TransNav
http://www.transnav.eu

the International Journal
on Marine Navigation
and Safety of Sea Transportation

Volume 19
Number 2
June 2025

DOI: 10.12716/1001.19.02.05

Design and Implement an Automatic Smart Buoy System for a Bulgarian Safe Beach Areas – Part 1

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ABSTRACT: Drowning is the third leading cause of unintentional injury-related deaths, accounting for 9% of all injury fatalities, with over 300,250 cases reported annually by the World Health Organization (WHO) in 2021. Addressing this issue necessitates the implementation of affordable and accessible safety measures at local beaches. This paper presents an innovative, cost-effective automated system designed to improve beach safety through real-time environmental monitoring. The system consists of three primary subsystems: sensors, information processing, and action mechanisms. At its core are smart buoys, equipped with sensors and communication modules, which transmit data to an onshore station and a cloud-based platform. This platform processes, stores, and monitors the data against predefined thresholds, generating alerts when necessary. A web application provides real-time data access, enabling fault monitoring, system operation forecasting, and performance optimization.

1 INTRODUCTION

According to the latest data from the World Health Organization (WHO), the global number of drowning fatalities in 2021 was approximately 300,000 [15]. However, WHO highlights that these figures are likely underreported by 30 to 50 percent, as they do not account for drowning deaths related to water transportation, environmental disasters, self-harm, or assaults.

In 2023, Bulgaria reported 5,753 rescues from drowning, with the number of drowning fatalities significantly decreased compared to previous years. Despite these positive trends, drowning remains a critical public health concern, with more than 30 individuals drowning every hour and 300,000 drowning deaths recorded in 2021 alone. Nearly half of all drowning deaths occur among individuals under the age of 29, and one-quarter involve children under the age of 5. One promising approach to mitigating these fatalities is the development and implementation of intelligent systems that assist lifeguards and provide beachgoers with the necessary information to make informed decisions regarding the safety of specific beach zones. The deployment of smart buoys is one such method that holds potential for reducing drowning statistics.

Various types of buoys are employed across a broad spectrum of applications, ranging from military purposes, such as monitoring the sea surface and underwater environments [3], to environmental monitoring systems for remote ocean observation [4], [2]. Additionally, buoys are utilized as integral components of safety systems designed to assist lifeguards in preventing drowning incidents [8] and for real-time drowning detection [7]. They also play a vital role in enhancing navigational safety and maintaining environmental standards in port areas [1], [10], as well as supporting research efforts in marine science [6], [9].

In European coastal areas, buoys are widely deployed to delineate safe bathing zones, primarily to protect swimmers from watercraft, separate swimming areas from potentially hazardous regions, and signal water conditions. The use of buoys in these contexts is governed by both international and national regulations, which aim to ensure public safety and safeguard the marine environment.

Furthermore, the beach flag system, managed by lifeguards, provides an additional layer of communication to beachgoers. This system uses visual cues to convey current sea and weather conditions, alerting individuals to potential risks and ensuring their safety.

Beach flags are routinely adjusted to reflect significant risks such as rip currents, high waves, strong tides, and adverse weather conditions, all of which pose hazards to swimmers. The integration of smart buoys that collect real-time data on these environmental risks greatly enhances beach safety. These buoys supply lifeguards with critical, up-to-date information, facilitating faster response times to hazardous situations and improving the accuracy of flag warning decisions. By automating environmental monitoring, smart buoys contribute to more efficient lifeguard operations and offer enhanced protection for swimmers, ensuring a safer beach environment overall.

In this paper, the authors present an innovative and cost-effective solution in the form of an automated system that utilizes a network of smart buoys and onshore stations. The system is designed to collect, store, and analyse critical environmental data, enabling precise interventions by lifeguards and, when necessary, fully automating the flag signalling process. The implementation of this system holds the potential to substantially improve safety within designated beach areas, providing real-time monitoring and more efficient responses to emerging risks.

2 REGULATIONS

The regulations governing the use of beach buoys in Bulgaria exhibit some minor differences from broader European standards, although they generally share the same objective of ensuring swimmer safety and managing water traffic. In Europe, similar standards are established under the EU Bathing Water Directive (2006/7/EC) and ISO 20712-3:2024 safety guidelines [13]. The yellow colour code is universally adopted for buoys that mark safe swimming zones. Despite these broadly accepted norms, the International Organization for Standardization (ISO) does not provide specific rules or recommendations regarding the operation, replacement, or maintenance of buoys in beach zones.

While Bulgarian regulations largely align with European standards, there are notable discrepancies in certain areas, such as the distances used to delineate swimming zones and the precise responsibilities assigned to local authorities for buoy maintenance and supervision. Although the use of buoys to demarcate swimming areas is stipulated by the Bulgarian Water Act and local regulations, instances of improper application of the colour code or incorrect buoy placement, such as the use of 11 L water bottles painted yellow (Fig. 1), are not uncommon.

Figure 1. Water bottles used as buoy

3 OPERATIONAL MECHANISM

The automated system developed by the research team seeks to improve the situational awareness of lifeguards while maintaining cost-effectiveness. The primary objective is to provide municipalities with limited financial resources an affordable alternative to the less efficient plastic bottles currently used for marking swimming zones.

The smart buoy automated system (Fig. 2) consists of three core components: hardware, data processing, and action mechanisms. These elements work synergistically to offer real-time environmental monitoring, thereby enhancing safety measures at coastal areas.

Figure 2. Automated system – basic diagram

The hardware of the system incorporates a range of sensors and custom-built data collectors, including anemometers, temperature sensors, UV sensors, accelerometers, and gyroscopes, among others. These sensors are strategically placed both on the buoys and at onshore stations, such as lifeguard posts, to ensure comprehensive environmental monitoring.

The data gathered by the sensors is transmitted to onshore stations, where it is subsequently sent to a cloud server for storage. Once the data is stored, it undergoes a processing phase to extract meaningful information.

The processed data is then presented to users via interactive interfaces, providing real-time insights into environmental conditions. In addition, the system utilizes the processed data to generate alerts for hardware malfunctions or communication issues. Furthermore, it can trigger notifications for lifeguards to update the flag status or, in the absence of lifeguards, autonomously adjust the flag as needed. This automated flag signalling function is particularly critical in unguarded beach areas, where human intervention may not be available, potentially saving lives.

It is important to note, however, that individual judgment and personal adherence to safety guidelines should always complement the system's recommendations, even in the absence of a regulatory body.

4 CONSTRUCTION

The smart buoy is designed with a complex, modular structure aimed at enhancing functionality and simplifying maintenance. To create the desired model, the buoy's body was 3D printed using PLA+ material with a 10% infill (Fig. 3). To ensure waterproofing and increase durability, Dichtol (a polymer that forms a waterproof layer) and resin (a viscous substance also used for waterproofing) were applied to seal any openings, effectively protecting the internal components from water ingress and enhancing the buoy's longevity.

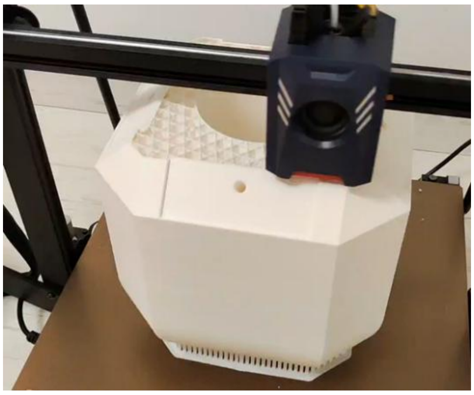

Figure 3. Smart Buoy model – 3D printing process

The modular design (Fig. 4) incorporates several distinctive features, with the three primary components being the main body, the chamber, and the cylinder. The main body is equipped with angled slots specifically designed to house solar panels, optimized to achieve maximum performance based on Bulgaria's geographic location. Each slot is connected to a channel that leads to the chamber at the bottom of the buoy. Additionally, a central hole is included for the precise placement of the cylinder, with an extra rib ensuring proper alignment.

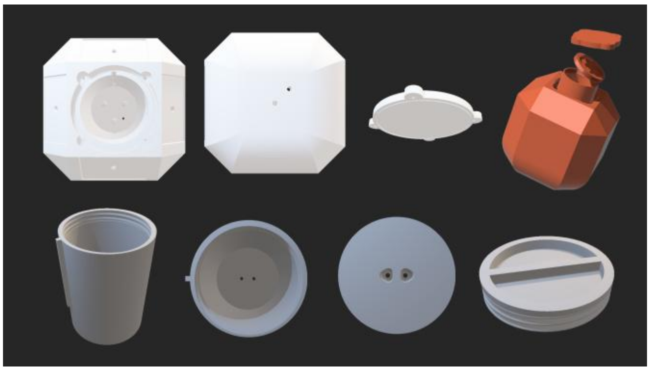

Figure 4. Smart Buoy model – general view

The central hole is sealed by a lid that includes a special groove to house an O-ring, providing airtight waterproofing. A dedicated hole at the bottom of the buoy accommodates the water temperature sensor, and a specialized hook attachment point is included, allowing the buoy to be securely tethered by a rope (Fig. 5)

Figure 5. Smart Buoy model – water temperature sensor and hook attachment point

The chamber is located at the base of the buoy and is connected to the solar panels via channels running through the body, as well as to the water temperature sensor. Both the solar panels and the sensor are permanently fixed, and the chamber is sealed to prevent water ingress. Its lid is designed with openings only for two sockets, which connect the chamber to other electronics housed in the cylinder.

The cylinder, comprising a lid and body, has a specific orientation for placement within the buoy, a critical feature for ensuring proper alignment of the two sockets that connect the water temperature sensor and supply power from the solar panels to the microcontroller. This modular configuration not only ensures correct placement but also facilitates ease of maintenance for lifeguards, enabling quick and simple replacement of the electronics in the cylinder in case of technical issues.

4.1 *Sensing Subsystem*

The developed sensing subsystem is physically divided into two parts: onshore and offshore sensor circuits, each collecting different types of data.

On the buoy, measurements related to position tracking, such as acceleration, angular velocity, and spatial orientation, are made using the onboard 9-axis inertial measurement unit (IMU) of the Arduino NANO 33 BLE microcontroller. Additionally, water temperature is sensed using a waterproof DS18B20 temperature sensor.

The static onshore station collects data related to environmental conditions, including wind speed and direction, through a custom-made plastic wind indicator. This device detects the orientation of the rotor using an electronic compass that measures the magnetic field of a magnet attached to the moving part, alongside an anemometer that utilizes a Hall sensor for revolution counting. Furthermore, the system is capable of analysing air quality, humidity, and temperature using the BOSH BME688 air quality sensor. An additional feature of the onshore station is the detection of UV radiation index, providing valuable environmental data for both lifeguards and individuals on the shore.

4.2 *Communication*

The communication scheme is modelled into long-range and short-range infrastructure for effective data exchange.

Data transfer between the buoys and the onshore station is facilitated by Bluetooth Low Energy (BLE) technology, which is available on the Arduino NANO 33 BLE. To extend the communication range to approximately 200 meters, modifications to the underlying Mbed OS are necessary. These adjustments include the use of the maximum transmit power (+8 dBm) on the nRF52840 microcontroller and enabling the hardware-optimized Bluetooth Long-Range feature to improve signal reception.

The BLE protocol supports the Generic Attribute Profile (GATT) specification, which will be implemented in the initial phase of the project. The communication hierarchy consists of central (client) and peripheral (server) devices. In this setup, the onshore station acts as the central device (client), while the buoys function as peripheral devices (servers) (Fig. 6). The client device periodically scans for nearby peripherals and requests the data they have available.

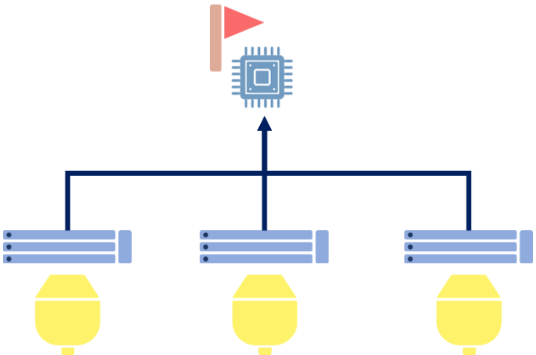

Figure 6. Normal communication between the buoys and the station

In the event of a lost connection between a buoy and its designated onshore station, the communication system is designed to support a MESH profile (Fig. 7) for auxiliary data exchange directly between buoys and stations. In this mode, a cluster of connected devices will relay information from a buoy in need to the nearest operational onshore station. The primary advantage of utilizing this operation mode is that it ensures continuous data flow even in the event of partial system failures, preventing data loss and aiding in the identification and localization of malfunctions.

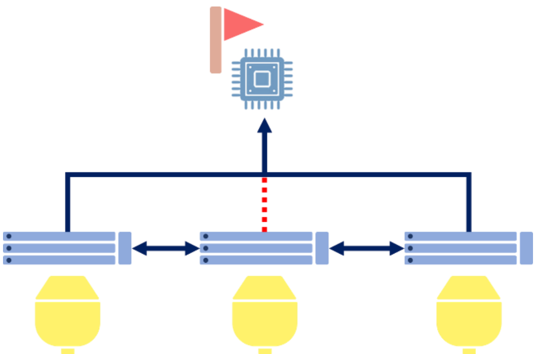

Figure 7. Example of broken connection between a buoy and the station – switch to MESH profile

Long-range communication for data transfer from the onshore station to the central information system is facilitated by a GPRS module installed on the onshore controller board. Although based on the now-obsolete 2G cellular standard, GPRS remains widely available and widely used due to its compatibility with most mobile devices. Notably, GPRS supports IPv4, which is used to transfer data from the onshore station to the central information system via a REST API. Once received, the data is aggregated, summarized, and displayed on a web interface for further analysis.

4.3 *Energy Management*

Both the onshore and offshore systems are designed to be autonomous and self-sustained in terms of energy management. To achieve this, a set of solar cells with a nominal power output of 1 W will generate electrical energy during the day, part of which will be stored in a lithium-ion battery for use during the night.

To maximize power production, the solar cells (one on the stations and four on the buoys) are oriented with a tilt angle corresponding to the latitude of the target location, with a southward orientation for locations in the northern hemisphere and a northward orientation for locations in the southern hemisphere.

Power consumption measurements were made for the main electronic components in both configurations, and the average power requirements of the systems were calculated. When supplied with 5 V, the microcontroller board required 350 mA of current during Bluetooth Low Energy (BLE) data transmission and only 2 mA in an idle state. Thus, the total power used for communication can be calculated as follows [5]:

$$\eta_{trans} = \frac{t_{trans}}{T} \approx \frac{5s}{1min} = \frac{1}{12} = 0.0833$$
$$P_{comm} = 5V \cdot \left(\eta_{trans} \cdot 350mA + \left(1 - \eta_{trans}\right) \cdot 2mA\right) \qquad (1)$$
$$P_{comm} \approx 155mW$$

where:
P_{comm} – Power Consumption;
η_{trans} – Transmission Efficiency (the fraction of time the system spends in transmission mode);
T- Total time;
t_{trans} – Duty Circle.

The interpretation of the result means that the system spends about 8.33% of the time in transmission mode and about 91.67% of the time in idle mode.

This indicates that data transmission occurs only for a small fraction of the total time, which is typical for energy-efficient systems

Furthermore, sensors that consume more than 1 mW of power, such as the water temperature sensor in the buoy and the air quality detection circuit, must also be considered. These sensors are essential for real-time environmental data collection and significantly contribute to the system's overall energy consumption. The water temperature sensor continuously monitors temperature variations, while the air quality detection circuit measures various environmental factors, including humidity, temperature, and the air quality index. Both sensors are critical to the system's functionality and must be factored in when calculating the total power demand, ensuring that the solar power system and battery capacity can support their operation over extended periods, especially during low-light conditions or at night. Their maximum power consumption is as follows [11], [12]:

$$P_{BME688} = 5V \cdot 5mA = 25mW$$
$$P_{DS18B20} = 5V \cdot 1.5mA = 7.5mW \quad (2)$$

Thus, the total energy consumption is 180 mW for the station and 162.5 mW for the buoy. A 3200 mAh Li-Ion battery cell, managed by a DFR 0559 solar power management board, serves as a buffer between the energy produced by the solar cells and the energy consumed by the electronics in each device. Based on these figures, it can be estimated that the devices would operate for approximately 2 to 3 days without any solar energy input.

4.4 *Web Application*

The smart buoy system will be accessible through a dedicated web application (Fig. 8) [14], which is organized into four main sections: an informational page, a data-access map, an API (Application Programming Interface), and an administrative panel.

Figure 8. Web Application – main page

The informational page provides details about the project, the team behind it, and any awards or recognitions it has received. The map section is especially useful for general users, enabling them to select beaches with the most favorable conditions for their visit. This feature enhances the beachgoer experience, promoting safer and more enjoyable summer tourism in areas where the smart buoy system has been implemented.

The API page allows users interested in accessing the data collected by the system to obtain access tokens, providing personalized data retrieval options for further analysis or integration with other platforms.

The administrative panel is reserved for the project team, providing real-time monitoring of the buoys. It offers live updates on data, battery levels, and the operational status of each station or buoy. This ensures that the team can efficiently manage and maintain the system's functionality.

To further facilitate user access, QR codes linking to the web application will be placed in key locations corresponding to areas monitored by the smart buoy system. This will allow users to easily access up-to-date information on beach conditions and enhance their overall experience.

5 DISCUSSION

The current study focused on designing and simulating an IoT-based smart buoy system aimed at enhancing safety in beach areas. Further research and development are planned to address critical aspects of the system's performance and reliability.

A subsequent paper will explore the physical implementation of the system, including the 3D printing of components, the assembly process, and testing within a controlled environment. This upcoming study will provide detailed insights into the practical challenges encountered during system construction and initial deployment.

Moreover, a dedicated paper is planned to investigate data transmission resilience, specifically addressing scenarios involving communication loss between individual buoys and the shore station. The analysis will include the behavior of the system under such conditions, focusing on the underlying algorithms – particularly the MESH network approach – to ensure continuous data flow and operational stability.

Future research will also encompass field deployment in a real-world, operational beach zone managed by the Nikola Vaptsarov Naval Academy (NVNA). This phase aims to evaluate the system's functionality under diverse conditions, including different operational modes and varying weather patterns. The performance metrics will cover data acquisition reliability, energy consumption, and the system’s ability to adapt to environmental changes, contributing to a comprehensive understanding of its practical feasibility and potential for large-scale implementation.

Additionally, the web application designed to monitor and manage the buoy system will undergo rigorous testing. This evaluation will focus on user interface efficiency, real-time data visualization, and system control capabilities to ensure seamless interaction between lifeguards, operators, and the buoy network.

6 CONCLUSIONS

Ultimately, the integration of applied technologies, such as the proposed automated system using smart buoys, presents a promising solution for enhancing beach safety. By providing real-time environmental data to lifeguards and automating flag warnings, this system has the potential to significantly reduce drowning incidents.

Moreover, the data collected by the smart buoys can be further analyzed to advance our understanding of water phenomena, such as rip currents, and contribute to early-warning systems for natural disasters like tsunamis. This dual benefit not only improves immediate safety measures but also supports long-term research, pushing the boundaries of knowledge on coastal hazards and further strengthening coastal safety protocols.

In the next article, the research team will provide detailed information about the actual development of the beach safety zone system. This will include insights into the design process, challenges faced, and the technical implementation steps taken to ensure the system’s functionality and effectiveness in real-world conditions.

Future work could focus on integrating the system with other IoT technologies, such as water and air quality sensors, automated traffic management systems, and drones for beach monitoring. This would allow for a more comprehensive analysis of conditions and a more effective response to emergency situations.

ACKNOWLEDGEMENT

This research paper has received funding from project “Safe beach zones” sponsored by Nikola Vaptsarov Naval Academy.

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