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Lake Environmental Data Harvester (LED) for Alpine Lake Monitoring with Autonomous Surface Vehicles (ASVs)

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Abstract: This article introduces the Lake Environmental Data Harvester (LED) System, a robotic platform designed for the development of an innovative solution for monitoring remote alpine lakes. LED is intended as the first step in creating portable robotic tools that are lightweight, cost-effective, and highly reliable for monitoring remote water bodies. The LED system is based on the Shallow-Water Autonomous Multipurpose Platform (SWAMP), a groundbreaking Autonomous Surface Vehicle (ASV) originally designed for monitoring wetlands. The objective of LED is to achieve the comprehensive monitoring of remote lakes by outfitting the SWAMP with a suite of sensors, integrating an IoT infrastructure, and adhering to FAIR principles for structured data management. SWAMP's modular design and open architecture facilitate the easy integration of payloads, while its compact size and construction with a reduced weight ensure portability. Equipped with four azimuth thrusters and a flexible hull structure, SWAMP offers a high degree of maneuverability and position-keeping ability for precise surveys in the shallow waters that are typical of remote lakes. In this project, SWAMP was equipped with a suite of sensors, including a single-beam dual-frequency echosounder, water-quality sensors, a winch for sensor deployment, and AirQino, a low-cost air quality analysis system, along with an RTK-GNSS (Global Navigation Satellite System) receiver for precise positioning. Utilizing commercial off-the-shelf (COTS) components, a Multipurpose Data-Acquisition System forms the basis for an Internet of Things (IoT) infrastructure, enabling data acquisition, storage, and long-range communication. This data-centric system design ensures that acquired variables from both sensors and the robotic platform are structured and managed according to the FAIR principles.

Keywords: environmental monitoring; Autonomous Surface Vehicle (ASV); Unmanned Surface Vehicle (USV); hydrology; air quality sensors; water sensors; IoT infrastructure; FAIR data

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1. Introduction

Lakes are dynamic ecosystems undergoing continuous changes in water quality, sediment distribution, and submerged topography, serving as key sentinels of climate change [1]. They reflect various physical, chemical, and biological responses to climate variations, contributing significantly to the Earth's climate characterization. Climate change acts as a threat multiplier [2], magnifying environmental stressors such as eutrophication, cross-boundary contamination, and the spread of invasive species, especially in lakes with seasonal ice cover, disrupting trophic links and altering food webs [3].

The mountain hydrology in the European Alps has changed due to climate change, changes in land use, and changes in water consumption, affecting droughts, floods, and water quality [4]. Industrialization, urbanization, and tourism exacerbate these effects, leading to new hydrological challenges such as flooding and droughts. Methodological and political challenges hinder the effective monitoring and management of remote water bodies, calling for stable collaborations among scientists, stakeholders, and decision-makers [5]. In particular, effective data exchange mechanisms and the adoption of innovative practices play indispensable roles in facilitating sustainable water management strategies, especially within mountainous regions [6].

The European Environment Agency (EEA) leads the protection of water bodies, notably through initiatives like the Water Framework Directive (2000/60/EC) [7], enforced in Italy through the Environmental Consolidation Act (Testo Unico Ambientale (T.U.A.)) [8]. This directive emphasizes the critical need to understand the ecosystems of water bodies for sustainable resource management.

In this context, anthropogenic pressures and accelerated climate change have reduced glaciers significantly, primarily due to increased air temperatures [9] and reduced snowfall, accelerating ablation [10] and consequent deglaciation of the European Alps . The vulnerability of remote alpine glacial lakes to climate-induced changes and external factors highlights their importance as indicators of global processes [1,11], especially in terms of the impacts of glacier shrinkage [10] and the release of stored pollutants [12] in their hydrochemical characteristics.

However, direct measurements in these areas are challenging due to the dangers posed by cold water and the complexity of transporting heavy equipment to remote locations accessible only on foot or by helicopter. Reaching remote areas on foot minimizes the ecological impact, but presents challenges like physical exertion and limited equipment transport. Helicopter transport offers speed and efficiency, facilitating data collection, but it is costly, environmentally impactful, and disruptive to wildlife. Researchers must balance these factors when selecting transportation methods.

The monitoring and preservation of remote lakes face significant challenges due to their unique characteristics and environmental significance [13]. Inaccessibility, harsh environmental conditions, and limited resources hinder traditional monitoring efforts.

In recent years, innovative technological solutions, such as robotic platforms for remote area monitoring, have emerged, although they often require complex assembly and are heavyweight. The Lake Environmental Data Harvester (LED) System demonstrates the design evolution of a cost-effective system towards a portable and ergonomic architecture tailored for remote lake operations for high-altitude alpine lake operations.

Previous studies have demonstrated how traditional survey methods [14] are time-consuming and labor-intensive and have a limited physical range of action. Traditional survey methods often put personnel in harm's way, especially in challenging environments, such as wetlands. Unmanned Surface Vehicles (USVs) present a game-changing solution by overcoming these limitations. Unlike manned systems, USVs can operate autonomously, eliminating the need for constant human supervision and reducing the associated safety risks. Moreover, USVs equipped with state-of-the-art technologies, such as the Shallow-Water Autonomous Multipurpose Platform (SWAMP), offer enhanced efficiency and precision in environmental monitoring tasks. These robotic systems can navigate through complex terrain with ease, accessing areas that are classically inaccessible or hazardous for manned vessels. Furthermore, USVs can collect vast amounts of data over extended periods, providing researchers with comprehensive insights into environmental dynamics. Overall, USVs not only improve the effectiveness and safety of survey missions but also enable broader spatial coverage and reliable data collection, ultimately advancing our understanding and management of aquatic ecosystems.

The LED system incorporates cutting-edge technologies by harnessing the capabilities of the Shallow-Water Autonomous Multipurpose Platform (SWAMP), an Autonomous Surface Vehicle (ASV) initially designed for wetland environments [15,16]. These capabilities are further enhanced through the integration of various sensors, including a single-beam dual-frequency echosounder, water quality sensors, an air quality analysis system (AirQino) [17,18], and an RTK-GNSS receiver. This comprehensive sensor suite is fully integrated, enabling real-time data collection, storage, and communication, hence establishing a robust monitoring infrastructure.

Using robotics and IoT technologies, this study aims to overcome the logistic and operational constraints of the associated with traditional monitoring approaches, contributing to moving towards the design of a system capable of increasing the conservation of high-altitude proglacial lakes and sustainable management in mountainous regions.

Background, Motivation, and Objectives

In the context of developing a prototype for monitoring alpine lakes, recent polar expeditions led by the CNR-INM demonstrated an increasing demand for technological tools to monitor fragile ecosystems in remote regions affected by human activities [19–22]. Data scarcity hinders both the understanding of environmental processes and the implementation of conservation actions. Autonomous robotic systems serve as vital data-gathering tools, offering unique spatio-temporal resolutions and enabling the collection of otherwise unobtainable data [23].

Transmitting environmental data online enables real-time monitoring, crucial for addressing issues such as deteriorating water quality and declining freshwater biodiversity [24]. The integration of IoT sensors allows continuous monitoring, providing insight into complex interrelationships among water quality parameters [25–27]. This facilitates prompt anomaly detection and informed conservation efforts, including citizen science [28].

Despite the recent technological growth, the scarcity of suitable equipment limits surveys in remote lakes. Although UAVs offer a solution [29], they have limited endurance and reduced water sampling capacity. Similarly, underwater vehicles are unsuitable for shallow remote lake shores. Recent surveys [30–32] have showcased a proliferation of research efforts dedicated to Autonomous Surface Vehicles (ASVs), resulting in the development of numerous commercial products of small dimensions [33]. However, conducting surveys in remote lakes requires comprehensive solutions that address challenges such as streamlined logistics and portability along high mountain trails, suitable propulsion for shallow shores, and the ability to integrate a plethora of lightweight sensors and tools for high-quality surveys. Additionally, the remoteness of these areas demands innovative autonomous techniques to enhance localization accuracy and suitable path planning strategies [34].

Recent developments include self-powered USVs equipped with environmental sensors for extended missions, allowing real-time data analysis and autonomous decision-making [35]. USVs with ADCP and electrochemical sensors were used to monitor water quality and quantity in a South Korean lake, emphasizing the importance of continued monitoring for sustainable environmental management [36]. Cost-effective USVs are crucial for widespread monitoring technologies [37,38].

The USVs were used in Plitvice Lakes National Park as a case study [39] for effective environmental monitoring. Surveys in remote lakes remain limited: geomorphological monitoring using drones in alpine lakes of Piedmont and FVG Regions [40]; joint LiDAR and echo sounding for Lake Truchillas Natural Monument's 3D profile with manned rafts [41]; Kapuche Lake's evolution and bathymetry via a sensored boat [42]; Tarfala (SE) glacial lake bathymetry with USVs transported by helicopters [43]; bed mapping at Mt. Zao Okama (JP) lake with low-quality, human-portable USVs [44]; and field experiments of an open-source, low-cost, small-sized USV in the USA and Peru [45].

Alpine lakes, known as "water towers" of lowland [46], are pivotal in alpine ecosystems' hydrological dynamics, especially with the accelerated formation of new glacial lakes due to glacier retreat [47]. As glaciers recede, meltwater accumulates in depressions, forming proglacial lakes. These lakes, often in rugged terrains, are vital indicators of environmental change and impacts of mountain ecosystems. Their formation at higher altitudes makes them remote elements, necessitating specialized monitoring tools.

The LED project aims to develop a portable autonomous ASV equipped with air quality and water sensors for remote lake monitoring. Although not directly targeting alpine lakes due to demanding logistical requirements, the project seeks to create a solution applicable to monitoring remote lakes with moderate logistical demands. Additionally, the project aims to implement an architectural solution that can be further miniaturized in future developments.

2. Methodology-Integrated Environmental Monitoring Systems

The LED project focuses on improving the portability, modularity, and reliability of robotic platforms, facilitating the acquisition of high-quality real-time data in areas where data are usually scarce or nonexistent. The LED datasets will be not only georeferenced and time-stamped but also openly distributed within the scientific community, fostering collaboration and deepening the understanding of remote lakes. Overcoming various challenges is central to the project's objectives, such as operating in remote locations with moderate logistical support, balancing cost-effectiveness with good performance, adeptly navigating remote environments, integrating diverse sensor data seamlessly, and implementing robust telemetry systems to ensure precise and reliable data collection.

The methodology includes adapting the portable ASV SWAMP designed for extremely shallow waters, integrating sensor modules and implementing communication protocols to enable extensive testing in remote lake environments.

The SWAMP Autonomous Surface Vehicle (ASV) [15] is equipped with a sensor suite and comprehensive data acquisition, storage, and communication systems, as shown in Figure 1. The adaptation of the ASV facilitated the integration of various lightweight, low-logistics, and low-computational-efforts sensors, including the AirQino [18] platform for air quality monitoring, two high-cost and one low-cost multiparameter probes for the monitoring of water status, and a dual-frequency single-beam echosounder for lake-bed mapping. Additionally, the integration encompassed essential components for NGC (navigation, guidance, and control), such as a dual-frequency GNSS module with a multiband antenna that is also useful for precise georeferencing, an Inertial Measurement Unit (IMU), and a surface camera for remote control and Simultaneous Localization And Mapping (SLAM) techniques.

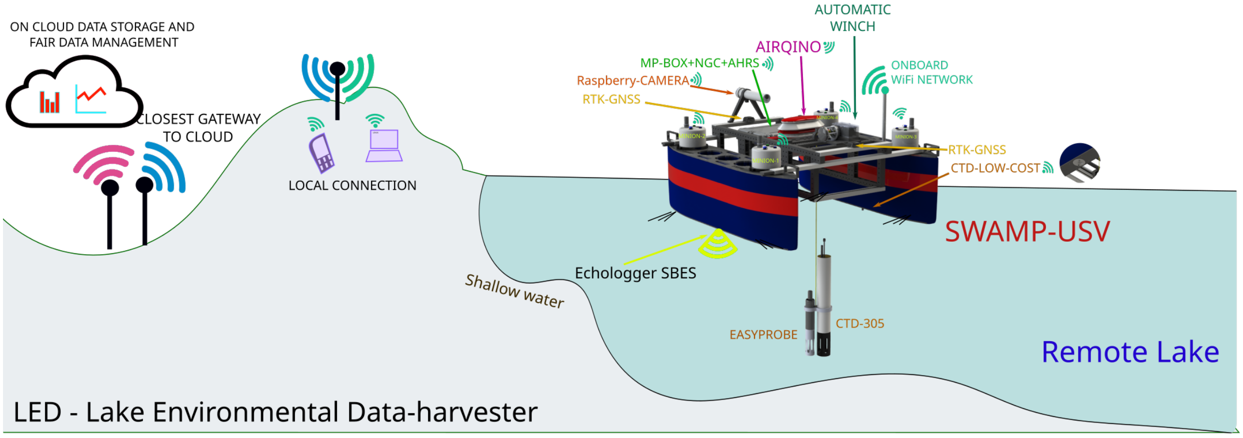


Figure 1. The LED concept.

To ensure uninterrupted network connectivity, the system features various communication technologies capable of facilitating seamless handover based on the prevailing conditions. This includes leveraging nearby Wi-Fi hotspots, a GSM/UMTS module with a data SIM for cellular network connectivity when Wi-Fi is unavailable, and a Long Range (LoRa) radio module at 433 MHz for transmitting data to the nearest gateway in areas lacking cellular coverage. Furthermore, operators can establish a direct connection with the ASV using the vehicle's onboard Wi-Fi hotspot when alternative networks are absent.

As shown in Figure 1, depicting the LED concept, the SWAMP Autonomous Surface Vehicle serves as the primary platform, offering mobility and flexibility for operating in the lake environment. It facilitates the integration and operation of various sensors and systems with an onboard Wi-Fi network for fast and cable-less integration.

The MultiPurpose Box (MPBox) with NGC and RTK-GNSS serves as a central hub housing the navigation, guidance, and control (NGC) system, along with the Real-Time Kinematic Global Navigation Satellite System (RTK-GNSS) and AHRS, ensuring precise positioning and navigation of the ASV.

The Raspberry-based camera is integrated for navigation and for SLAM, capturing visual data to implement real-time environment mapping and to enhance the autonomy and navigation of the vehicle in confined environments and in cases of GNSS fault.

The IoT Infrastructure and Ground Station includes necessary hardware and software components for establishing communication networks, transmitting data in real time, and remotely managing ASV operations from a Ground Station.

The winch facilitates the deployment and retrieval of water quality sensors, enabling precise positioning at different depths along the water column.

The water quality sensors are a suite of sensors tailored for monitoring parameters such as conductivity, temperature, and depth (CTD), and other characteristics of the water body.

The Bathymetry Sensor, a dual-frequency echosounder, enables the mapping of the lake bed topography, providing insights into underwater terrain morphology and into water column characteristics.

The air quality sensors (AirQino) are composed of off-the-shelf sensors capable of measuring various air pollutants and meteorological parameters, and the air quality monitoring system contributes to understanding atmospheric conditions and assessing potential environmental impacts.

The Data Management Infrastructure manages the storage, processing, and transmission capabilities of data. This infrastructure ensures the efficient handling of large amounts of sensor data collected by the ASV, allowing subsequent analysis and decision-making.

Together, all these integrated components form a versatile system capable of performing comprehensive environmental monitoring and mapping tasks in aquatic environments, thus contributing to scientific research, resource management, and regulatory environmental efforts.

The power consumption analysis of the system was conducted to ensure both efficient operation and extended autonomy during monitoring missions, which are critical for sustaining continuous data collection in lake environments. The battery system operates at 24 V and undergoes continuous monitoring through a network of distributed sensing boards. As detailed in Table 1, the vehicle's maximum power consumption reaches approximately 400 W when operating at its top speed of 1.5 m/s, which decreases to around 120 W at the expected operational speed of 1.0 m/s. Meanwhile, the LED sensor package exhibits a maximum power consumption of approximately 35 W. Assuming transects with a mean power consumption of 120 W for the vehicle and 35 W for the LED system, the total average power consumption remains below 200 W. This indicates that the LED system can sustain continuous operation for up to 10 h and can extend its operational duration further with intelligent power management strategies. Future advancements include the integration of regeneration sources such as hydrogen fuel cells [48] and solar panels.

Compared to conventional monitoring methodologies, robotic systems offer distinct advantages by delivering more precise, dense, and effective data. This enhanced data quality fosters a deeper understanding of environmental dynamics and facilitates well-informed decision-making processes.

Table 1. Specifications of the system made of the SWAMP Catamaran and LED Sensors Package. The table reports the power consumption and endurance of the systems.

Type:	**USV/ASV, Catamaran**	
Characteristic:	**Unit**	**Value**
Overall Length	[mm]	1230
Overall Breadth	[mm]	1150
Overall Height	[mm]	1100
Draft	[mm]	100
Pump-Jet Propulsion Units	nr	4 × 15 N—Steerable 360°
Operative Speed	$[\frac{m}{s}]$	0.5–1.5
Communication		Wi-Fi, LoRa 433 Mhz
Navigation Sensors	nr	4 × GNSS, IMU
Light Weight	[kg]	35
Nominal Battery Voltage	[V]	24
Power Consumption	[W]	70 (@0.5$\frac{m}{s}$) $-$ 120 (@1.0$\frac{m}{s}$) $-$ 380 (@1.5$\frac{m}{s}$)
Single Battery (4×)	[Ah]	13
Endurance	[h]	16 (@0.5$\frac{m}{s}$) $-$ 10 (@1.0$\frac{m}{s}$) $-$ 3 (@1.5$\frac{m}{s}$)
LED Sensors Package		
Main NGC Sensors		D-RTK-GNSS, AHRS, Camera
Winch with rope	[m]	70
Water Sensors	nr	2 × CTD + Ph + Redox + DO SBES Echologger
Weight	[kg]	9
Nominal Battery Voltage	[V]	24
Power Consumption	[W]	35
Battery	[Ah]	13
Endurance	[h]	10
Air quality sensors		AirQino Sensors
Weight	[kg]	1
Nominal Battery Voltage	[V]	5
Power Consumption	[W]	1.5
Battery	[Ah]	10
Endurance	[h]	32

3. Design and Implementation

3.1. SWAMP ASV Design

The Shallow-Water Autonomous Multipurpose Platform (SWAMP) [15] vehicle is designed to meet a variety of requirements, balancing functionality and versatility for operations in shallow and confined waters. SWAMP was designed by summarizing different innovative concepts: the ability to work in extremely shallow water (down to 15 cm) for measurements in water shallower than 1 m [49]; thrusters and sensors placed within the hull and flush with the hull; a structure made of soft materials for robot safety and payload; unsinkability for safety and recovery in extreme environments; modularity for adaptability in a remote environment; and the connection of all components through Wi-Fi.

This fully electric Catamaran measures 1.23 m in length with a variable breadth ranging from 0.7 m to 1.25 m, achieved through a sliding structure. Its hull is 0.4 m in height, with an overall height of 1.1 m including the structure and antennas. Weighing 35 kg, SWAMP boasts a draft of 0.1 m and can accommodate a standard payload of 25 kg, extendable to 60 kg with its buoyancy reserve. These compact dimensions facilitate easy logistics.

Inspired by the double-ended Wigley series, SWAMP features a flat-bottom hull shape that houses four Pump-Jet-type 360° azimuth thrusters [50]. This innovative propulsion system, characterized by its modular design, offers high controllability and maneuverability that are especially required in shallow water zones for high-quality surveying and performance [51].

Figure 2 shows the SWAMP vehicle during a survey campaign in a polar environment.

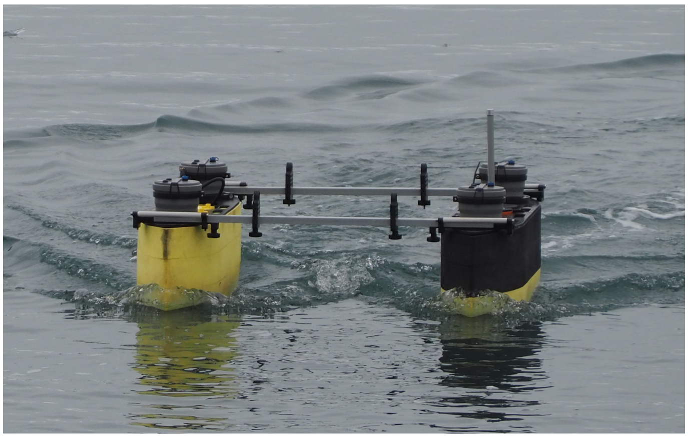


Figure 2. The SWAMP vehicle in action in Svalbard Archipelago.

The structure, crafted from a lightweight, impact-resistant sandwich of soft closed-cell PE foam, HDPE plates, and HDPE bars, ensures survival and protection in the event of an impact while also providing ample buoyancy. The selected materials, when in contact with water, are inert. They include PE Ffoam, chosen from materials compliant with CE guidelines for children's games, and HDPE plates of food-and-beverage-grade quality. These materials have been carefully chosen to ensure safety and durability, meeting rigorous standards for use in aquatic environments.

This design allows for easy disassembly and reconfiguration to accommodate various tools, control systems, samplers, and sensors, making SWAMP a highly adaptable and modular vehicle.

The Pump Jet, operating on the principle of a vertical axis pump, generates thrust through a nozzle integrated into the hull silhouette. Its advantages include lower operating speeds, higher structural integrity, and superior maneuverability, making it suitable for both main thrusting and maneuvering functions.

Each thruster is a module, named Modular and Independent Navigational Intelligent Orientable Nozzle-Thruster (MINION), which is a modular propulsion unit designed for Unmanned Surface Vehicles, encompassing power (24 V Li-ion battery), communication (Wi-Fi), intelligence (Raspberry Pi 3 Model B+), sensoring (Adafruit BNO055 Bosch Absolute-orientation-sensor and GNSS Ublox ZED F9P), thrust (13 N), and thrust directionality (continuous 360° rotation) within a single watertight and compact element. The MINION offers autonomy, adaptability, and maneuverability, using the Pump-Jet principle for precise control and efficient propulsion in marine environments. The MINION serves as a propulsion and steering unit, computing unit, navigation unit, and energy unit. Additionally, MINION aims to incorporate automated FAIR data compliance, improving the interoperability and reusability of data collected by marine robotic systems.

Each SWAMP hull, which hosts two MINIONs, functions as an Autonomous Surface Vehicle (ASV), equipped with its own propulsion, navigation, guidance, and control unit (NGC) powered by Li-Ion batteries. The intelligent core of each hull ensures redundancy and fault tolerance, enabling control transfer in the case of core failure, facilitated by a distributed, Wi-Fi-based (Groove 52HPn-2GHz/5GHz-RouterBOARD outdoor unit) communication architecture contained in a watertight canister with its own 24 V battery.

Tested extensively, also in shallow water conditions, SWAMP has a maximum speed of 1.6 m/s at full payload in deep waters, with reduced speeds in extremely shallow waters due to changes in hydrodynamic characteristics.

Overall, the SWAMP vehicle offers remote-controlled and autonomous operation capabilities, leveraging GNSS, AHRS, and onboard sensors for effective performance in various applications.

The SWAMP platform weighs 35 kg but can be disassembled into two hulls, each weighing 15 kg, with an additional 5 kg for connecting pieces.

The LED project is based on SWAMP ASV due to its key characteristics:

- The Wi-Fi architecture facilitates the rapid installation of heterogeneous sensors, minimizing wiring needs. Most of the sensors are provided with their powering (battery) and dedicated Wi-Fi modules to communicate.
- The flat bottom and soft-hull design [52] allow operation in extremely shallow water, with environmental sensors and sonars contained within the hull to mitigate the risk of damage and loss caused by external impacts.
- Its shallow-water capability makes it suitable for applications in lakes and rivers.
- The mountable nature of SWAMP makes it suitable for transportation even if future reductions in weight and size are foreseen for high-altitude alpine lakes.

SWAMP has already proved its reliability, having been used in campaigns on lakes like Laghi del Gorzente (Italy) [53] and rivers like Roja (Italy) [54], where it was transported and disassembled. Furthermore, SWAMP showcased its adaptability to extreme environments during campaigns in front of tidewater glaciers in the Svalbard (Norway) [23].

3.2. MPBox: Data Acquisition Control System and Communication Manager

A system called MultiPurpose Box (MPBox) for controlling the data acquisition of the numerous sensors and for managing the multiple communication channels was designed and built in the framework of the LED project. The main goal was to develop a system as modular and expandable as possible while maintaining low costs, sizes, and weights. The final choice was to use commercial off-the-shelf components and to use a Raspberry Pi 3 B+ SBC (Single-Board Computer) as the computational module. The architecture of the MPBox system is shown in Figure 3. First of all, a DS3231 Real-Time Clock was connected to the Raspberry SBC to provide a reliable and precise time reference (useful, for example, for synchronization with other systems). Secondly, thanks to the presence of four USB ports on the Raspberry SBC, two of them were connected to two four-port USB hubs, which were in turn used to connect to the various instruments (both data sensors and communication systems). The other two available USB ports were used for connecting the Raspberry SBC to a USB-to-SATA adapter (for recording the acquired data to a SSD) and to a Wi-Fi adapter. Moreover, an additional Ethernet switch was also added to expand the network's capabilities. This switch allows for the connection of more devices to the local area network, enhancing network flexibility and scalability. Finally, a serial console from the Raspberry SBC GPIO (General-Purpose Input Output) was made available for debugging purposes. As far as the GPIO is concerned, a number of the available I/O digital channels were used to control SSRs (Solid State Relays), allowing one to switch on/off sensors and communication systems. Several applications developed in C/C++ are running on the Raspberry SBC, managing sensor acquisition, data logging, and communication systems. The behavior of all the applications is easily configurable by means of relevant configuration files.

The MPBox is composed of a waterproof suitcase that contains

- The PCBs, wiring, and SBC as described above;
- A 24 V battery for powerand various DC-DC converters (+-12 V, 5 V, 3.3 V);
- Connectors for external sensors and tools;
- SSD for data storage;
- A Microstrain AHRS sensor (see Section 3.5);
- RTK2-GNSS boards (see Section 3.5);
- A GSM/UMTS module with a data SIM card for RTK-GNSS corrections and communication;
- Sub-GHz (433 MHz) module with Arduino Nano for data interface and transmission (see Section 3.3).

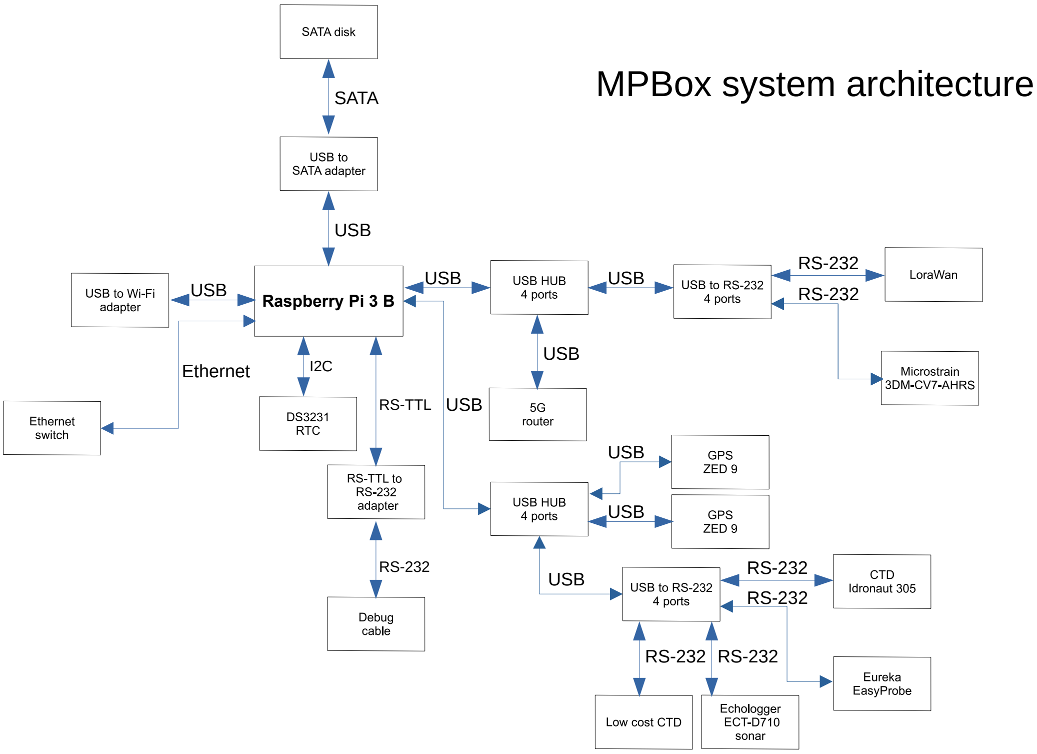


Figure 3. Block diagram of the MPBox system architecture.

3.3. IoT System Architecture

The design of the IoT system architecture encompasses the integration of sensor data with cloud-based infrastructure, ensuring seamless acquisition, storage, connectivity, and data transmission in remote alpine environments. Emphasis is placed on ensuring compatibility, reliability, and efficiency in handling sensor data, as well as robust communication with cloud-based services.

At the edge side (i.e., on the ASV), Argos [55,56] is the core software running on the Raspberry Pi 3B+ companion computer, allowing us to

1. Harvest raw data from sensors;
2. Process raw data (e.g., structuring data according to standard formats);
3. Provide a Wi-Fi local area network (WLAN);
4. Publish information through a socket service and a web application in the WLAN;
5. Accept commands from the land station and/or web interface;
6. Ensure communication through a sub-GHz radio to the closest end-point (in case there are no Internet connections available).

Thanks to the Wi-Fi local hotspot, users in the surroundings of the ASV can easily monitor and control the data flow provided by the Raspberry Pi device, using their smartphones, tablets, etc.

More precisely, the edge architecture is shown in Figure 4. The Raspberry Pi plays the role of the data collector, since every sensor onboard the ASV is connected to it, via USB, GPIO, or network sockets; see the lower part of Figure 4, denoted as "ASV Sensors".

The system has a multi-tiered architecture, in order to make it robust, easy to maintain, and extensible. Immediately above the sensors, there is the first software layer of the system, namely the operating system RaspOS. It provides the drivers to manage USB ports, GPIO pins, and the Wi-Fi adapter, and the network daemon to manage connections with clients and to establish the WLAN. Then, we have the Argos process, which (i) reads data in real-time, and stores them in log files; (ii) processes raw data in suitable data structures and formats them in the main memory; (iii) sends such information to clients via a socket service. At this level, another important process is the local Apache web server, which provides the dynamic pages of the web interface to clients in the WLAN.

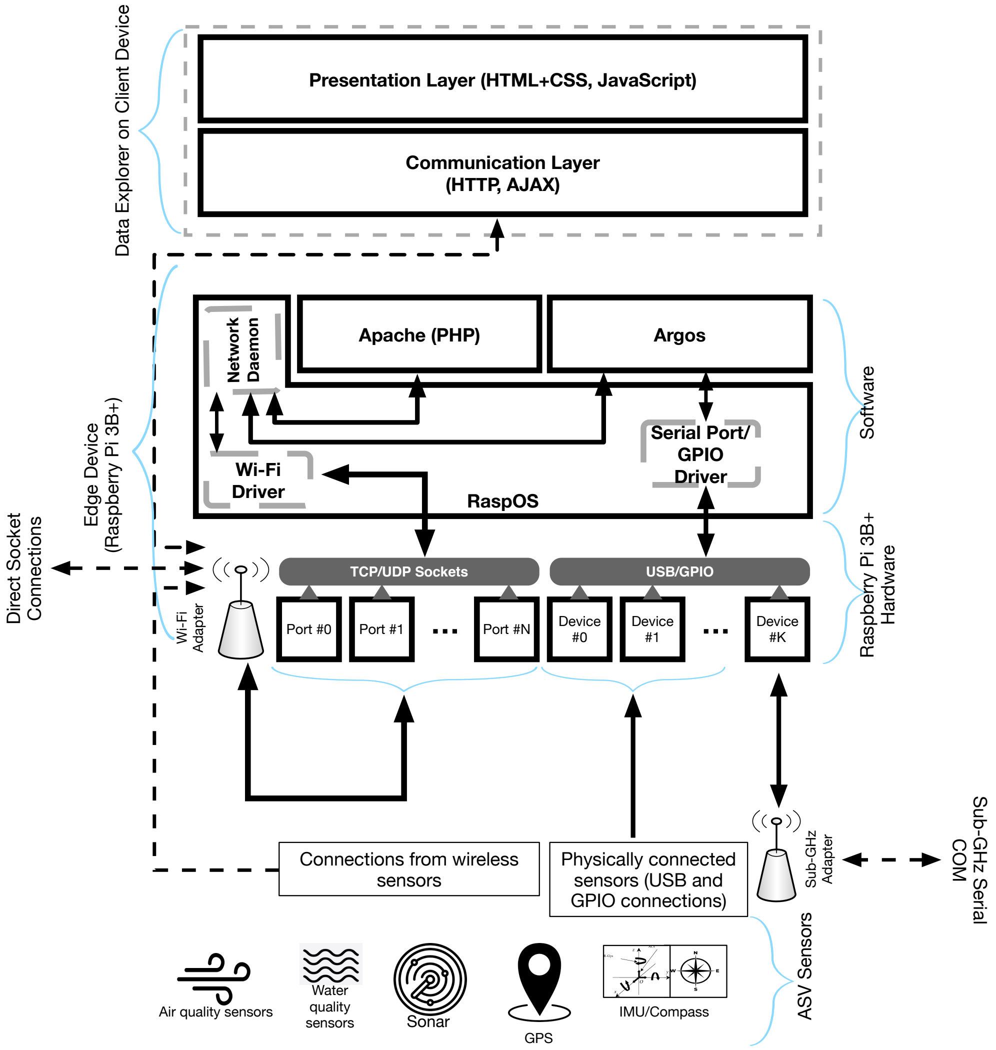


Figure 4. The IoT system architecture.

The client layer consists of a web application with two modules: (i) the communication layer (i.e., the code communicating with Argos and Apache) and (ii) the presentation layer (i.e., the graphical UI). The inner workings will be explained later in Section 4.2.

With the aid of Figure 5, we will describe the internal organization and the working behavior of Argos.

In order to cope with the different features (e.g., hardware interface, protocols, speed, parity and stop bits, etc.) of the sensors connected to the USB ports/GPIO pins/TCP and UDP sockets, the *Main thread* reads the configuration of such devices from a configuration file in YAML format (YAML stands for *YAML Ain't a Markup Language*, and it is essentially a human-readable data serialization language; see the official website for further details: http://yaml.org/, accessed on 26 May 2024). Then, it spawns a dedicated reading thread for each detected device (*Reading Thread #1*, *Reading Thread #2*, ..., i.e, the Argos Eyes (Argos is also known as Argus Panoptes, i.e., the *all-seeing* primordial giant with 100 eyes of the Greek mythology) in Figure 5). Each eye represents a capability to acquire data from the environment, storing incoming raw data in a queue. Then, a *data-processing thread* applies several functions, allowing the system to polish data from reading errors and to synthesize more structured and meaningful information in memory in a suitable thread-shared structure (named *Structured data* in Figure 5).

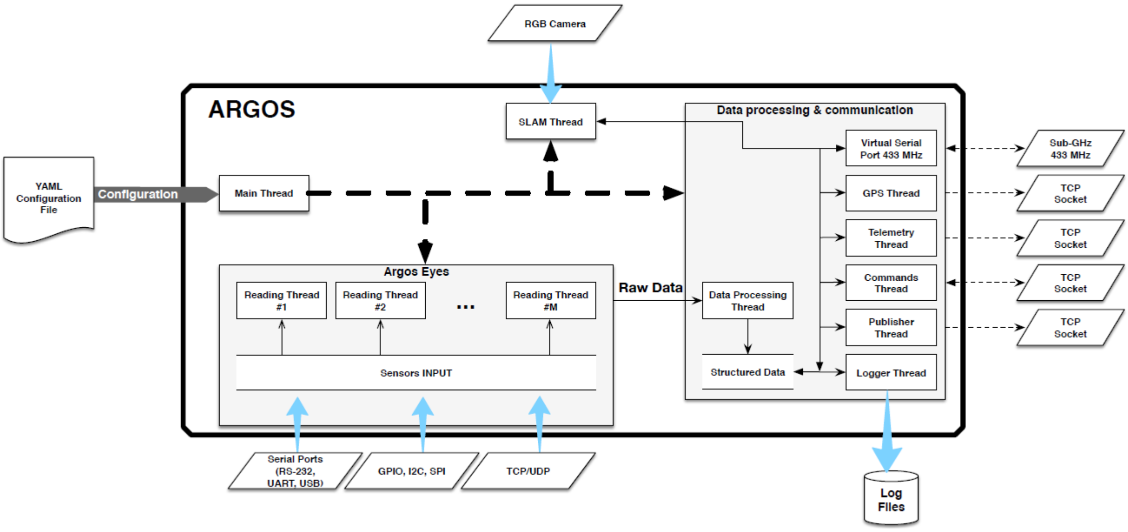


Figure 5. Argos: software architecture.

Raw data are also logged in the Raspberry Pi file system for backup purposes. To avoid an excessive I/O load, we schedule a suitable *Logger thread* (see Figure 5) to intervene every 30 s, saving the current queue to the file system and emptying it for subsequent use by the eye threads. To avoid slowing down the reading threads, we opted for a double buffered queue, where: (i) one buffer contains the current queue of raw data and the second buffer stays empty; (ii) when the logging thread must save it to disk, the buffers are switched—the one full of data is given to the logging thread, while the empty one is assigned to the reading threads. Thus, the logging and reading threads are not affected by the relative execution speeds.

The purposes of the remaining threads in Figure 5 are as follows:

- *Publisher*: it accepts connections on a TCP socket, providing clients with a JSON object containing current data stored in the shared structure.
- *Commands*: it accepts connections on a TCP socket: clients may send commands either to the ASV autopilot or to the *Data processing thread*.
- *Telemetry*: it connects to a remote server, sending telemetry and sensor data.
- *GPS*: it connects to a remote server, sending the current position of the ASV.
- *Virtual Serial Port*: it uses a sub-GHz radio (at 433 MHz) to communicate with a remote end point, providing a serial connection between the ASV and the remote end point.
- *SLAM*: it uses an RGB camera connected to the Raspberry Pi to estimate the position of the ASV by exploiting computer vision algorithms.

If an Internet connection is available, the *Telemetry* and *GPS* threads can reach not only the land station but also a Cloud infrastructure, connecting the ASV with a server system capable of storing, processing, visualizing, and sharing data with clients spread worldwide, completing the IoT architecture of the project.

However, even when an Internet connection is not available, a long-range (although with limited bandwidth) communication is still possible, using the *Virtual Serial Port* thread. Indeed, exploiting the sub-GHz radio, the ASV can communicate with a remote land station installed in, e.g., an alpine refuge connected to the Internet. Hence, we have a rather robust communication framework to connect from Edge to Cloud, as depicted in Figure 6.

In particular, the sub-GHz radio system has been recently tested to determine the maximum deployment distance from the nearest alpine refuge in the absence of other communication technologies. In Figure 7, we can see on the left the LoRa radio module TEL0116 connected to an Arduino Nano to provide a serial interface (the latter is in turn connected via a USB cable to the Raspberry Pi 3 on board the ASV). On the right part of Figure 7 is the 30 cm dipole external antenna connected to the radio module. One radio system is mounted onboard the ASV, while the other is connected to another Raspberry Pi

3 inside the MPBox (see the LoRaWan module in Figure 3). During our tests, we deployed one system in the gardens of our labs, and we went around driving a car with the other end-point. Hence, the testing environment was not an easy one, being full of buildings, infrastructure, and sources of radio interference. However, we reached a distance of 3.5 Km, still being able to communicate data between the two end points at 9600 bps. This is a decent speed of communication to receive telemetry data and send commands to the ASV. Hence, we are confident that the system will also behave quite well in alpine lakes, where the environment is certainly less adverse to radio communications than an urban one.

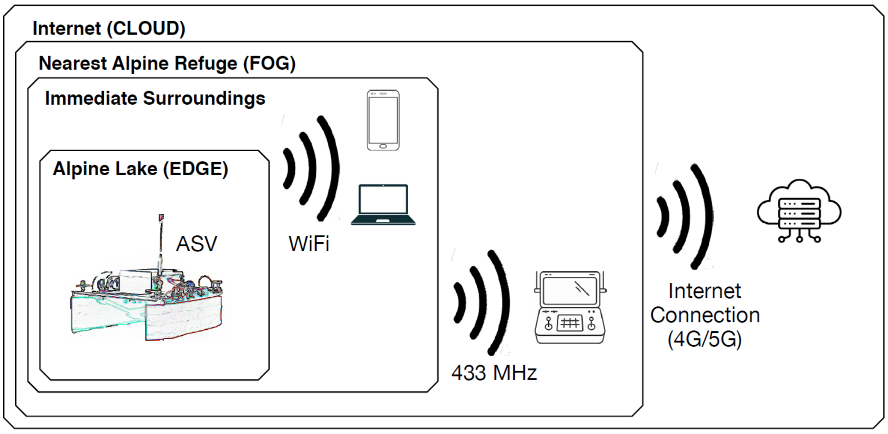


Figure 6. From Edge to Cloud: the communication framework.

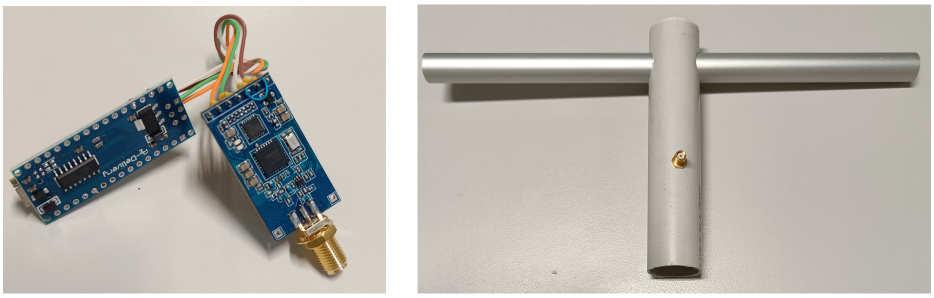


Figure 7. The sub-GHz radio system: (**left**) the TEL0116 Radio and Arduino Nano—(**right**) the 30 cm dipole external antenna.

3.4. Ground Station

The Ground Station is used by the operators to remotely control and interact with the LED systems (the SWAMP vehicle, the sensors, the communication devices, etc.). The architecture of the Ground Station system is very similar to that of the MPBox and is shown in Figure 8. Also, in this case, the core of the system is a Raspberry Pi 3 B+ Single-Board Computer that, thanks to its numerous communication links (USB, I2C, GPIO channels, etc.), allows easy integration with different types of devices.

Imitating the MPBbox idea, the Ground Station is composed of a watertight suitcase containing:

- The PCBs, wiring and SBC as described above;
- A 24 V battery for powering and various DC-DC converters (+-12 V, 5 V, 3.3 V);
- An SSD for data storage
- Connectors for external sensors and tools
- A sub-GHz (433 MHz) module with Arduino Nano for data interface and transmission enabling long-range data transmission and control functionalities (see Section 3.3);
- Microstrain AHRS sensor (see Section 3.5);
- RTK2-GNSS Board;
- Network Switch (Hub USB).

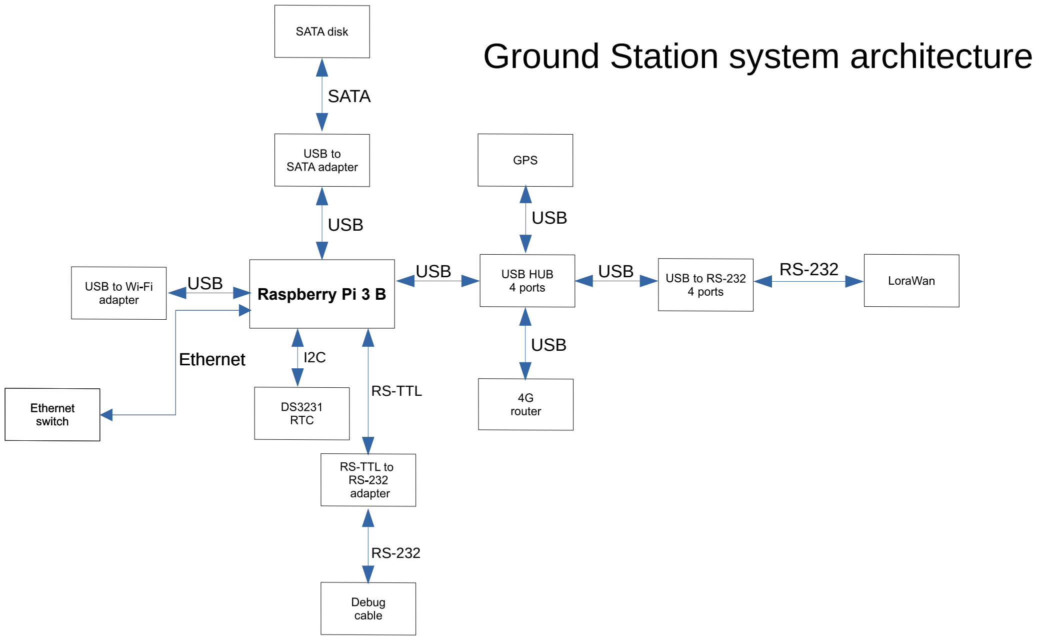


Figure 8. Block diagram of the Ground Station system's architecture.

3.5. Navigation Sensors

The navigation payload of LED features a differential dual frequency RTK-GNSS with two receivers onboard for precise positioning and heading calculation during navigation and an Attitude Heading Reference System (AHRS) providing orientation (yaw, pitch, and roll) and absolute heading.

The GNSS receivers for the LED project are the SparkFun GPS-RTK2 Board, ZED-F9P, paired with the GNSS L1/L2 Multi-Band Magnetic Mount Antenna ANN-MB-00. The ZED-F9P is a simultaneous GNSS receiver capable of tracking multiple constellations (GPS, GLONASS, Galileo, and BeiDou) with its multi-band RF front end. The ANN-MB-00 antenna is designed for both L1 and L2 GPS bands, providing fast, reliable multiband solutions for precise positioning with centimeter-level accuracy. The advantage of using L1/L2 Multi-Band in GNSS in remote and narrow areas is its enhanced accuracy and reliability, achieved by mitigating ionospheric delays, which are crucial for precise positioning in remote or obstructed areas with reduced satellite visibility. It also enhances differentiation between satellite signals, boosting overall navigation performance.

In the field of navigation and the precise control of autonomous and remotely operated robotic platforms, an Attitude and Heading Reference System (AHRS) also plays a crucial role as it provides real-time information on the orientation and heading of the platform relative to the Earth's surface. It calculates the pitch, roll, and yaw—the three axes of rotational motion, essential for understanding an object's orientation in three-dimensional space. As part of the LED project, SWAMP is equipped with the Microstrain 3DM-CV7-AHRS—Inertial Measurement Unit (IMU) and Attitude Heading Reference System, a high-performance, miniature system.

The positioning data, characterized by centimeter precision, along with the attitude and orientation of the robotic platform, not only provide valuable information for the guidance, navigation, and control of the vehicle during surveys but also serve to accurately geolocate the data. Furthermore, this offers a preliminary method for validating and ensuring the quality of data acquired through water quality sensors.

3.6. Navigation and SLAM Camera

The camera system is based on a Raspberry Pi Single-Board Computer (SBC), crafted by CNR-INM, and is used for remote piloting and for navigation with the SLAM technique. The system integrates a Raspberry Pi 3B+ Single-Board Computer (SBC) with a Raspberry

Pi HQ Camera and an SSD. The systems are online and configurable in real time. Moreover, the Raspberry Pi SBC is equipped with a very precise Real-Time Clock (RTC) that allows camera data synchronization with other LED systems. The SSD provides fast and large onboard storage for both pictures and videos. The camera communicates via Wi-Fi to the onboard network of SWAMP, and it is equipped with its own battery pack.

3.7. Water Quality Sensors

This subsection details the integration of water quality sensors with the SWAMP ASV, aiming for accurate and reliable environmental data collection across varying conditions [57]. Multiparametric probes play a crucial role in environmental monitoring [58,59] and provide simultaneous measurements of various parameters. In the LED project framework, conductivity, temperature, depth, redox, pH, EH, and dissolved oxygen are acquired and recorded by different probes:

- CTD Idronaut: OCEAN Seven 305 Plus CTD, a high-quality multiparametric probe, measures various parameters for oceanographic applications.
- CTD (+Ph), medium cost: Eureka EasyProbe20 offers good accuracy in measuring water properties, suitable for various applications.
- CTD (+Ph), low cost: Developed by CNR-INM, this low-cost multiparametric probe utilizes ATLAS scientific probes.

CTDs can be mounted onboard SWAMP or lowered into water using an automatic winch. They operate in self-recording mode or linked to the MPBox. Comprehensive datasets acquired by CTDs enable the assessment of water quality, the understanding of ecosystem dynamics, and informed decisions regarding resource management and conservation efforts. *Conductivity* measures water's ability to conduct electricity, indicating salinity and dissolved solids. *Temperature* fluctuations affect chemical reactions and biological processes. *Depth* measurement is vital for understanding water dynamics and habitat characterization, often used with conductivity and temperature to determine salinity. *Redox* potential evaluates water quality and nutrient cycling. *pH* influences chemical reactions and ecosystem health. *Dissolved oxygen* is crucial for aquatic life and water quality assessment, indicating ecosystem health and the effectiveness of aeration processes.

3.8. Automatic Winch

For carrying out data acquisition in the water column, release systems based on an automatic winch can be installed on the SWAMP. The winch is made up of a customized fishing reel with a thread guide that was adapted so that a brushless electric motor, placed in a 3D-printed watertight container, can move the winch by means of a reduction box with a worm screw. The worm screw on the one hand allows the intrinsic brake of the winch and prevents it from being freely unrolled, and on the other hand, it reduces the power consumption of the motor. The winch can be remotely controlled by MPBox via an Ethernet connection.

The management of the underwater winch is performed by using the data provided by the Single Beam Echo Sounder (SBES) to prevent the possibility of grounding and the deadlock of the lowered sensors.

3.9. Single-Beam echosounder

Single-beam echosounder (SBES) acquisition is preferred for bathymetry data collection in lake and river environments due to its efficiency, low cost, accessibility [51,54,60], and especially its compactness and low weight. In the LED project, bathymetric surveys will use the ultra-compact dual-frequency Echologger ECT D710S. High frequencies (750 kHz/1 MHz) are preferred for shallow waters like lakes. The ECT D710S excels in shallow environments, providing precise data collection and real-time backscatter data up to depths of 30/50 m, depending on the frequency. Range measurements will be synchronized with Microstrain 3DM-CV7-AHRS and u-blox ZED-F9P GNSS for data validation and precise positioning. As per IHO standards [61], the survey falls under category 1b, which is suitable for lake environments and is not related to navigation safety [53]. Depth measurements depend on acoustic pulse travel time, requiring sound speed information from a CTD probe [60,62]. The dual-frequency SBES will be housed within the SWAMP hull, providing depth information along the vehicle's track line with sub-millimeter resolution and capturing acoustic backscatter signals. While SBES offers precise and cost-effective data acquisition, its narrow acoustic beam limits bottom coverage, necessitating data interpolation. Although the Multi-Beam echosounder (MBES) provides broader coverage, the SBES remains cost-effective in stable lake environments [63].

The sonar system Echologger ECT D710S records raw data corresponding to the power spectra of returning echoes, enabling depth calculation and the inference of bottom acoustic properties. Acoustic reflectance reveals information about bottom composition, while dual frequencies enable various analyses [64,65]. Field tests will further explore these capabilities based on acquired data.

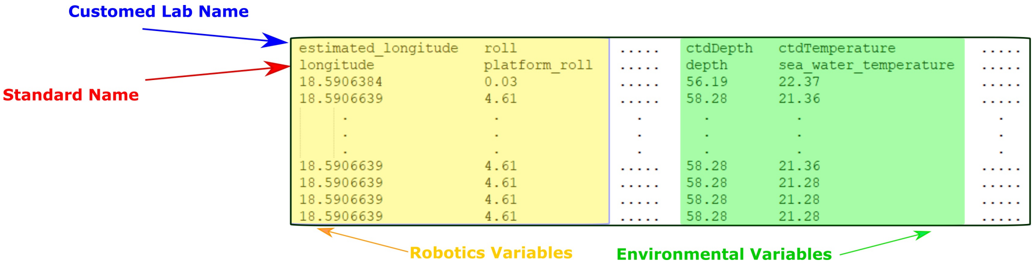
3.10. Air Quality Sensors—AirQino

An AirQino [66,67] is an open-source air quality monitoring device. It is designed to measure various meteorological parameters (temperature, humidity, pressure) and air pollutants such as particulate matter (PM 2.5 and 10), CO_2, CO, NO, NO_2, and O_3 [68].

AirQino consists of sensors, a microcontroller, a communication module, and a power-bank, allowing it to collect data on air quality and transmit them to a central system or display them locally. It is used for environmental monitoring efforts due to its affordability, accessibility, and ease of use. AirQino's low-cost nature makes it an accessible solution for environmental monitoring projects, particularly in resource-constrained settings. Additionally, its lightweight design minimizes the impact on the overall weight and mobility of a SWAMP robotic platform, ensuring efficient deployment and operation in remote terrain. Its open system architecture enables easy integration into the LED IoT system, and it communicates via Wi-Fi, transmitting in real time air quality data (in ASCII comma-formatted strings) within the LED-acquiring device. The monitoring stations can be configured with a wide range of sensors, calibrated by CNR using the UE reference stations (ARPA). In general, the high costs associated with logistics and commercial sensors and probes impede the establishment of extensive monitoring observatories. Notably, certain commercial sensors impose operational demands that are difficult to meet in pristine remote regions. Consequently, there is a growing trend toward utilizing low-cost, open-source microcontrollers for data collection [69,70]. However, these microcontrollers frequently exhibit low resolution and stability, rendering them unsuitable for many applications. To address these limitations, rigorous calibration protocols are employed to quantify the sensitivity and stability of the low-cost sensors relative to reference sensors, thereby establishing correction factors and defining operational environments. This approach has already been implemented by LED researchers [71,72] in extreme environments such as the Arctic Ocean, tundra, and the planetary boundary layer.

3.11. FAIR Data Management

Creating robotics specifically designed to navigate extreme and remote areas is vital to safeguarding fragile end unexplored ecosystems that are inaccessible to commercialized platforms. This mission is paramount during the Anthropocene [73] to understand how human activities interact with the Earth's system and how we can adapt to a changing climate. The uptake of emerging ecorobotics in Earth sciences is bound to the resonance of the collected data; therefore, in situ LED missions are designed to maximize data visibility to facilitate its interpretation and dissemination to the wider community. FAIR principles [74] encapsulate this approach. By rendering the data findable, accessible, interoperable, and reusable, LED effectively embraces the values of open science [75], advocated, among others, by UNESCO [76]. The data policies adopted during the project development seep through all phases of design, payload selection, and integration and ultimately impact the data quality and the interdisciplinary relevance of the study. FAIR principles, in fact, are especially important when applied to novel observational platforms because they allow for the creation of coupled datasets, linking robotic sciences to Earth sciences in the same product. Both branches of research mutually benefit from the compilation of such data collections. LED applies state-of-the-art protocols and standard recommendations for meticulous metadata compilation and data formatting, exploiting a Free and Open Source Software developed by CNR-INM to join all the FAIR requirements into a final data product [77]. Lake hydrology data are hardly standardized [78,79], as they are still subject to local policies and normally oriented towards satellite observations [80]; therefore, LED embeds additional specifics when logging the observed variables both in the form of ancillary data [81] or in the variable name itself [82,83]. LED's data products, e.g., the one shown in Figure 9, will be readily available on Zenodo [84] in a NetCDF format. The FAIR principles are framed within the more general data management strategy of the LED project, which develops during all phases of the data life cycle, including data collection, storage, metadata standardization, sharing, and long-term preservation, in order to ensure data integrity and transparency while promoting collaboration and the long-term usability of the dataset acquired during the project.



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estimated_longitude   roll            .....   ctdDepth   ctdTemperature          .....
longitude             platform_roll   .....   depth      sea_water_temperature   .....
18.5906384            0.03            .....   56.19      22.37                   .....
18.5906639            4.61            .....   58.28      21.36                   .....
       .                .               .        .           .                     .
       .                .               .        .           .                     .
       .                .               .        .           .                     .
18.5906639            4.61            .....   58.28      21.36                   .....
18.5906639            4.61            .....   58.28      21.28                   .....
18.5906639            4.61            .....   58.28      21.28                   .....
18.5906639            4.61            .....   58.28      21.28                   .....
```

Figure 9. An example of the data provided by LED in a unique coupled dataset, including both robotics and environmental data.

4. Integration

So far, we have described all the components, both hardware and software, involved in the LED project. Each one is quite sophisticated, being the result of years of previous research, carried out in several application scenarios. In this section, we provide an integrated perspective of the whole system, which is not a mere sum of its parts. The integration required both hardware and software integration.

4.1. Hardware Integration

The physical integration of sensor modules, communication devices, and embedded systems within the ASV framework is schematized in Figure 10, where two views of SWAMP platform are shown.

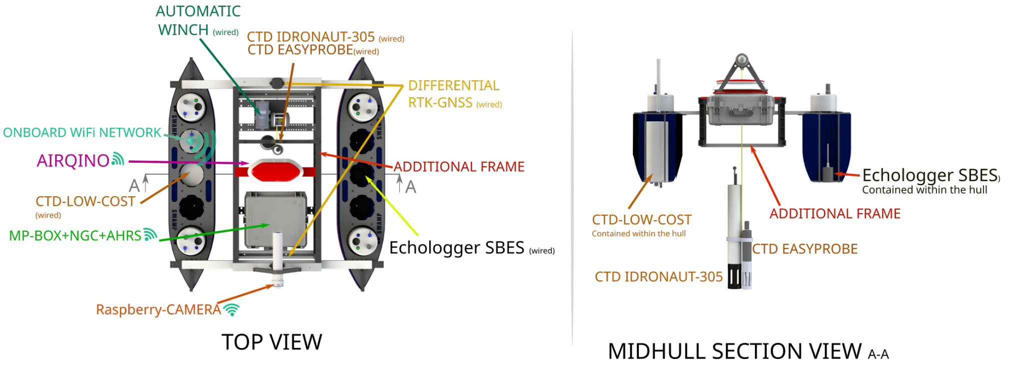


Figure 10. LED hardware integration on the SWAMP platform is depicted through two views: a top view on the left and a mid-hull section view on the right. The latter illustrates the placement of the Echologger and CTD-Low-Cost devices that are integrated within the hulls and flush with their bottom surfaces.

Constructed from twin-wall sheets of high-density polyethylene (HDPE), the frame comprises assembled elements designed to accommodate various payloads. Positioned atop the transversal bars of SWAMP, it occupies a space dedicated to payload integration, as all vehicle functionalities (MINIONS, Wi-Fi) are housed within the catamaran hulls. This design attribute not only enables reconfiguring the setup in accordance with specific requirements or mission objectives, but the pre-drilled structure of the frame also facilitates the process of attaching or detaching tools from the vehicle, while also ensuring the possible adjustment of the positions of MPBox sensors, cameras, and other components.

The additional frame accommodates the MultiPurpose Box, housing both the AHRS and the boards of the two RTK-GNSS units. The MPBox establishes communication with SWAMP and with the Ground Station via Wi-Fi. Differential RTK-GNSS receivers are connected to the MPBox via cables and are positioned on the additional frame at a distance of 1 m to provide differential RTK-GNSS for precise heading.

Also connected to the MPBox are the automatic winch, controlled by the Raspberry Pi contained within the MPBox, the low-cost CTD, and the SBES Echologger. The latter two are installed inside two of the payload holes of the SWAMP hulls. Specifically, the Echologger is positioned on top of the bottom HDPE plate constituting the hull of SWAMP, as depicted in Figure 10, ensuring protection from external impacts.

The automatic winch is mounted on the HDPE frame and is responsible for lowering and recovering the droppable CTDs, which can either be self-recording and droppable underwater or wired to the MPBox for continuous online monitoring. It is noteworthy that wired winches with slipring are foreseen and can be installed on SWAMP.

Furthermore, the frame hosts the AirQino and the Raspberry Camera, communicating via the SWAMP Wi-Fi with the MPBox, which integrates telemetry data, including information from AirQino and from the camera.

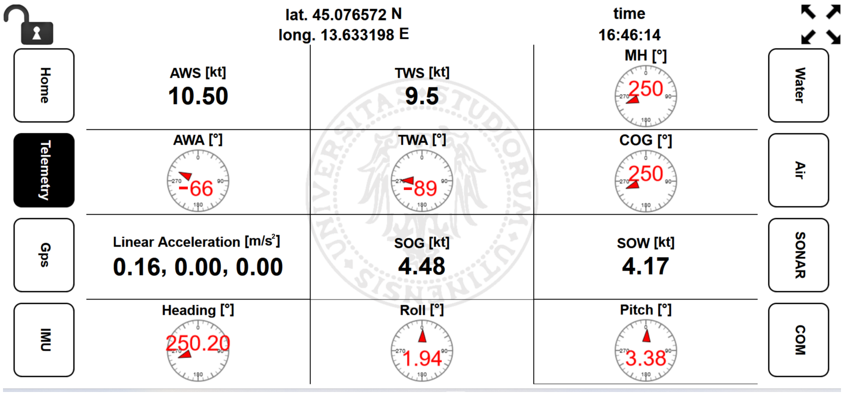
The total weight of the LED system and frame is around 10 kg, and it can be easily transported by hand by two operators.

4.2. Software Integration and Mobile Application Development

As far as software aspects are concerned, integration is rather straightforward. Indeed, all sensors are directly connected to the Raspberry Pi through USB, serial interfaces, or I2C (see Figure 3). Hence, either Argos directly handles them or, if there is a need to carry out specific preprocessing actions and/or to use specific device drivers by means of third-party programs, the latter can communicate to Argos via a network socket.

From the user's point of view, the most visible integrating component is the mobile application named *Data Explorer* (see Section 3.3 and the top part of Figure 4). Indeed, it allows one to interact with the ASV, start surveying missions, and accessing real-time data from a user-friendly interface. In order to allow the largest class of mobile devices to display such a user interface without platform-specific issues, *Data Explorer* was developed as a web application and deployed on the Raspberry Pi. Hence, when the user joins the ASV Wi-Fi hotspot, they can open their web browser to connect to a predetermined URL to display the application interface. Another advantage of this approach is that future updates of the application will be installed only on the companion computer of the ASV, without the need to be publicly distributed via app stores or the World Wide Web upon connection to the predetermined URL; the mobile client will automatically download and use the latest version

As an example of the application UI, in Figure 11, the ASV telemetry page is shown. In particular, besides the latitude, the longitude, and the current time, which are displayed in every page on top, the telemetry page displays the values of Apparent and True Wind Speed (AWS, TWS), Apparent and True Wind Angle (AWA, TWA), Magnetic Heading (MH), Course Over Ground (COG), Speed Over Ground (SOG), Speed Over Water (SOW), linear acceleration, and Euler angles (Heading, Roll, and Pitch).



lat. 45.076572 N
long. 13.633198 E
time 16:46:14
AWS [kt] 10.50
TWS [kt] 9.5
MH [°] 250
AWA [°] -66
TWA [°] -89
COG [°] 250
Linear Acceleration [m/s^2] 0.16, 0.00, 0.00
SOG [kt] 4.48
SOW [kt] 4.17
Heading [°] 250.20
Roll [°] 1.94
Pitch [°] 3.38

Figure 11. A screenshot of the Data Explorer Interface showing ASV telemetry data.

Other sections of the UI also allow one to input simple commands to the ASV, e.g., loading a list of GPS points for an automatic mission or taking a screenshot or video footage of the surroundings.

The UI is very clean and minimal. Moreover, very few colors are used, ensuring high-contrast graphics even in direct sunlight. Finally, the UI can also be accessed using an e-ink device, e.g., an Amazon Kindle. In this case, the visibility is very sharp, equivalent to looking at a sheet of paper.

Technically, every second, a JavaScript code makes an AJAX call to a PHP page, opening a socket connection to port 4545 of Argos. As a result, Argos provides a JSON object with all the current data (both telemetry and sensor data) processed by the Raspberry Pi. Such an object will then be passed to the JavaScript code which will update the related fields of the web interface, populating the cells shown, e.g., in Figure 11.

5. Outlook

5.1. Future Developments

This article highlighted the development of the LED system, which was designed with a dual purpose: serving as a tool for monitoring remote environments and as an architectural solution, representing a pivotal step within the ongoing MARMOT project. Looking ahead, the future roadmap encompasses architectural tests of the LED system and a crucial miniaturization effort aimed at improving ease of transport and assembly, particularly in areas with limited access such as high-altitude regions. These advances, focusing on reducing weight and complexity, are paramount for the development of a portable monitoring system. It is noteworthy that SWAMP has already proven its adaptability in various areas, including lakes like *Laghi del Gorzente* [53] and rivers like *Roja* [54], where it was transported disassembled. Furthermore, SWAMP showcased its adaptability to extreme environments during campaigns in front of tidewater glaciers in the Svalbard archipelago [23].

For future developments, we have identified that the requirements for a UXV for remote lakes analysis encompass several key features. Firstly, it must be portable, lightweight, and capable of autonomous operation in harsh environments. To achieve portability, the robot must be ergonomically designed for shoulder or chairlift transport, using suitable materials, shape, and size for easy transportation.

Regarding weight, we determined that the total weight should not exceed 15 kg for a two-day excursion, carrying 20% to 25% of a person's weight or 10 kg for a one-day trip. The robot itself should weigh between 5 and 7 kg, with a structure that includes impact protection for sensors and tools, utilizing a light and soft closed-cell foam such as the one used in the SWAMP.

Navigation requirements specify a low draft hull for shallow waters and a propulsion system made of multiple thrusters to ensure enhanced maneuverability and redundancy.

Architecturally, modularity is emphasized with hardware and software based on commercial off-the-shelf (COTS) components. Power is provided by Li-Ion batteries designed for endurance and power density, featuring a low-power design for long-range autonomous surveys lasting between 10 and 30 days. The basic payload includes a camera, a communication system with a range between 500 and 4.5 km, IMU + AHRS, and RTK GNSS. Environmental payloads may include additional sensors for air quality, underwater operations, sonar capabilities, and watersamplers with the possibility of preserving the sampled amount.

5.2. Conclusions

The article outlines the potential impact of a comprehensive approach addressing the urgent need for environmental monitoring in remote lakes. By leveraging autonomous robotic systems and advanced sensor technologies, the LED project aims to provide a promising solution for gathering real-time data to support conservation efforts and ecosystem management in inaccessible areas. Specifically, it focuses on the increasing importance of utilizing autonomous robotic systems equipped with lightweight and reliable sensor technologies to monitor and collect data in challenging environments where human access is limited.

The key points of LED projects can be listed as follows:

- Adaptation of the ASV SWAMP: The adaptation of the ASV SWAMP, originally designed for specific operations, to serve as the primary platform for the LED project signifies a novel approach. This adaptation involves leveraging its modular structure, flat-bottom hull shape, and compact thrusters to enhance controllability and maneuverability, making it suitable for diverse environmental monitoring tasks.
- Versatility for Environmental Monitoring: The integration of lightweight sensors, communication technologies, and navigation components transforms the ASV into a versatile system for environmental monitoring in aquatic environments. This versatility allows the system to collect various types of data efficiently, making it adaptable to different monitoring scenarios.
- MPBox and IoT Infrastructure: The incorporation of the MultiPurpose Box (MPBox) for central hub functions and payload integration within the Wi-Fi architecture of SWAMP, along with an Internet of Things (IoT) infrastructure for data transmission, introduces an advanced level of connectivity and data management within the LED system. This infrastructure enhances data collection, processing, and transmission capabilities, contributing to more comprehensive and efficient monitoring.
- Integrated Environmental and Navigation Payload: The integration of NGC sensors, water quality sensors, an automatic winch, a single-beam echosounder, and air quality sensors into the ASV platform represents a comprehensive scientific and navigation payload. This integration enables the system to gather diverse environmental data simultaneously, enhancing its capabilities.
- Software Integration with “Data Explorer” Application: The development of the “Data Explorer” mobile application for user interaction with the ASV introduces a user-friendly interface for initiating survey missions, accessing real-time data, and sending commands to the ASV. This software integration enhances user accessibility and facilitates seamless operation of the LED system, even in challenging environments.

In conclusion, the LED project represents a holistic approach to building an autonomous system to monitor alpine lakes. It should be noted that the SWAMP platform weighs 35 kg but can be disassembled into two hulls, each weighing 15 kg, with an additional 5 kg for connecting pieces. The weight of the LED sensors and frame is around 10 kg, and it can be easily transported by hand by two operators. While the system can be transported in individual pieces, this requires a significant number of people due to its weight and volume. Nonetheless, it signifies an initial architectural step toward developing a portable platform with the same and improved characteristics for monitoring remote lakes in high mountains. The ultimate goal is to create an innovative, portable, and lightweight platform capable of autonomously collecting, storing, and communicating environmental data in mountain lake environments.

The LED has prepared the way for the development of a compact observational solution for remote water bodies. This study showed how portable robotic platforms can be deployed in remote lakes, contributing to the monitoring of poorly studied waters.

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