Team Caleuche Technical Design Paper for the RobotX Challenge 2024

Octavio Águila, Néstor Arispe, Ignacio Gajardo, Diego Galleguillos, Cristián López, Vicente Sufán, José Tomás Unger, Gustavo Vidal.

***Abstract*— For the RobotX 2024 Challenge, Caleuche has finally reached a reliable and functional Autonomous Surface Vehicle (ASV), capable of collaborating with its integrated Unmanned Aerial Vehicle (UAV). Significant hardware and software upgrades, executed while preserving the system's simplicity, made this achievement possible, maintaining the system's modularity to ensure ease of integration and future scalability.**

I. Introduction

Team Caleuche makes its second appearance at the RobotX Challenge, with a team made up of undergraduate and master students sharing a common interest in maritime robotics. From the last 2022 competition, the team has focused on improving and upgrading the ASV's power supply, perception systems, component arrangement, and autonomous algorithms while integrating the completely new UAV to enhance its capabilities and overall system performance.

II. Design Strategy

Due to logistical issues beyond the team's control, Caleuche's ASV was unable to arrive at the 2022 RobotX Challenge, preventing the team from deploying its own system in a real competition environment. Moreover, the previous ASV version, while also functional, needed more robustness, as it needed the necessary hardware, power supply, sensors and software integration to operate autonomously in real-competition scenarios.

The development for the 2024 competition platform started in April of this year, delayed by a reorganization of the team. With only seven months remaining, the team decided to focus on keeping the system as simple as possible. Rather than introducing overly complex features, the team's goal was to refine the core systems to arrive at the competition with a competitive platform.

A. Storage

The storage system for the 2022 version, was composed of two stainless steel grids bolted to the ceiling, to which the two pelican cases were anchored. The high load generated bending in the roof, required intervention on the cases to be able to attach them to the grids and presented a risk for people and pontoons due to the corners of the structure. Thus, improvements were needed, so after an extensive analysis, the team developed a new system for storage located under the payload tray of the ASV, inspired by the design of other competitors [1].

The team also identified that the previous sensor tower needed to be replaced. The mounting of the sensors proved to be unnecessarily complex, impractical and generated temperature concentration because of the geometry and positioning that ended up affecting the normal functioning of the sensors, making it difficult to develop precision positioning of the LiDAR, cameras, GNSS and antenna that was needed to complete the tasks.

For this 2024 edition, the design of mechanical components aims for a simple and user-friendliness system, ensuring that the mechanisms can be assembled by a person with little or no experience, and without big interventions on the ASV.

To achieve this, the design of all structures was standardized after a long period of evaluation and iteration on different materials and manufacturing processes, to work principally with extruded aluminum profiles 30x30 mm and PETG 3D prints, reducing weight and making it easy for prototype and iterations.

This standardization allows the system to adapt to continuous changes with low cost and adaptation time, in addition to facilitating assembly by reducing the number of tools required and facilitating repairs with commercially available products everywhere.

B. Propulsion

The 2022 version consisted of a four-motor configuration, with two Torqeedo 1103CL 1,1 kW (total dry weight of 35,4 kg including batteries) halfway the hulls from the stern perspective, and two Spirit 1.0 Evo 1 kW from Epropulsion, located in the pods (total of 40 kg), allowing a holonomic movement.

For this edition, the team discarded the holonomic configuration and decided to aim for a two-motor system with the Torqeedos. This decision was driven by three key constraints: development, budget and time. The previous four motor configuration was never fully operational and had not been tested under real-competition conditions. Moreover, implementing a holonomic configuration ideally requires four identical motors to achieve the best possible control and efficiency, meaning that the team would have to acquire motors, integrate them, and develop control algorithms in less than seven months to be able to achieve the holonomic movement.

Considering Caleuche's goal to have a simple and competitive system by November, using two motors seemed to be the best option for the team. By using two motors the logistics and development became simpler. Although the holonomic motion capability is lost, the team believes that it is only strictly necessary for the dock and deliver task, which was decided not to address to focus the work on the other seven tasks.

C. Power Supply and Distribution System

Caleuche's 2022 electrical system utilized a 48 V scooter battery to power the main sensors and communication hardware, including the LiDAR, GNSS, antenna, switch, kill switchboard and operational status lighting system.

Meanwhile, the onboard computers, consisting of multiple Jetson Nano units and a single Raspberry Pi, were powered by individual LiPo batteries with the appropriate voltage. Lastly, the propulsion system was powered by the thrusters' original batteries. This configuration provided 5 hours of autonomy for the ASV.

To avoid any issues with the antenna, the team used the original Power over Ethernet (PoE) injector provided by Ubiquiti, which required AC voltage. Therefore, a 220 V AC power inverter, designed to work with a 12 V battery, was installed.

The team conducted a thorough analysis of the ASV's 2022 electrical system and identified four major areas for improvement:

1. Limited battery autonomy was further impacted by the inclusion of a new onboard computer, which reduced the time available for water testing.
2. Lack of robustness and hardware are still in the early stages of development, occasionally leading to errors during system testing.
3. System setup and debugging required significant time.
4. Dangerous voltage within the system, with 220 V AC posing a risk to the safety of team members.

The combination of system fragility and a time-consuming setup often meant that a significant portion of water testing days was spent debugging, rather than testing software and algorithms.

To address these issues, the team committed to a complete redesign of the power supply and distribution system, while also improving the system's modularity to ensure ease of integration and future scalability.

Since the team aimed to incorporate new, higher-standard sensors and hardware, this redesign required selecting a new main battery with sufficient capacity to handle increased power consumption and extend the previous system's autonomy.

This approach allowed for a seamless addition of new sensors and hardware without requiring changes to the overall structure of the electrical system.

D. Perception System

One of the major topics the software team worked on the past two years was the change in our hardware. The vehicle's 2022 version was equipped with three sensors: an OS0 LiDAR, an OAK-D-PoE camera, and a Microstrain GNSS. For the 2024 version, a hydrophone was added and the LiDAR was upgraded.

The LiDAR allows for the sensing of 3D objects in the environment such as buoys, and obstacles. The camera is crucial for the scan the code task, as is the hydrophone for the entrance and exit gates. Finally, the GNSS is necessary for the optimal control of the vehicle allowing precise measurements in terms of position and orientation.

The OS0 LiDAR (OS0-32) had to be upgraded to a newer version (OS1-64) due to the limited range capabilities of the previous, where our vision algorithms began having problems with detecting buoys farther than 10m. The LiDAR change led to a redesign of the hardware used for perception, which caused us to upgrade the main computer to a Jetson AGX Orin, this model was chosen over the option of building a custom computer due to it saving us the work of designing a cooling system for the computer from scratch and having to power it with 220V (AC value used in Chile).

The design strategy for the project centered on utilizing the Virtual RobotX (VRX) simulation environment [2], to replicate the competition's conditions, including objects, physical environment properties, and sensor simulations like LiDAR, camera, IMU, and GPS. This simulation environment allowed for efficient software development and testing without reliance on physical hardware. Machine Learning (ML) techniques were employed for processing LiDAR-generated point clouds, as LiDAR effectively detected objects in marine conditions, making it ideal for clustering algorithms and ML classifiers.

E. Robust Control Module

The control module, together with the instructions provided by the algorithms designed for each task, determines the capability of our ASV to navigate. For the 2022 competition, this module did not perform well, largely due to the limited time we had for tuning and testing on water, the absence of an obstacle avoidance system, and the complexity of working with two different types of thrusters. This made it challenging to map the forces to each motor and achieve movement in the desired directions. Considering these factors, the team decided to design a new control module with the following objectives:

1. Simple and effective performance in controlling the ASV's movement.
2. Easy to tune for the specific environment where it will be deployed.
3. Inclusion of a submodule for reactive obstacle avoidance.

F. Task State Machines and Obstacle Avoidance

Most of the work done by the software team during the past two years has been on improving the system used in the previous competition. The first major change was the transition from Robot Operating System (ROS) to Robot Operating System 2 (ROS2). Furthermore, to reduce code complexity, all tasks were modeled and developed as state machines using the YASMIN state machine library [3]. This allowed us to focus on the behavior required for the task and then solve each substep in a more modular way. To achieve this, ROS2 Actions/services became the baseline for the system that was developed. In the ASV, the software runs on multiple processing units that communicate through the ROS2 multi-machine package since they are on the same local network. All of the chosen tasks were first tested on the Virtual RobotX simulator using custom-built tracks for each of the different tasks based on the competition handbook; these tests were later verified on terrain.

The tasks were chosen based on our hardware capabilities and time constraints to better prepare for the competition. These were tasks 0 (safety inspection), task 1 (Situational Awareness & Reporting), 2 (Entrance and Exit Gates), 3 (Follow the Path), 4 (Wildlife Encounter), 5 (Scan the Code), 7 (UAV Replenishment) and 8 (Search and Report). Tasks 0 and 3 were modeled similarly, both using a state machine with three key states —FindPortal, PassPortal, and PortalCounter—which served as a foundation for solving future tasks.

G. UAV strategy and integration

The UAV platform was completely redesigned, taking in the lessons learned in the development cycle and participation in the RobotX Challenge 2022. The focus during development was for the new UAV to be as flexible and extendable as possible, allowing the team to change or add components in case it was deemed necessary or the competition rules changed.

The team decided to move to a bigger platform, mainly driven by the design constraints posed by Task 7: UAV Replenishment, the team did not participate in this task in 2022 because of the weight limitations of the old UAV, so having a new UAV capable of meeting all the weight requirements for task 7 and 8 was a key driving decision for moving to a bigger platform.

In addition to a comprehensive redesign of the UAV's hardware, the team focused on making the integration of the UAV with the ASV as seamless as possible. To achieve this, the team focused its efforts on two main areas, a new software architecture and a new wireless network. The team moved away from Ardupilot as the flight control software and into PX4 [4], allowing the team to program the high-level behavior using ROS2.

To leverage the advantages the ROS2 brings in multi-robot operations, the team decided to include a Wi-Fi point-to-point connection from the UAV to the team's ASV network, allowing both vehicles to share information via the ROS2 DDS.

III. Vehicle Design

A. Storage

As shown in Fig. 1, the main element of the storage system is the central profile, which is constructed from stainless steel 304 and is attached to both the front tube of the payload tray and the rear arch. In simulations under critical static conditions, a safety factor of 10 was obtained. Three trays for the pelican cases are mounted on the central axis, and fixed using 3D print spacers. Straps and 3D print supports are used to fix the pelican cases inside the trays to ensure safety and accessibility.

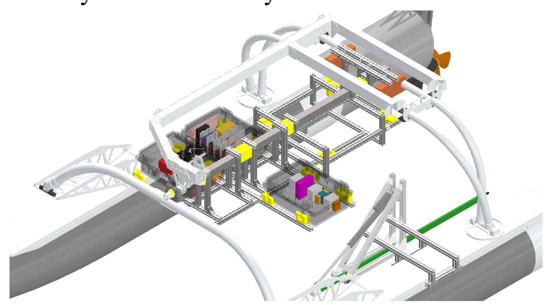

Fig 1. Sub-roof CAD assembly on the ASV.

The sensor tower consists of an aluminum profile mechanism bolted to the payload tray, with a front profile that positions the LiDAR 300 mm above the roof, a crossbar where the status lighting system and the antenna are mounted, and a rear profile dedicated to protect the components from a possible collision with the drone as shown in Fig. 2. The OAK-D camera and the GNSS are coupled, as well as the rest of the components with 3D printing parts standardized by the team.

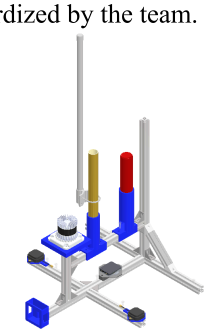

Fig 2. Sensor tower CAD assembly.

B. Propulsion

As previously mentioned, the team competes with 2 Torqeedo Travel 1103CL motors, which are coupled with 3D-printed adapters to avoid interventions on the pods, and are powered by their original batteries.

For the 2024 system, the team developed a new low-level throttle control system. Each motor is controlled by an ESP32 that acts as a driver with microROS, required to integrate speed commands with the ROS2 messaging system used by the onboard computers. Additionally, the team researched the motor communication protocol and implemented feedback on the current status of the motors, including RPM, battery charge, and Torqeedo error codes during operation, which streamlined the debugging process.

C. Power Supply and Distribution System

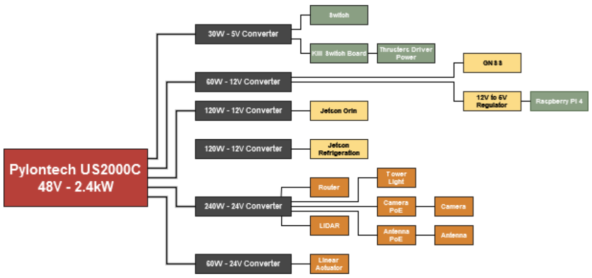

Fig 3. 2024 Power Distribution System, designed to isolate electrical failures by voltage, streamline the ASV's setup and debugging processes, and enhance the overall robustness of the system.

The team designed a new power supply and distribution system aimed at addressing the challenges identified in the 2022 system. For the 2024 competition, Caleuche's primary power source is the 48 V Pylontech US2000C lithium battery, with a capacity of 2,4 kWh. This battery powers nearly all of the platform hardware, including the onboard computers, sensors, and thruster drivers, as well as other peripherals and safety systems, such as the status lighting system and the kill switch.

To improve robustness compared to the 2022 system, the power delivered by the main battery is routed through a distribution system consisting of DC regulators and circuit breakers, which supply power and protect the hardware from short circuits and unexpected high power consumption. This design not only ensures that all powered components are safeguarded against critical electrical failures but also enhances the safety of team members during the setup and operation of the ASV platform.

In terms of the ASV's setup, the 2024 electrical system is organized into four Pelican cases mounted on the ASV. The first case contains the main battery and its monitoring system. The second case houses the distribution system. The third case contains the components responsible for powering, controlling, and communicating with the sensors and peripherals, as well as a Raspberry Pi 4 (Rpi4)—Caleuche's first onboard computer—and the kill switchboard, which manages power distribution to the propulsion system. Finally, the fourth case holds the Jetson Orin, the second onboard computer, along with its Peltier cooling system and an amplifier for a hydrophone. Is relevant to note that, as the antenna is powered by 24 V DC via passive PoE, thus the AC power inverter is no longer needed in the electrical system, ensuring a safer workplace for our members.

The connections between the four Pelican cases and the peripherals followed the principle of 'different voltage, different connector.' This approach enhances system robustness by preventing incorrect connections, ensuring that a component cannot be powered by the wrong voltage, as its connector will not fit unless it is the correct one. This design protects the hardware from potential damage caused by human error and additionally allows for a faster assembly of the electrical system.

D. Software Architecture

The system software architecture comprises two primary components: the Base Architecture and the ASV Architecture, as shown in Fig. 4.

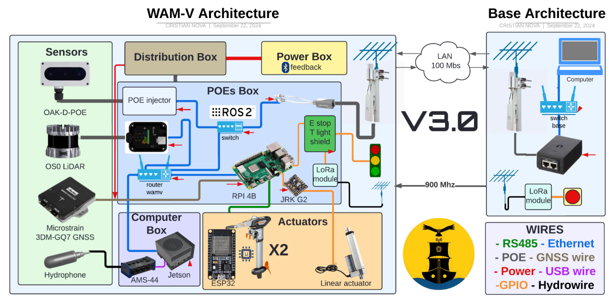

Fig 4. Diagram of the base and ASV architecture described in previous paragraphs. The diagram illustrates the type of connections between components.

In the Base Architecture, the home base computer is connected to an antenna through a PoE cable available on the base router. This antenna is paired with its twin on the ASV through a LAN connection at 100 Mbps. At the base, there is also an independent emergency stop button which connects through a LoRa to the Robot to shut it down in case of emergency.

The ASV architecture is composed of four sensors, an OS0 LiDAR, an OAK-D-PoE camera, a hydrophone and a Microstrain GNSS. The camera and LiDAR are powered through PoE connectors out of the ASV's router which simplifies the power distribution while the hydrophone and GNSS are connected to the Jetson which is the main processing unit. There is a Rpi4 that communicates the Jetson to the ESP32 that controls each motor, this Rpi4 also communicates with the emergency stop system that gets the feedback required for the switching status of the lighting system.

The main computer is a Jetson AGX Orin where all of the tasks are run, it communicates through ROS2 with the Rpi4 using the LAN connection through the switch and router and to include the ESP32 microcontrollers better into the system, microRos is used. The whole system can be shut down either manually from the ASV emergency stop buttons or digitally with the base computer or remotely with the base emergency stop button.

E. Robust Control Module

For the ASV control system, two independent PID controllers [5] were developed: one for angular position (heading) and another for surge velocity. The controllers receive as input the reference value for each variable, as well as the current state of the vehicle, and output a signal in the range [-1000, 1000] for each of the thrusters, with these limits corresponding to the throttle of full reverse and full forward movement, respectively.

The reference values for angular position (heading) and surge velocity are derived from the control actions developed. Meanwhile, the current state of the vehicle, specifically the angular position and surge velocity, is obtained from the fusion of GPS and IMU data within an Extended Kalman Filter.

To prevent the vehicle from colliding with obstacles during navigation, a reactive control submodule was developed. This submodule takes as input the position of the obstacle, the vehicle's position, and the position of the target waypoint. If the obstacle is located within a triangular area defined by a ±30° field of view and a 5 m range from the vehicle's bow (looking forward), the system adjusts the heading reference.

This is achieved by solving an optimization problem that minimizes the angular distance between the vehicle's current heading and the desired heading, subject to the constraint that the obstacle remains outside the specified triangular area.

F. UAV Design

The frame chosen for the UAV is a Hexsoon EDU-650 V2, this frame is 500 mm by 550 mm, it was chosen because it has a low center of gravity and a four point landing gear configuration, allowing stable recovery of the UAV and a easier mounting option for the task 7 tin can gripper. Also the frame allows the team to run 15in. propellers with 370 kV motors, the slow moving large propellers help with flight efficiency, boosting flight time. The rest of the powertrain of the UAV are four 40 A ESCs and a 6S 10000 mAh LiPo battery.

The flight controller chosen is Pixhawk 6C, running PX4, this flight controller allows us to expose low level flight control topics as ROS2 topics using uXRCE-DSS middleware. For the companion computer, the LattePanda 3 Delta was selected because it has a small form factor and powerful Intel x86 4-core CPU, while at the same time not drawing too much power. To communicate the UAV with the ASV network, a Wi-Fi HaLoW bridge was selected, because of the low weight of the radios and the not so demanding bandwidth requirements.

For perception, a downfacing OAK-1-W camera was mounted on the UAV, this camera can run on-board neural networks, this allows the team to run custom YOLOv8 models in the camera, offloading this workload from the LattePanda 3 Delta. Also, OAK-1-W was chosen due to the large field of view of 120°, this FOV allows the UAV to only utilize a downward facing camera, simplifying the overall perception configuration.

To pick up the tin cans a novel gripper concept was designed and implemented. The gripper is mounted using the four landing legs on the UAV, it consists of a solid outer square area with a moving sweeper that is pulled by two stepper motors with the use of belts. This configuration allows a 0,25 m^2 pick up area, if the tin can is anywhere inside the pick up area, the sweeper will pin the can against the solid wall and allow the UAV to pick it up. The advantage of this configuration is that it allows the UAV to pick up cans without the need of an extremely precise landing.

Finally, to increase the UAV's landing and take-off maneuvering margin, a helipad bolted to the ceiling of the ASV was built with aluminum profiles and MDF sheets, extending the useful landing surface to 1,8x1,8 m.

IV. Experimental Results

The team carried out tests on the VRX simulator for tasks prior to their development on the real ASV. The selected tasks were always implemented and tested initially in this simulation environment. To accomplish this, custom Gazebo worlds were designed to test specific components, and a detailed replica of Caleuche's ASV was created in the simulator. This allowed the team to identify potential issues, fine-tune algorithms, and validate system performance before transitioning to real-world testing.

For the real environment, the team followed a three-week cycle for design, implementation, and testing, centered around two key events: land testing and water testing. During this cycle, the team conducted various land testing sessions, setting up the system and network either in the laboratory or mounted on the ASV while on land, to test the implementation of new hardware and algorithms, identify errors, and outline next steps. The process culminated in a water testing day, where the team assessed whether the systems developed up to the land testing phase performed correctly in real conditions and gathered data for future development.

A. Controller calibration

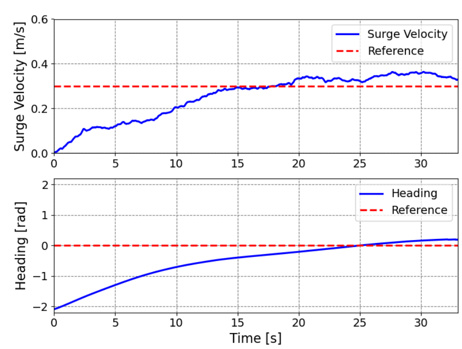

Fig 5. Time response of the ASV's surge velocity and heading to a step change in the reference signal, demonstrating the controller's rapid and accurate adjustment in order to achieve the desired setpoints and the effectiveness of the PID tuning in achieving stable control.

Both PID controllers were initially tuned in simulation to obtain preliminary parameters and were then fine-tuned during field tests to achieve optimal real-world performance. Fig. 5 shows the time response of the surge velocity and heading of the ASV to a change in the reference, demonstrating effective performance.

B. *Computer Vision algorithm*

The vision algorithm developed for scanning the code can be broken down into 5 steps: Pre-processing, Region of Interest (ROI) Selection, LED Buoy Segmentation, Color Classification, Color Pattern Formation.

The following diagram shows the typical results of the algorithm.

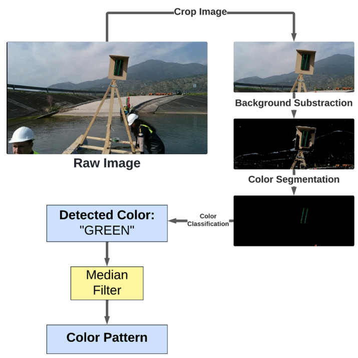

Fig 6. Vision algorithm flowchart and results.

Based on field test performance, the following observations were made: 1) The optimal distance between the ASV and the LED buoy is approximately 4-5 m. Performance degrades at greater distances. 2) The median filter significantly reduces the probability of generating incorrect patterns. In tests with this change, no incorrect results were observed. 3) The time to generate a complete pattern is roughly equal to the time it takes for the LED buoy to emit the pattern twice.

C. *Hydrophone*

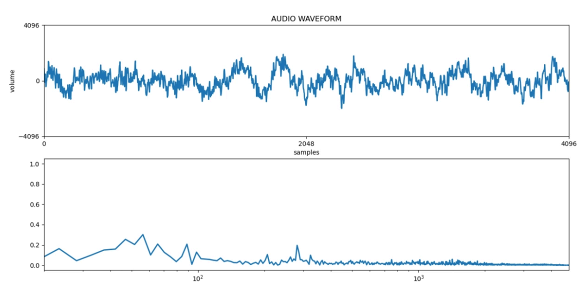

Fig .7 Hydrophone recording processing.

The second device tested was the hydrophone. A mount, bolted to the ASV's Ski, and a linear actuator allows the hydrophone to be lowered into the water only when it's needed. There are two main procedures that had to be tested in order to ensure the system was operating correctly. The first one was the linear actuator deploying the system correctly, this part was tested in the lab and later on the ASV. The second procedure and the most important one was the functionality of the code that filters frequencies was first tested using a depth sensor, taking advantage of its 40 kHz emission frequency.

In order to process the information, the fourier transform of the signal was calculated in order to separate the decibels by frequency and get a better understanding of the signal

It was then tested during a field trial to confirm that there was no significant noise produced by the motors. It was also confirmed that the sensor was able to pick up on small variations on distance to de source.

D. *Assembly and testing times*

The team significantly reduced assembly times compared to its previous version, from 3.5 hours to just 1 hour with only 6 people. This achievement translates into an increase in water testing times, from an average of only 2 hours for the previous system to a 5.5 hour testing window.

E. *Battery discharge curve*

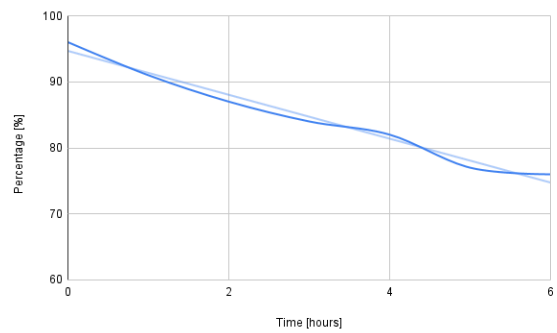

Fig 8. Battery discharge curve during a real water testing day

The provided graph shows the performance of the battery under real conditions. After six hours the system ended with 76% of available charge. This behavior was unexpected, as we had estimated an autonomy of six hours with 370 W of load, the results of the system says otherwise, as it had an average consumption of 75 W with peaks of 130 W, this behavior could allow us to reach up to 17 hours of autonomy without considering the motor's consumption.

V. Conclusions and Acknowledgements

The 2024 version of Caleuche's ASV demonstrates significant improvements over its predecessor, marking an important milestone for the team in achieving greater autonomy and effective collaborative behavior with the integrated UAV. Thanks to the robust development of core system components, the team has acquired all the necessary tools to be a competitive contender. Moreover, this progress lays a solid foundation for future team members, who will be able to build upon a solid system.

We would like to thank our generous sponsors and supporters who have made it possible for Caleuche to develop and compete in this RobotX Challenge edition. Thanks to RoboNation, ONR, Aguas Andinas, Multiaceros, and the PUC Mechanical Engineering Department for encouraging innovation and supporting the robotics advancement in Latin America.

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