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Design and Implement an Automatic Smart Buoy System for a Bulgarian Safe Beach Areas – Part 2

I. Dimitrov[1], I. Iliev[1], D. Hristov[1], D. Dinkov[1] & T. Mavrodiev[2]
[1] *Nikola Vaptsarov Naval Academy, Varna, Bulgaria*
[2] *Technical University of Munich, Munich, Germany*

ABSTRACT: The Internet of Things (IoT) is undergoing rapid expansion, transforming industries and everyday life through interconnected devices and data-driven decision-making. As IoT adoption accelerates, ensuring its accessibility and usability for non-technical users becomes increasingly critical. Simplified interaction with IoT systems facilitates broader adoption and maximizes their potential to improve safety, efficiency, and convenience. This aspect is particularly crucial in the domain of coastal safety, where IoT technologies can play a pivotal role. By integrating IoT into a smart buoy system, real-time data on water conditions, weather patterns, and swimmer safety can be continuously monitored and seamlessly communicated to lifeguards and beach visitors. The effectiveness of such a system relies on an intuitive and user-friendly design, enabling individuals without technical expertise to engage with its functionalities effortlessly. IoT serves as the foundation of this innovation, providing seamless connectivity, data sharing, and automation. Prioritizing IoT integration in critical safety solutions such as smart buoys underscores its potential to enhance life-saving measures while contributing to the development of more intelligent, secure, and interconnected environment.

1 INTRODUCTION

The initial phase of this research, as outlined in the preceding work [1], focused on the conceptualization and development of a safe beach zone system. This system was designed to improve coastal safety through the deployment of smart buoys equipped with specialized sensors. The buoy design was meticulously engineered to meet specific operational requirements, emphasizing modularity and manufacturability using 3D printing technology [9], [5]. Critical parameters of the buoys, as well as the coastal station, were rigorously calculated to ensure optimal performance. Additionally, the system’s electrical characteristics were analysed to guarantee reliability and efficiency. Following the design and computational phases, two fully functional buoys and a coastal station (Fig. 1) were successfully fabricated.

By integrating IoT into this smart buoy system, real-time data on water conditions, weather patterns, and swimmer safety can be continuously monitored and seamlessly communicated to lifeguards and beach visitors. The success of such a system depends on an intuitive and user-friendly design, allowing individuals without technical expertise to engage with its functionalities effortlessly. IoT serves as the cornerstone of this innovation, enabling seamless connectivity, data sharing, and automation. Prioritizing IoT integration in critical safety solutions such as smart buoys highlights its potential to enhance life-saving measures while fostering the development of more intelligent, secure, and interconnected environments.

The subsequent phase of this project involves comprehensive hardware testing to validate the system's durability and functionality under realistic environmental conditions. A series of stress tests [10] were conducted to evaluate the physical resilience of the buoy casings and their ability to withstand harsh marine environments. These tests were performed in a controlled setting at the Sea Survival Centre of the Nikola Vaptsarov Naval Academy, where the buoys were submerged in a deep-water pool for five days. Additionally, the facility's wave-generating apparatus was employed to simulate dynamic wave conditions, offering valuable insights into the system's performance under realistic maritime stresses. Footage and video documentation of these wave simulations are available for reference [4].

This testing phase represents a crucial step in ensuring the system's reliability and operational readiness for real-world deployment. The insights gained contribute significantly to the enhancement of coastal safety measures, reinforcing the role of IoT-driven smart buoy systems in creating safer and more resilient maritime environments.

2 ASSEMBLY PROCESS

The assembly process of the smart buoy commences with the 3D printing of the hull and inner container. These components provide a durable structural foundation and serve as enclosures for the onboard electronics. Following the printing phase, the buoy is painted yellow in compliance with national and international maritime regulations, enhancing both visibility and safety in marine environments. To further protect the system, protective coating layers are applied to the exterior surfaces, ensuring corrosion resistance and waterproofing. This protective layer prevents water ingress, safeguarding the buoy's internal electronics and contributing to the system's long-term operational reliability.

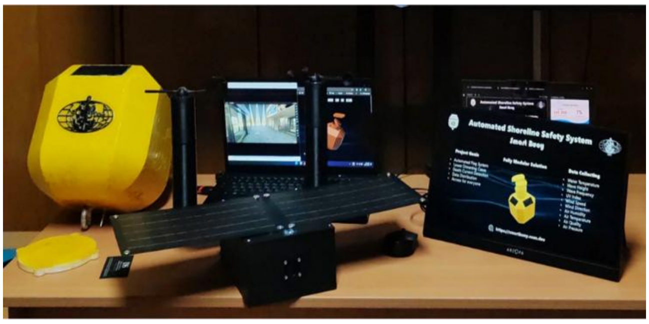

Figure 1. Smart Buoy Prototype (left) onshore station (center)

It is important to note that materials used in the buoy's construction are environmentally friendly, posing no threat to biodiversity or the marine ecosystem.

The next step is the integration of electronics, which involves the installation of contact pins, wiring, and other essential components (Fig. 2 and Fig. 3).

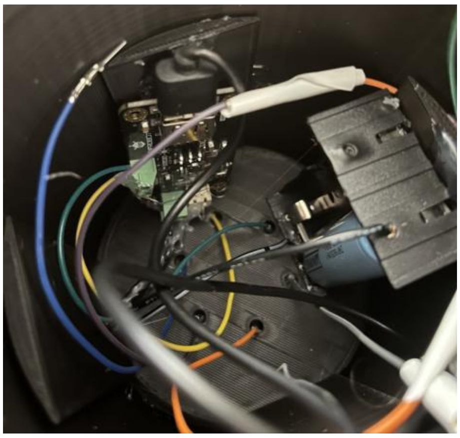

Figure 2. An internal view of the container. The layout of the electronics and wiring

Figure 3. Contact pins between the solar panels and the interior of the buoy

The assembly process of the buoy follows a structured approach similar to the operational methodology of a 3D printer. During this phase, the electronic components and individual plastic elements are systematically integrated. The process continues until the solar panels are securely affixed, the sealing mechanism is properly installed, and the O-ring along with the cover is precisely positioned. This meticulous assembly ensures structural integrity, water resistance, and the long-term reliability of the buoy in marine environments.

3 EXPERIMENTAL SETUP

To assess various parameters and analyse the operational behaviour of the constructed system - comprising smart buoys and the coastal receiving station - a dedicated test setup was established, as illustrated in Fig. 4. This experimental configuration enables systematic evaluation under controlled conditions, ensuring the system's reliability and performance in real-world maritime environments.

Prior to conducting the actual experiments, the communication range of the BLE system was evaluated both empirically and experimentally. The results indicated that the system operated without interruptions within a range of 50 meters. However, the buoy's casing significantly attenuated the module's effective range, reducing it from the documented 200 meters.

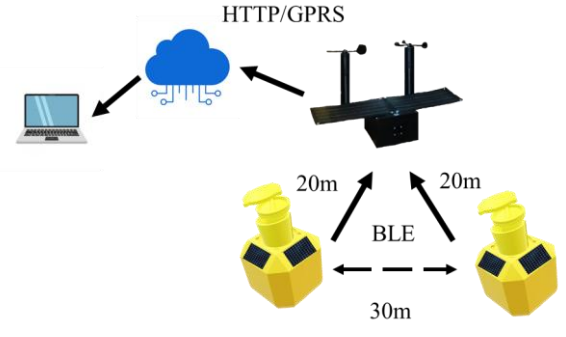

Figure 4. Experimental setup scheme

Testing confirmed that a stable connection between buoys is maintained at a distance of 50 meters, which aligns with the system's operational requirements. In real-world maritime deployments, the spacing between adjacent buoys should not exceed this range. For applications requiring extended coverage, the communication module can be replaced with a more suitable alternative, such as LoRaWAN [7] or Raspberry Pi [3].

Nevertheless, the established communication range is sufficient for deploying buoys to delineate a designated safe beach zone. Following the successful assessment of the system's communication channel, anchors were manufactured (Fig. 5) to secure the buoys in position. The anchor’s weight, dimensions, and rope length were carefully pre-determined to ensure stability while accounting for the buoy’s flotation characteristics.

The system was deployed within a controlled test environment at the Sea Survival Centre of the Nikola Vaptsarov Naval Academy to evaluate its performance under realistic maritime conditions. The specialized pool is equipped with a wave generator able to simulate realistic sea environment with wave height of up to around 0.9 meters.

Figure 5. Smart Buoy (in yellow) prepared for the setup and specially designed anchor (bottom right)

In addition to the other tests, it was confirmed that the buoys maintained their buoyancy and effectively prevented any water from penetrating the electronics and internal compartment. By the fifth day of operation, the battery of one buoy had been completely discharged. Upon analysing the data, it was determined that this particular buoy was positioned too close to the pool wall, where sunlight could not adequately reach the solar panels (Fig. 6). This observation highlights the importance of proper buoy placement to ensure optimal solar panel performance and battery life.

Figure 6. General view. In the background the buoy located near the pool wall

After positioning the buoys at the maximum feasible distance, the system was activated, and the initialization process for the buoys commenced. The control station, used for monitoring and analysing traffic, successfully received data regarding the buoys and the functionality of their sensors.

Upon successful initialization, the system transitioned to actively transmitting data from the sensors to the coastal station while simultaneously streaming the data to an open-access internet platform and cloud database. During the test, wave fluctuations and water temperature (°C) were measured. The results of these measurements are presented in Fig. 7.

4 DATA PROCESSING

After the successful transfer of data from the buoys to the station device, the raw IMU data must undergo further processing and analysis to extract valuable information about the waves. This includes key parameters such as wave height (h), period (T), speed (V), and direction of propagation.

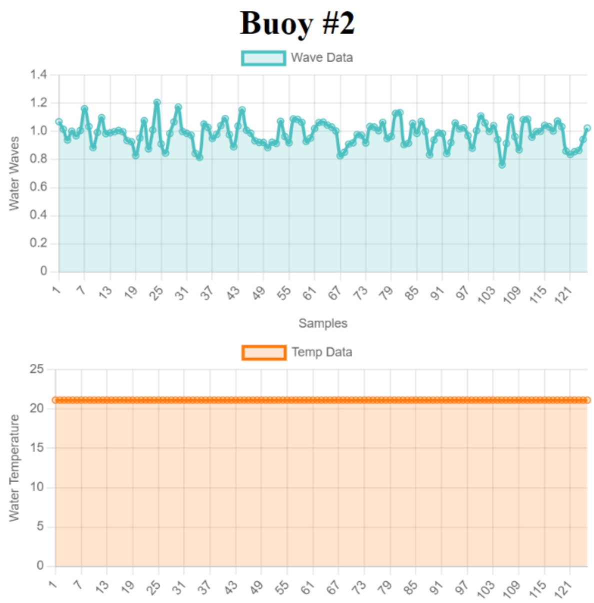

Figure 7. Temperature and raw wave data measurement results

First, the data must be filtered and prepared for further processing. This involves using a low-pass filter for acceleration measurements and a complementary filter, which is specifically tuned to combine data from the accelerometer and gyroscope to estimate the tilt angle of the buoy. Once the tilt angle is calculated, it allows for the isolation of the pure acceleration responsible for the periodic motion by subtracting the gravitational component from the filtered measurements.

To effectively analyse periodic measurement data, spectral analysis is the most common and efficient approach. Therefore, the authors opted to use the discrete fast Fourier transform (FFT) algorithm [6] to convert the filtered accelerometer data into its frequency domain representation. This enables the calculation of the wave height distribution in the frequency domain using the following relationship [6]:

$$x(t) = A \cdot sin(\omega \cdot t + \varphi)$$
$$\ddot{x}(t) = -A \cdot \omega^2 \cdot sin(\omega \cdot t + \varphi) = -\omega^2 \cdot x(t)$$
$$\ddot{X}[f] = \sum_{i=0}^{N-1} \ddot{x}[i] \cdot e^{-2\pi i j f/N}, \quad N - number\ of\ samples$$
$$H[f] = \frac{1}{(2\pi f)^2} \left|\ddot{X}[f]\right| \tag{1}$$

Without loss of generality, it can be assumed that φ = 0 for the sake of simplifying calculations, as this assumption does not affect the final result of interest — the amplitude of the complex signal $\ddot{X}(\omega)$.

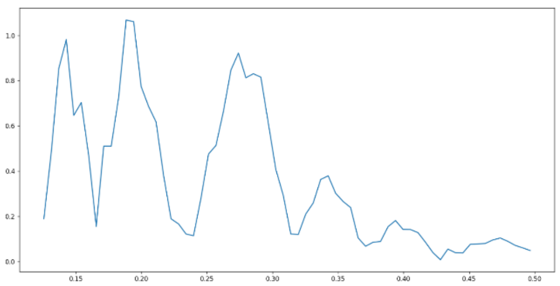

Figure 8. Wave height distribution H[f] in the frequency domain

The graph clearly shows three main peaks, corresponding to the primary frequency of the generated waves at 0.2 Hz and its harmonics. Therefore, the period of the main component of the sea wave can also be calculated.

Subsequently, an error-state Kalman filter [2] with Rauch-Tung-Striebel smoothing [8] is applied to the raw IMU data for trajectory estimation, which is crucial for further calculating the length and velocity of the sea wave. Knowing the relative tilt angle and the fact that the trajectory follows an elliptical shape, an algorithm is used to detect the section of the trajectory corresponding to the wave crest, or the "forward" movement, and determine the cardinal direction of propagation.

5 DATA STORAGE, AGGREGATION AND DISTRIBUTION

During the tests and experimental setup, the device used at the edge (Raspberry Pi 5), simulating the coastal station, demonstrated the computational capability to run all the necessary data processing algorithms in real time. This made it a critical component in the communication hierarchy, responsible for both processing and distributing the data collected from the buoys. In a more realistic deployment scenario, this device would be replaced with a less powerful alternative to reduce energy consumption. The data received at the edge device would be further aggregated before being transmitted through the uplink to the backend, thereby helping to minimize the bandwidth requirements for this connection.

As a complementary feature to this IoT infrastructure, a backend application programming interface (API) was developed to provide other researchers with access to the data. The API offers both free and authenticated access to the database containing raw and processed data. The underlying technologies include a simple HTTPS web server implementing a REST architecture, accessible over the internet, a MySQL database hosted in a cloud environment, and an intuitive HTML/CSS-based frontend application. The authentication system is implemented through API tokens, which are issued to users by an authentication server.

6 RESULTS

The implementation of the smart buoy system, as demonstrated in this study, highlights its considerable potential for improving port operations. This specific application illustrates the system's ability to autonomously collect real-time data, leading to significant time and cost savings. More importantly, it provides users with comprehensive and relevant information critical for evaluating maritime safety and optimizing port efficiency. The successful deployment of this system emphasizes its practical advantages, including enhanced decision-making, improved situational awareness, and increased operational reliability. These results confirm the value of integrating smart buoy technology into port systems, presenting a proven solution for modernizing maritime infrastructure and ensuring safety.

7 DISCUSSION

The authors' conceptual framework for developing a beach safety zone system is structured across three key phases, each detailed in a dedicated publication. The first phase encompasses the inception of the idea and the creation of the project, providing a foundation that outlines the rationale, objectives, and initial design considerations. The second phase delves into the hardware and software implementation, followed by extensive testing within a controlled environment to ensure operational stability and performance integrity.

The final, forthcoming phase aims to deploy the system in a real-world beach environment during a suitable tourist season, specifically within a coastal area managed by the Nikola Vaptsarov Naval Academy (NVNA). This conclusive stage is pivotal, focusing on the acquisition of environmental data, evaluation of the automated flag display mechanism, stress testing the web application under high user loads, and verifying system resilience in scenarios involving communication loss between individual buoys.

The culmination of these efforts is expected to provide empirical insights into the system’s operational robustness, ensuring that it meets the demanding conditions of a dynamic maritime environment. This holistic approach integrates marine technology, safety protocols, and real-time data acquisition, fostering a comprehensive and scalable solution for enhancing beach safety zone management.

8 CONCLUSIONS

The smart buoy system represents a transformative advancement in maritime technology, demonstrating significant potential to revolutionize maritime operations, particularly in port approaches and basins. By leveraging IoT technology, the system enables continuous and automated data collection on maritime traffic and environmental conditions, providing real-time insights that enhance navigational safety, ecological standards, and operational efficiency. The system’s flexibility allows for seamless integration into a wide range of port infrastructures, adapting to specific operational needs across various maritime environments.

One of the key strengths of the system is its adaptability. The smart buoys can be customized for different environmental and operational contexts, making them suitable for diverse maritime challenges. The system’s design also supports integration with other IoT technologies and automated systems in ports, such as automated cargo handling or weather forecasting systems, further enhancing port efficiency and safety.

The smart buoy system has shown its ability to operate effectively under challenging environmental conditions, including sea waves, with real-time monitoring providing valuable data for improving maritime safety, optimizing traffic management, and conducting environmental assessments.

Additionally, with the proper deployment of sensors, the system plays a critical role in detecting illegal activities such as unauthorized anchoring and fishing, supporting pollution monitoring, and assisting in port area inventories. The data collected can also contribute to scientific research, maritime studies, and risk assessments, further underscoring the system's versatility.

Designed with energy efficiency in mind, the system utilizes solar panels and other sustainable energy sources, ensuring long-term operation without compromising performance. The energy consumption has been optimized to meet modern sustainability requirements, making it a reliable solution for environmentally conscious deployment.

In conclusion, the smart buoy project sets a strong foundation for future innovations in smart maritime systems. Its ability to provide reliable, real-time data, coupled with its adaptability and energy efficiency, makes it an invaluable tool for enhancing safety, sustainability, and efficiency in maritime operations, paving the way for safer and more sustainable seas.

In the next article, the research team will provide data not only from experiments conducted in a controlled environment but also from the real-world deployment of the system in one of the beach zones in the Varna Bay, Bulgaria. This will offer valuable insights into the system's performance and effectiveness under actual operating conditions.

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