Design, Operation, and Field Testing of MoBI: A Smart Buoy for Coastal Monitoring

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***Abstract*—This paper presents a smart buoy system designed for monitoring environmental conditions in coastal and marine areas. The proposed solution addresses the need for reliable, in situ data collection through the use of embedded hardware, multi-parameter sensors, and redundant communication technologies. This contribution aligns with the conference topics on intelligent sensing and autonomous systems for environmental applications. The work introduces a novel system architecture and reports original field test results obtained during real missions. The paper concludes that the system is robust and scalable, and that it offers a practical approach for improving data quality and transmission reliability in marine monitoring scenarios.**

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

I. INTRODUCTION

Marine environmental monitoring represents a central challenge for the sustainable management of natural resources and the prevention of risks related to climate change and human activity. The EcoMonitoring project addresses this challenge by proposing an integrated solution based on autonomous buoys and surface drones, aimed at collecting environmental data in an efficient, scalable, and low-impact way [1].

The Monitoring Buoy Interface (MoBI) is one of the key components of this system. Constructed from Three-Dimensional (3D) printed High-Density Poly-Ethylene (HDPE), MoBI is designed to operate in a semi-autonomous mode, towed by an Unmanned Surface Vehicle (USV) to predefined positions where it performs targeted environmental measurements. Equipped with sensors for wave dynamics and water quality parameters, the buoy is capable of acquiring, processing, and transmitting data even under limited connectivity conditions, following an approach consistent with other recently proposed intelligent environmental monitoring systems [2].

This paper provides a detailed description of the MoBI system, including its architecture, operational logic, communication methods, and the results obtained from field testing. The following section outlines the system hardware and communication strategy, followed by a description of the data acquisition subsystems and, finally, an analysis of the field test campaigns and experimental results.

The remainder of the paper is organized as follows: Section II presents the hardware and software architecture of the MoBI system, including communication strategies and control logic. Section III details the environmental data acquisition process using the multi-parameter probe. Section IV focuses on the wave monitoring subsystem and its signal processing approach. Section V reports on the field test campaigns and discusses the observed performance. Finally, Section VI provides the conclusion and outlines future developments.

II. SYSTEM DESIGN AND ARCHITECTURE

The MoBI system has been developed with the goal of providing a robust, modular, and economically sustainable solution for autonomous environmental monitoring in coastal and marine contexts. Its architecture combines low-power embedded processing, real-time interfacing with multiple sensors, and a dual communication strategy to ensure data integrity even under limited or absent connectivity conditions.

At the core of the system are two processing units: a Raspberry Pi 3B+ microcomputer and an Arduino Mega 2560 R3 microcontroller. These components are co-located inside the watertight structure of the buoy and are powered by a regulated circuit that provides 5V to the system. A step-up converter is used to generate the 12V required by the multiparameter probe.

The Raspberry Pi handles high-level operations, including communication with the multiparameter probe, data formatting, and log file generation. The Arduino, on the other hand, manages low-level data acquisition from inertial and positioning sensors, including Global Positioning System (GPS), accelerometer, gyroscope, and magnetometer, as well as the operation of the Long Range (LoRa) module for fallback data transmission.

Communication and synchronization between the Raspberry Pi and Arduino Mega take place via a Universal Serial Bus (USB) serial connection, which enables bidirectional exchange of data and commands between the two boards. This setup also allows the Arduino Mega to be powered directly through the Raspberry Pi using the same USB cable employed for data transmission, thereby simplifying the overall system wiring.

The communication protocol used is Universal Asynchronous Receiver-Transmitter (UART), a full-duplex asynchronous protocol that enables simultaneous transmission and reception of data through two separate channels. In a traditional UART connection, the Transmit (TX) pin of one device is connected to the Receive (RX) pin of the other, and vice versa. In the case of a USB connection, this link occurs indirectly, as each device includes a USB-to-Serial converter chip that translates UART signals into data compatible with the USB protocol, and vice versa. This communication is managed by dedicated software libraries.

Being an asynchronous protocol, UART does not require a shared clock between devices. To ensure correct communication, both devices must be configured with the same baud rate, i.e., the number of bits transmitted per second. This parameter is defined during software initialization.

On the Arduino Mega side, communication is handled using the Serial library, which allows the use of the four available hardware serial ports. The USB port is associated with Serial0, which uses pins 0 (RX) and 1 (TX), leaving the other ports free for connection with additional modules (for example, one is dedicated to the GPS module).

On the Raspberry Pi side, the pySerial Python library is used to access the serial port via USB and to manage the asynchronous exchange of commands in American Standard Code for Information Interchange (ASCII) format. This lightweight approach enables efficient synchronization between the two devices, avoiding system overload and ensuring smooth coordination of operations such as data acquisition, storage, and transmission.

To ensure continuous data transmission, MoBI implements a dual communication strategy. When Fourth Generation / Long-Term Evolution (4G/LTE) connectivity is available, the Raspberry Pi sends structured environmental data to a remote server. In the case of weak or absent signal, data are transmitted via LoRa [3]–[5]. The communication strategy is based on the combined use of 4G/LTE and LoRa, selected for their complementary characteristics in terms of bandwidth, coverage, and energy efficiency.

4G/LTE was chosen as the main transmission channel because it offers high data throughput, low latency, and broad coverage in most coastal and inland regions, enabling reliable and timely communication with remote servers.

LoRa was integrated as a fallback option to ensure data transmission in areas with limited or no cellular coverage. Its low energy consumption and long-range capabilities make it particularly suitable for transmitting environmental data in remote or hard-to-reach locations.

This dual approach increases the robustness and adaptability of the system, ensuring operational continuity and efficient data transfer across different deployment scenarios. In both cases, data are saved locally to a Secure Digital (SD) card to allow later transmission in the event of fallback failure. The system automatically verifies at the end of each mission whether the platform successfully received the data and, if needed, initiates retransmission via 4G.

The power system consists of a charge regulator and voltage converters (12V, 5V, 3.3V), supporting all connected electronic modules.

From a mechanical perspective, the MoBI buoy (shown in Figure 1) is made of 3D-printed HDPE. Its modular structure allows for easy maintenance and component replacement or upgrades, while the internal layout ensures watertight protection of the electronics, optimal antenna exposure (LTE, GPS, and LoRa), and proper probe immersion.

The system firmware was developed in Python (for Raspberry Pi) and C++ (for Arduino), following a finite-state machine logic to manage the mission flow. Each mission includes the following phases: sensor and communication initialization,

Figure 1. MoBI buoy.

movement to the acquisition points, data collection, and transmission. Figure 2 shows the complete operational software scheme of MoBI.

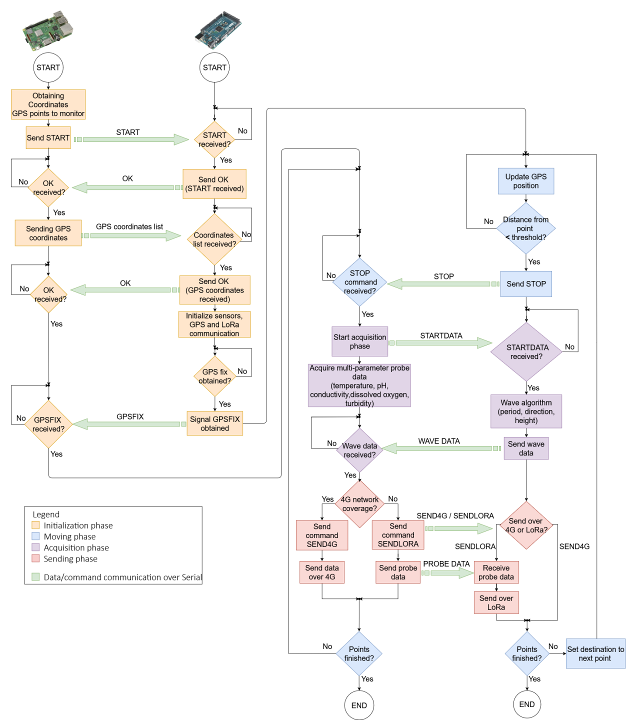

Figure 2. Software design.

At system startup, serial communication is established between the Arduino Mega and the Raspberry Pi, which is necessary for the continuous exchange of commands and data.

The mission begins with a request to the remote platform to obtain the GPS coordinates of the measurement points. Once the start command (START) is received, the Raspberry Pi retrieves the coordinates and transmits them to the Arduino.

After confirming successful reception, the Arduino proceeds with the initialization of the inertial sensors, the GPS module, and the LoRa communication. At the end of this phase, once a valid GPS fix is obtained, the Arduino sends a completion signal (GPSFIX), indicating that it is ready to start the mission.

Once initialization is complete, the system enters the navigation phase: the smart buoy (which may be towed manually or via USV) moves toward the first measurement point. During this phase, the Arduino Mega continuously updates the GPS position and compares the distance to the target point. When the distance falls below the configured threshold, the system sends the STOP command to the Arduino to indicate that the target has been reached and to proceed to the next phase.

The acquisition phase then follows: the Raspberry Pi sends the start command (STARTDATA) to the Arduino to initialize the wave motion analysis algorithm. From this moment on, inertial parameters related to wave period, direction, and height are recorded for a predefined duration.

In parallel, 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 the acquisition, the Arduino transmits the wave data to the Raspberry Pi, thereby completing the data collection phase.

The data gathered by both units are then handled during the transmission phase, which depends on the available connectivity: if a 4G network is present, the data is sent immediately via the mobile network (SEND4G); otherwise, it is transmitted via LoRa to the receiving node (SENDLORA).

After transmission, the system checks whether there are additional points to visit. If so, it sets the next target and repeats the entire cycle. If all points have been visited, the mission is concluded.

The transmission frequency is variable and depends on the number of configured measurement points. Specifically, one data transmission is performed for each point.

III. Environmental Data Acquisition

The MoBI system is designed to collect two main categories of data: physical-chemical parameters of the water and wave-related measurements. The entire acquisition process is organized in automated cycles, ensuring both data integrity and compatibility with the transmission and storage systems.

For the acquisition of environmental data, the buoy is equipped with a multiparameter probe, model WMP6, connected to the Raspberry Pi via an Recommended Standard 485 (RS485) USB serial interface. This probe is capable of measuring several key water quality parameters in real time, including temperature, pH, electrical conductivity, dissolved oxygen, and turbidity. The probe remains immersed throughout the mission, ensuring continuous exposure to the environmental conditions being measured.

The acquisition cycle involves the Raspberry Pi sending read command sequences to the probe. The received data are processed using a software module based on regular expressions, allowing extraction and validation of each individual value. For each parameter, the system performs three consecutive readings spaced a few seconds apart; the resulting values are then averaged and stored in a structured JavaScript Object Notation (JSON) file, ready for transmission or local archiving. Similar open-source and modular architectures have already been adopted in long-term water monitoring projects [6].

Special attention has been given to the management of turbidity, a parameter that often proves critical in saltwater testing. In some cases, the probe has returned anomalous or negative values during the initial moments of immersion. For this reason, a stabilization period was introduced before the actual sampling begins, to ensure representative measurements.

Collected data are saved to an SD card and simultaneously queued for transmission to the remote server via 4G/LTE network. In the absence of a network, the LoRa channel is used as a fallback. In both cases, the use of local SD storage ensures data availability for retransmission in case the initial transfer fails. At the end of each measurement cycle, the system verifies whether all data points have been successfully received by the platform and, if needed, selectively retransmits any missing data. Each measurement is timestamped and associated with GPS coordinates and a mission identifier code.

The acquisition cycle can be executed for each measurement point pre-configured on the web platform or triggered manually in the field. The flexibility of the system allows it to adapt to various operational scenarios, from short missions with a few points to extended campaigns involving dozens of successive readings.

IV. Wave Motion Detection

In addition to the physical-chemical parameters of the water, MoBI is capable of detecting the dynamic characteristics of wave motion, which are essential for coastal stability analysis and navigation safety. This functional module relies on a combination of inertial sensors (accelerometer and gyroscope) mounted on an X-NUCLEO-IKS01A3 board, integrated with a magnetometer for directional orientation.

The wave detection algorithm is based on a four-phase model, designed to identify full wave cycles through the analysis of vertical acceleration. Specifically, the system monitors variations along the Z-axis to detect acceleration and deceleration phases during both the rising and falling parts of the wave.

Once a complete wave cycle is detected, the system calculates the time interval between two consecutive peaks to estimate the wave period. The amplitude is estimated via double numerical integration of the accelerometer signal. Although this method introduces a degree of error due to sensor noise and drift, the results are sufficiently accurate for operational field use. A similar approach has also been adopted in professional systems for wave monitoring in coastal environments [7].

Wave motion data are acquired over a predefined period, configurable at the start of each measurement campaign. The results are averaged to ensure a representative statistical profile while avoiding overloading the transmission system. Like other environmental data, wave parameters are georeferenced and stored in JSON format, ready for subsequent processing.

Field test campaigns have shown that the system can reliably detect waves greater than 5–10 cm in height, even in the presence of minor disturbances or buoy oscillations. This behavior is consistent with findings from low-cost prototype devices tested in lagoon environments [8]. However, a slight imprecision was observed in estimating wave periods under particularly calm conditions, due to difficulties in distinguishing buoy micro-movements from actual incident waves. Optimizations of the algorithm are planned to reduce this ambiguity.

V. Test Campaign and Experimental Results

To validate the functionalities of the MoBI system under real operating conditions, a field test campaign was carried out between January and March 2025 in the area surrounding Cagliari, with particular focus on the Sant'Elmo pier and the Palma channel. The goal was to evaluate the system's stability, the quality of the collected data, and the reliability of the communication subsystems in coastal scenarios characterized by variable environmental dynamics.

We first present the objectives and methodology of the testing activities, followed by a summary of the main experimental results.

A. Objectives and Methodology

The tests focused on verifying several key aspects of the system:

- GPS positioning accuracy during missions;
- Correct acquisition and structuring of environmental data;
- Robustness of 4G/LTE communications and fallback capability via LoRa;
- Behavior of the multiparameter probe in saline environments;
- Integration of the platform with backend systems (dashboard and storage).

During the operations, the buoy was transported to the target locations and kept stationary to enable data acquisition. Each cycle included coordinate logging, stabilization of the probe, and repeated sampling. Acquired data were transmitted in real-time when a 4G connection was available, or alternatively through LoRa when the primary connection was unavailable.

B. Main Results

Positioning. The GPS module showed an average error of approximately 10 meters relative to the configured targets. Although this deviation is within the platform's operational limits, the use of a Global Navigation Satellite System (GNSS) module in later tests helped reduce both the fix acquisition time and average positioning error.

Environmental Data Quality. The multiparameter probe returned consistent values across all parameters, except for turbidity, which occasionally produced null or negative readings. In response, invalid values (such as negative turbidity) were discarded to preserve data integrity.

Communication Reliability. The system successfully transmitted data over LTE in areas with good coverage. During periods without network access, the fallback and retransmission logic worked as expected: data were stored locally and later sent via LoRa. At the end of the mission, the system correctly checked the presence of any missing data by querying the platform. If any records were absent, they were retrieved from the SD card and retransmitted via 4G until confirmation of successful reception.

Integration and Visualization. The collected data were later imported into a cloud-based visualization and aggregation platform, where they were converted into interactive graphs and geospatial representations. Dashboards allowed real-time visualization of parameters, such as temperature, pH, and dissolved oxygen, giving operators direct control over water quality. The combined use of LoRa and a cloud dashboard has also been validated in professional systems, such as the CB-150 buoy deployed in Green Bay [9].

Operational Observations. From a logistical standpoint, the field deployment of the buoy confirmed the practicality of its modular design, which facilitated post-mission inspection and battery recharging. No hardware failures or water ingress were observed, confirming the watertight integrity of the 3D-printed HDPE structure.

VI. Conclusion and Future Work

The MoBI system has proven to be a reliable, flexible, and suitable platform for environmental monitoring in marine and coastal settings. Its dual-processor architecture, integrated sensor suite, and redundant communication strategy enabled the system to effectively overcome the operational challenges encountered in the field.

The test campaigns confirmed the system's robustness in terms of data acquisition, transmission, and backend integration. In most cases, the environmental measurements were consistent and stable. The wave analysis module delivered satisfactory performance for wave heights above 5 cm, while the software infrastructure ensured data logging and recovery even during periods of temporary network unavailability.

The experience gained during the field trials also highlighted several areas for improvement, which will guide future developments:

- improved power management to optimize consumption [10];
- further testing in more demanding wave conditions;
- extension of support for additional sensor protocols and automated long-term mission handling;
- native integration with cloud platforms for historical analysis and real-time alert generation.

Overall, MoBI represents a concrete step toward the automation of environmental monitoring, combining technological reliability with ease of use in a compact system ready for operational deployment in real coastal scenarios.

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