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# AUV

## Autonomous Underwater Vehicle

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The authors declare that they are the sole authors of this report and that they have not used any sources other than those listed in the bibliography and identified as references.

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# Abstract

Autonomous Underwater Vehicles (AUVs) are increasingly used in applications such as environmental monitoring, underwater inspection, and seabed mapping. However, many existing systems are either expensive, mechanically complex, or difficult to adapt for small-scale development projects. The purpose of this project was therefore to design and develop a compact and modular AUV platform using commercially available components and open-source software.

The project focused on the integration of mechanical design, propulsion, control systems, navigation architecture, and waterproof structural design into a functional underwater platform. The developed system was based on a cylindrical acrylic pressure hull combined with externally mounted thrusters controlled through a Pixhawk flight controller and a Raspberry Pi 5. A waypoint-based navigation architecture using QGroundControl and a GNSS-based buoy positioning concept was also developed as part of the system design.

The implemented platform was validated through subsystem testing and integrated underwater operation. The tests verified watertight integrity, propulsion functionality, communication between the Raspberry Pi and Pixhawk, and stable manual underwater maneuvering. In addition, simplified autonomous control sequences and mission-planning functionality were successfully demonstrated. However, fully autonomous underwater waypoint navigation could not be completely validated due to limitations related to communication, sensor integration, and project timeframe.

The project demonstrates that a modular low-cost AUV platform can be developed using commercially available hardware and open-source software while still providing a flexible foundation for future autonomous functionality and sensor integration. The results further highlight the multidisciplinary challenges associated with underwater system integration, particularly regarding waterproofing, localization, communication, and autonomous control.

**AUV, Autonomous Underwater Vehicle, Pixhawk, Raspberry Pi, Underwater Robotics**

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# Sammanfattning

Autonoma undervattensfarkoster (AUV:er) används i allt större utsträckning inom områden såsom miljöövervakning, undervattensinspektion och kartläggning av havsbottnar. Många existerande system är dock kostsamma, mekaniskt komplexa eller svåra att anpassa för mindre utvecklingsprojekt. Syftet med detta projekt var därför att utveckla en kompakt och modulär AUV-plattform baserad på kommersiellt tillgängliga komponenter och mjukvara med öppen källkod.

Projektet fokuserade på integration av mekanisk konstruktion, framdrivning, styrsystem, navigationsarkitektur samt utveckling av en trycktålig och vattentät struktur. Det utvecklade systemet baserades på ett cylindriskt akrylskrov med externa thruster som styrdes genom en Pixhawk-baserad flygkontroller och en Raspberry Pi 5. Som en del av systemarkitekturen utvecklades även ett waypoint-baserat navigationskoncept med hjälp av QGroundControl och en GNSS-baserad bojlösning för positionsbestämning.

Systemet verifierades genom delsystemstester och integrerade undervattenstester. Tester genomfördes för att verifiera vattentätighet, framdrivningsfunktion, kommunikation mellan Raspberry Pi och Pixhawk samt stabil manuell manövrering under vatten. Förenklade autonoma styrsekvenser och missionsplanering kunde också demonstreras. Fullt autonom waypoint-navigering under vatten kunde däremot inte verifieras fullständigt på grund av begränsningar relaterade till kommunikation, sensorintegration och projektets tidsram.

Projektet visar att det är möjligt att utveckla en modulär och kostnadseffektiv AUV-plattform med hjälp av kommersiellt tillgänglig hårdvara och mjukvara med öppen källkod, samtidigt som systemet erbjuder goda möjligheter för framtida vidareutveckling inom autonomi och sensorintegration. Resultaten belyser även de multidisciplinära utmaningar som uppstår vid utveckling av autonoma undervattenssystem, särskilt inom områden såsom vattentätning, positionering, kommunikation och autonom styrning.

**Nyckelord:** AUV, autonom undervattensfarkost, Pixhawk, Raspberry Pi, undervattensrobotik

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Autonomous Underwater Vehicles (AUVs) have become increasingly important in a wide range of marine applications, including environmental monitoring, seabed mapping, and underwater inspection. Their ability to operate without direct human control makes them particularly well-suited for complex, inaccessible underwater environments. This chapter introduces the background and motivation for the project, presents the problem statement, and defines the scope of the work. It also provides an overview of the report's structure.

## 1.1 On the content

Autonomous Underwater Vehicles (AUVs) have become increasingly important in applications such as environmental monitoring, seabed mapping, and underwater inspection. Their ability to operate without direct human control makes them particularly valuable in environments where communication is limited or impractical [10].

Despite significant advances in AUV technology, many existing systems are either complex and costly or limited in terms of maneuverability and flexibility. In particular, achieving a balance between efficient propulsion and precise control remains a key challenge, especially for small-scale and resource-constrained designs [4].

The aim of this project is to design and develop a compact AUV that balances these trade-offs by combining a streamlined structure with a multi-thruster configuration. The focus is on creating a system that is both practical to implement and capable of controlled underwater operation.

## 1.2 Scope

This project focuses on the design and development of a compact Autonomous Underwater Vehicle (AUV) intended for small-scale applications. The primary objective is to investigate how a torpedo-shaped structure can be combined with a multi-thruster configuration to improve maneuverability while maintaining a relatively simple and practical design.

Initially, the project was intended to include onboard sensors to enable the AUV to perform a specific, verifiable task. However, after further evaluation, it was con-

cluded that integrating such systems would significantly increase the complexity, cost, and development time. As a result, the scope was refined to focus on the vehicle's core functionality.

Another key design consideration involved the construction of a pressure-resistant and watertight hull that could still be opened for maintenance, battery replacement, and component access. While this was identified as a major challenge, the project also revealed that control and autonomous operation introduced significant complexity, particularly in achieving stable and reliable behavior.

The scope of the project is therefore limited to system design, basic control, and physical implementation using commercially available components. Advanced topics such as sensor-based task execution, high-precision navigation, and hydrodynamic optimization are not considered within this work. Instead, the focus is on developing a functional and accessible AUV platform while addressing key practical challenges in design and control.

### 1.3 Outline

The remainder of this report is structured as follows. Chapter 3 presents the theoretical background and related work, including key concepts in AUV design as well as a review of existing approaches and design trade-offs. Chapter 4 describes the methodology and system design, including mechanical construction, propulsion configuration, and control implementation. Chapter 5 presents the results and evaluation of the developed system, focusing on functionality, maneuverability, and practical performance. Finally, Chapter 6 concludes the report and discusses the main findings, limitations, and potential directions for future work.

## Chapter 2

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# Theoretical Background and Related Work

This chapter presents the theoretical background and related work relevant to the design and development of Autonomous Underwater Vehicles (AUVs). It introduces the fundamental principles underlying AUV systems, followed by a review of existing research and approaches in the field. Together, these sections provide the necessary context for understanding the design choices and implementation presented in this report.

## 2.1 Theoretical Background

This section presents the theoretical background relevant to the design and operation of Autonomous Underwater Vehicles (AUVs). It introduces the fundamental concepts required to understand the system, including vehicle structure, propulsion, sensing, control, and buoyancy. These principles form the basis for the design choices and implementation described in later sections of the report.

### 2.1.1 Autonomous Underwater Vehicle (AUV)

An Autonomous Underwater Vehicle (AUV) is an unmanned underwater system capable of operating without real-time human control. These vehicles are designed to perform a wide range of tasks beneath the water surface, including environmental monitoring, seabed mapping, inspection, and military applications. AUVs operate in environments where direct communication with operators is limited, placing high demands on onboard autonomy, navigation, and control systems. Smaller AUVs, which are the focus of this report, are typically equipped with electric propulsion systems, onboard control electronics, pressure-resistant hulls, and sensors selected based on the intended mission. These components together enable the vehicle to navigate, maintain stability, and perform its assigned tasks underwater. This makes compact and efficient system design particularly important in small-scale AUV applications.

### 2.1.2 Sensors and navigation

Autonomous operation in underwater environments requires accurate estimation of both position and orientation. Since direct communication with external systems is limited underwater, AUVs rely heavily on onboard sensors for navigation and control. A fundamental component in this process is the Inertial Measurement Unit (IMU), which provides information about the vehicle's motion and orientation. An

IMU typically consists of accelerometers, gyroscopes, and sometimes magnetometers, which measure linear acceleration, angular velocity, and magnetic field direction, respectively [6].

From a theoretical perspective, these measurements are used in a process known as state estimation, in which the vehicle's position, velocity, and orientation are estimated from sensor data. This is typically achieved by integrating acceleration and rotational rates over time. However, this approach introduces accumulated errors, known as drift, due to sensor noise and bias, which reduces accuracy over time without external correction. This limitation is particularly relevant for AUV systems, where GPS signals cannot be used underwater due to the attenuation of electromagnetic waves [6].

For surface or near-surface operations, GPS can provide absolute position references, whereas fully submerged operations require alternative methods such as acoustic positioning or dead reckoning [10]. In some practical implementations, external communication links, such as tethered connections to surface units, are used to enable positioning and control. This approach is widely used in remotely operated vehicles (ROVs), where a cable provides power and transmits data between the vehicle and a surface operator [3] [8] [11]. The combination of multiple sensor sources, often referred to as sensor fusion, allows the AUV to estimate its state more accurately, enabling stable control, trajectory tracking, and response to environmental disturbances [6].

### 2.1.3 Propulsion

AUV propulsion is typically achieved using electrically driven thrusters, which generate thrust by accelerating water through a propeller. From a physical perspective, this process is based on Newton's third law, where the acceleration of water produces an equal and opposite reaction force that propels the vehicle forward. These thrusters are responsible for both forward motion and maneuvering of the vehicle.

By placing multiple thrusters at different positions and orientations, it is possible to control the vehicle's movement in several degrees of freedom. The forces and moments generated by the thrusters determine the resulting motion of the vehicle [1]. This can be achieved through differential thrust, where variations in thrust between individual thrusters produce both rotational and translational motion, enabling control of yaw, pitch, and in some cases vertical movement.

The number and configuration of thrusters vary depending on the intended application and design complexity. Systems with multiple thrusters offer improved maneuverability and precise control, but at the cost of increased mechanical and control complexity. Simpler AUV designs may use a single thruster for forward propulsion, relying on additional mechanisms such as control surfaces or buoyancy adjustments to achieve directional and depth control. In contrast, multi-thruster configurations provide improved maneuverability and allow for more flexible operation, particularly in complex environments, but increase system complexity [4].

### 2.1.4 Steering and control

Steering and control of an AUV involve regulating its motion and orientation based on sensor input and predefined objectives. From a theoretical perspective, this can be described as a feedback control problem, where control inputs are continuously adjusted based on the difference between the desired and estimated state of the system. The control system processes data from onboard sensors, such as the IMU and positioning systems, to estimate the current state of the vehicle, and control algorithms determine how the propulsion system should be actuated to achieve the desired motion [1].

The motion of the vehicle is governed by forces and moments acting on it, and can be described using a mathematical model with six degrees of freedom, representing both linear and rotational motion [1]. Based on this model, control systems determine how thrust and torque should be applied to achieve the desired trajectory and orientation. Propulsion systems generate thrust by accelerating water, resulting in a reaction force according to Newton's third law. When multiple thrusters are used, the resulting forces and moments determine the vehicle's motion. In multi-thruster configurations, steering can be achieved through differential thrust, where variations in thrust between thrusters produce torque and enable rotational motion around the vehicle's axes, allowing control of yaw, pitch, and in some cases roll depending on the thruster arrangement.

An alternative approach to steering is the use of control surfaces, such as fins or rudders, which generate hydrodynamic forces when the vehicle is in motion. These forces depend on the flow of water over the surfaces and are therefore only effective when the vehicle has sufficient forward velocity [9]. The choice of steering method depends on the design requirements, including maneuverability, energy efficiency, and system complexity. Thruster-based control offers high flexibility and precise maneuvering, while control surfaces provide a simpler and often more energy-efficient solution.

### 2.1.5 Bouyancy and depth control

Buoyancy plays a fundamental role in the operation of underwater vehicles, as it determines whether the vehicle sinks, floats, or remains at a constant depth. From a physical perspective, the buoyant force acting on the vehicle is described by Archimedes' principle, which states that an object submerged in a fluid experiences an upward force equal to the weight of the displaced fluid [5].

A common design approach is to achieve neutral buoyancy, where the overall weight of the vehicle is equal to the buoyant force from the surrounding water. In this state, the AUV neither sinks nor rises, allowing it to maintain a constant depth with minimal energy consumption. In some designs, a slightly positive buoyancy is preferred, ensuring that the vehicle will naturally ascend to the surface in the event of system failure, which improves operational safety [2]. Depth adjustments can then be performed using the propulsion system, for example, by generating vertical thrust.

An alternative method for depth control is the use of active buoyancy systems, such as ballast tanks or variable buoyancy systems. These systems adjust the vehicle's buoyancy by controlling the amount of water or fluid inside an internal volume. By increasing the mass of the vehicle, it becomes negatively buoyant and sinks, while removing fluid makes it positively buoyant and causes it to rise. Such approaches are also inspired by both conventional submarine ballast systems and biological mechanisms found in marine animals [2]. Compared to thruster-based depth control, buoyancy-based systems can offer improved energy efficiency, as they do not require continuous power to maintain depth. However, they introduce additional mechanical complexity and often respond more slowly to changes in depth. The choice between these approaches depends on the intended application, as well as constraints related to system complexity, responsiveness, and energy consumption.

## 2.2 Related Work

Autonomous Underwater Vehicles (AUVs) are widely used in scientific, commercial, and military applications, particularly for seabed mapping and environmental monitoring [10]. Previous research has shown that AUVs enable high-resolution data collection and can operate independently of support vessels, making them well-suited for exploration of complex and remote underwater environments. In addition to their applications, significant research has focused on the underlying technologies required for AUV operation, including propulsion systems, navigation and sensing techniques, and control algorithms [1, 6, 9]. These technologies are essential for enabling stable motion, accurate positioning, and reliable operation in challenging underwater conditions. Furthermore, practical underwater systems such as ROVs demonstrate how similar technologies are applied in real-world environments, particularly in cases where communication and control are required [3, 8]. However, many existing AUV systems are designed for large-scale research missions and often rely on advanced and complex technologies.

### 2.2.1 Small scale AUV

In addition to conventional torpedo-shaped AUVs, recent research has explored alternative vehicle designs aimed at improving maneuverability in complex underwater environments, particularly near the seafloor. Traditional AUV configurations are optimized for efficient forward motion, but their limited maneuverability can make it challenging to operate in close proximity to the seabed. To address these limitations, new concepts such as Autonomous Underwater Helicopters (AUHs) have been proposed [4]. These vehicles typically feature a disc-shaped design and are capable of hovering, landing, and operating at varying altitudes above the seafloor, enabling more flexible interaction with the environment.

While AUHs differ significantly from traditional AUVs in both structure and propulsion principles, they illustrate a broader trend in AUV research towards improved maneuverability and adaptability. This is particularly relevant for small-scale sys-

tems, where precise control and the ability to operate in confined or complex environments are important design considerations.

Conventional torpedo-shaped AUVs, on the other hand, typically rely on a single main thruster for forward propulsion, combined with control surfaces such as fins or rudders for steering [10]. This configuration is highly efficient for forward motion but offers limited maneuverability, especially at low speeds or in hovering conditions [9]. To overcome these limitations, multi-thruster configurations are often employed in smaller-scale and practical implementations, where maneuverability is prioritized. By using differential thrust, these systems can generate both translational and rotational motion, allowing more flexible control of the vehicle [4]. However, this increased flexibility comes at the cost of higher system complexity and reduced hydrodynamic efficiency.

Beyond structural design, different control and propulsion strategies also play a central role in AUV performance. Systems based on control surfaces emphasize efficiency and are well-suited for steady forward motion, while multi-thruster configurations enable operation at low speeds and in hovering conditions through differential thrust [4]. In addition, buoyancy-based approaches, such as ballast tanks or variable buoyancy systems, provide an alternative method for depth control by adjusting the vehicle's density without continuous propulsion [2, 9].

Taken together, these approaches reflect different design priorities and highlight a fundamental trade-off between efficiency and maneuverability, which is a key consideration in the development of small-scale AUV systems.

### 2.2.2 DIY AUV Projects

While this type of hybrid approach is less commonly addressed in academic research, it is more frequently explored in practical implementations. In particular, small-scale AUV designs that combine a torpedo-shaped structure with multiple thrusters are often documented through online platforms such as YouTube. These projects typically focus on accessibility, using commercially available components and simplified control systems to achieve functional underwater vehicles [11].

A representative example is presented in [11], where a small-scale autonomous underwater vehicle is developed using off-the-shelf components and a multi-thruster configuration. The project demonstrates how compact underwater systems can be constructed with a focus on practical functionality, and highlights key challenges such as system integration, waterproofing, and control. It also illustrates a practical solution for communication and positioning, where a floating surface unit connected via a cable enables access to GPS data and real-time signal transmission.

While fewer examples of fully autonomous small-scale AUVs are available, a larger number of practical implementations are documented as remotely operated vehicles (ROVs) [12, 13]. These projects provide valuable insight into the construction of compact underwater vehicles, including structural design, component integration,

and practical waterproofing techniques. They also demonstrate a range of design approaches, such as the use of control surfaces for steering and simple ballast systems for depth control. Although these systems are not fully autonomous, they illustrate how key technologies such as propulsion, buoyancy control, and mechanical design can be implemented in practice. As such, they complement academic research by highlighting real-world constraints and practical engineering considerations that are particularly relevant for the development of small-scale AUV systems.

This chapter presents the design methodology used in the development of the AUV system. The process is based on a User-Driven Design (UDD) approach, where system requirements, constraints, and design decisions are derived from intended applications and user needs. The chapter describes how these factors influenced key design choices, including system functionality, component selection, and overall architecture, ultimately resulting in a compact, practically implementable solution.

### 3.0.1 Defining Design Method

To address the demand for an Autonomous Underwater Vehicle (AUV), a User-Driven Design (UDD) approach was applied. By first developing a UDD table, the project could be structured around the intended user needs, application areas, constraints, and possible technical solutions. The complete UDD table is presented in Appendix A.1. It divides the project into smaller functional areas, making it easier to understand why specific design decisions were made.

It should be noted that the UDD mainly established the foundation for identifying relevant applications and user needs. The final design solutions were also strongly influenced by practical limitations, such as budget, component availability, technical feasibility, and the limited time frame of the project.

The application areas considered relevant to the project were selected based on potential market needs, including environmental monitoring, seabed mapping, and underwater inspection tasks. Later in the project, potential military applications were also identified. Although several of these tasks could be performed using a Remotely Operated Vehicle (ROV), an AUV can simplify the operation by reducing the need for continuous manual control. This can increase efficiency, especially in missions where predefined navigation paths and autonomous operation are beneficial.

The primary users of the system are expected to be engineers, researchers, and military operators. These user groups require a reliable and easy-to-operate vehicle that can perform underwater missions without requiring extensive knowledge of the internal system design. Therefore, simplicity, robustness, and autonomous functionality were identified as important design drivers.

### 3.0.2 Functional Requirements

Based on the UDD analysis, the system requirements were divided into general and itemized functionalities, defining what the AUV must be capable of achieving.

The system's general functionality is to operate as a fully autonomous underwater vehicle capable of navigation, propulsion, and data collection. This includes maintaining structural integrity under pressure, generating controlled movement, and executing predefined missions without external interaction.

More specifically, the itemized functionalities include autonomous waypoint navigation, depth measurement and control, and onboard data logging. The AUV must be able to follow predefined waypoints with acceptable accuracy despite limitations in positioning, as well as maintain a target depth using pressure-based sensing.

### 3.0.3 Constraints

To reduce the project's scope and ensure feasibility, several constraints were defined. These constraints guided key design decisions and helped optimize the development process in order to achieve the best possible result within the given limitations. The restrictions were primarily based on time, budget, and technical feasibility, requiring certain solutions to be modified or completely excluded.

One example of this is the initial concept of implementing a ballast tank system using a DC motor to drive a syringe mechanism that controls buoyancy by pumping water in and out. However, due to limited internal space within the AUV, this solution was not feasible. Instead, an additional thruster was implemented to control the vertical position of the vehicle, providing a simpler and more compact solution.

Another important design adaptation concerns the navigation system. A Pixhawk flight controller was selected to handle waypoint storage and autonomous control. However, this system requires access to GPS data, which is not available underwater. To overcome this constraint, a Raspberry Pi 5 equipped with a GNSS HAT module was implemented. GPS data is obtained via a buoy-mounted receiver at the surface and transmitted to the Pixhawk, enabling the AUV to execute its mission [7].

Mechanical constraints also play a significant role, as the vehicle must fit within a compact cylindrical structure while maintaining sufficient buoyancy and internal space for components. Additionally, the structure must withstand pressures corresponding to depths of up to 10 meters, requiring a robust and fully sealed design. To address this, a pressure-resistant enclosure was developed using a cylindrical tube combined with CNC-machined end caps, ensuring both watertight sealing and structural integrity.

Energy constraints are also significant, as the system must operate for a limited time on battery power. This requires efficient use of propulsion and onboard electronics, further influencing the overall system design.

### 3.0.4 Design Choices

Based on the identified needs and constraints, a cylindrical design was selected to optimize hydrodynamic performance while allowing efficient placement of internal components. This geometry simplifies the integration of electronics and mechanical parts within a compact volume. Additionally, a cylindrical structure provides favorable mechanical properties under external pressure, making it well-suited for underwater applications where structural integrity is critical.

For propulsion and maneuverability, a thruster-based system was chosen over more complex alternatives such as control fins. This decision was motivated by the need for robustness, simplicity, and reliable control in low-speed underwater conditions. By using differential thrust, the system can generate both forward motion and yaw control without introducing additional mechanical complexity.

Furthermore, the use of multiple thrusters enables greater flexibility in controlling the vehicle's movement, including vertical positioning. This became particularly important after the initial ballast system was excluded due to space limitations. As a result, the propulsion system not only provides horizontal movement but also contributes to depth control, simplifying the overall system design.

### 3.0.5 System Architecture Considerations

To enable autonomous waypoint navigation, a system architecture separating high-level processing from low-level control was implemented. A dedicated flight controller was used for real-time control and mission execution, ensuring stable and reliable operation during autonomous missions.

Due to the limitations of underwater environments, particularly the lack of direct access to global positioning signals, an auxiliary system was introduced to provide positional data. A single-board computer equipped with a GNSS module was used to acquire positioning information at the surface via a buoy-based solution. This data is then relayed to the control system, enabling mission execution despite the absence of direct GPS availability underwater.

This architecture allows the system to maintain autonomous functionality while addressing environmental limitations, illustrating how the overall system design was shaped by the constraints identified in the UDD analysis.

The purpose of this section is to present the conceptual design and modeling of the developed AUV system. Based on the design methodology described in Chapter 4, the system is here described from a system-level perspective, focusing on how the different subsystems interact and how the overall functionality is achieved.

The conceptualization provides a structured overview of the system architecture, while the modeling introduces simplified mathematical representations of the vehicle's motion and control. Together, these descriptions form the foundation for understanding how the AUV operates and how the design choices are translated into a functional system.

### 4.1 Conceptualization and modeling

#### 4.1.1 Early Design Concepts

During the early stages of the design process, several alternative concepts for the mechanical structure and vehicle configuration were evaluated. A major focus of the initial design phase was the selection of propulsion, maneuverability, buoyancy control, and hull construction principles.

##### 4.1.1.1 Propulsion and Maneuverability

The use of control fins for steering was considered early in the project but was quickly discarded. Although fins are commonly used in traditional torpedo-shaped AUVs, their implementation would require additional moving mechanical components and dynamic shaft seals, significantly increasing the complexity of waterproofing and mechanical integration. Instead, a differential-thrust configuration was selected, where maneuverability is achieved through independently controlled thrusters.

Another important factor influencing this decision was the selected control architecture. The Pixhawk flight controller and the ArduSub software environment were primarily optimized for multi-thruster configurations, supporting up to eight independently controlled thrusters directly through the control system. This simplified both software integration and actuator control compared to implementing fin-based

steering mechanisms.

The selected thrusters were commercially available underwater thrusters equipped with integrated Electronic Speed Controllers (ESCs). These units were already waterproofed by the manufacturer, relatively inexpensive, and simplified the overall electrical integration process by eliminating the need for separate ESC waterproofing and external motor controller integration. Furthermore, the overall dimensions and expected mass of the AUV required relatively powerful thrusters in order to provide sufficient propulsion and maneuverability.

Due to the physical dimensions of the selected thrusters, placing both units in the stern section was not mechanically feasible within the available hull geometry. In addition, maneuverability could be improved by orienting the steering thruster perpendicular to the longitudinal axis of the vehicle. As a result, the AUV was designed with one thruster mounted in the stern for forward propulsion and a second thruster mounted perpendicular to the hull in the bow section for yaw control. An early prototype of the redesigned bow and stern sections is shown in Figure 4.1.



(a) Bow section



(b) Stern section

Figure 4.1: Early 3D-printed prototypes of the bow and stern sections. The bow section illustrates the internal integration geometry for the thruster configuration, while the stern section shows the integration of the primary propulsion thruster and surrounding hydrodynamic support structure.

#### 4.1.1.2 Depth Control and Buoyancy

To control depth, the initial design concept involved the implementation of a ballast-based buoyancy control system. Such a system would allow the vehicle to actively regulate its buoyancy and maintain a more stable operating depth while also reducing the precision required for buoyancy balancing during assembly.

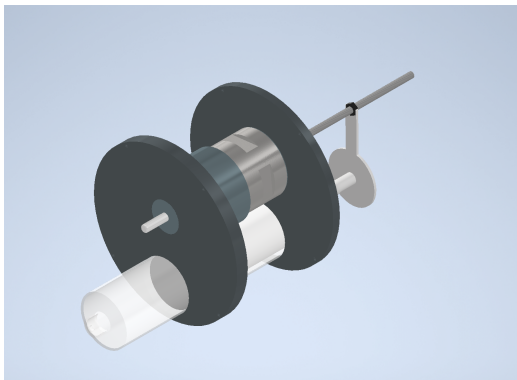
Following an evaluation of potential components, early CAD models were developed in Autodesk Inventor to estimate the required installation space and visualize subsystem integration. A syringe-based solution was identified as the most practical ballast mechanism due to its inherent watertightness, pressure capability, and compatibility with flexible tubing. The syringe was intended to be actuated using a DC motor-driven mechanism. An early conceptual design of the ballast-based buoyancy

control system is shown in Figure 4.2.

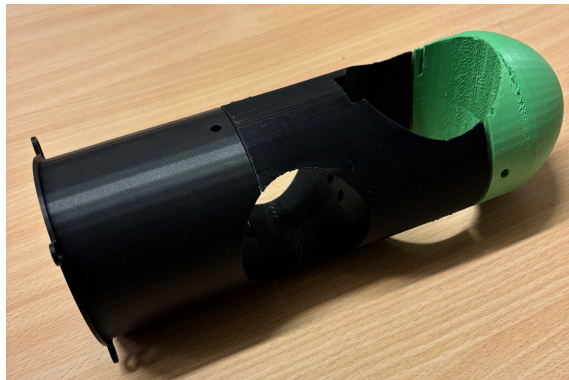
However, as the CAD models evolved, it became clear that the ballast system and its associated mechanical components would occupy too much internal volume within the intended hull geometry. At this stage, a transparent acrylic tube with a diameter of 90 mm had already been selected as the primary pressure hull. The transparent acrylic material was chosen mainly to simplify early testing and troubleshooting, as the internal components and possible leakage could easily be visually inspected during operation. In addition, larger diameter pressure tubes would significantly increase material costs, making the selected diameter a practical compromise between internal volume, manufacturability, and overall project budget.

Since the ballast system was already considered mechanically complex and space-consuming, an alternative depth-control solution was required. The final solution was to integrate an additional vertically oriented thruster responsible for depth regulation, which can be seen in Figure 4.2. This decision was motivated both by the compatibility of the Pixhawk control architecture with multi-thruster configurations and by the relatively low cost of adding an additional thruster compared to implementing a complete ballast system. Consequently, the bow section required further redesign to accommodate the vertical thruster, while the buoyancy balancing of the vehicle became increasingly important.

To prevent the AUV from either sinking or floating uncontrollably, the vehicle was designed to achieve approximately neutral buoyancy, meaning that the total vehicle weight corresponded closely to the buoyant force generated by the displaced water.



(a) Ballast system concept



(b) Redesigned bow section

Figure 4.2: Design iterations during the early development phase of the AUV. Figure (a) shows the proposed ballast-based buoyancy control system utilizing a syringe-driven mechanism actuated by a DC motor. Figure (b) shows a later redesign of the bow section following the transition from ballast-based depth regulation to a vertically oriented thruster configuration.

### 4.1.1.3 Hull and Sealing Design

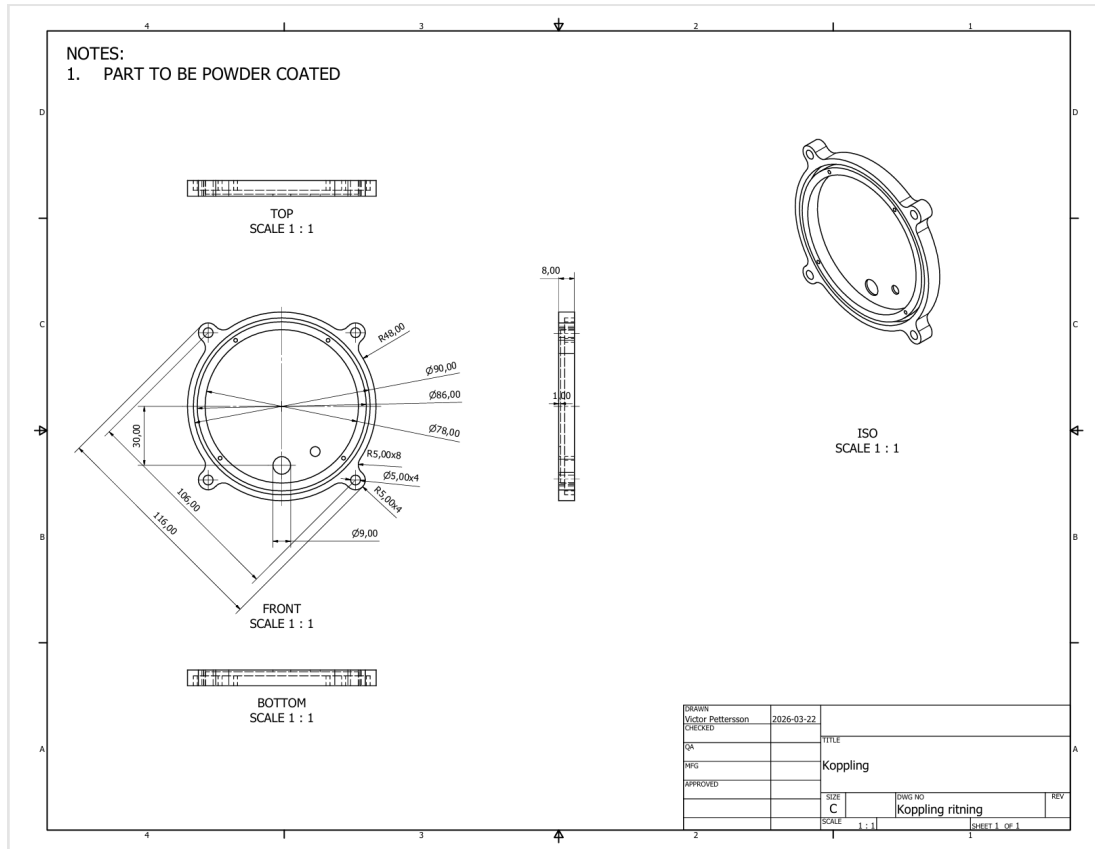
An early design decision was that only the central acrylic pressure hull needed to be fully watertight, since all sensitive electronics and power systems would be located inside this compartment. The bow and stern sections were therefore primarily designed for hydrodynamic shaping and external component integration rather than pressure resistance.

Initially, the sealing solution involved 3D-printed transition components with integrated O-ring grooves positioned between the acrylic tube and the bow and stern assemblies. The intention was to create a precise mechanical fit while maintaining watertightness. However, this concept was quickly abandoned because the available 3D-printing materials and manufacturing tolerances could not guarantee sufficient watertight reliability or structural rigidity under pressure.

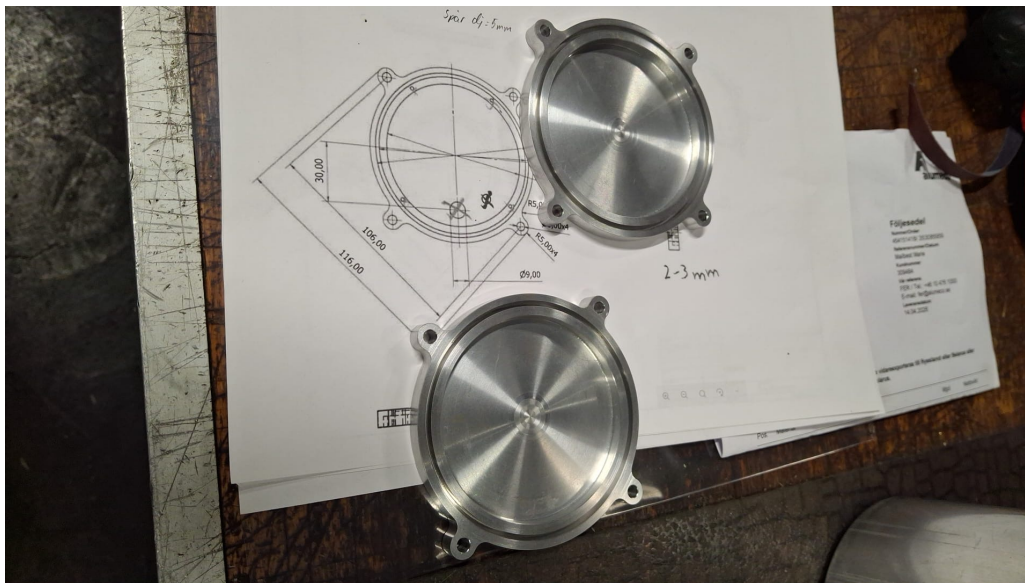
As a result, the sealing interfaces instead had to be manufactured in metal to ensure dimensional stability, reliable O-ring compression, and long-term sealing performance. Despite this improvement, the original concept still relied on the acrylic tube itself carrying significant structural loads, which introduced concerns regarding deformation and sealing reliability due to flexing of the tube.

To address these issues, inspiration was taken from traditional cylindrical pressure-vessel designs, where rigid end caps compress O-rings against the tube from both sides. The complete sealing system was designed in Autodesk Inventor, and aluminum was selected as the material for the end caps due to its low weight, corrosion resistance, and manufacturability.

To guarantee sufficient machining precision for the O-ring grooves and sealing surfaces, a mechanical workshop, Burseryds Mekaniska AB, was contacted. The company sponsored both the aluminum material and the machining process required to manufacture the final pressure-hull end caps. The technical manufacturing drawing is shown in Figure 4.3(a), while the completed machined components are shown in Figure 4.3(b).



(a) Technical drawing



(b) Manufactured aluminum end caps

Figure 4.3: Development and manufacturing of the aluminum sealing interfaces for the acrylic pressure hull. Figure (a) shows the technical drawing used for manufacturing, including the O-ring groove geometry and mounting features. Figure (b) shows the completed machined aluminum end caps manufactured for the final pressure-hull assembly.

### 4.1.2 Navigation, Control, and Power Distribution

To enable vehicle control, navigation, and future autonomous functionality, the system was developed around two primary control units: a Pixhawk flight controller and a Raspberry Pi 5. The Pixhawk was responsible for low-level control and propulsion management, while the Raspberry Pi handled higher-level data processing, communication, and integration with external systems.

By combining the Raspberry Pi and Pixhawk, a bidirectional communication link was established between the flight controller and an external computer through the MAVLink protocol. This communication architecture enabled mission data and control commands to be transmitted from the external computer to the Pixhawk while simultaneously allowing telemetry and sensor data to be transferred back in real time. Through QGroundControl, information such as compass heading, orientation, and positional data could be accessed and monitored during operation. The system architecture, therefore, created the foundation for future waypoint-based autonomous navigation and mission planning.

The Pixhawk's internal IMU, consisting of a gyroscope, accelerometer, and magnetometer, provided orientation and motion data through the MAVLink interface. This enabled sensor information from the flight controller to be accessed externally through the Raspberry Pi and QGroundControl, creating a flexible architecture for future implementation of more advanced navigation and autonomous control systems.

For future implementation, an external GNSS-based positioning system was planned in which the GPS receiver would be placed above the water surface using a buoy connected to the AUV through a cable. Since GPS signals cannot penetrate water, this solution would enable continuous positional updates even while the vehicle is submerged. However, this functionality was not fully implemented within the timeframe of the project and therefore remained at the conceptual stage.

The power distribution system was based on a LiPo battery supplying power to both the propulsion system and the onboard electronics. Since the different subsystems required different operating voltages, DC-DC step-down converters were implemented to provide stable and reliable voltage regulation for components such as the Raspberry Pi and Pixhawk. The electrical system was also designed with separation between high-current propulsion components and sensitive electronics in order to reduce the risk of electrical interference and system instability during operation.

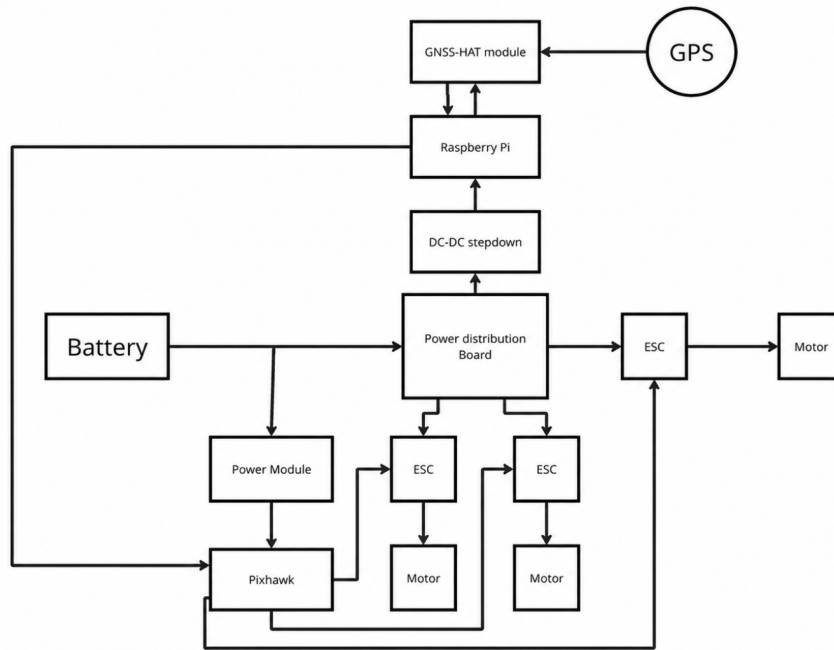


Figure 4.4: System architecture of the AUV showing power distribution, control system, and sensor integration.

## 4.2 Implementation

### 4.2.1 The Hull

The hull was constructed as a three-part structure consisting of a central section, a bow, and a stern. The central section forms the core of the vehicle and is designed to be both pressure-resistant and watertight, while the bow and stern sections are designed to allow water flow and accommodate external components such as thrusters.

The bow and stern sections were designed using CAD software (Autodesk Inventor) and manufactured using 3D printing in PLA. Due to the size limitations of the printer and routing constraints for internal cabling, the bow was divided into three separate parts, which were later assembled. These parts were equipped with alignment features such as recesses and plugs to simplify assembly. Similarly, the stern was divided into two parts and assembled using screws and nuts.

The central hull section was constructed using an acrylic tube. Custom aluminum end caps were manufactured to seal both ends of the tube. Each end cap included a machined groove for O-ring placement, enabling watertight sealing. The end caps were mounted by tightening stainless steel threaded rods between them, compressing the O-rings against the acrylic tube to achieve a sealed enclosure. The tightening force was applied using a torque wrench to ensure sufficient sealing without damaging the threads. The aluminum components were manufactured in a mechanical workshop, where the sealing grooves were turned, and the external geometry was milled.

To verify watertight integrity, the hull was tested progressively during assembly. Initially, the central section was sealed and submerged in water for approximately 16 hours, with absorbent material placed inside to detect leakage. Finally, the hull was submerged to greater depths to verify structural integrity and sealing performance under increased external pressure.

After successful testing, holes were drilled in the aluminum end caps to allow the passage of cables for thrusters and the GPS communication system. These penetrations were sealed using waterproof cable glands. The complete hull assembly, including the bow, stern, and thrusters, was then assembled and subjected to additional testing.

### 4.2.2 Propulsion and Control System

The propulsion system consists of electrically driven thrusters equipped with integrated electronic speed controllers (ESCs), mounted externally on the vehicle. These thrusters are controlled by a Pixhawk flight controller, which generates PWM signals to regulate the thrust output of each unit. By varying the speed of individual thrusters, the system enables differential thrust, allowing both forward motion and rotational control of the vehicle. The control architecture is divided into two levels. A Raspberry Pi is used for high-level control and navigation, while the Pixhawk handles low-level control and actuation. A predefined mission path is created in QGroundControl, where a sequence of waypoints is defined. During operation, the Raspberry Pi reads this mission data and compares the desired position with the current position obtained from an external GPS system. Based on this comparison, the Raspberry Pi generates control inputs that are transmitted to the Pixhawk. The flight controller then translates these inputs into actuator commands, adjusting the thrust of each motor to achieve the desired motion. This architecture enables the system to perform controlled and autonomous navigation by combining high-level decision-making with real-time control of the propulsion system.

The system is powered by an onboard battery, connected via a power distribution module, which supplies power to the different subsystems. A step-down converter is used to provide appropriate voltage levels for the low-power component, Raspberry Pi, while the power module provides a stable 5 V supply to the Pixhawk directly from the battery. The internal components are mounted using custom-designed 3D-printed brackets, which provide structural support and ensure proper positioning of the electronics within the enclosure.

### 4.2.3 Navigation and Communication

The navigation and communication system is based on an external GPS solution mounted on a surface buoy. Since GPS signals cannot be received underwater, positioning data is obtained at the surface and transmitted to the vehicle via a tethered connection.

The Raspberry Pi is responsible for receiving and processing this data. It com-

municates with the Pixhawk flight controller using a serial connection, enabling the transfer of navigation information and control commands. This setup allows the system to maintain positional awareness and execute waypoint-based navigation despite the limitations of the underwater environment.



Figure 4.5: Final prototype of the developed AUV showing the modular hull structure, transparent electronics compartment, and integrated propulsion system.

The following section presents the evaluation and verification of the implemented AUV system. Due to the limitations associated with underwater communication and the lack of continuous quantitative measurement data during submerged operation, large parts of the verification process relied primarily on direct visual observation, recorded video footage, and functional subsystem testing. Although several limitations affected the extent of the final validation process, a substantial effort was made to evaluate the integrated system under realistic operating conditions in order to assess the practical functionality and feasibility of the implemented AUV platform.

## 5.1 Validation

This chapter presents the validation and verification process used to evaluate the implemented AUV system. The objective of the testing was to determine whether the system fulfilled the functional and technical requirements defined during the design process. Verification was performed on both subsystem and system level, including structural integrity, propulsion, control, communication, and navigation functionality.

The following subsystems and functionalities were selected for validation and verification:

- Watertight integrity of the hull
- Pressure resistance of the hull structure
- Thruster functionality and propulsion control
- Differential thrust and maneuverability
- Communication between the Raspberry Pi and Pixhawk
- GPS data acquisition and transmission
- Waypoint-based navigation
- Power distribution and voltage regulation
- Integration and operation of the complete AUV system

### 5.1.1 Watertightness and pressure resistance tests

The watertight integrity of the hull was verified in three stages. Initially, the general sealing solution was tested by placing absorbent paper inside the hull to simplify the detection of possible leakage during submersion. As shown in Figure 5.1, the initial sealing test was performed by submerging the central hull section while absorbent paper was placed inside the enclosure to detect leakage.

After the initial validation, all cable penetrations and sealing interfaces were installed, and the test was repeated to verify the watertight integrity of the complete enclosure configuration. As shown in Figure 5.2, the assembled hull was submerged during pressure and watertightness testing to verify sealing performance under realistic operating conditions.



Figure 5.1: Initial watertightness test of the central hull section.



Figure 5.2: Watertightness testing of the assembled AUV hull with all cables during submersion.

Finally, the hull was tested under increased external pressure to verify structural integrity and pressure resistance. As shown in Figure 5.3, the hull was submerged using a tethered line during pressure testing. Absorbent paper was again placed inside the enclosure, after which the vehicle was submerged to a depth of approximately 2.5 meters for 10 minutes. After recovery, no signs of internal water intrusion were observed.



Figure 5.3: Execution of the pressure resistance test, where the AUV hull was submerged using a tethered line to evaluate sealing performance under increased external pressure.

Test	Condition	Result
Initial sealing test	Water submersion, 16 hours	No leakage detected
Cable penetration test	Water submersion, 1 hours	No leakage detected
Pressure test	2.5 m depth, 10 min	No leakage detected

Table 5.1: Summary of hull sealing and pressure tests

### 5.1.2 Thruster tests

The propulsion and control system was verified through both QGroundControl and manual controller testing. Initial testing confirmed that the Pixhawk flight controller could successfully arm the thrusters and establish correct communication with the propulsion system. Each thruster was tested individually to verify correct actuation and response to control inputs.

Further verification was performed using the Raspberry Pi control interface, where

manual control commands were transmitted to the Pixhawk through a handheld controller. During testing, the thrust output of each motor could be monitored in real time through the control interface, allowing verification that each thruster corresponded to its designated control input. The propulsion system was also verified to respond proportionally to varying input levels, where increased controller input resulted in increased thrust output.

Finally, the rotational direction of each thruster was verified to ensure correct maneuverability and steering response during differential thrust operation.

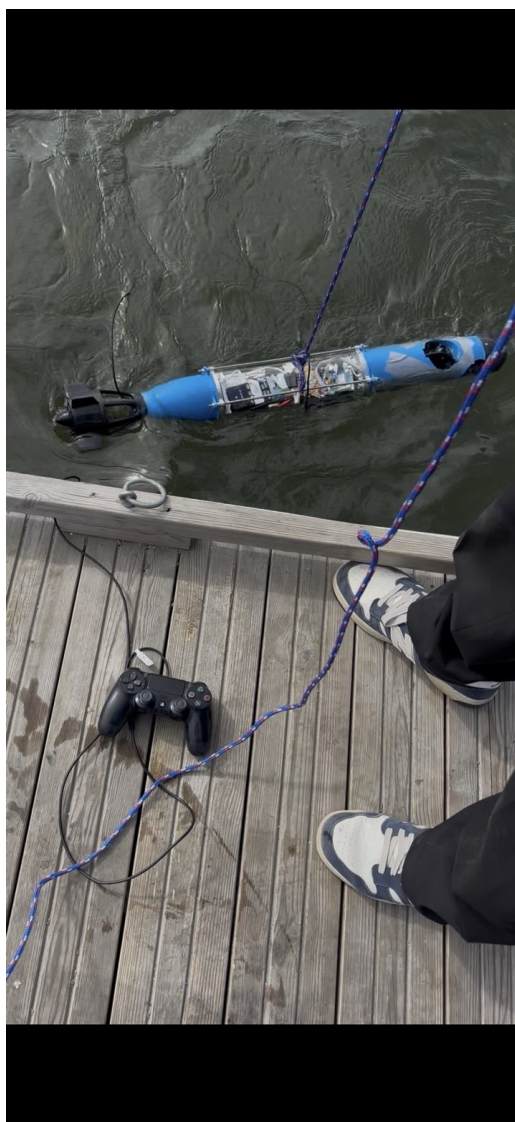


Figure 5.4: Underwater testing and validation of the developed AUV platform during manual maneuvering and operational verification.

### 5.1.3 Navigation and Communication System

The waypoint-based navigation system was partially validated through testing of the communication and control architecture. Mission paths and waypoints could suc-

cessfully be defined in QGroundControl and processed by the Raspberry Pi control system. In addition, GPS position data obtained through the external GNSS-based buoy solution could be received and displayed within the control environment, verifying that external positioning data could be integrated into the navigation system.

Due to previously discussed implementation limitations, the fully autonomous waypoint navigation system could not be completely validated during the project. Nevertheless, the tests successfully verified the underlying communication architecture between the GNSS system, Raspberry Pi, QGroundControl, and Pixhawk flight controller, demonstrating the feasibility of the implemented navigation approach. As shown in Figure 5.5, waypoint routes could successfully be created and visualized within QGroundControl while receiving real-time positional data from the external GNSS-based buoy system. As shown in Figure 5.6, real-time telemetry data could be monitored through QGroundControl during operation near the water surface. However, the telemetry system relied on wireless communication with the Raspberry Pi, limiting data transmission when the vehicle submerged or exceeded the effective communication range.

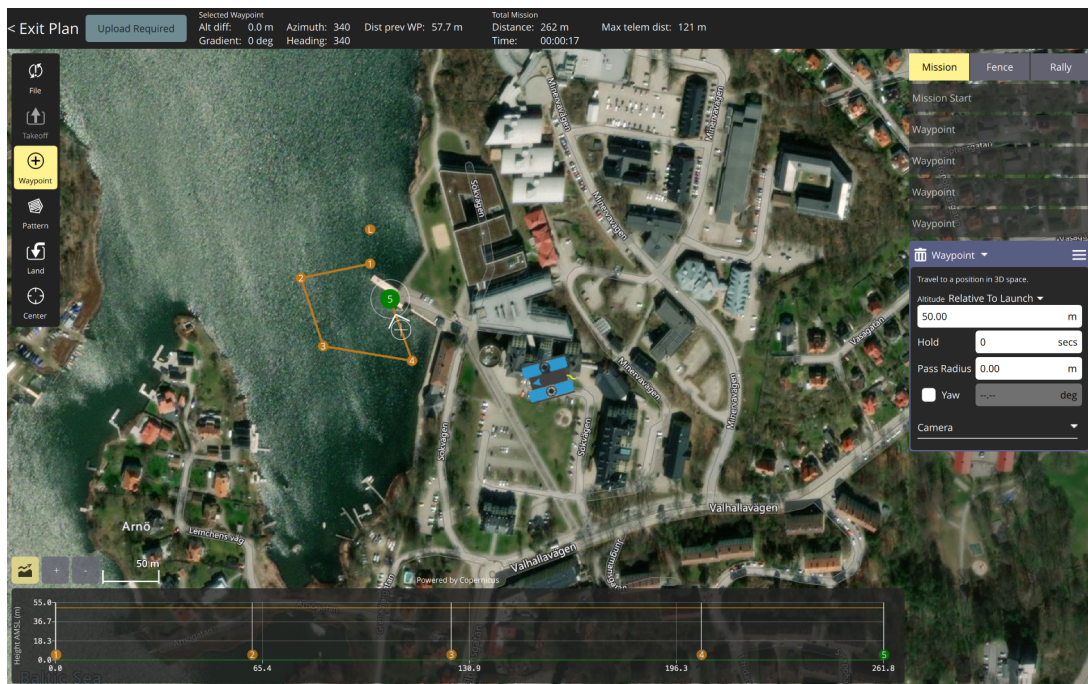


Figure 5.5: Mission planning interface in QGroundControl showing the predefined waypoint route and the real-time GNSS position of the vehicle. The interface also displays mission distance and waypoint information.

In addition to manual controller testing, a simplified autonomous control sequence was implemented and tested. The control system executed predefined timed propulsion commands without real-time operator input or positional feedback. The sequence consisted of timed forward movement and rotational maneuvers intended to approximate a predefined movement pattern.

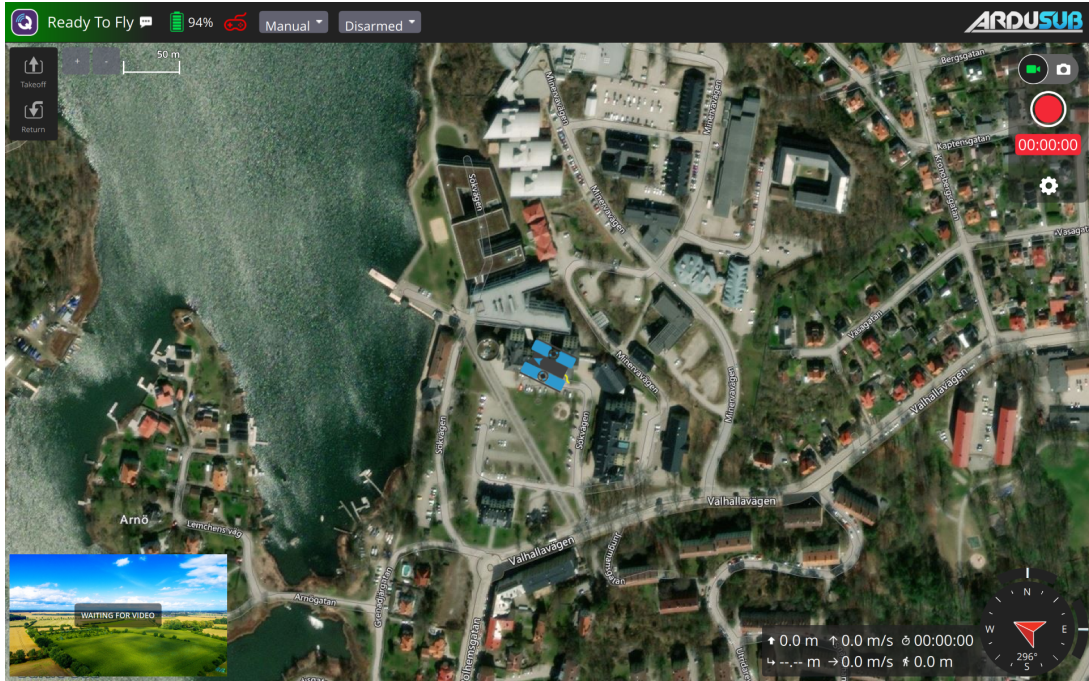


Figure 5.6: Real-time telemetry interface in QGroundControl showing the vehicle position, orientation, velocity, and system status during testing.

Due to the absence of active position tracking and external feedback, the movement was highly sensitive to drift and environmental disturbances. As a result, the test was evaluated primarily through visual observation rather than quantitative measurements. Although the test could not verify accurate autonomous navigation, it demonstrated that the control system was capable of executing automated propulsion sequences without manual intervention.

#### 5.1.4 Power distribution and voltage measure

Subsystem	Operating Voltage	Current Requirement	Status
Battery System	14.8 V	–	Functional
Step-Down Converter	14.8 V $\rightarrow$ 5.1 V	–	Functional
Raspberry Pi	5.1 V	2 A	Functional
Pixhawk Flight Controller	5.0 V	3 A	Functional
Thruster System	14.8 V supply	Variable current draw	Functional

Table 5.2: Measured operating voltages and current requirements for the electrical subsystems during integration testing.

The power distribution system was validated by measuring voltage levels throughout the integrated electrical system during operation. The measured values, presented in Table 5.2, corresponded well with the required operating conditions for the connected subsystems, including the Raspberry Pi, Pixhawk flight controller, and propulsion

system.

The step-down converter successfully reduced the battery voltage from 14.8 V to a stable 5.1 V supply for the Raspberry Pi, while the Pixhawk flight controller received a stable 5 V supply directly through the power module. No abnormal voltage drops or instability were observed during testing.

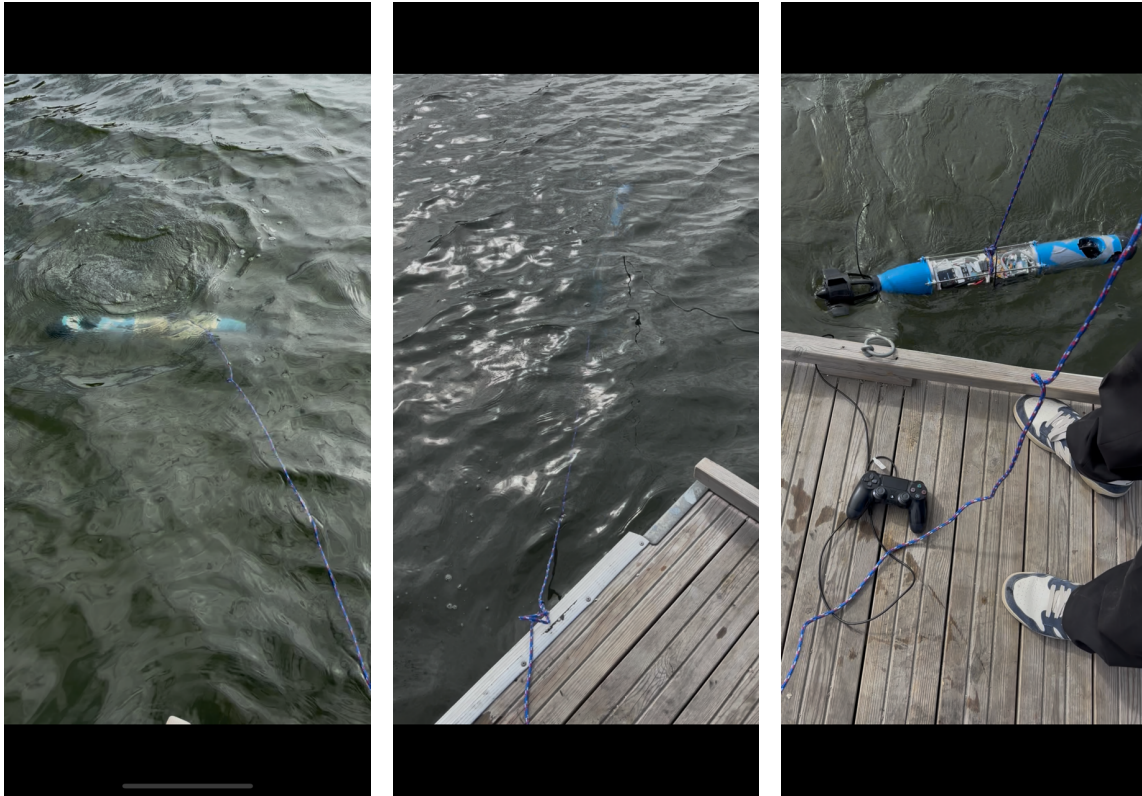
The thrusters were powered directly from the 14.8 V battery system through integrated ESC units. Since the propulsion system was controlled through PWM-based throttle regulation, the effective power delivered to the motors varied depending on throttle input and operating conditions. As a result, exact current consumption and thrust output were not evaluated quantitatively. However, the observed operating behavior corresponded well with the manufacturer's specifications, verifying that the propulsion system operated within the intended electrical range during testing.

### 5.1.5 Integrated AUV System Validation

The complete AUV system was validated through integrated operation tests performed in water. During these tests, the propulsion system, control architecture, power distribution system, telemetry interface, and watertight enclosure operated simultaneously as a unified system.

The vehicle could successfully be powered, maneuvered, and controlled during testing while maintaining stable operation of the onboard electronics and communication systems. All integrated operational tests were conducted using handheld controller operation to verify propulsion, maneuverability, buoyancy, and overall system behavior under practical conditions.

Although real-time telemetry data from the Pixhawk flight controller could be monitored through QGroundControl near the water surface, this feature was never exploited because testing was conducted beneath the water surface. As a result, underwater tests were evaluated primarily through direct visual observation rather than continuous telemetry measurements. Fully autonomous underwater navigation was not tested during the integrated system trials due to the previously discussed implementation limitations and communication constraints associated with underwater operation.



(a) Submerged operation during testing. (b) Integrated system operation near the surface. (c) Manual controller operation during testing.

Figure 5.7: Integrated underwater operation tests of the complete AUV system. The tests were evaluated primarily through direct visual observation and recorded video footage.

## 5.2 Evaluation

The performed tests demonstrated that the implemented system could function as a small-scale AUV platform during manual underwater operation. During the integrated underwater tests, the propulsion system, power distribution architecture, watertight enclosure, Raspberry Pi, and Pixhawk flight controller operated simultaneously as a unified system. The vehicle could successfully be maneuvered underwater using handheld controller operation, where the propulsion system responded consistently to varying control inputs and differential thrust commands. Visual observation and recorded video footage showed that the vehicle was capable of forward propulsion, rotational maneuvering, and stable underwater operation during testing.

The integrated tests also demonstrated successful communication between the Raspberry Pi and Pixhawk flight controller during operation. Real-time telemetry, positional information, and system status could be monitored through QGroundControl while the vehicle remained near the water surface. In addition, predefined waypoint routes could successfully be created and processed within the control architecture. However, the telemetry link relied on wireless communication with the Raspberry Pi,

which became unreliable once the vehicle submerged or moved outside the effective communication range. As a result, continuous telemetry monitoring and positional tracking could not be maintained during underwater operation.

Although parts of the autonomous navigation architecture were successfully implemented and verified, fully autonomous underwater navigation was never tested during the final integrated system trials. The project initially prioritized manual operation in order to first validate propulsion, maneuverability, buoyancy, and general subsystem integration before transitioning to autonomous operation. Due to the limited project timeframe and ongoing integration challenges encountered during the manual testing phase, the autonomous functionality could not be completely implemented and evaluated before the conclusion of the project.

Another important limitation concerned the lack of several sensors originally intended for later stages of autonomous system validation. During the later stages of development, increasing space constraints within the compact cylindrical hull limited the possibility of integrating additional hardware components. Budget limitations also affected the availability of certain sensors during the final implementation phase. Since the mechanical dimensions and internal subsystem layout had already been finalized, further sensor integration became increasingly difficult without a major redesign of the enclosure and internal mounting structure.

In particular, the absence of a pressure sensor significantly affected the possibility of evaluating autonomous underwater operation within the ArduSub environment. Several autonomous functions within the flight control software relied on depth-related sensor input in order to operate reliably underwater. Without this sensor integration, the autonomous control architecture could not be fully configured or safely evaluated during submerged operation.

Furthermore, the absence of continuous underwater telemetry and quantitative positional tracking meant that large parts of the verification process relied primarily on qualitative evaluation through direct visual observation and recorded video footage rather than quantitative measurements. This particularly affected the evaluation of propulsion performance, maneuverability, drift behavior, and autonomous movement accuracy, where no external underwater positioning or tracking system was available. Consequently, the verification process focused primarily on demonstrating practical subsystem integration and operational functionality rather than precise autonomous navigation performance.

However, since simplified autonomous tests using hardcoded maneuver sequences were successfully implemented, together with successful communication between the GNSS system, Raspberry Pi, and Pixhawk flight controller, the concept of a fully autonomous navigation system appears technically feasible. Given additional development and testing time, further autonomous underwater trials could likely have been performed.

Furthermore, the implemented buoy-based GNSS solution would have enabled real-

time position tracking of the vehicle during autonomous operation, allowing the overall route and positional behavior of the AUV to be monitored through QGroundControl. However, limitations would still remain regarding the verification of the internal control behavior of the Pixhawk flight controller during submerged operation. While the vehicle position could be observed externally through the GNSS system, the real-time control inputs, actuator commands, and detailed onboard decision-making processes would have been difficult to evaluate continuously underwater due to communication limitations during submerged operation.

Consequently, future autonomous testing would still benefit from additional sensor integration, onboard telemetry logging, or external underwater tracking systems in order to enable more precise verification and performance evaluation of the autonomous control system.

## Chapter 6

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# Conclusions and Future Work

## 6.1 Conclusions

The aim of this project was to design and develop a compact Autonomous Underwater Vehicle (AUV) capable of controlled underwater operation using commercially available components. The project focused on combining mechanical design, propulsion, navigation, and control into a functional and practically implementable system.

The developed system successfully demonstrated several core functionalities required for AUV operation. A pressure-resistant and watertight hull was designed and verified through underwater testing, while the propulsion and control architecture enabled controlled maneuvering of the vehicle. Communication between the Raspberry Pi and the Pixhawk flight controller was successfully implemented, allowing higher-level control logic and integration with external positioning data.

The project also demonstrated the feasibility of implementing a modular low-cost AUV platform using commercially available hardware and open-source software solutions such as Pixhawk, Raspberry Pi, ArduSub, and QGroundControl. Although fully autonomous waypoint navigation could not be completely validated within the scope of the project, the implemented system architecture verified that communication, mission planning, telemetry, and autonomous control principles could be integrated into a functional underwater platform.

### 6.1.1 Implementation Challenges

The development process demonstrated the complexity of integrating mechanical, electrical, and autonomous control systems within a compact underwater platform. Although the final system architecture proved to be functional, the project highlighted how closely connected the different subsystems are within an AUV design. Modifications to the mechanical structure often required adjustments to cable routing, sensor placement, internal mounting solutions, and power distribution, illustrating the iterative nature of underwater vehicle development.

Particular attention was required for the design of the watertight electronics compartment. Achieving reliable waterproofing while simultaneously maintaining accessibility, compactness, and structural stability proved to be one of the most critical engineering challenges during the project. The integration of electrical components,

cable penetrations, and internal power systems further emphasized the importance of balancing mechanical robustness with practical system integration.

The project also demonstrated that the development of autonomous underwater systems extends beyond software implementation alone. Reliable operation depends heavily on the interaction between sensor systems, mechanical design, electrical reliability, and environmental protection. These observations highlight the multidisciplinary nature of AUV development and the importance of iterative system integration throughout the engineering process.

Despite these engineering challenges, the project successfully demonstrated the feasibility of constructing a modular low-cost AUV platform using commercially available components and open-source software. The resulting platform provides a strong foundation for future development of more advanced autonomous underwater capabilities and additional sensor integration.

### **6.1.2 Project Contributions and Future Potential**

Overall, the project demonstrated that it is possible to develop a functional and modular AUV platform using commercially available components and open-source software solutions. The implemented system successfully combined mechanical construction, propulsion, control, communication, and navigation into an integrated underwater platform capable of controlled operation and partial autonomous functionality.

The project also highlighted the challenges associated with underwater autonomy, particularly regarding localization, communication, sensor integration, and system reliability. At the same time, the developed architecture demonstrated significant potential for future expansion, where additional sensors, improved telemetry systems, and more advanced autonomous control algorithms could further increase the operational capabilities of the platform.

By combining low-cost hardware with a modular system architecture, the project contributes to the growing accessibility of small-scale autonomous underwater systems. The resulting platform, therefore, serves both as a proof-of-concept for autonomous underwater operation and as a foundation for continued development of more advanced AUV technologies in future work.

## **6.2 Future work**

Although the developed AUV system achieved several of the intended objectives, there are still multiple areas that could be further improved and expanded in future development. Due to limitations in time, resources, and testing conditions, certain functionalities and optimizations could not be fully implemented within the scope of this project. Future work may therefore focus on improving the vehicle's autonomy, reliability, navigation capabilities, underwater performance, and structural design.

### 6.2.1 Autonomy reliability

One area with significant potential for future improvement is the autonomous control system. Although autonomous movement was partially demonstrated during testing, the system was limited by the available equipment and time constraints. In the current implementation, the Raspberry Pi is responsible for the higher-level control logic and continuously sends manual control commands to the Pixhawk. The vehicle movement was not based on fully autonomous GPS navigation, but instead relied on manual control inputs combined with orientation data from the Pixhawk's onboard gyroscope. This allowed the system to perform controlled rotations, such as turning the vehicle by a specified angle.

Future development could focus on implementing fully autonomous waypoint-based navigation through the Pixhawk autopilot system and QGroundControl mission planning. Using QGroundControl, predefined GPS waypoints can be assigned before deployment, allowing the AUV to autonomously navigate between multiple target positions without continuous user input. The software also provides the possibility to define operational boundaries and safety zones, preventing the vehicle from traveling outside a specified area during missions.

In addition to waypoint navigation, QGroundControl offers several advanced mission-planning capabilities that could be further explored in future development. Examples include automated mission sequences, return-to-home functions, depth control, speed adjustments, and autonomous task execution based on predefined conditions. Such functionality could significantly improve the operational flexibility and autonomy of the AUV.

For fully autonomous operation, additional sensor integration is also required. In the current system configuration, the Pixhawk requires a pressure sensor to enable autonomous arming and underwater navigation modes. Future versions of the AUV should therefore integrate a suitable pressure sensor to allow reliable depth estimation and improve the stability and safety of autonomous underwater operation.

### 6.2.2 Sensor Integration and Safety

Another important area for future work is the integration of internal monitoring sensors to improve the operational safety and reliability of the AUV. Since the vehicle contains sensitive electronic components, it is important to detect abnormal conditions inside the hull before they cause permanent damage to the system.

A humidity sensor could be integrated inside the watertight compartment to detect water leakage or increased moisture levels. If the humidity exceeds a defined safety threshold, the control system could trigger a fail-safe response. This could include shutting down non-essential electronics, stopping the thrusters, or commanding the vehicle to surface immediately to prevent further damage.

A pressure sensor would also be important for future development, both for depth

estimation and for improving autonomous operation. By monitoring the external pressure, the AUV could maintain a safer operating depth and detect if it is moving outside the intended depth range. Together, humidity and pressure measurements could provide a more reliable safety system and reduce the risk of damage during underwater missions.

In future versions, these sensors could be connected to the onboard control system so that automatic fail-safe actions are triggered when abnormal values are detected. This would increase the robustness of the AUV and make it more suitable for longer and more demanding autonomous missions.

Additional sensors, such as sonar or underwater cameras, could also be integrated in future versions of the AUV to expand its operational capabilities. By using sonar or vision-based systems, the vehicle could perform more advanced underwater tasks, such as seabed mapping, underwater inspection, or object detection. Since the current AUV platform already provides the fundamental hardware and control architecture, these systems could be integrated to further extend the functionality of the vehicle.

Another possible improvement would be the implementation of a Doppler Velocity Log (DVL). A DVL could improve underwater localization and navigation accuracy by measuring the vehicle's movement relative to the seabed. This would reduce the dependency on surface-based positioning systems and improve navigation during submerged operation. However, due to budget limitations and the high cost of DVL systems, this technology could not be implemented within the scope of the current project.

### 6.2.3 Mechanical structure

Another important area for future development is the mechanical design and structural reliability of the AUV. Although the current hull configuration functioned adequately during testing, several structural limitations were identified during operation that could be improved in future iterations of the system.

The bow and stern sections, where the thrusters are mounted, are currently manufactured using 3D-printed components. During testing, these sections were exposed to relatively high mechanical loads and vibrations generated by the propulsion system. Future designs could therefore benefit from replacing certain highly stressed structural components with aluminum or other mechanically stronger materials. This would increase the rigidity of the structure, improve long-term durability, and reduce the risk of structural deformation during extended underwater missions.

Testing also revealed that the forces generated by the front thrusters affected the side-mounted motor brackets and surrounding structural supports. Additional reinforcement between the different structural sections would therefore improve the overall mechanical stability of the vehicle. Future designs should include a more

robust mounting solution for the thrusters, together with improved load distribution throughout the hull structure.

Another limitation identified during development was the relatively small internal volume of the watertight electronics compartment. The limited available space complicated cable management, sensor integration, and future system expansion. As additional sensors and monitoring systems are introduced, a larger internal compartment or a more modular internal layout would significantly simplify maintenance, integration, and future upgrades.

During testing, it was also observed that small openings and structural imperfections in some of the 3D-printed sections could allow water intrusion under certain operating conditions. This highlights the importance of improving the sealing methods, print tolerances, and overall structural integrity of future hull designs. Improved waterproofing and pressure-resistant construction methods would increase the operational reliability of the system.

An advantage of the current design is that only the central electronics compartment is required to be fully watertight, while external components such as thrusters and future sensor modules remain mounted outside the sealed enclosure. Since cables can be routed through dedicated waterproof cable penetrations, future modules such as sonar systems, underwater cameras, or additional sensing equipment could be integrated externally along the hull without requiring major modifications to the watertight compartment itself. This creates a more modular platform architecture and simplifies future expansion of the AUV system.

#### 6.2.4 Testing and Validation

Another area for future improvement is the testing and validation process. In the current project, the system validation was mainly based on practical observations during testing. Although this confirmed that several core functions were working, more detailed measurement data would be required to evaluate the performance of the AUV more accurately.

Future versions could include a dedicated data logging system on the Raspberry Pi, where sensor data from the Pixhawk is continuously stored on the SD card during operation. This could include values such as heading, velocity, acceleration, gyroscope data, GPS position, battery status, and control commands sent to the thrusters. After each test, the stored data could be extracted and analyzed to evaluate how the vehicle behaved during the mission.

In addition, a buoy-based telemetry system could be implemented to provide live data during testing. By routing communication from the Raspberry Pi to a surface buoy, real-time information such as heading, speed, system status, and sensor readings could be transmitted to the operator. This would make it easier to monitor the AUV during autonomous operation, identify errors, and validate the system performance under real operating conditions.

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## Use of AI Tools

Artificial intelligence tools, including ChatGPT developed by OpenAI, were used during the preparation of this report for language refinement, structural feedback, and improvement of academic phrasing. The authors remained fully responsible for the technical content, system design, implementation, analysis, and final evaluation presented in the report.

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### A.1 User-Driven Design Table

The complete User-Driven Design (UDD) table, which serves as the foundation for the design process, is presented below.

Functionalities			Constrains	Possible tech and/or Algorithms	Comments
General	Itemized				
Localization	Ocean		Depth	Pressure meter	
			Tracking	GPS, Sonar, gyro and accelerometer	
Autonomy	Battery		Size		Construct the best possible form for its missions
	Structure		Scale		
	Travel		Time		
Monitoring	See values depth, speed, location		Underwater	Bouy with cable, DVL. WiFi, Bluetooth, cloud, store onboard	Verifying the AUV works as intended

Functionalities	Constraints	Possible tech and/or Algorithms	Comments
Autonomous waypoint navigation	No GPS underwater	DVL, buoy with a GPS, Gyroscope + accelerometer and sonar	Standard solutions for AUVs
Real-time localization	Drift accumulation	Extended Kalman filter	Critical for long missions
Depth control	No GPS underwater	Pressure sensor, Sonar	Need to know which depth the AUV are working on. For future missions on mapping the seabed.
Mission upload / download	No continuous link	Pre-programmed missions	Typical AUV workflow
Emergency recovery	Safety risks	Auto-surface	No trash in the environment
Easy handling	Limited personnel	Easy deployment, one button starts	Fast operations, built for easy use.
Waterproof	Harsh environment	Marine-rated connectors	Increases reliability
Power train	Forward drift and steering	Singel motor or dubble motors, servos for steering	Achieve the best handling in the ocean



