Integrated Design and Field Validation of MoBI: An Intelligent Buoy for Environmental Data Acquisition

Alessio Chirigu[1], Alberto Mancosu[1], Sara Pinna[2], Mariella Sole[2], Matteo Anedda[2], and Daniele D Giusto[2]

[1]Hedya srl - Cagliari, Italy
[2]University of Cagliari, Department of Electrical and Electronic Engineering - UdR CNIT Cagliari, Cagliari, Italy
[1]Emails: alessio.chirigu@hedya.it, alberto.mancosu@hedya.it
[2]Emails: s.pinna62@studenti.unica.it, mariella.sole@unica.it, matteo.anedda@unica.it, ddgiusto@gmail.com

***Abstract*—This study details an advanced marine monitoring system based on smart buoys, designed to detect environmental conditions in coastal and open-sea areas. To meet the critical need for secure and accurate on-site data collection, the solution utilizes embedded hardware, multi-parameter sensors, and redundant data transmission technologies. This work is perfectly aligned with the conference topics focusing on intelligent sensing and autonomous systems for environmental protection. The main contribution lies in introducing a novel system architecture and presenting real-world results obtained during field tests. The conclusions demonstrate that the platform is robust, easily expandable, and represents an effective approach for optimizing the quality of information and the reliability of its communicationin maritime surveillance scenarios.**

Keywords-smart buoy; environmental monitoring; LoRaWAN; LTE; marine data.

I. INTRODUCTION

Marine environmental monitoring represents one of the major challenges for the sustainable management of natural resources and for mitigating the risks associated with climate change and human activities. A significant contribution in this field is represented by the coastal monitoring framework proposed in [1], which introduced an IoT-based architecture integrating smart buoys and onshore stations for real-time environmental and crowd data collection along the Sardinian coast. Building upon these concepts, the EcoMonitoring project extends this approach by combining smart buoys and surface drones, enabling efficient, scalable, and low-impact data acquisition in coastal and open-sea areas [2].

A key component of the system is the Monitoring Buoy (MoBI). Built from High-Density Polyethylene (HDPE) using 3D printing technology, MoBI is designed to operate in a semi-autonomous mode: it can be towed by an Unmanned Surface Vehicle (USV) to predefined locations, where it performs targeted environmental measurements. The buoy is equipped with sensors for both wave dynamics and water quality parameters, and it can acquire, process, and transmit data even under limited connectivity conditions. This approach is consistent with other recently developed intelligent systems for marine monitoring [3].

This paper provides a detailed description of the MoBI system, including its architecture, operational logic, communication strategies, and the results of field testing. The remainder of the document is structured as follows: Section II, hardware and software architecture, communication strategies, and control logic; Section III, acquisition of environmental data through the multiparametric probe; Section IV, wave monitoring subsystem and signal processing approach; Section V, results of field campaigns and performance analysis; Section VI, conclusions and future development directions.

II. SYSTEM CONCEPT AND ARCHITECTURE

The MoBI system has been designed to provide a robust, adaptable, and cost-effective platform for maritime and coastal environmental monitoring. Its architecture integrates low-power processing (on internal components), continuous interfacing with multiple sensors, and a dual transmission mode to ensure data consistency even in cases of weak or absent connectivity. At the technological core of the system are two processing units: a Raspberry Pi 3B+ micro-computer and an Arduino Mega 2560 R3 microcontroller. These units are housed inside the buoy's sealed hull and powered by a stabilized 5V supply. A voltage booster converts the supply to 12V, required for the multiparametric probe. The Raspberry Pi handles higher-level tasks, including probe management, data standardization, and log creation. The Arduino, on the other hand, manages the acquisition of fundamental data from orientation and positioning sensors: GPS, accelerometer, gyroscope, and magnetometer. It also controls the LoRa module for emergency communications. Similar modular IoT-based buoy architectures combining embedded controllers and multiple communication interfaces have been described in [4]. Communication and synchronization between the Raspberry Pi and the Arduino Mega are achieved through a USB serial connection, enabling bidirectional data and command exchange. This setup also allows the Raspberry Pi to directly power the Arduino Mega through the same USB cable used for data transmission, thereby reducing wiring complexity. The protocol used for communication is Universal Asynchronous Receiver-Transmitter (UART), a full-duplex asynchronous system that enables simultaneous transmission and reception of data on separate channels. In a classic UART configuration, the transmit (TX) pin is connected to the receive (RX) pin of the counterpart device. With USB, this bridging is indirectly managed by a USB-to-Serial converter chip, which translates UART signals for USB compatibility. Communication is handled by dedicated software libraries. Since UART is asynchronous, it does not require a shared clock. To ensure reliable data exchange, both devices must be configured with the same baud rate (bits per second), set during software initialization. On the Arduino Mega, the Serial library manages communication, leveraging its four available hardware serial ports. The USB port is mapped to Serial0 (pins 0 and 1), leaving the remaining ports available for external modules (e.g., one is reserved for GPS). On the Raspberry Pi, the Python pySerial library handles access to the USB serial port and manages asynchronous command exchange in ASCII format. This lightweight method ensures effective coordination between the two devices, avoiding overload and ensuring smooth acquisition, storage, and transmission of data. To guarantee uninterrupted data flow, MoBI employs a dual transmission strategy. When 4G/LTE connectivity is available, the Raspberry Pi transmits environmental data to a remote server. In cases of weak or absent coverage, data is sent via LoRa [5] [6]. This strategy leverages the complementary features of 4G/LTE and LoRa in terms of speed, coverage, and energy efficiency. 4G/LTE serves as the primary channel, offering high data transfer rates, low latency, and wide coverage across coastal and inland areas, thus ensuring reliable and immediate communication. LoRa acts as a fallback option, enabling data transmission in areas with limited or no cellular coverage. Its low power consumption and long range make it ideal for remote or hard-to-access environments. This dual system enhances the buoy's resilience and versatility, ensuring continuous operation and efficient data delivery under diverse conditions. In all cases, data are also logged locally on an SD card, allowing deferred transmission in case both primary and backup channels fail. At the end of each mission, the system checks whether the remote platform has received the data and, if necessary, initiates retransmission via 4G. The electrical system includes a charge controller and voltage converters (12V, 5V, 3.3V) that supply all electronic modules. Comparable surface gateway platforms designed for shallow-water underwater networks, integrating solar power management and embedded processing, have been presented in [7]. From a structural perspective, the MoBI buoy (shown in Figure 1) is built from HDPE using 3D printing. Its modular design facilitates maintenance and component replacement/upgrades. The internal arrangement protects the electronics from water while ensuring optimal exposure of antennas (LTE, GPS, and LoRa) and correct placement of the probe in the water. Similar smart buoy solutions have been reported in [8].

The control software (firmware) is written in Python (for Raspberry Pi) and C++ (for Arduino), following a finite state machine (FSM) approach to manage the operational protocol. Each mission is structured into the following phases: sensor and communication preparation, navigation to target points, data collection, and transmission. Figure 2 illustrates the complete operational software flow of MoBI. Upon startup, serial communication between the Arduino Mega and Raspberry Pi is established, enabling constant exchange of information and commands.

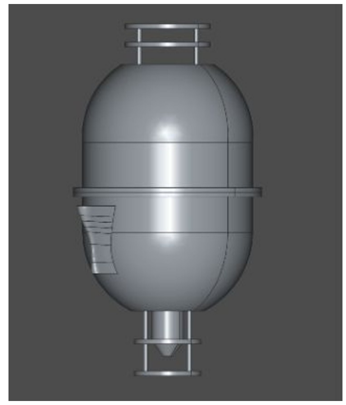

Figure 1. MoBI buoy.

The mission begins with a request to the remote platform to obtain the GPS coordinates of the measurement sites. Upon receiving the start command (START), the Raspberry Pi forwards the coordinates to the Arduino. After acknowledgment, the Arduino initializes the inertial sensors, GPS module, and LoRa communication. Once a stable GPS signal (fix) is acquired, the Arduino sends a confirmation (GPSFIX), indicating operational readiness.

The displacement phase then begins: the buoy, either manually or USV-towed, moves toward the first measurement point. During transit, the Arduino Mega continuously updates the GPS position and computes the distance to the destination. When this distance falls below the predefined threshold, a STOP command is issued to signal target arrival and transition to the next phase. In the measurement phase, the Raspberry Pi sends a start acquisition command (STARTDATA) to the Arduino, triggering the wave motion analysis algorithm. During this interval, inertial parameters such as wave period, direction, and height are recorded.

Simultaneously, the Raspberry Pi collects data from the environmental probe, which measures parameters such as temperature, pH, conductivity, dissolved oxygen, and turbidity. At the end of acquisition, the Arduino sends the wave data to the Raspberry Pi, completing the collection process.

The data gathered by both units are then managed in the transmission phase, which depends on connectivity: if 4G is available, the data are sent immediately (SEND4G); otherwise, they are transmitted via LoRa to the receiving node (SENDLORA).

After transmission, the system checks whether additional points need to be visited. If so, the next destination is set, and the cycle repeats. If all sites have been covered, the mission is concluded. The transmission frequency is variable and directly related to the number of configured measurement points, since data are sent after each acquisition cycle.

III. Integrated Environmental Data Acquisition

The MoBI system is engineered to collect both physico-chemical properties of water and wave dynamics data. Its acquisition workflow is structured into automated cycles,

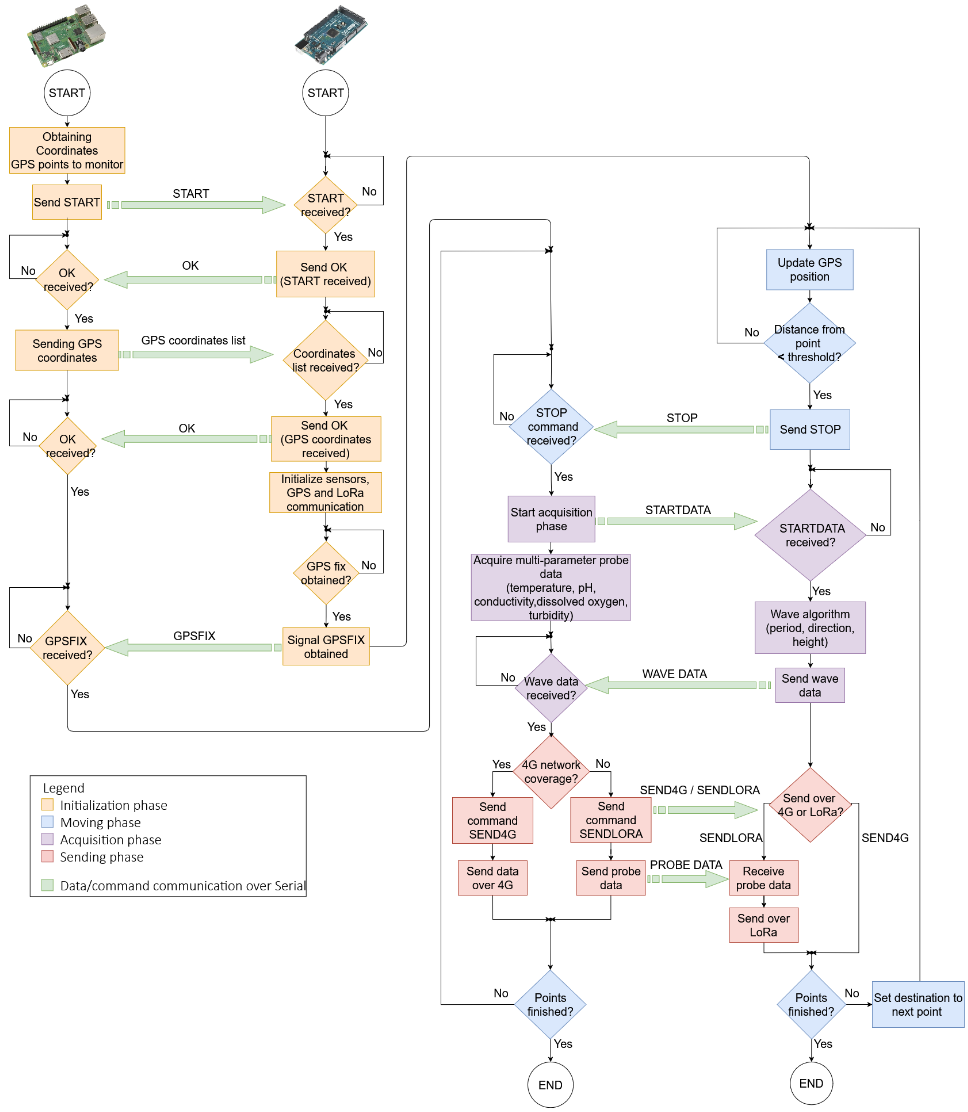

Figure 2. Software design.

guaranteeing measurement accuracy and seamless integration with data transmission and storage systems.

For monitoring environmental conditions, the buoy is equipped with a multiparametric probe WMP6, connected to a Raspberry Pi via a USB serial interface RS485. This sensor can record in real time several key indicators of water quality, including temperature, pH, electrical conductivity, dissolved oxygen, and turbidity. The probe remains submerged throughout the mission, ensuring continuous exposure to the measured environmental conditions.

During each cycle, the Raspberry Pi sends interrogation commands to the probe. The acquired values are processed by a software module that uses regular expressions to extract and validate each measurement. For every parameter, the system performs three consecutive readings a few seconds apart; the results are then averaged and stored in a structured JSON file, ready for transmission or local storage. Similar solutions, based on modular and open-source architectures, have already been implemented in long-term water monitoring projects.

Special attention has been given to turbidity, a parameter that often proves critical in saltwater testing. In several cases, the probe produced irregular or negative values during the initial immersion phase. To prevent distortions, a preliminary stabilization period was introduced before the actual sampling phase, in order to ensure representative measurements.

The collected data are saved on an SD card and simultaneously queued for transmission to the remote server via 4G/LTE network. If the connection is unavailable, the system switches to the LoRa channel as an alternative. In all cases, local SD storage guarantees data availability for retransmission in case of transfer failure. At the end of each measurement cycle, the system checks that all data packets have been successfully received by the platform and, if necessary, selectively resends the missing ones. Each measurement is timestamped and associated with

GPS coordinates and a unique mission identifier.

The acquisition cycle can be executed for preconfigured measurement points defined on the web platform or manually activated in the field. This flexibility allows the system to adapt to a variety of operational scenarios, ranging from short missions with a few points to extended campaigns involving dozens of successive readings.

IV. Monitoring of Wave Dynamics

Beyond monitoring the physico-chemical properties of water, the MoBI system also records wave motion dynamics, a crucial dataset for assessing coastal stability and ensuring maritime safety. This functionality relies on a suite of inertial sensors (accelerometer and gyroscope) mounted on an X-NUCLEO-IKS01A3 board, complemented by a magnetometer that provides directional orientation.

The wave analysis employs a four-phase algorithm designed to identify complete wave cycles through the examination of vertical acceleration. Specifically, fluctuations along the Z-axis are tracked to discern the acceleration and deceleration phases during both the cresting and trough movements. Similar low-cost smart buoy systems for real-time wave height measurement have been proposed in [9].

When a full cycle is detected, the system determines the wave period by measuring the interval between two successive peaks, while the wave height is estimated using double numerical integration of the accelerometer data. Although this technique is sensitive to sensor drift and noise, the level of precision achieved is sufficient for practical field applications. Comparable strategies have been implemented in professional-grade coastal wave monitoring systems [2].

Wave measurements are collected over a configurable time window, defined at the start of each deployment. The acquired data are then averaged to produce a representative statistical profile while minimizing transmission overhead. As with other environmental parameters, wave-related data are georeferenced and stored in JSON format, enabling subsequent processing.

Field evaluations confirmed the system's capability to reliably detect waves taller than 5–10 cm, even under minor buoy oscillations or environmental noise. These findings are consistent with results obtained from other low-cost prototypes tested in lagoon conditions [3].

Nevertheless, during periods of very calm water, small inaccuracies in wave period estimation were observed, primarily due to difficulties in distinguishing buoy micro-movements from actual wave patterns. Future improvements to the algorithm are planned to address this limitation.

V. Test Campaign and Experimental Results

To assess the performance of the MoBI system in realistic operational contexts, a series of field trials was conducted between January and March 2025 in the coastal area of Cagliari, with particular reference to the Sant'Elmo pier and the Palma channel. The campaign was aimed at verifying system stability, evaluating the accuracy and consistency of the acquired data, and testing the robustness of the communication subsystems under variable environmental conditions. The following section outlines the testing objectives and adopted methodology, and subsequently provides a synthesis of the key experimental outcomes.

A. Objectives and Methodology

The testing campaign aimed to evaluate several critical aspects of the system:

- Accuracy of GPS positioning throughout missions;
- Proper acquisition, validation, and structuring of environmental measurements;
- Reliability of 4G/LTE communication and the effectiveness of LoRa as a backup channel;
- Performance of the multiparameter probe in saline conditions;
- Seamless integration of the platform with backend systems, including the dashboard and data storage.

During the field operations, the buoy was transported to designated locations and maintained in a stationary position to facilitate data collection. Each measurement cycle involved logging coordinates, stabilizing the probe, and performing repeated sampling. Data were transmitted in real time whenever a 4G connection was available, with LoRa serving as an alternative communication channel when the primary network was inaccessible.

B. Main Results

Positioning. The GPS module exhibited an average positional deviation of around 10 meters with respect to the predefined target points. While this discrepancy falls within the operational tolerance of the platform, subsequent tests using a Global Navigation Satellite System (GNSS) module demonstrated improvements, reducing both the time required to obtain a satellite fix and the mean positioning error.

Environmental Data Quality. The multiparametric probe provided stable and reliable measurements for all parameters, with the exception of turbidity, which intermittently yielded zero or negative readings. To ensure the integrity of the dataset, such invalid measurements were systematically excluded from the analysis.

Communication Reliability. The system effectively transmitted data over LTE in regions with sufficient network coverage. In areas lacking connectivity, the fallback and retransmission mechanisms functioned as designed: data were temporarily stored locally and subsequently transmitted via LoRa. Comparable LoRa-based communication systems for marine buoy monitoring achieved stable GPS data transmission with low packet loss, confirming the suitability of this protocol for long-range maritime links [10]. Upon mission completion, the system verified the presence of any missing records by querying the platform. Any absent data were retrieved from the SD card and retransmitted over 4G until successful reception was confirmed.

Integration and Visualization. The acquired data were subsequently uploaded to a cloud-based platform for visualization and aggregation, where they were transformed into interactive charts and geospatial maps. The dashboards enabled real-time monitoring of parameters such as temperature, pH, and dissolved oxygen, providing operators with immediate insight into water quality. The integration of LoRa communication with cloud-based dashboards has also been successfully implemented in professional systems, such as the CB-150 buoy deployed in Green Bay [5].

Operational Observations. From an operational perspective, the field deployment of the buoy demonstrated the effectiveness of its modular design, which simplified post-mission inspections and battery maintenance. No instances of hardware malfunction or water penetration were detected, confirming the reliability and watertight performance of the 3D-printed HDPE hull.

VI. Conclusion and Next Step

The MoBI system has demonstrated itself as a dependable, versatile, and effective platform for environmental monitoring in marine and coastal environments. Its dual-processor configuration, comprehensive sensor suite, and redundant communication architecture allowed the system to successfully address the operational challenges encountered during field deployments.

Field testing validated the platform's robustness in terms of data acquisition, transmission, and integration with backend systems. Environmental measurements were generally consistent and reliable, while the wave monitoring module performed adequately for waves exceeding 5 cm in height. The software infrastructure supported continuous data logging and ensured recovery even during temporary network outages.

Insights from the field campaigns also identified several areas for enhancement, which will inform future developments:

- optimization of power management to reduce energy consumption [6];
- additional testing under more demanding wave conditions;
- expanded compatibility with diverse sensor protocols and automated long-term mission management;
- native integration with cloud platforms to enable historical data analysis and real-time alerts.

In summary, MoBI constitutes a significant advancement toward the automation of environmental monitoring, merging technological reliability with user-friendly operation in a compact system ready for deployment in real-world coastal scenarios.

Acknowledgment

This research activity was partially funded by the European Union - NextGenerationEU and by the Ministry of University and Research (MUR), National Recovery and Resilience Plan (NRRP), Mission 4, Component 2, Investment 1.5, project "RAISE - Robotics and AI for Socio-economic Empowerment" (ECS00000035).

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