vessel incapable of surfacing. This introduces a risk of miscalculating the remaining air in the tank, potentially leading to a catastrophic loss of the vessel that can’t return to the surface independently.

- **Water Pump System:**

Water pump systems provide effective control over buoyancy, and their continuous operation allows for fine-tuning during submersion. Since there is no risk of running out of water to pump in and out of the ballast tank, this system is self-sustained, eliminating the need for the entire submarine to pause operations solely for air refueling, as was the case in the previous system.
However, challenges arise during the water expulsion phase from the ballast tank. This action generates a vacuum inside the tank, necessitating exceptional durability and pressure resistance. The vacuum becomes even more problematic when considering the immense external water pressure at the submarine's operating depth. This makes the ballast tank less effective due to factors such as size (wall thickness), material, and the manufacturing method to build a tank that could withstand the pressure.

Thus, it leads me to the system I am currently exploring as the ideal solution for my underwater vehicle, which is a recirculating compressed air ballast system.

- **Recirculating Compressed Air Ballast System**

It utilizes air pumps to compress air that is used to expel water from the ballast tank. It is similar to the compressed gas ballast system explained earlier, with a few differences. Air is not lost during the cycle, due to a complex system of vents, valves, and air pipes that keeps the air in circulation. This system's primary drawback lies in its intricate design, demanding the use of costly microvalves and pumps (see Parker’s microvalves and pumps [10]), along with the implementation of complex control algorithms. These elements are essential for achieving precise control over the submarine's diving and surfacing cycles.
Unfortunately, due to time limitations and a tight budget, I was unable to build a compressed air system and decided to focus on a more accessible and cost-effective solution.
Given that this thesis revolves around the first prototype and initial concept, certain proposed solutions may not be optimal, considering various constraints that accompany the inception of this innovative project. Recognizing the challenges inherent in designing the inaugural prototype, I opted for a simpler and more economical approach.
Thus, I decided to employ a basic water pump capable of generating a pressure of approximately 2-3 Bar, sufficient to facilitate a dive to around 20 meters.
Additionally, I selected a solenoid valve for regulating water flow to and from the ballast tanks. These components were purchased in Botland (https://botland.com.pl/).

Figure 4.24 Water pump 12V 110l/h - 7mm

Figure 4.23 Solenoid valve 12V - 0,02-0,8MPa

4.6. MAIN POWER SHAFT SYSTEM

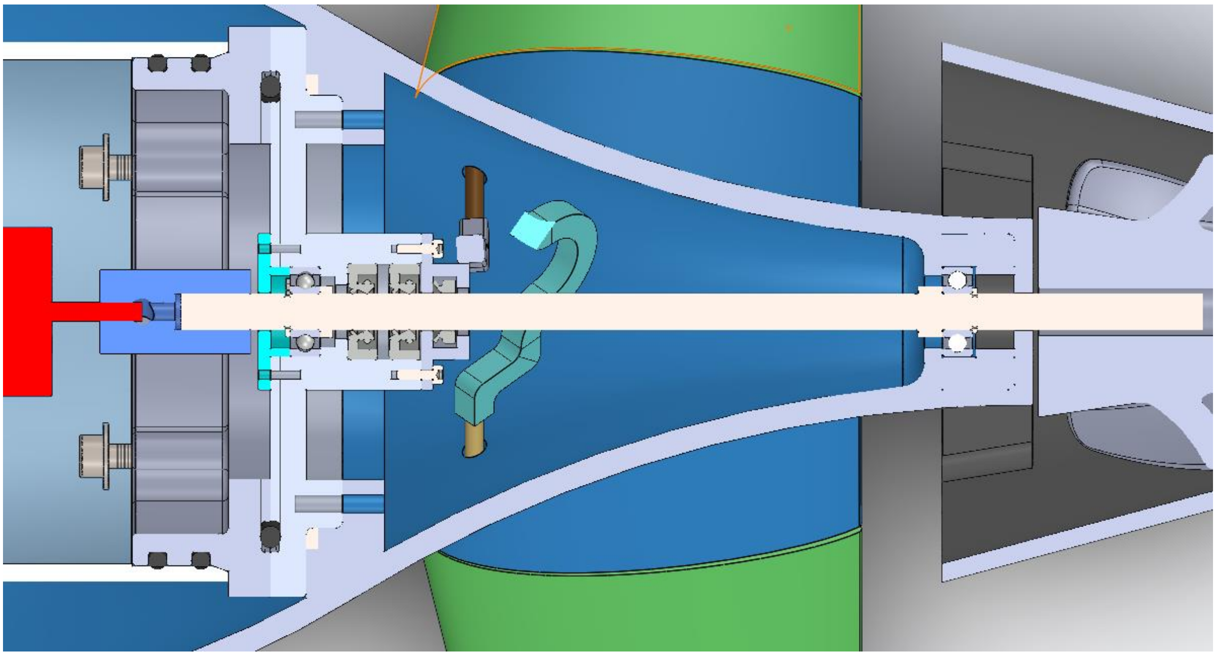


Figure 4.25 Main power shaft design - cross-sectional view.

The design and construction of the power shaft were critical components in ensuring the seamless operation of the BLDC motor within the dry hull. In addition to its primary function of facilitating efficient power transmission from the motor to the propeller inside the diffuser, the power shaft played a pivotal role in maintaining the structural integrity of the entire propulsion system.

Its primary objective was to ensure efficient power transmission while enabling effective sealing solutions to prevent the dry hull from leaking. Special tolerances and surface roughness had to be ensured for the seals to work effectively while staying in accordance with many industry standards [11].

A key challenge in the design process was achieving the fine balance between tight tolerances and optimal surface roughness to facilitate effective sealing. The seals, positioned strategically along the power shaft, required specific tolerances to prevent any leakage while accommodating the rotational movements of the shaft.

5. ELECTRONICS

In this section, I will describe the foundations of the electronic framework critical to the realization of my submarine prototype's objectives. I will start by analyzing the construction of a power distribution system, ensuring efficient energy delivery from the vehicle's batteries to all components. Subsequently, I will present the implementation of a data collection infrastructure, including internal functions like leak detection and temperature monitoring, along with external data acquisition such as pressure and temperature readings.
Moreover, I will delve into the comprehensive communication network and algorithm designed to facilitate an efficient dialogue among the onboard computer, the end-user, and the transmission of data collected by various sensors.
The heart of the system lies in the collaborative efforts of two controllers: the ESP32 and Raspberry Pi. Together, they provide the functionality of the submarine, enabling reliable underwater exploration capabilities.
Given that the ESP32 is a microcontroller, its design is optimized for efficiently managing the various mechanical capabilities of the submarine, including motor and servo control, water pump system, rudder adjustment, etc. Its role as the primary controller ensures precise and responsive handling of these components.
The Raspberry Pi, due to its significant processing power and more advanced connectivity options, including USB cameras, ethernet connections, HDMI ports, and other external peripherals, excels in analyzing data acquired from the diverse sensors connected via the ESP32.
The Raspberry Pi serves as the brain of the operation, making informed decisions on submarine control strategies based on the analyzed data. These decisions are then executed by the ESP32, maintaining a distributed and collaborative approach to submarine control, where the Raspberry Pi's analytical capabilities complement the ESP32's execution functionalities.

Figure 5.1 Raspberry Pi 3B+ (Botland)

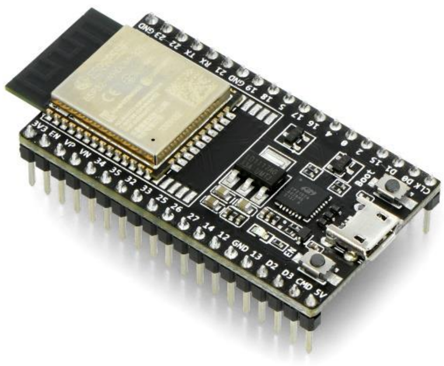


Figure 5.2 ESP32 microcontroller - prototyping board (Botland)

The basic concept of how the system should work is shown in the diagram (Figure 5.3):

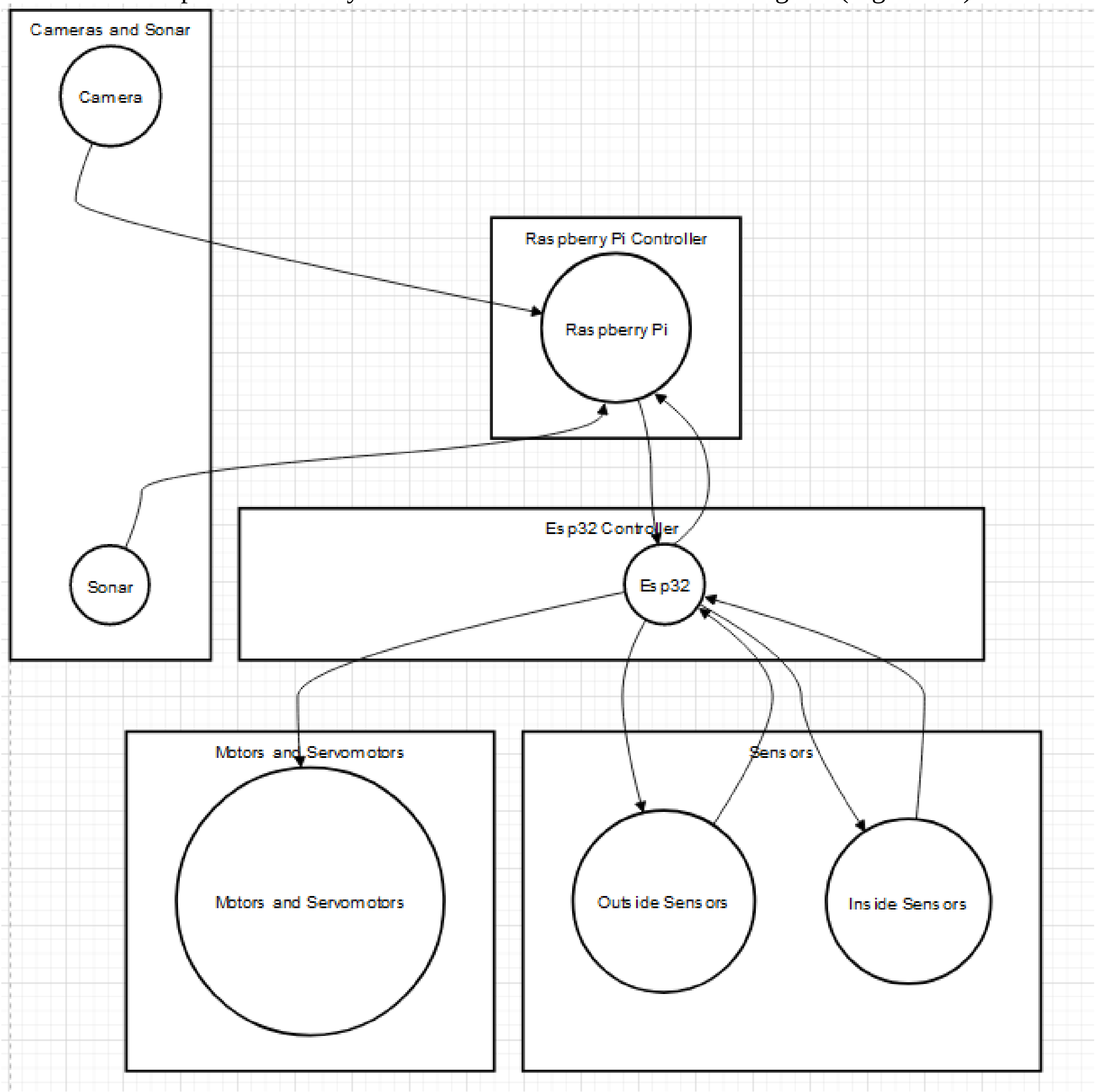


Figure 5.3 Simplified structure of the submarine electric and software system.

ESP32:

The ESP32 serves as the central controlling system of the submarine, managing critical functions such as motor control, servomotor operation, and the collection of essential sensor data. Almost all the sensors are strategically connected to the ESP32. This allows the controller to continuously monitor the underwater environment, ensuring the safety and optimal performance of the submarine.

Sensor Integration:

The ESP32 interfaces with an array of external sensors both inside and outside the submarine. Pressure sensors gauge the depth, temperature sensors monitor the water temperature, conductivity sensors assess water salinity, and the O2 sensor measures the oxygen levels. These sensors work in harmony to provide real-time environmental data crucial for navigation and mission success.

The system is designed to easily accommodate upgrades with additional sensors, thereby enhancing its capabilities, especially during exploration missions where various biological sensors can be easily integrated and incorporated to further expand its functionality. I won't dive more into different parameters that scientists are interested in measuring to acquire valuable insights into underwater environments, but I will note here a very interesting article about those aquatic parameters [12]. I will use information from it to equip future versions of my underwater vehicle with different biological sensors.

Internal and External Sensors:

External sensors include pressure sensors, temperature sensors, conductivity sensors, and an O2 sensor. In addition to external sensors, the ESP32 manages internal sensors, including a leakage sensor, temperature sensors, pressure sensor as well as gyroscope, magnetometer, and accelerometer.

The internal sensors focus on the submarine's structural integrity, internal conditions, and overall health, allowing the ESP32 to respond promptly to any anomalies or potential issues.

Figure 5.4 Outside temperature sensor in a waterproof probe (Botland)

Figure 5.5 Pressure sensor in MEMS technology ([14])

Except temperature probe that is fully waterproof and pressure-resistant, as well as the pressure sensor that is manufactured in MEMS technology (micro-electro-mechanical-systems) one of the most important sensors on board is the leakage sensor shown below:

Figure 5.6 Leak Sensor made by BlueRobotics - https://bluerobotics.com/store/sensors-cameras/leak-sensor/sos-leak-sensor

The leakage sensor, a vital component in the submarine's safety infrastructure, is designed to detect and alert the system to the presence of any unwanted water penetration. It uses sensitive probes or sensors, to identify even minor changes in moisture levels, triggering an immediate response to mitigate potential damage. Incorporating this sensor into the submarine's architecture is crucial for early detection of leaks, allowing for prompt intervention and rapid surfacing to prevent further damage to the vessel’s integrity and sensitive electronics.

Thanks to BlueRobotics [13], the company that sells and provides many different marine equipments, I was able to replicate their leakage sensor and position it around the main shaft seal and near servo linkages – two critical areas particularly susceptible to potential leaks.
The electrical schematic that shows how this sensor works is shown below ().

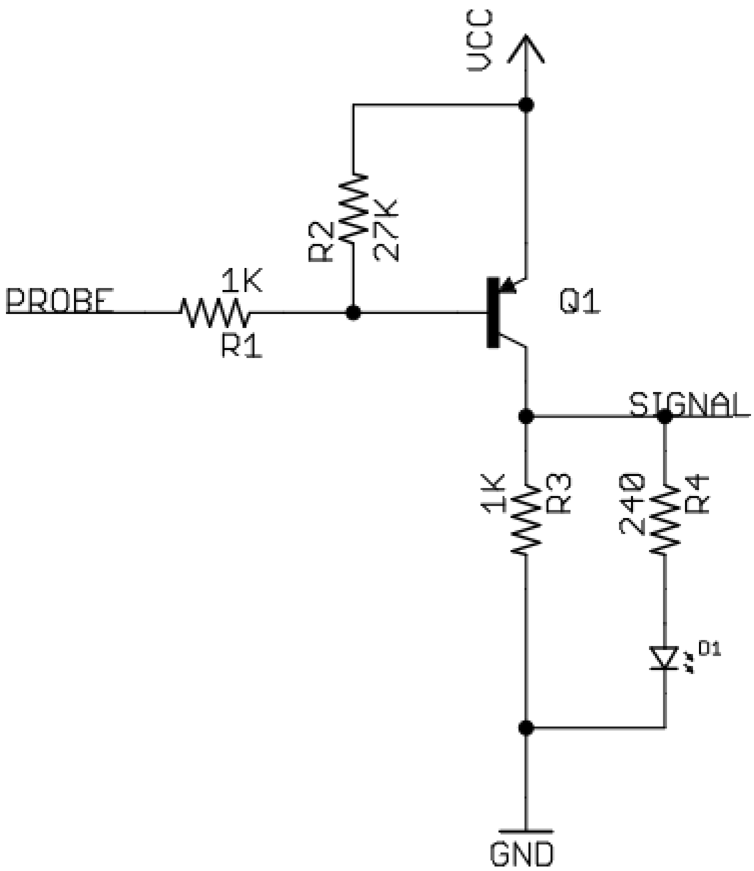


Figure 5.7 Leakage detecting sensor - electric schematic (bluerobotics)

In addition to the leakage sensor, two other integral components in the submarine system include an ultrasonic distance sensor (intended for the development of a sonar device) and a module featuring a magnetometer, gyroscope, and accelerometer.

Figure 5.9 HC-SR04 Ultrasonic Distance Sensor (Botland)

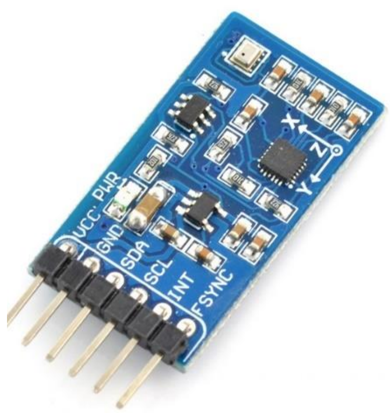


Figure 5.8 IMU 10DoF 3-osiowy akcelerometr, żyroskop i magnetometr

Raspberry Pi:
Raspberry Pi is the main processing power unit, which complements the ESP32 with advanced sensors like cameras and sonar. The camera provides visual data, capturing the underwater surroundings in high resolution. The sonar system enhances navigational capabilities and obstacle detection. The main objective of utilizing such a powerful mini-computer as Raspberry Pi is to analyze and process data acquired from all the sensors by the ESP32.

Data Processing and User Interface:
Raspberry Pi processes data and analyzes information received from both the ESP32 and camera and sonar modules. It establishes a connection with the surface through an Ethernet cable, enabling real-time communication with the end user.
The end user, stationed on the surface, utilizes data sent to it by the Raspberry Pi, and it is the user's responsibility to analyze the data and manually control the submarine.
However, in the future, Raspberry Pi equipped with advanced algorithms, will evolve into the central intelligence directing the operation autonomously.

Batteries and Battery Management System (BMS):
To meet the specific needs of my project, I decided to integrate a Battery Management System (BMS) into the battery pack (made out of 18650 Li-ion batteries) that I plan to build for this project (Figure 5.11).
A Battery Management System (BMS) is a crucial component that monitors, manages, and safeguards the performance of a battery pack. It ensures the optimal operation of individual cells within the pack, preventing overcharging, over-discharging, and balancing the cells to prolong battery life. It also facilitates a smooth and optimized charging cycle tailored to the specific characteristics of the battery cells in use.
The selected BMS model is readily available in the market and has ample current capacity to effectively handle the power consumption requirements of the motors and other essential components within the system. It shares similarities with those commonly employed in RC cars and planes.

Figure 5.11 Li-Ion Panasonic NCR-18650B 3400 mAh (Botland)

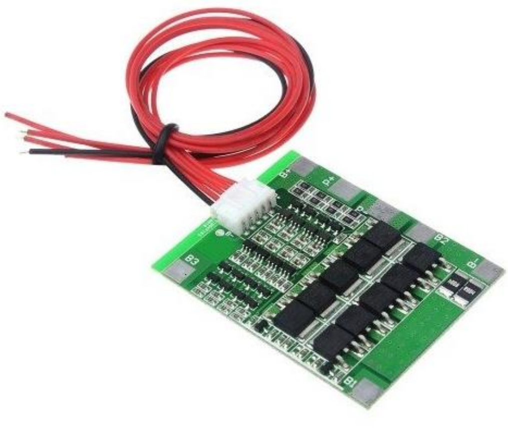


Figure 5.10 Battery Management Unit (AliExpress)

6. CONCLUSIONS AND FUTURE WORK

In the pursuit of developing a **Submersible Vehicle for Research and Exploration Purposes**, this engineering thesis navigated through a series of challenges, necessitating strategic decisions and innovative solutions. The initial calculations as the surrounding buoyancy, center of gravity, and rudder configuration underscored the delicate balance required for optimal underwater performance. Unforeseen issues emerged when the vessel proved too light, demanding a reevaluation of the design approach. The decision has been made to utilize aluminum for components manufacturing instead of PETg (or other polymeric material) exemplifies the commitment to maintaining an optimal weight distribution.

Incorporating both dive planes and a ballast tank system helped to ensure fast, responsive, and precise depth management.

A critical aspect of submarine stability was also addressed, emphasizing the need to position the center of gravity below the center of buoyancy. This consideration ensures stability during resurfacing and prevents potential rollovers.

As this project moves forward, the lessons learned and the insights gained will undoubtedly pave the way for continuous improvement and refinement in the field of underwater exploration.

While the current choice for selecting regular ball bearings is sufficient for the initial prototype with their load capacity and cost-effectiveness, the plans of larger-scale iterations with evolving size, speed, and greater axial forces transmitting through the main shaft prompt a future shift towards angular bearings.

The motor selection, which prioritizes an inrunner BLDC motor due to its efficiency and heat dissipation features, and the decision to position it inside the pressure tube for protection against the corrosive nature of salty water, remains unchanged.

To validate this as an optimal solution, future efforts will concentrate on exploring alternatives, such as developing fully waterproof thrusters with outrunner BLDC motors placed outside the pressure and the wet hull.

The rudder system's adoption of an x-plane configuration over a cross-plane design, along with the incorporation of two servomotors and auxiliary linkages is yet to be tested. The primary challenge associated with this configuration, involving the intricate linkage and steering design, as well as the transfer of rotary motion from the servos to linear motion, has been successfully resolved.

The addition of a diffuser to the propulsion system is meant to optimize hydrodynamic efficiency, reducing energy consumption and noise, but also acts as a protective measure for the propeller's blades. This solution is yet to be tested on a physical prototype. But before that, a numerical simulation (CFD) study is planned to optimize the process of evaluating new and innovative ideas before building any physical prototypes. This approach when developed and refined should prove cost- and time-effective.

The design and functionality of the ballast tank system represent the most crucial yet challenging element in the entire steering system. A key advantage, compared to traditional, inefficient thruster-based depth control systems, is energy efficiency.
Exploring various ballast tank systems revealed the intricacies and trade-offs associated with each design [14]. The common piston tank system, while precise, introduced challenges in weight distribution. Compressed gas systems exhibited quick response times but faced limitations in air supply, risking a catastrophic loss of resurfacing capabilities. Water pump systems, while continuous and self-sustaining, grappled with challenges regarding increased pressure outside ballast tanks during water expulsion, impacting overall effectiveness.
The proposed recirculating compressed air ballast system emerged as an ideal solution, ensuring air conservation through a complex circulation mechanism.
However, time constraints, budget considerations, and challenges in finding miniature valves, pumps, and other components essential for establishing a reliable and self-sufficient ballast system led to the adoption of a more accessible approach for the initial prototype.
Consequently, the prototype will incorporate a basic water pump, capable of generating sufficient pressure for a dive to 20 meters, with a solenoid valve to regulate the water flow within the ballast tanks.

In the electronic framework of the submarine prototype, the synergy between the ESP32 and Raspberry Pi controllers was chosen to establish communication, precise data acquisition, and efficient transmission. The ESP32, optimized as a microcontroller, efficiently manages mechanical functionalities, including motor and servo control, water pump operation, and rudder adjustments. Meanwhile, the Raspberry Pi, with its significant processing power and advanced connectivity options, is tasked with data analysis from sensors connected and managed via the ESP32.
External sensors such as pressure, temperature, conductivity, and O2 sensors contribute to real-time environmental data crucial for navigation and mission success. The system's modular design facilitates easy upgrades with additional sensors, enhancing its capabilities, especially during exploration missions where biological sensors can be integrated.
Internal sensors, including a leakage sensor, temperature sensors, pressure sensors, gyroscope, magnetometer, and accelerometer, focus on the submarine's structural integrity, internal conditions, and overall health. The leakage sensor, a critical safety component, detects and alerts the system of dangerous water penetration, allowing for prompt resurfacing and prevention of any further damage.
The adaptability and modularity of the electronic system ensure continuous improvement, making it well-positioned to work with the next generation of underwater exploration vehicles.

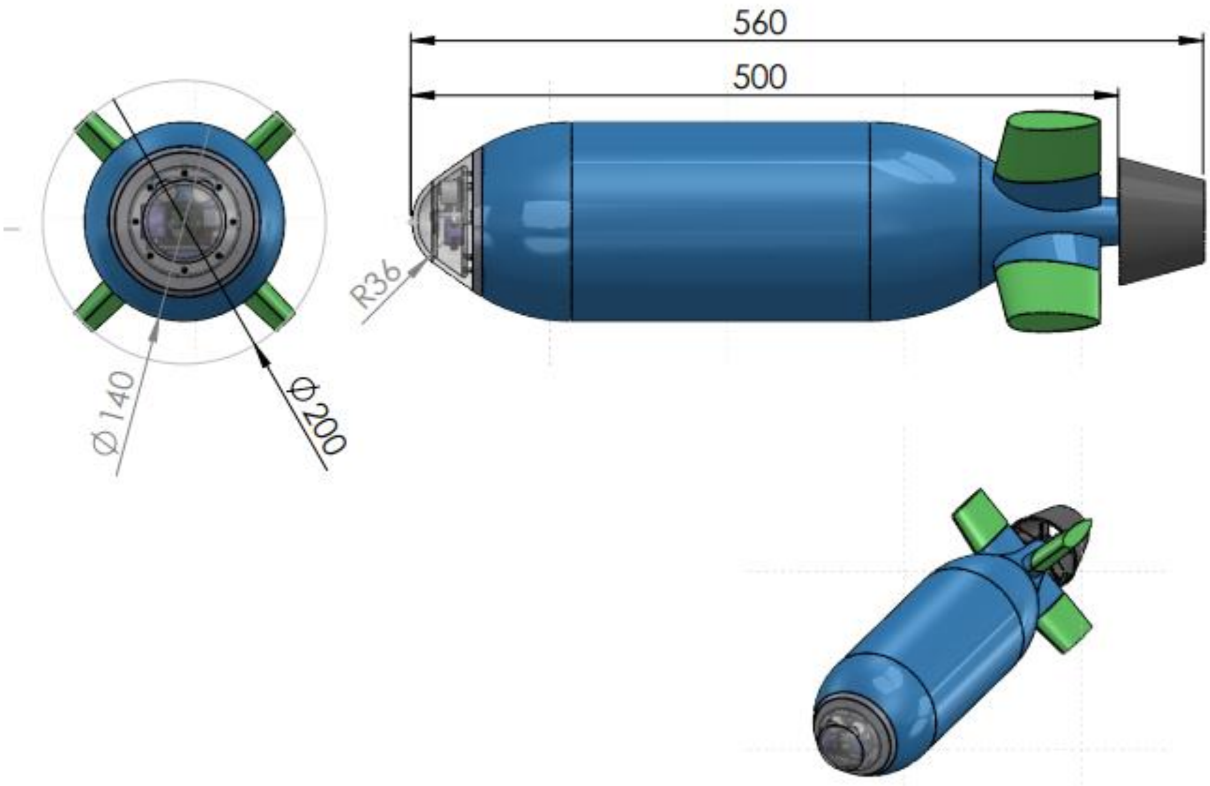


Figure 6.1 General dimensions of the Underwater Vehicle in [mm].

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