ESCUELA TÉCNICA SUPERIOR DE INGENIEROS
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Trabajo Fin de Grado

DESARROLLO DE UN ROBOT ACUÁTICO AUTÓNOMO PARA LEVANTAMIENTOS BATIMÉTRICOS

(Development of an Autonomous Aquatic Robot for Bathymetric Surveys)

Para acceder al Titulo de

Graduado en
Ingeniería de Tecnologías de Telecomunicación

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GRADUADO EN INGENIERÍA DE TECNOLOGÍAS DE TELECOMUNICACIÓN

CALIFICACIÓN DEL TRABAJO FIN DE GRADO

Realizado por: Luis Miguel Torre Gutiérrez
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Vº Bº del Subdirector Trabajo Fin de Grado Nº
(a asignar por Secretaría)

Dedication

To my parents, for the support, love, comfort, and wisdom you have given me over the years.

To my grandparents, for always looking out for me.

To José Andrés, for showing me the way. To Javi, for keeping me on it.

To Lucía, the great woman behind the man who aspires to be great.

Acknowledgments

This project would not have been possible without the guidance and patience of my project supervisor, Adolfo. I would also like to thank the Photonic Engineering Group (GIF) at the University of Cantabria for allowing me to use their laboratory to carry out the project and for welcoming me as one of their own from the very first day.

Abstract

The bachelor's thesis consists of the design, programming and construction of an aquatic boat-type robot, capable of navigating autonomously by following a route previously designed by an operator. In case of a system failure, it can be manually operated.

The purpose of this autonomous navigation is to conduct bathymetric surveys of confined water bodies, such as lakes or reservoirs.

The project is based on hardware selected by the project supervisor and involves both the design of the platform and its programming, using mostly open-source hardware and software.

Keywords: USV, autonomous robot, drone, open-source hardware and software, bathymetric survey, 3D printing, GNSS, Ardupilot, Mission Planner, Raspberry Pi, barometer, motors, RC transmitter, telemetry, batteries.

Resumen

El Trabajo Fin de Grado consiste en el diseño, programación y construcción de un robot acuático, tipo lancha, que tenga la capacidad de navegar autónomamente siguiendo una ruta diseñada previamente por el operador, y que en caso de fallo de este sistema, pueda pilotarse manualmente.

El propósito de esta navegación autónoma es la realización de estudios batimétricos de cuerpos de agua, como lagos o embalses.

El proyecto toma como punto de partida un hardware seleccionado por el director del trabajo, y consiste tanto en el diseño de plataforma, como de la programación de la misma, usando hardware y software de código abierto.

Palabras clave: USV, robot autónomo, drone, hardware libre, software libre, batimetría, impresión 3D, GNSS, Ardupilot, Mission Planner, Raspberry Pi, barómetro, motores, emisora radiocontrol, telemetría, baterías.

List of Acronyms

APM: *ArduPilot Mega.*

SONAR: *Sound Navigation and Ranging*.

UUV: *Unmanned Underwater Vehicle*.

USV: *Unmanned Surface Vessel*.

UAV: *Unmanned Aerial Vehicle*.

UGV: *Unmanned Ground Vehicle*.

GNSS: *Global Navigation Satellite System*.

GPS: *Global Positioning System*.

RTK: *Real-Time Kinematic*.

LiDAR: *Light Detection and Ranging*.

SLAM: *Simultaneous Localization and Mapping*.

GCS: *Ground Control Station*.

IMU: *Inertial Measurement Unit*.

ESC: *Electronic Speed Controller*.

RC: *Remote Control*.

PWM: *Pulse Width Modulation*.

GND: *Ground*.

VCC: *Voltage*.

WP: *Waypoint*.

RCTM: *Radio Technical Commission for Maritime Services*.

NTRIP: *Networked Transport of RTCM via Internet Protocol*.

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He who learns but does not think, is lost. He who thinks but does not learn is in great danger.

Confucius

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Chapter 1: Introduction

1.1 Motives

The automation of bathymetric surveys presents a significant opportunity to reduce costs and environmental impacto of this practice. To understand the importance of this project, it is first necessary to explore what bathymetry is, how it is conducted, and why it is performed.

1.1.1 What is Bathymetry?

Bathymetry is the study and measurement of the depth of underwater floors, in any kind of bodies of water, such as oceans, lakes or reservoirs. It involves mapping the depth and contours of the seafloor or waterbed [1], which is typically achieved through sonar or other remote sensing techniques [2] [3]. These surveys provide crucial data on the underwater landscape, including the identification of underwater features such as valleys, mountains, ridges, and trenches [2].

1.1.2 Why are Bathymetric Surveys Important?

The importance of conducting bathymetric surveys lies in their wide range of applications. They are vital for navigation, as they help to identify safe shipping routes, avoid submerged hazards, and ensure the safety of vessels [3]. They play a crucial role in civil engineering projects, especially those involving coastal, marine, and freshwater infrastructure. Accurate underwater topography data is essential for designing and constructing hydraulic structures. Bathymetric surveys help engineers assess sedimentation, erosion, and water depth variations, ensuring the stability and safety of constructions [4], as well as preventing environmental disasters caused by river floods, reservoir overflows, or the overflow of other bodies of water.

1.1.3 How are Bathymetric Surveys Conducted?

Bathymetric surveys require three basic components to be conducted:

- A mobile platform, such as a vessel, boat or USV [4].
- A GNSS module to track the position of the area being measured [4].
- A depth sonar or echosounder [4]. This device measures the distance between the seafloor and the surface by transmitting acoustic signals at an specific frequency and receiving their echoes [5][6]. The time between the transmitted signal and the received echo is measured, and with that data, the distance to the seafloor can be calculated [5][6]. Depending on the characteristics of the waterbody, a multibeam or singlebeam sonar may be more suitable.

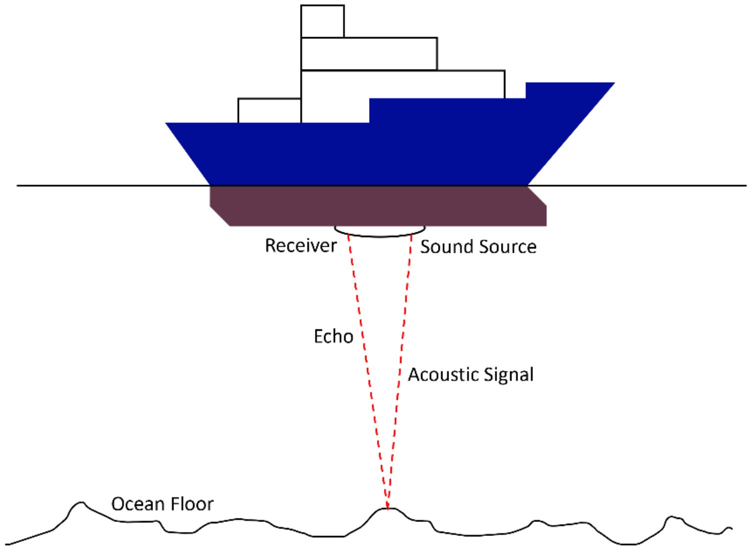

Figure 1.1: Ilustration of the operation of the depth sonar

A singlebeam sonar, also known as a split-beam sonar, is a fundamental echosounding system that operates with a single transmitter and receiver. It emits an acoustic pulse downward and determines depth at a specific point by analyzing the returning echo [5]. This technology is widely used by various types of vessels, including boats for navigation assistance and fishing and oceanographic vessels to detect fish and analyze biomass [5]. Additionally, singlebeam sonar provides information about the ocean floor, making it particularly suitable for shallow waters, such as rivers, lakes, or reservoirs, where basic depth measurements are required [4].

While singlebeam sonar is effective for certain applications, its coverage is limited. In contrast, multibeam sonar integrates multiple transmitters and receivers, enabling it to emit several beams simultaneously [6], thereby covering a wider swath of the seafloor [6]. This capability allows for faster and more detailed surveys, offering higher accuracy, which makes it particularly advantageous for deep-water mapping, such as in seas and oceans [4].

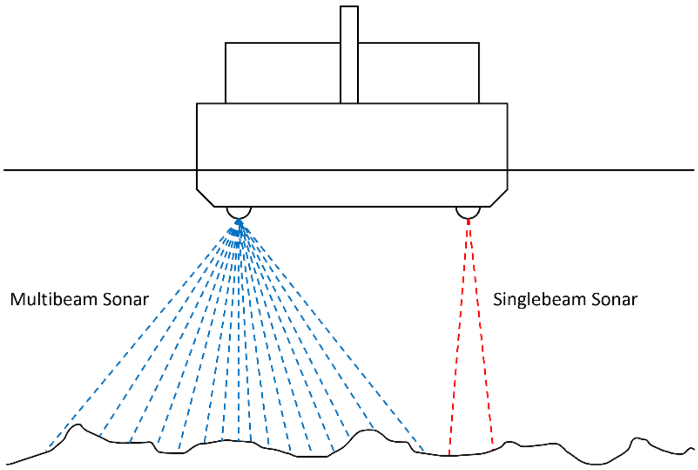

Figure 1.2: Ilustration comparing singlebeam sonar and multibeam sonar

1.1.4 Why Use a Robot for Bathymetric Surveys?

Typically, bathymetric surveys in shallow waters require a small boat equipped with the necessary devices and a minimum of two people: a skipper and an equipment operator [4]. The costs associated with this method can be considerable, as it requires hiring a qualified skipper, covering fuel expenses, and, if the organization conducting the survey does not own a boat, renting one. Additionally, the environmental impact can be significant, as the boat must navigate in areas with protected species and fragile ecosystems that may be affected by pollution [7]. In many cases, larger boats are unable to navigate these shallow waters, making alternative solutions, such as small robotic systems, necessary.

While traditional bathymetric surveys using boats equipped with depth sonars are effective and remain irreplaceable for deep and open bodies of water, they entail high costs and pose significant environmental impacts when applied to shallow waters. In such scenarios, where larger boats cannot operate, small autonomous robots present a more efficient and eco-friendly alternative, significantly reducing both costs and environmental risks.

1.2 Project objectives

The objective of this project is to develop a drone-type autonomous robot to conduct bathymetric surveys, using hardware selected by the project supervisor and open-source software. To achieve this, several milestones have been identified:

- Developing the robotic platform by selecting the necessary components, choosing the appropriate batteries, designing a solution to securely attach the components to the platform's mainframe, and assembling everything.
- Implementing autonomous navigation using the open-source software Mission Planner, as well as a manual navigation mode via an RC transmitter in case of autonomous navigation failure.
- Integrating the depth sonar to perform measurements while navigating and mapping the seafloor.
- Enhancing the accuracy of the GNSS module by adding RTK technology.

1.3 Structure

The report is divided into six chapters: an introduction and five additional chapters covering the following aspects of the project:

- **Chapter 2: Backgorund.** This chapter reviews the current trends in aerial and aquatic drones, highlighting their relevance to the solution developed in this project. It also covers the pre-selected hardware.

- **Chapter 3: Platform Development.** The design of the robotic platform is presented, detailing the selection of materials, the design and 3D printing of necessary mechanical parts, and the assembly of the platform. Additionally, the manual navigation mode is set up and tested.

- **Chapter 4: Implementation os Autonomous Navigation and Bathymetry.** After the USV (Unmanned Surface Vehicle) can be remotely operated, autonomous navigation is implemented. A depth sonar is integrated to perform bathymetric surveys. Once this is functional, RTK technology is added to improve the accuracy of the GNSS module.

- **Chapter 5: Results, Conclusions and Future Improvements.** This chapter summarizes the results and objectives. It discusses the challenges encountered during the project and suggests improvements for future projects.

Chapter 2: Background

2.1 Autonomous Drones

Autonomous drones, or unmanned vehicles, constitute an increasingly significant technological field with a wide range of applications across various domains. Among these, aerial drones UAVs have garnered substantial attention due to their versatility and accessibility. These platforms are commonly equipped with cameras, sensors, or other devices, enabling them to perform tasks such as aerial photography, environmental monitoring, infrastructure inspection, and package delivery [8]. Advances in GNSS, computer vision, and obstacle avoidance technologies have enhanced their autonomy, thereby reducing the need for direct human control and enabling safer and more efficient operations [8].

Figure 2.1: Quadcopter-type aerial drone equipped with a camera

Ground-based autonomous vehicles, referred to as UGVs, also play a crucial role in sectors such as agriculture, mining, logistics, and defense [9]. These vehicles are capable of navigating through complex terrain, transporting heavy loads, and carrying out repetitive tasks with high precision. Technologies such as LiDAR, machine learning, and SLAM have significantly improved their navigational and perception capabilities, rendering them reliable in hazardous or remote environments [9].

Particularly noteworthy is the development of autonomous aquatic drones, encompassing both USVs and UUVs. USVs are deployed in a variety of applications, including environmental monitoring, hydrographic surveying, and maritime security [4]. They are typically equipped with GNSS modules for accurate navigation, sonar systems for bathymetric surveys, and telemetry systems for real-time data transmission. USVs are especially valuable in shallow or confined waters, where conventional manned vessels may encounter navigational challenges [10].

Conversely, UUVs operate beneath the water surface, often at significant depths. They are equipped with advanced sensors, including multi-beam and single-beam sonars, cameras, and water quality monitoring instruments. These vehicles are capable of collecting essential data on underwater ecosystems, seabed morphology, and submerged infrastructure [11]. UUVs can follow pre-programmed paths or adapt their routes based on sensor inputs, which makes them indispensable for scientific research, resource exploration, and subsea inspections [11].

It has been observed that both USVs and UUVs can integrate similar sensors and operate autonomously by following pre-programmed missions. For that reason, considering the specific objective of conducting bathymetric surveys, the development of a USV is the most appropriate choice for this project, as it enables efficient data collection of water depth in confined water bodies.

2.2 ArduPilot and Mission Planner

ArduPilot is an open-source autopilot software suite that enables the control of various autonomous vehicles, including aerial, terrestrial, and aquatic platforms. Initially developed for drones and based in the Arduino platform, ArduPilot has evolved into a versatile and widely adopted system in academic research, commercial applications and hobbyists' projects [12]. Its open-source nature, allows it to be customized and extended to accommodate different sensor configurations, control algorithms, and mission requirements [12]. This flexibility makes it particularly valuable for projects that are intended for non-critical applications that can be implemented cost-effectively.

Mission Planner is an open-source GCS software developed specifically to interface with ArduPilot-based systems [13]. In this program, all the necessary autopilot parameters can be configured to develop the autonomous vehicle. It provides an intuitive graphical user interface for mission planning, vehicle configuration, and real-time monitoring. Through Mission Planner, users can define waypoints, configure autonomous missions, visualize telemetry data, and perform essential pre-flight checks. Its compatibility with a wide range of sensors and modules, including GPS, sonar, and telemetry links, ensures that users can tailor their vehicles' behavior to meet specific operational goals [13], in their autonomous unmanned vehicle.

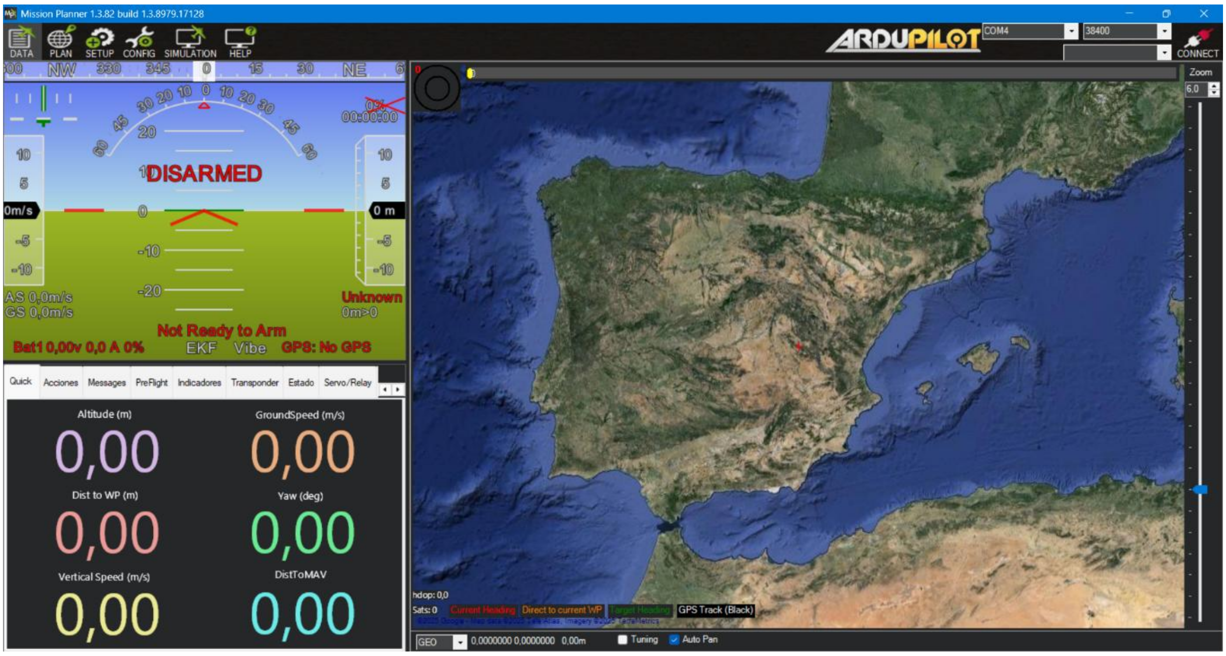

Figure 2.2: Screenshot of the main screen of Mission Planner

2.3 Hardware Selection

The hardware used for this project was selected in advance by the project supervisor. This decision was based on the availability of components from previous projects.

2.3.1 APM

An APM is an Arduino-based flight controller, also known as an autopilot, that manages the motors of an autonomous or manually operated vehicle. This device not only controls the motors to enable navigation but also integrates the wide range of sensors that can be connected to it. It collects data from these sensors for post-mission analysis or real-time monitoring via telemetry. The APM serves as the central hub where motors, GPS modules, sensors, and telemetry systems are connected [12].

The APM is a device that enables autonomous navigation by integrating an IMU, which forms the core of its autonomous navigation capabilities. The IMU integrates several critical sensors necessary for estimating the vehicle's orientation and motion: an accelerometer (to measure linear acceleration on three axes), a gyroscope (to measure angular velocity on three axes), and a magnetometer (to detect the Earth's magnetic field direction and thus compute heading). This combination of sensors allows the flight controller to accurately estimate the vehicle’s position and attitude in real time, which is essential for the proper functioning of autonomous navigation [14].

The device used is the Pixhawk Hex Cube Black, also referred to as Pixhawk 2. It features two ports designated for GPS, two ports for sensors or telemetry, and eight ports for motor connections, among other functionalities [14].

Figure 2.3: Pixhawk Hex Cube Black autopilot

2.3.2 Companion Computer

A companion computer is an onboard computer that works alongside the flight controller in a drone. It typically runs a full operating system like Linux and can handle tasks that are too complex or computationally intensive for the flight controller alone, such as capturing video through a camera for real-time viewing, or running computer vision algorithms. The companion computer communicates with the flight controller to share information and coordinate actions, effectively expanding the drone's capabilities [15].

The companion computer chosen for this project is the Raspberry Pi 4 Model B, a low-cost, high-performance board running a special distribution of the Linux operating system. This board features a quad-core 1.5 GHz processor and up to 8 GB of RAM [16].

Figure 2.4: Raspberry Pi 4 Model 4

The Raspberry Pi will run an operating system based on Linux called Maverick [17]. This system is specifically designed for companion computers, providing optimized tools and configurations for integration with autopilot platforms such as ArduPilot. In this project, the Raspberry Pi will not be actively used; it is included solely to allow for the potential integration of additional functionalities in the future.

2.3.3 GNSS Module

The drone requires precise positioning to navigate and complete its pre-loaded mission accurately. Additionally, knowing the exact coordinates of depth measurements taken by the sonar is essential for conducting proper bathymetry. For this purpose, a GNSS module is needed. The selected module is the SparkFun ZED-F9R GPS-RTK Breakout, which offers a baseline accuracy of ±2 meters, and can achieve up to ±1 centimeter precision by implementing RTK technology [18].

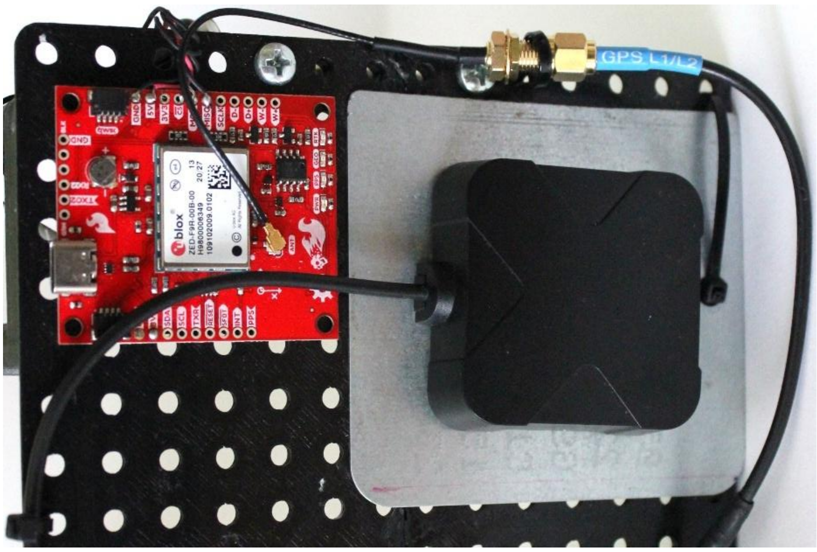

Figure 2.5: GNSS module along with its antenna

2.3.4 Motors

The USV will be equipped with two motors for navigation. It will move in a straight line at a constant speed by running both motors equally and will turn by varying their speeds. The motors will be fully submerged beneath the robotic platform. The selected motors are the ROVmaker 2216 model [19], powered by an 11.1 V supply. Each motor includes an ESC that controls speed through a 5 V PWM signal received from the autopilot. These motors are specifically designed for aquatic robots, so both the motors and their ESCs are waterproof and can operate fully submerged without damage [19].

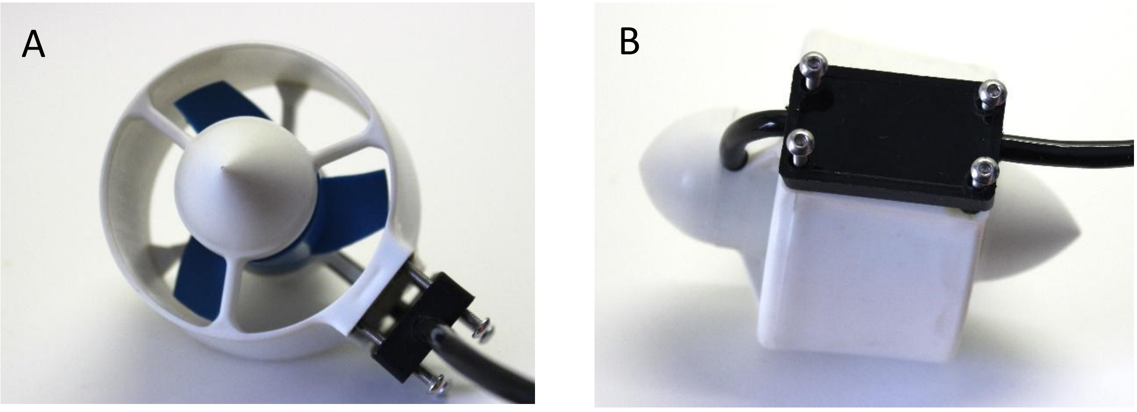

Figure 2.6: Front view of the motor (A) and ESC beneath the motor (B)

2.3.5 Depth Sonar

The depth sonar chosen for bathymetric measurements is the BlueRobotics Ping Sonar model. This single-beam sonar features a beamwidth of 25 degrees and is capable of measuring depths of up to 100 meters [20]. It interfaces with the autopilot via a TELEM port [21] and operates at a frequency of 115 kHz [20]. Power is supplied at 5V directly from the autopilot's TELEM port, ensuring seamless integration within the system.

Figure 2.7: Ping Sonar in its mount

2.3.6 SiK Radios

The wireless communication system between the USV and the PC will be established using SiK radios. One radio will be installed on the robot, while the other will be connected to the PC via USB [22]. These radios incorporate open-source firmware specifically designed for drone applications and operate at a frequency of 433 MHz [22], ensuring robust and reliable communication.

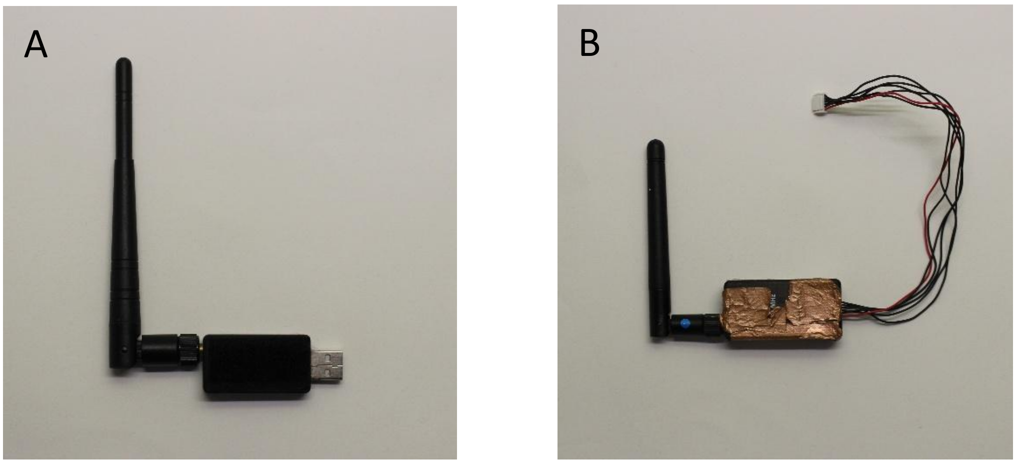

Figure 2.8: SiK radio connected to the PC (A) and SiK radio connected to the USV (B)

2.3.7 RC Transmitter

All autonomous systems require a manual control method for safety reasons. In this case, a standard RC transmitter, commonly used in various types of drones, will be employed. This transmitter will be pre-linked to a receiver antenna connected to the autopilot's RCIN port [21], allowing for manual override of the vehicle when necessary.

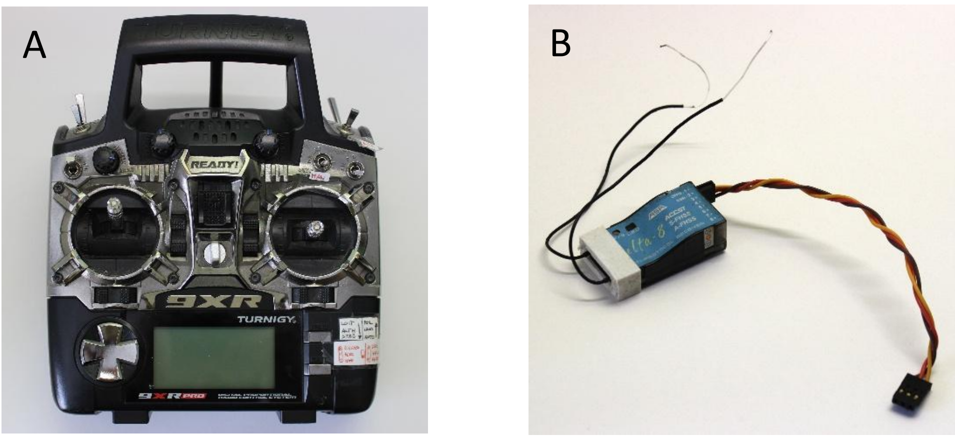

Figure 2.9: RC transmitter (A) and receiver antenna (B)

2.4 Layers of the Project

To understand how all the devices involved in the project will connect and communicate, two diagrams are developed: one representing the physical layer and another representing the virtual layer of the system.

2.4.1 Physical Layer

In the first diagram, the interconnection of the devices that make up the system is presented. In the diagram, it is possible to see the sources of communication signals and power supply for each device. A detailed description of the autopilot pins assigned to each device will be provided later, since each port on the device includes six pins, but depending on the connected component, not all of them are always used.

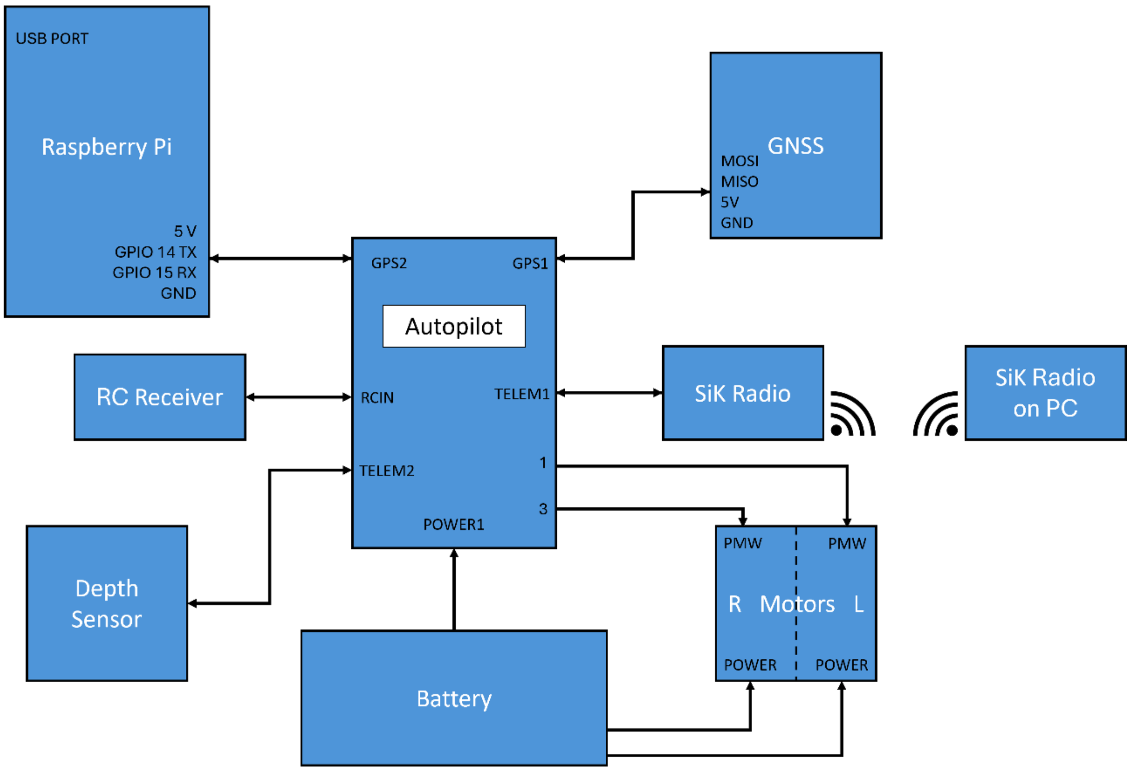

Figure 2.10: Diagram of the physical layer of the project

2.4.2 Virtual Layer

In the following diagram, the communication protocols used by each device are shown, along with the selected software version for both the autopilot and the Raspberry Pi. It is worth noting from this diagram the prominent use of the MAVLink protocol, as it forms the backbone of the entire ArduPilot ecosystem and is widely adopted among devices used in drones and model aircraft. The diagram also highlights the presence of protocols such as u-blox, which is proprietary to the manufacturer of the GNSS module's chip; ACCST, which is commonly found in RC controls for model aircraft; and Ping protocol, used in the depth sonar.

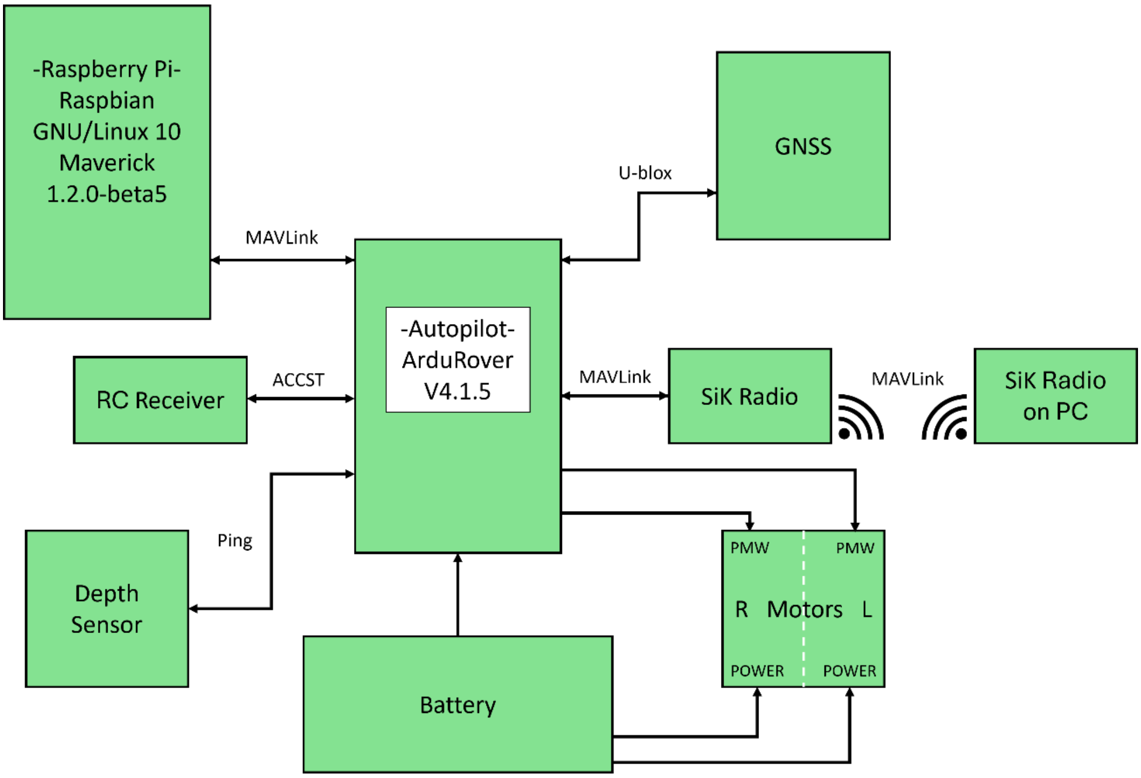

Figure 2.11: Diagram of the virtual layer of the project

Chapter 3: Platform Development

3.1 Design

In this section, the initial steps and design considerations taken to build the homemade boat are presented. It includes an overview of the fundamental design objectives, the selection of materials, and the conceptual layout, setting the foundation for the subsequent construction and integration of the vehicle's components.

3.1.1 Initial Approach

To initiate the design of the platform, an internet search was conducted to gather ideas and design references. Most of the commercially available USVs found in this search are of the catamaran type [23]. This type of design can offer technical advantages, such as reduced energy consumption during operation, since it has minimal surface area in contact with the water. However, constructing this structure at home presents significant challenges, making it difficult to build using readily available materials and tools.

Figure 3.1: Commercial USV (source: BlueRobotics [23])

The platform must be a floating structure capable of supporting the weight of the electronic devices. Additionally, it should be light enough to be effectively propelled by the motors and stable enough to prevent capsizing in the presence of waves. In the search for a suitable material that meets these requirements, it was determined that a type of plastic or foam could be appropriate. Upon researching structures made from such materials, it was concluded that a bodyboard could serve as an ideal base for the platform. This product is specifically designed to float and can support the weight of a small child, which is significantly more than the combined weight of the electronic devices. Moreover, it is lightweight, allowing it to be easily propelled by the motors, and its design for small waves ensures the necessary stability for the intended use. Additionally, a bodyboard is inexpensive and easy to obtain, making it an attractive option for the project.

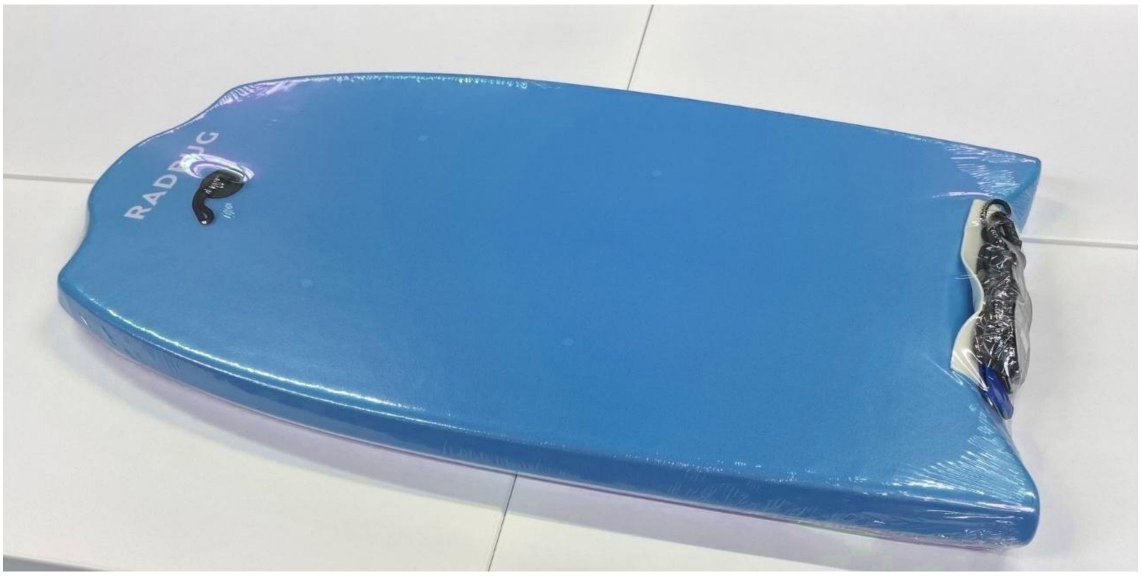

Figure 3.2: Selected bodyboard for the platform mainframe

The decision was made to use the bodyboard as the mainframe of the platform. Mounted on top of it will be a waterproof enclosure commonly used in outdoor electrical installations, which will house the electronic devices. The motors, which must be positioned beneath the bodyboard, will be installed on a 3D-printed mount secured to the board with screws, taking advantage of the foam material's ease of drilling.

3.1.2 Materials

The materials required to build the platform are as follows:

- A bodyboard.
- A 150 x 150 x 90 mm enclosure with IP65 protection.
- Two 3D-printed motor mounts.
- A total of twelve 6 x 70 mm hexagonal screws.
- Double-sided tape for attaching the waterproof enclosure to the top of the bodyboard.
- Batteries.
- Custom-made cables for connecting the batteries and motors to the autopilot.

3.1.3 Battery Sizing

The final component required to complete the USV development is the batteries. To properly size the batteries needed, two parameters are considered: their size and nominal voltage. The autopilot requires a nominal voltage of 5 V and will supply power to all other devices except the motors [13][14]. Although the motors are connected to the autopilot for control via a PWM signal, their power supply voltage ranges between 10 V and 25 V, with greater torque achieved at higher voltajes [19]. Lithium batteries consist of one or more cells, each with a nominal voltage of 3.7 V. Therefore, it is advisable to select batteries composed of three or more cells to meet the required voltage specifications.

A battery model suitable for this application was found on a popular e-commerce platform. It has a nominal voltage of 11.1 V, and its dimensions of 138 x 46 x 31 mm [24] fit within the waterproof enclosure housing the electronic devices. The pack includes two batteries, each with a capacity of 5200 mAh. Since the nominal voltage of each battery is sufficient to power the motors, and high torque is not required to move the USV's load, they were connected in parallel. This configuration sums their capacities, resulting in a total of 10,400 mAh, thereby extending the USV's operating time between battery charges.

Figure 3.3: Selected batteries

Considering that the motors may draw a maximum current of 7.5 A each and the combined capacity of both batteries connected in parallel is 10,400 mAh, the minimum estimated runtime is approximately 0.69 hours, equivalent to 41.4 minutes.

3.1.4 Design of the Motor Mounts

The 3D designs will be created using FreeCAD [25], an open-source software widely used for developing 3D models. FreeCAD is particularly useful for designing objects that can subsequently be 3D printed.

The mounting system is designed as a three-piece assembly. One piece will pass through the bodyboard and serve as the motor attachment point. This piece will be screwed to a second component located on the top side of the bodyboard, which in turn will be fastened to a third piece positioned underneath the bodyboard. The motors will be installed at the rear of the bodyboard, behind the waterproof enclosure, which will be centrally placed on the platform's upper surface.

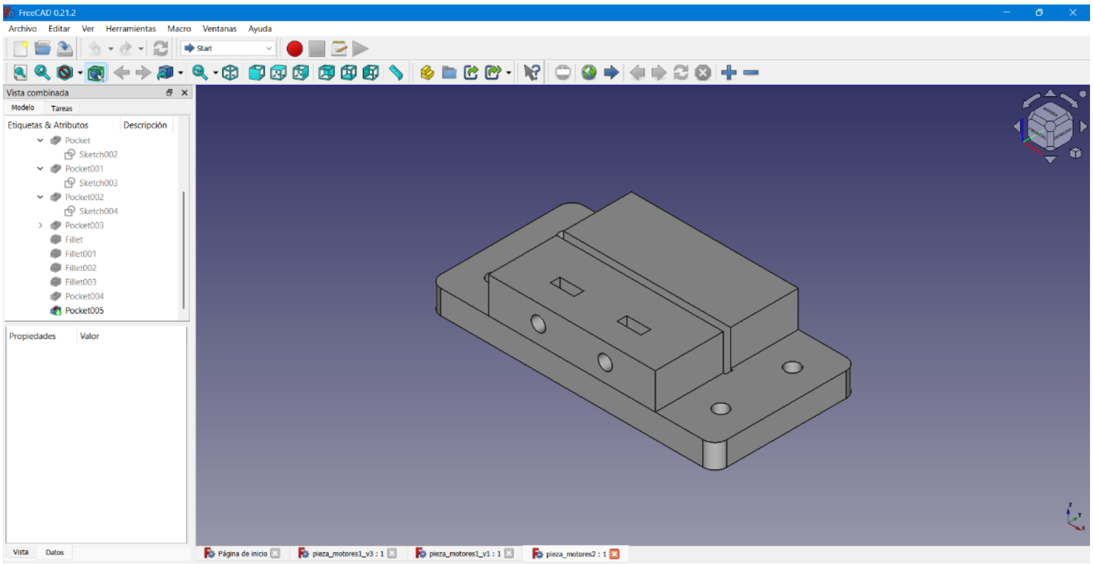

Figure 3.4: Screenshot of FreeCAD with the completed design of one of the pieces

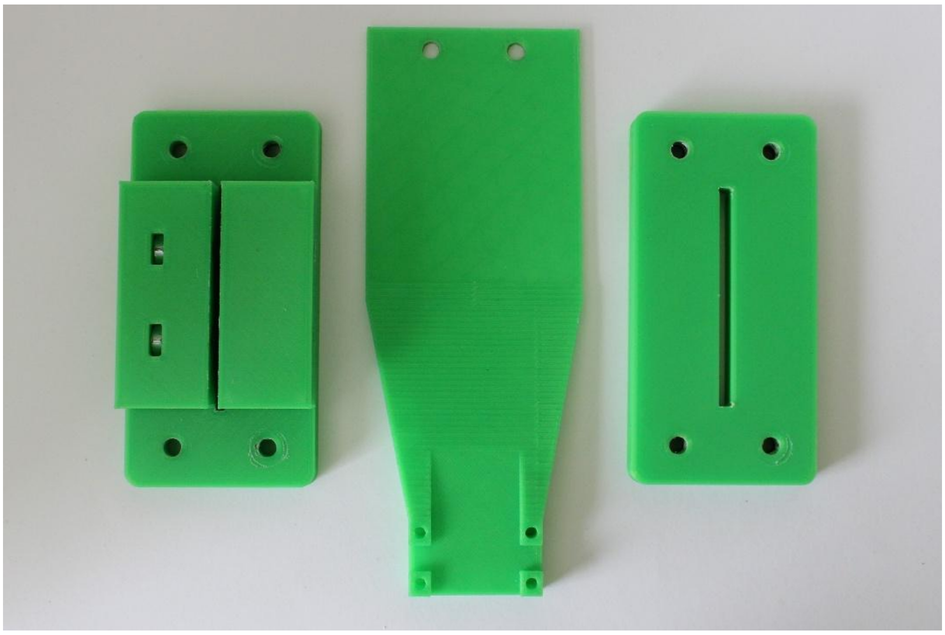

Figure 3.5: The three pieces of a printed mount

The pieces are designed with integrated cavities that securely house the nuts, precisely sized to prevent any movement when the screws are tightened. This design ensures that the components remain firmly fixed to the bodyboard.

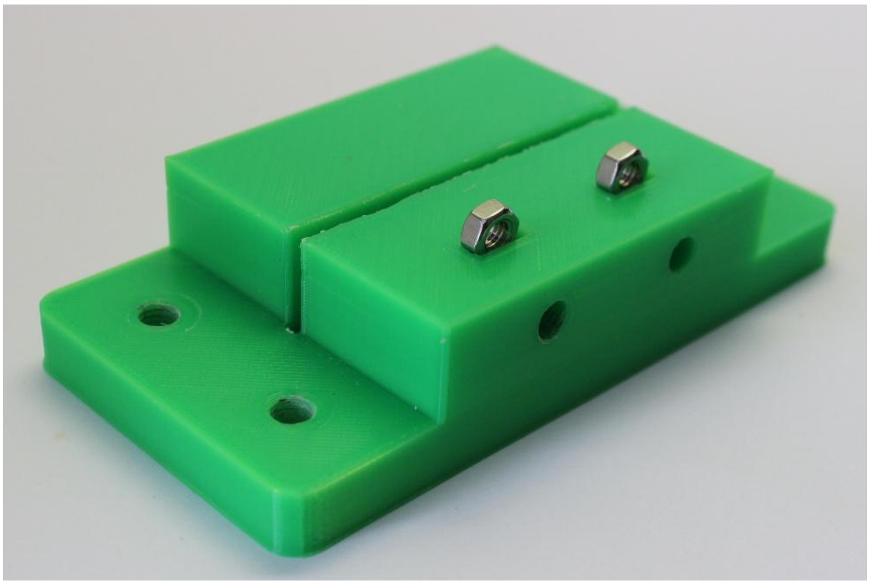

Figure 3.6: Example of the cavities designed to house the nuts

After printing all the pieces, a test assembly was performed on the bodyboard to verify that the design fits correctly.

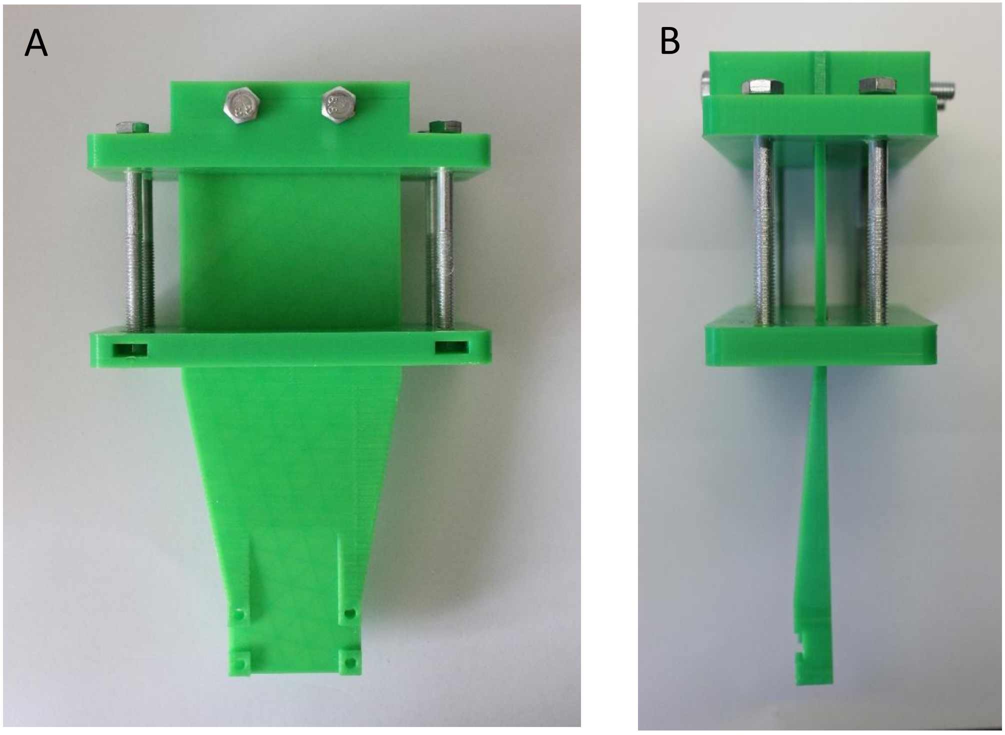

Figure 3.7: Mount assembly viewed from the front (A) and from the side (B)

The section of the piece where the motor will be mounted is designed so that the largest surface area of the ESC is exposed to water, enhancing its cooling. Additionally, when installing the motors, nuts are added to increase the gap between the ESC and the mounting piece, allowing greater water flow for improved heat dissipation.

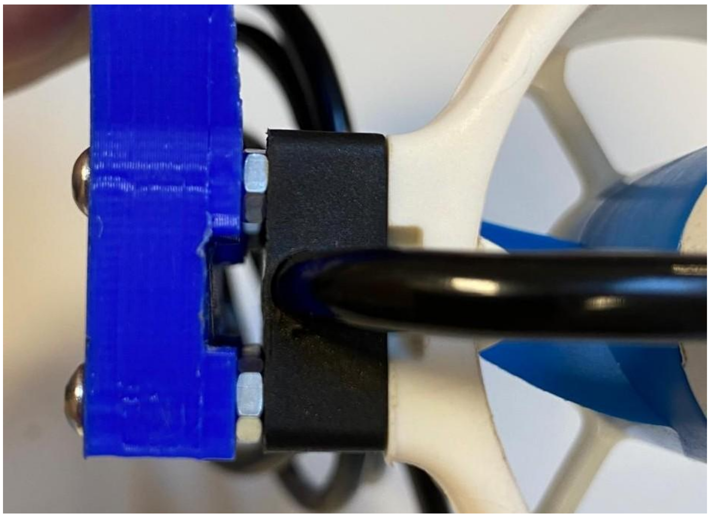

Figure 3.8: Close-up view of the space in the piece designed to facilitate ESC cooling

3.2 Assembly

3.2.1 Motor Assembly on the Mounts

To begin, all the nuts are placed into the cavities of the pieces. It may be necessary to use a hammer with moderate force, as the holes are designed to be very tight to ensure the nuts remain securely in place when the screws are inserted. Afterward, two cuts are made along the width of the bodyboard's rear section using a standard knife. Then, the piece designed to fit underneath the bodyboard is positioned so that its slot aligns with the cuts made. Next, the motor-mounting piece is slid first through the bottom piece and then into the bodyboard itself, with the motor section positioned beneath the bodyboard. Finally, the top piece is fitted over the bodyboard, interlocking with the piece that passes through it, and all components are secured together using six screws per mount. The foam material is soft enough that drilling pilot holes is unnecessary; applying sufficient force with an electric screwdriver is enough to fasten the screws securely. First, one complete mount is assembled, followed by the installation of the second. Finally, the motors are securely fastened, ensuring that their cables extend out from the rear.

Figure 3.9: Motors installed on the platform

3.2.2 Development of the Power Wiring and Motor Connections

Since the autopilot operates at 5V while the motors require 11.1V, a **power module** is utilized to interface with the batteries. This module allows the full 11.1V voltage to pass through one output, while simultaneously providing a regulated 5V output on another [26], enabling the safe and efficient distribution of power to both the autopilot and the propulsion system.

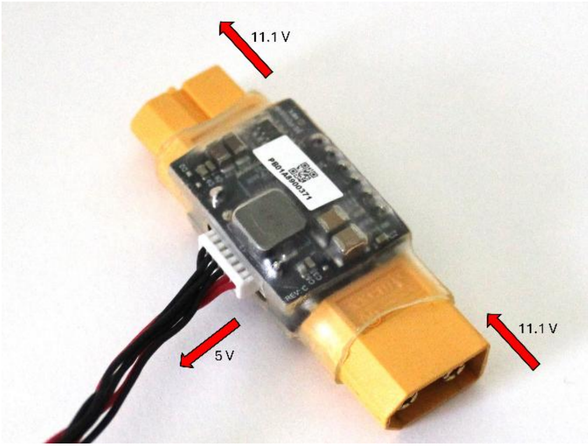

Figure 3.10: Operation of the power module

Next, two cables need to be fabricated: one to connect the two batteries in parallel and feed them into the power module, and another to deliver power from the power module to the motors. This second cable must also facilitate the connection of the motors to the PWM ports of the autopilot, enabling effective control and power distribution throughout the system.

First, the battery cable will be constructed. A terminal block will be used for this, along with a 2.5 mm² cable, matching the cross-section of the battery cables themselves, and a male XT60 connector to connect it to the power module. The following schematic will be followed:

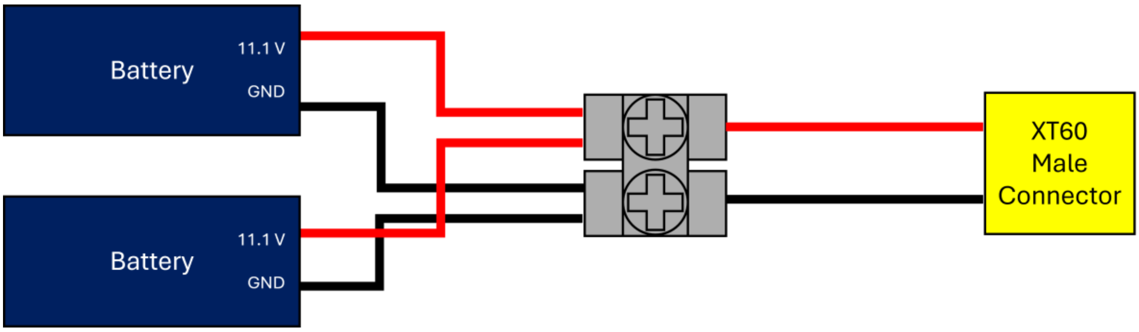

Figure 3.11: Diagram of the battery cable to be built

Three pairs of cables are cut to the appropriate length so that they fit properly in the enclosure. An XT60 connector is soldered to one end of each pair: one male connector that will exit the terminal block, and two female connectors that will connect to the batteries and enter the terminal block. The solder joints are covered with heat-shrink tubing. Since the cables are made of many fine strands, the tip of each cable that will enter the terminal block is tinned with solder to ensure that the screw clamps them securely. Once this is done, the tips are inserted into the terminal block, and the screws are tightened.

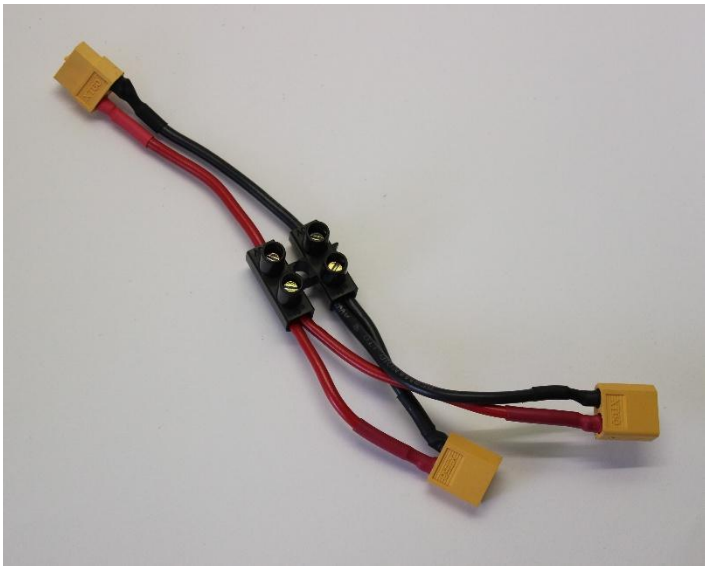

Figure 3.12: Final result of the battery cable

Next, the cables for the motors will be prepared. In this case, the following diagram will be followed:

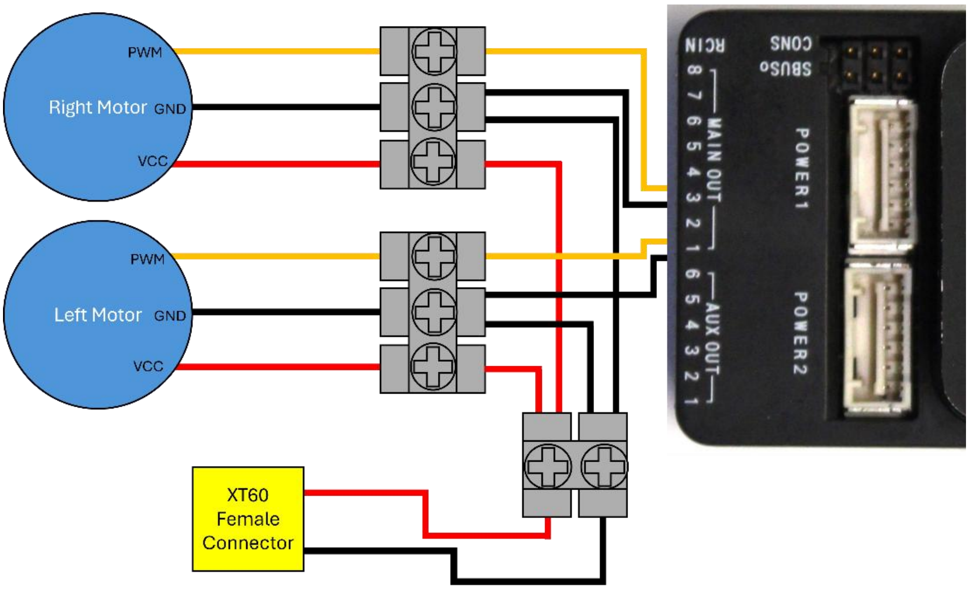

Figure 3.13: Diagram of the motor cables to be built

Three pairs of cables are cut again. This time, only a female XT60 connector needs to be soldered to one end, which will connect to the power module, while the other end of the cables will be connected to a terminal block. From this terminal block, two pairs of cables will exit and connect to another three-terminal block. On one side of this second terminal block, the motor's ground and power lines will be connected, while the third terminal will accommodate the motor's PWM cable along with another cable that goes to the autopilot. Additionally, a cable from the ground terminal will also be connected to the autopilot.

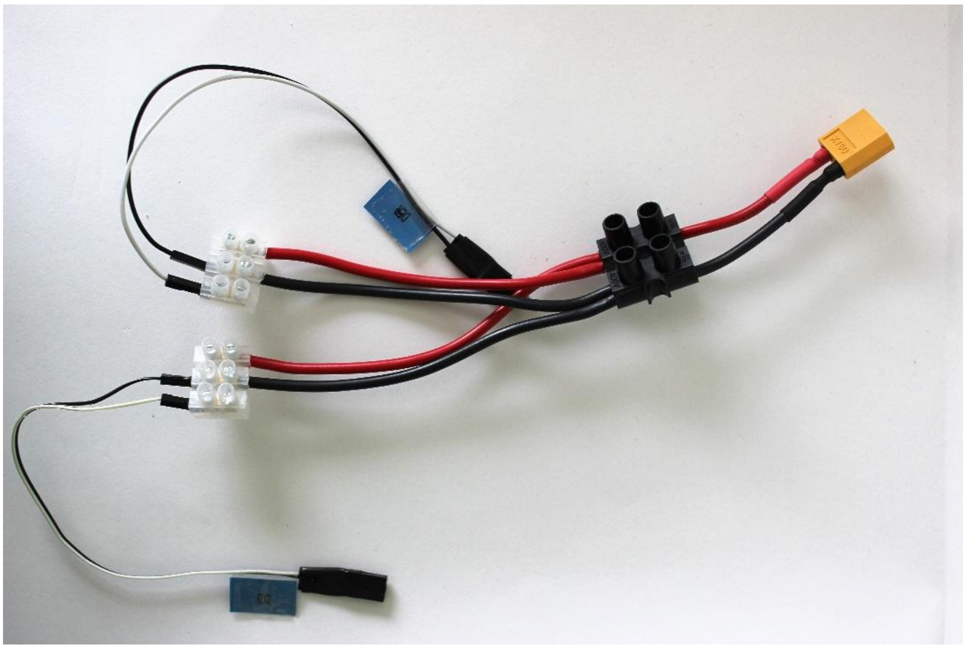

Figure 3.14: Final result of the motor cables

3.2.3 Component Wiring

To complete the assembly of the USV, only the electronic devices need to be connected and placed inside the enclosure. The devices connect to the autopilot ports using a connector called JST [27]. This cable has six wires, but not all are always used. To properly connect the devices, the wiring diagrams were consulted [27], resulting in the following diagrams:

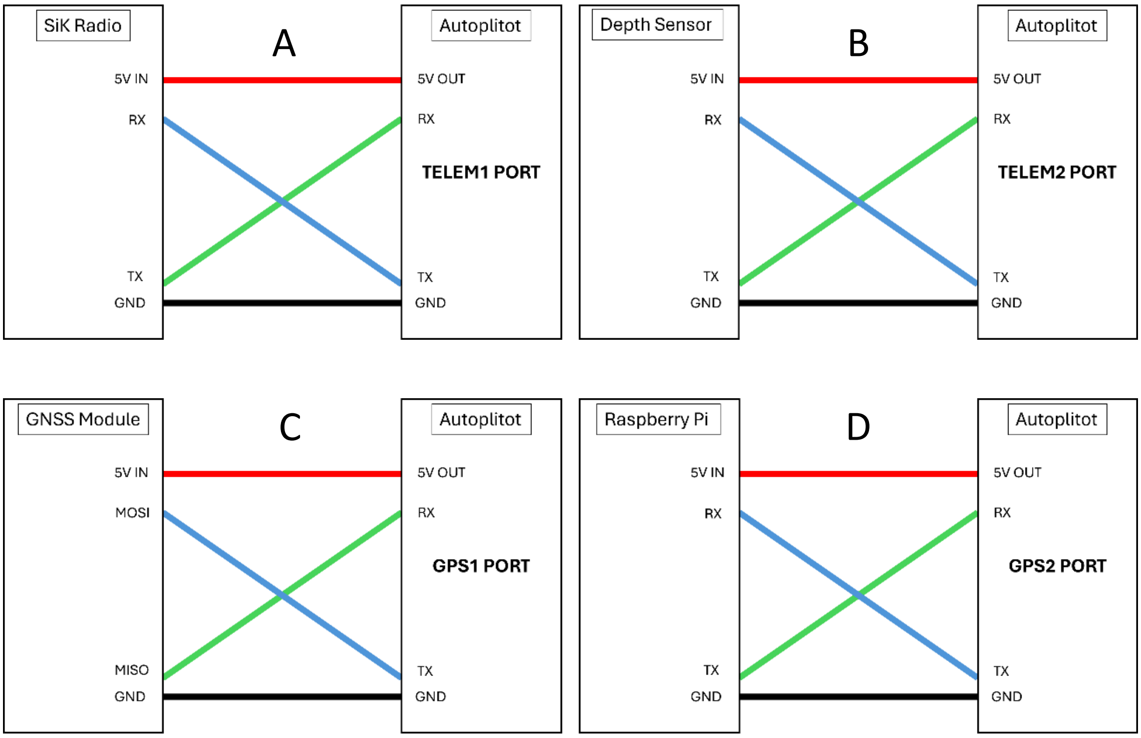

Figure 3.15: Diagram of the connections for the Sik radio (A), the depth sonar (B), the GNSS module (C), and the Raspberry Pi (D)

The RC receiver connects directly to the RCIN port [27]. The right motor is connected to MAIN OUT 3, and the left motor to MAIN OUT 1 [27], as previously shown. It is important to note that although the Raspberry Pi is connected to a GPS port, its configuration can be changed afterward to operate as a telemetry device[27]. After completing this step, the platform is fully assembled.

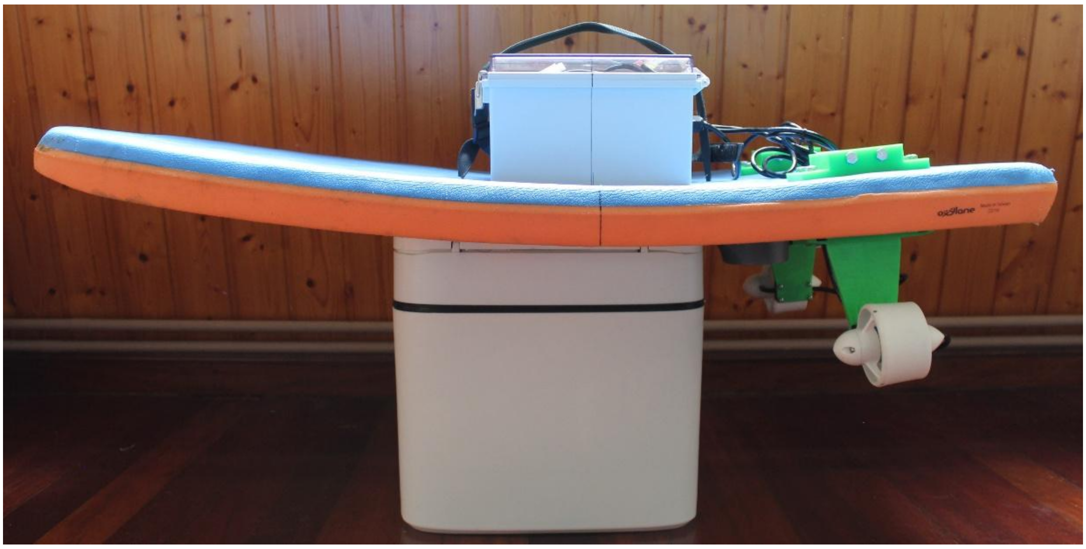

Figure 3.16: Final result of the platform assembly

Chapter 4: Implementation of Autonomous Navigation and Bathymetry

4.1 First Steps and Manual Navigation

Before implementing any autonomous functionalities, it is essential to ensure that the USV is fully operational in manual mode. This provides a foundation for verifying that all primary systems, such as propulsion, telemetry, positioning, and remote control are functioning correctly. The following steps describe the initial configuration process required to achieve this.

4.1.1 Initial Steps

The first step is to connect the autopilot to the PC using a cable and launch the Mission Planner software. Once the program is open, a connection to the autopilot is established. In the upper right corner of the interface, the "Connect" icon is displayed. The appropriate COM port corresponding to the device must be selected, along with the correct baud rate: 115200 for a direct cable connection, or 38400/57600 when using the Sik radio. After configuring these settings, the connection is initiated by clicking the "Connect" button [28].

Next, under the *Setup > Install Firmware* tab, several firmware options are displayed, depending on the type of vehicle to be developed. In this case, the latest version of the Rover firmware should be installed. This firmware is specifically designed for UGVs, but with a minor configuration adjustment, it can also be effectively used for USVs.

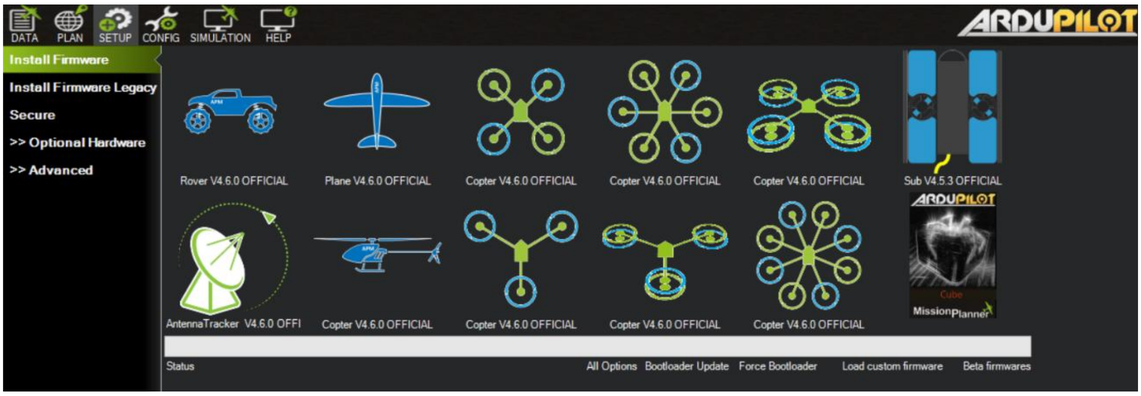

Figure 4.1: Firmware installation tab with several available variants

The small adjustment required involves accessing the *Config > Full Parameter List* tab in Mission Planner. This section contains all configurable parameters that define the behavior of the autopilot. By locating the parameter named FRAME_CLASS and setting its value to 2 [29], the system is informed that the vehicle being developed is a boat. This change ensures that the firmware interprets the platform as a water-based vehicle rather than a land-based. This configuration is important for the system to understand that the vehicle will operate in an aquatic environment, and to take this into account when in automatic mode and making decisions about its movements [29].

4.1.2 Radio Calibration and Control Mapping

It will now be necessary to calibrate the remote control to ensure that the USV responds correctly to user inputs. This process not only allows the operator to maneuver the vehicle using the desired control scheme, but also enables switching between flight modes directly from the transmitter. The RC antenna, previously paired with the remote control, is connected to the autopilot. In Mission Planner, the *Setup > Mandatory Hardware > Radio Calibration* section is accessed. The radio calibration process is initiated by selecting the "Calibrate Radio" option and moving all control sticks and switches on the remote transmitter through their full range of motion [30]. This procedure allows the system to record the maximum and minimum values of each control channel. After the calibration data is captured, the controls are returned to their neutral positions, and the calibration is completed [30].

Figure 4.2: Radio calibration tab prior to the calibration

Following the successful calibration of the remote controller, it is essential to assign specific functions to each control stick and switch to ensure effective manual operation of the USV. The left stick is designated exclusively for steering control, allowing the vehicle to turn left or right. In contrast, the right stick governs the forward and reverse motion of the vessel, thereby enabling linear propulsion.

Additionally, the upper-right switches on the controller are configured to manage the vehicle's flight modes. These modes determine the operational behavior of the USV and will be described in detail in subsequent sections. Proper mapping of these controls is crucial for intuitive and reliable manual navigation.

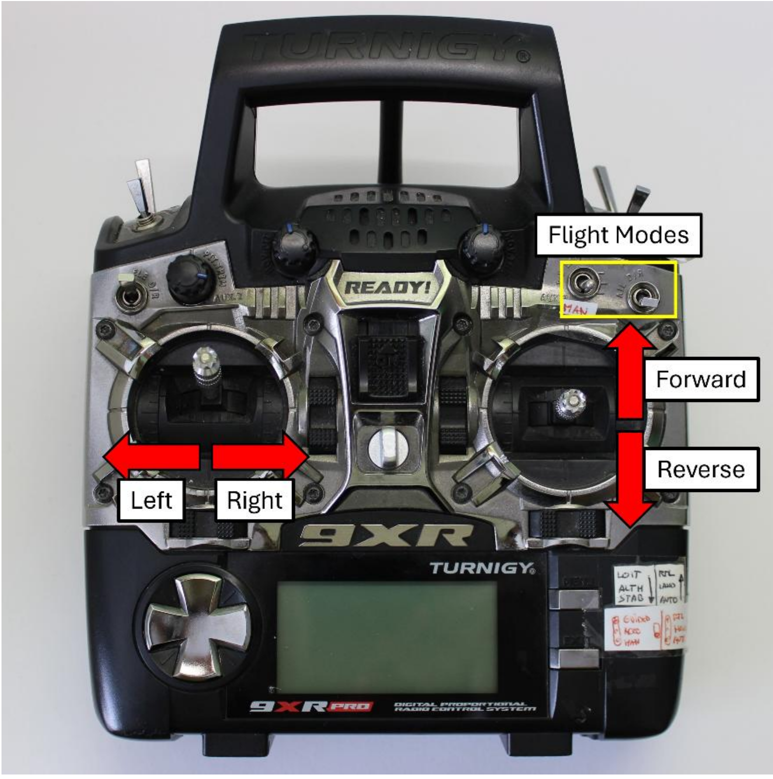

Figure 4.3: RC transmitter control diagram

To associate the control movements of the USV with the corresponding stick axes on the RC transmitter, certain parameters must be adjusted within the *Config > Full Parameter List* tab in Mission Planner [31].

First, the forward and backward movement of the vehicle is mapped to the Y-axis of the right stick, which corresponds to channel 2 on the RC transmitter. To achieve this, the RCMAP_THROTTLE parameter is set to 2 [31].

Similarly, turning left or right is controlled by the X-axis of the left stick, located on channel 4. Therefore, the RCMAP_ROLL parameter is assigned the value 4 [31].

To avoid assigning multiple functions to the same channel, the values of RCMAP_YAW and RCMAP_PITCH must be changed. These two movements are specific to aerial vehicles, and although they may still be mapped on the controller, they will not be executed by the USV [31], even if mistakenly activated, since such motions are not applicable to water-based platforms.

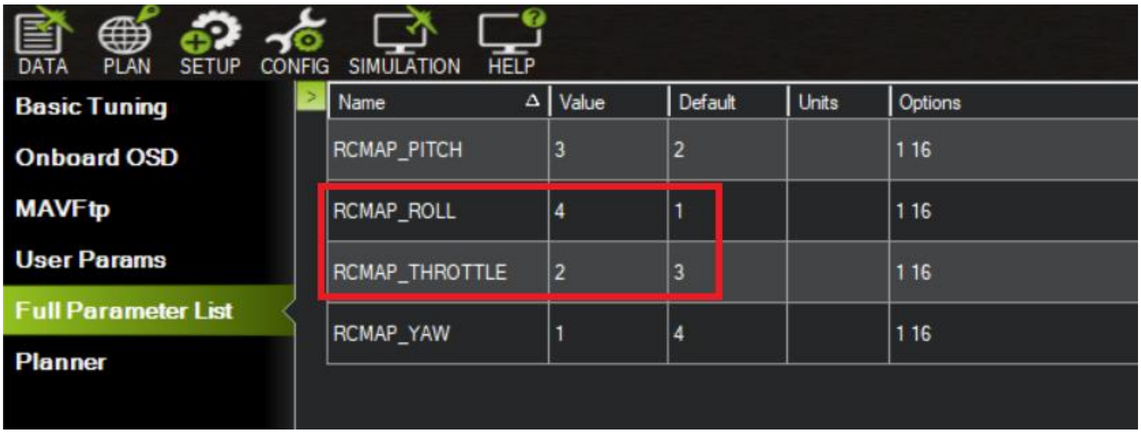

Figure 4.4: Parameters responsible for forward, backward, left, and right movement

4.1.3 Flight Modes

ArduPilot supports up to 25 different flight modes, each designed to enable specific behaviors or levels of autonomy in the vehicle. These modes allow the user to define how the system responds to control inputs and sensor data [32]. However, in this project, the RC transmitter is equipped with two switches, one with three positions and another with two, which allows for a maximum of six flight modes to be activated directly from the controller. This limitation is not restrictive, as six modes are more than sufficient for the intended operations of the USV. The six selected modes and their functions will be described in the following section:

- **Manual:** In this mode, the USV is fully controlled by the RC transmitter, with no assistance from the autopilot [32].
- **Auto:** When this mode is activated, the USV autonomously follows a pre-programmed mission uploaded to the autopilot [32].
- **Guided:** This allows real-time mission control from the Mission Planner interface. Waypoints can be placed manually on the map, and the USV will navigate to them immediately [32].
- **Acro:** The USV performs continuous rotation around its position. This mode is mostly used for diagnostic or experimental purposes [32].
- **RTL:** The USV autonomously returns to the launch point recorded at the time of arming the system [32].
- **Hold:** The vehicle maintains its current position, making it useful for pausing operations or stabilizing during testing [32].

Each unique combination of the two switches activates one of the six selected flight modes, allowing the user to easily toggle between manual control and different levels of autonomous behavior. The mapping scheme is as follows:

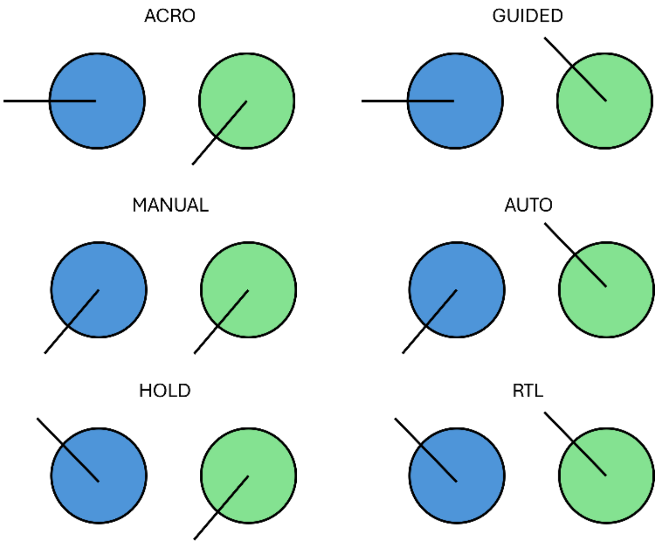

Figure 4.5: Diagram of the flight mode mapping on the RC transmitter

With the RC transmitter turned on, navigate to the *Setup > Flight Modes* tab. In the list of six available modes, the one corresponding to the currently active switch combination will be highlighted in green. Each mode can then be modified individually until the desired configuration is achieved.

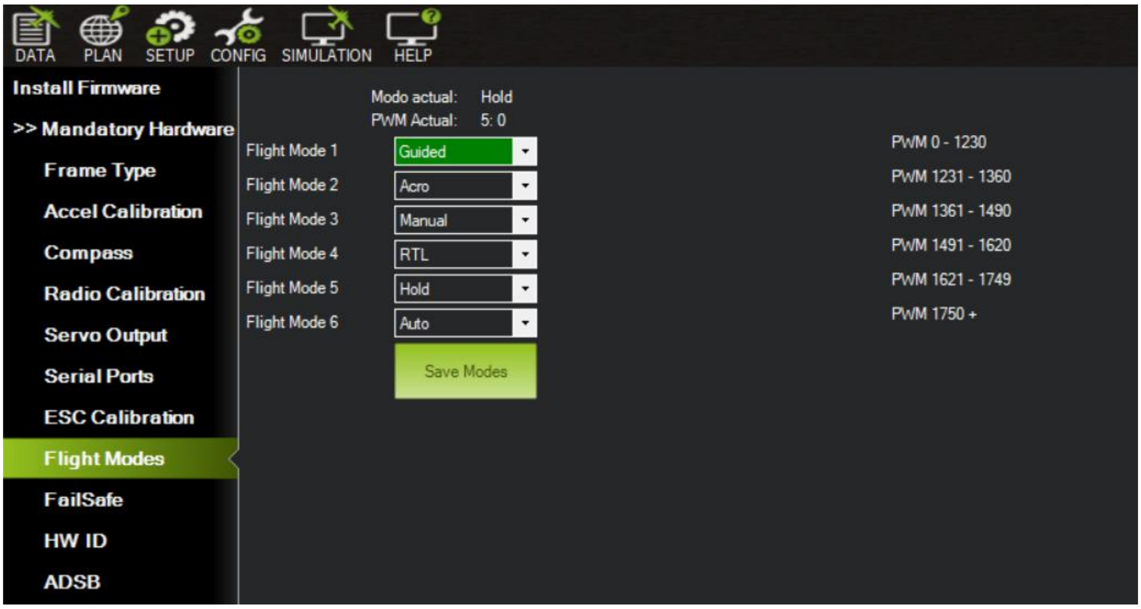

Figure 4.6: Flight modes screen

4.1.4 Registering the Depth Sonar and the Remaining Devices

The final step before planning the first autonomous mission is to register all the devices connected to the USV. These include the GNSS module, the depth sonar, the SiK radio module and the companion computer. Ensuring that each device is correctly recognized and configured within the autopilot system is essential for the proper execution of autonomous navigation and data acquisition. The registration of these devices will be carried out in the *Config > Full Parameter List* tab [33].

The first device to be registered is the SiK radio, which enables wireless connection to the autopilot through Mission Planner. This device operates at 38400 [22] baud and uses the MAVLink2 protocol [33]. To register it, the parameter SERIAL1_BAUD must be set to 38 [33], and SERIAL1_PROTOCOL must be set to 2 [33].

The GNSS module requires communication at 38400 baud and the use of a GNSS-specific protocol [18]. To meet these requirements, the parameter SERIAL3_BAUD must be set to 38 [33], and SERIAL3_PROTOCOL to 5 [33]. These parameters are typically set to the correct values by default, and upon verification, they were found to be properly configured.

The Raspberry Pi, which will be connected to the GPS2 port, requires communication at 115200 baud and the MAVLink2 protocol. Parameter SERIAL4_BAUD must be set to 115 [33], and SERIAL4_PROTOCOL must be set to 2 [33].

The sonar communicates at 115200 baud [20] and uses its own Ping protocol [20]. To register it, SERIAL2_BAUD is set to 115 [33] and SERIAL2_PROTOCOL to 9 [33]; the latter parameter indicates that a sonar protocol will be used, but not exactly which one. Through the RNGFND1_TYPE parameter, it is changed to 23 to specify that the protocol is Ping. Finally, the minimum and maximum distances measured by the sonar must be set. To do this, RNGFND1_MAX_CM is set to 10000 [20] [33] and RNGFND1_MIN_CM to 30 [20] [33].

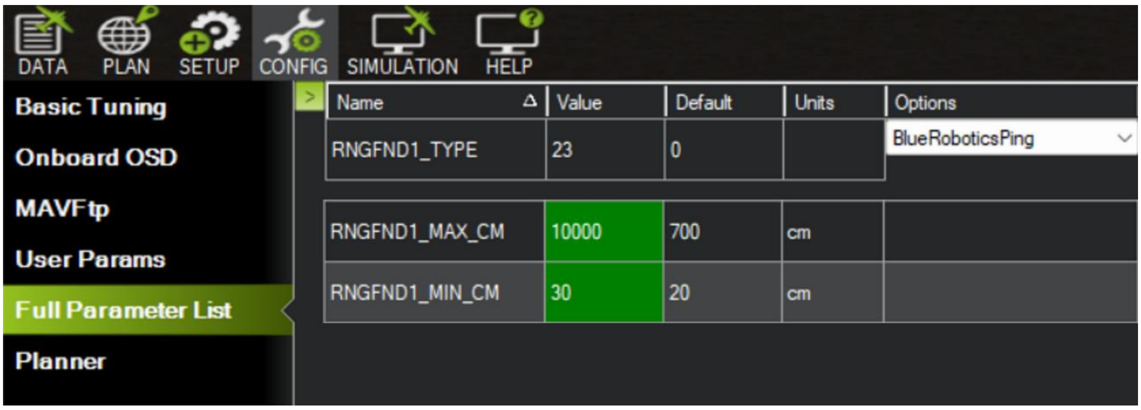

Figure 4.7: Advanced depth sonar parameters

Now that all devices are registered and manual mode is operational, the development of the autonomous mission can start.

Telem1: SiK radio

SERIAL1_BAUD	38	57
SERIAL1_OPTIONS	0	0
SERIAL1_PROTOCOL	2	2

Telem2: Depth Sonar

SERIAL2_BAUD	115	57
SERIAL2_OPTIONS	0	0
SERIAL2_PROTOCOL	9	2

GPS1: GNSS Module

SERIAL3_BAUD	38	230
SERIAL3_OPTIONS	0	0
SERIAL3_PROTOCOL	5	5

GPS2: Raspberry Pi

SERIAL4_BAUD	115	230
SERIAL4_OPTIONS	0	0
SERIAL4_PROTOCOL	2	5

Figure 4.8: Summary of the serial port parameters

4.2 First Autonomous Mission

4.2.1 Final Configurations

To operate the USV, it must first be armed. This arming process must be performed manually as a safety measure to prevent unintentional activation. If the battery is connected while the USV is in automatic mode, the vehicle could begin moving on its own. Arming requires passing several safety checks, such as ensuring a minimum battery level and proper telemetry function. While these checks are essential for aerial drones, which may pose significant risks if activated unintentionally, they are less critical for USVs, especially when the vessel is powered on while on solid ground. To streamline the operation and allow arming with a single button press, all pre-arming checks will be disabled. To disable all pre-arming checks, the parameter ARMING_CHECK must be set to 0 in the *Full Parameter List [34]*.

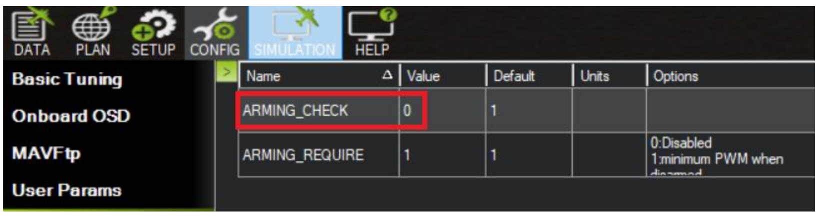

Figure 4.9: Disabling of pre-arming checks

During mission execution, the USV logs telemetry data onto a microSD card [35]. Given that the primary objective of the USV is to conduct bathymetric surveys, the most critical data recorded are the GNSS coordinates and the corresponding depth measurements obtained from the sonar at each location. To record data only from the GNSS module and the sonar, the LOG_BITMASK parameter in the *Full Parameter List* should be configured to enable only the GPS and Rangefinder options [35].

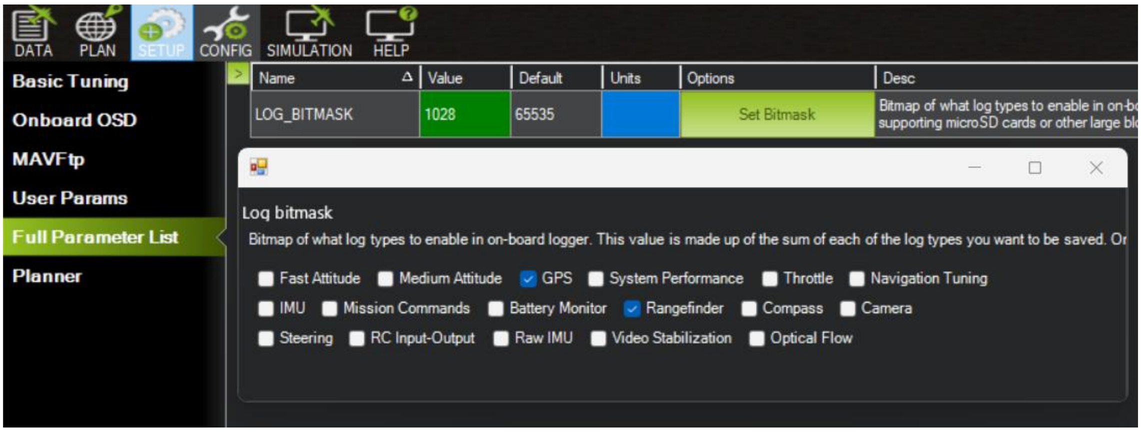

Figure 4.10: Data logging options

4.2.2 Autonomous Mission Deployment

To begin developing an autonomous mission, Mission Planner is opened and connected to the USV. The vehicle is then armed by clicking the *Arm/Disarm* button located in the *Data* tab, and subsequently disarmed. Next, the *Plan* tab is accessed, where the interface will display a layout similar to the following:

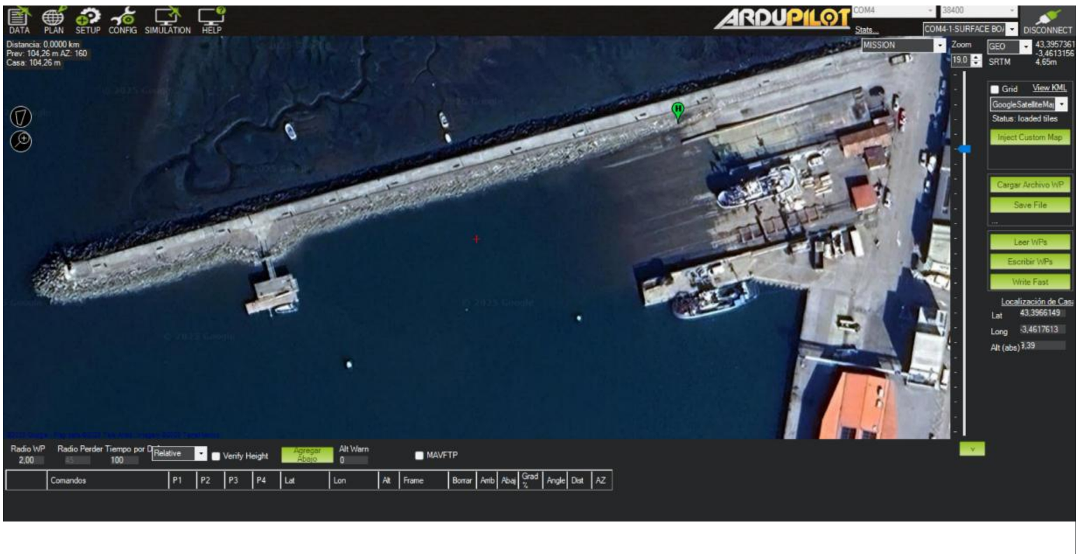

Figure 4.11: Plan tab

The green point marked with the letter *H* indicates the location where the USV was last armed. If the RTL mode is activated, the USV will return to this point [36]. From here, WPs can be designated by clicking on the desired locations on the map [36]. In Auto mode, the USV will follow the WPs in sequential order [36]. Each time a WP is added, its coordinates and index number appear at the bottom of the screen. In addition to the coordinates, the target altitude for each WP is also displayed. Since this is a water-based drone, the altitude should be set to zero. Once the desired route is complete, the *Write WP* button on the right side of the screen must be clicked to upload the mission to the autopilot.

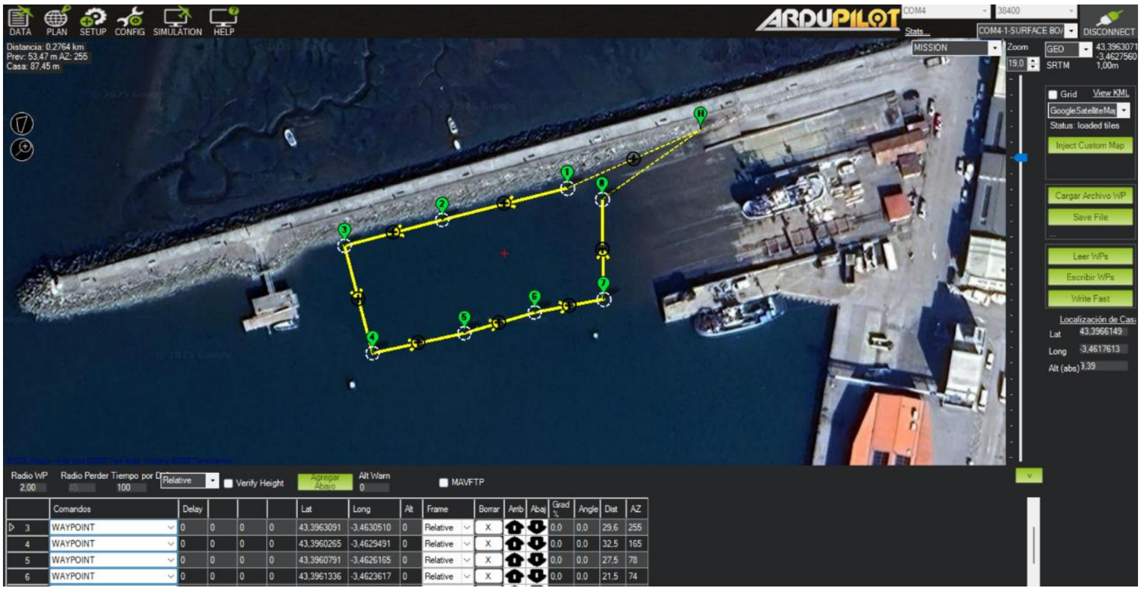

Figure 4.12: Autonomous mission planning process

The USV is now armed manually and placed in the water. Once Auto mode is activated, it will begin the preprogrammed route [36]. If the mode is changed during the mission, the USV will behave according to the new mode[36]. Upon returning to Auto mode, the mission will resume. From the moment the USV is armed, the echosounder starts measuring depth, and these measurements, along with the corresponding coordinates, are recorded on the microSD card for later analysis [36]. The USV's real-time position can be monitored on the Data screen, enabled by the telemetry connection.

Figure 4.13: Real-time monitoring of the USV's position during a mission

When Guided mode is activated, right-clicking on a point in the map on the Data screen presents the option *Fly Here*. Selecting this option commands the USV to move to the specified location [37], allowing direct control of the USV in Guided mode.

Figure 4.14: USV during an autonomous mission

4.2.3 Visualization of Bathymetric Data

To visualize the bathymetric data, the software ReefMaster [38] will be used. ArduPilot stores telemetry data in .bin files, which are not compatible with ReefMaster. Therefore, these files must be converted to .CSV format, which ReefMaster can read [38]. To do this, the microSD card is removed from the autopilot and inserted into the PC. With the USV connected, Mission Planner is opened, and the path *Data > Data Flash Logs > Review a Log* is followed [39]. The desired .bin file is then selected and opened for further processing. In the new window, the data can be viewed, although in a basic and limited format. At the bottom of the screen, a table displays various parameters recorded during the mission. By right-clicking on the *DPTH* row, the option *Export Visible* [39] can be selected to export the depth data. The newly exported file can be opened and visualized in ReefMaster for further analysis [39].

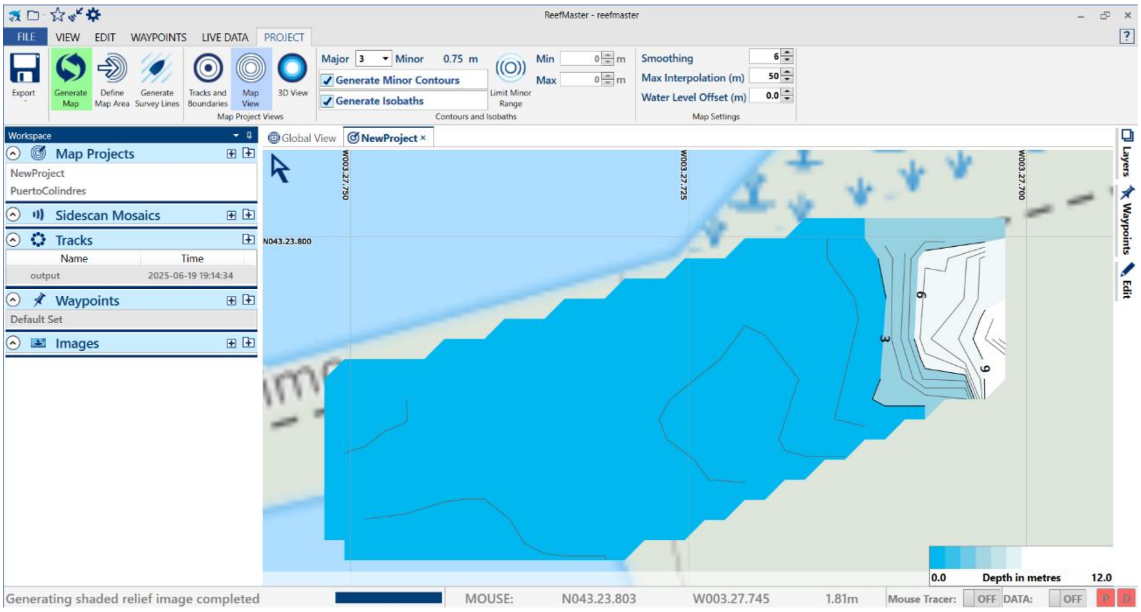

Figure 4.15: Bathymetry visualization in ReefMaster

4.3 Implementation of RTK Technology

RTK is a satellite navigation technique used to enhance the precision of position data derived from GNSS. Unlike standard GNSS, which typically provides accuracy within a few meters, RTK achieves centimeter-level accuracy by using carrier-phase measurements and real-time corrections [40].

The system operates with two main components: a base station and an unmanned vehicle. The base station is positioned at a known, fixed location and continuously receives satellite signals. It calculates the errors in the received signals and transmits correction data to the vehicle, called RCTM, via a communication link, such as radio or Internet [40]. The vehicle applies these corrections to its own GNSS data, significantly improving its positional accuracy [40].

RTK is particularly useful in bathymetric surveys because it improves USV navigation by providing centimeter-level accuracy, which is especially important in aquatic and terrestrial environments compared to aerial applications. Additionally, the bathymetric data collected would be of higher quality due to this enhanced positional precision.

With the current configuration of the USV, it is not possible to implement RTK technology, as there is no base station equipped with a second GNSS module available at this time. An alternative approach would involve providing the USV with internet connectivity, allowing it to access correction data from a fixed reference antena via NTRIP, such as one installed on a nearby building. However, this option is also neither feasible under the present conditions.

Chapter 5: Results, Conclusions and Future Improvements

5.1 Results

At the beginning of the project, four clear objectives were proposed. Each of these objectives will now be evaluated in the following sections.

The first objective was the development of the robotic platform. This objective has been achieved, as a fully functional USV was constructed using the hardware pre-selected by the project supervisor, along with batteries selected at a later stage. Custom wiring was developed to connect all devices, and 3D-designed mounts were created to attach the motors to the platform. The resulting USV possesses all the operational capabilities expected of such vehicles and has been shown to meet the initial project requirements.

The second objective was to implement autonomous navigation in the vehicle, including the ability to operate it manually via an RC controller. This objective has also been achieved. Several autonomous missions were successfully carried out, with their execution being intentionally interrupted to test manual control, and subsequently resumed in autonomous mode. Other modes, such as Hold, Acro, Guided, and RTL, have also been successfully tested.

The third objective was to integrate a depth sonar to perform seabed measurements and conduct bathymetric surveys. This objective has also been successfully achieved, as demonstrated in the results.

The final objective was to implement RTK technology to improve the accuracy of the GNSS module. This objective was not achieved, as, as previously explained, it would have required either a second GNSS module or internet connectivity on the USV to be implemented.

5.2 Conlusions

Given that the project has successfully resulted in the development of an autonomous USV for conducting bathymetric surveys, it is evident that ArduPilot and Mission Planner are suitable open-source technologies for this type of application. While they are often used in hobbyist contexts, they also demonstrate strong potential for real-world deployment.

5.3 Future Improvements

During the development of this work, several potential areas for future improvement have been identified.

- The companion computer included in the project was integrated from the outset with the intention of enabling future extensions of the USV's functionality. Some of these potential enhancements include the addition of sensors such as a LiDAR or a camera with computer vision for obstacle detection, as well as a water quality sensor to allow environmental monitoring alongside bathymetric surveys. Moreover, a 4G USB modem could be used to establish an internet connection, enabling real-time position tracking of the USV and extending the communication range with the ground station beyond the current limitations of the SiK radio system.
- Implementing RTK technology would enable safer navigation and more accurate bathymetric measurements. This could be achieved either by adding a second GNSS module or by utilizing a potential internet connection through the companion computer.
- Currently, the motors do not operate at the same speed, causing the USV to drift slightly to one side when following a straight trajectory. During autonomous navigation, this minor heading deviation is corrected without issue; however, it would be necessary to address this imbalance to achieve smoother navigation. Motor speeds can be adjusted to operate in coordination by modifying their advanced parameters.
- Finally, it would be advisable to implement a system to better organize the internal wiring within the waterproof enclosure. Due to the movement during transport, it is common for some cables to become disconnected, which can lead to certain devices becoming non-operational. This often requires removing all components from the enclosure to identify and reconnect the loose cable, making the process inefficient and time-consuming.

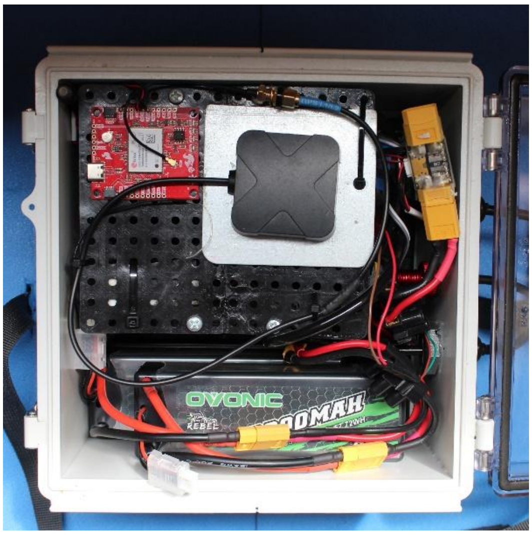

Figure 5.1: Wiring inside the enclosure

Figure 5.2: USV navigating through the port of Colindres, Cantabria

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