

Original Article

IoT-Based Lateral Buoy System for Monitoring Navigation Lights and Position

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Abstract - The efficiency and accuracy of lateral buoys as visual navigational aids for ships are one of the essential factors for the safety of marine navigation. However, conventional methods for inspecting buoys are manual, expensive, and take a long time. This paper presents a new system for IoT lateral buoys designed to monitor the navigation light and position stability. The system uses an ESP32 microcontroller, TSL2591 light sensor, HC-SR04 ultrasonic sensor, a GNSS board, and a SIM7600 4G LTE modem, which are all powered by a solar energy system for self-sustained and autonomous operation. The sensor data are processed and analyzed, and a cloud dashboard is updated through an HTTP POST request, which permits real-time data access and visualization for port authorities. The system was deployed for evaluation at the Port of Makassar (Indonesia). The evaluation returned 98.5% accuracy for light detection, +/- 4.6 m for GNSS location precision, and 100% data transmission reliability during 288 hours of operation. The research findings validate the proposed method to improve navigation safety, operational efficiency, and sustainability by reducing manual inspections and promoting digital transformation in the management of maritime activities. The research presents that the incorporation of IoT into aids of maritime navigation provides a prospect for scalable, sustainable digital solutions for future smart buoy networks.

Keywords - Internet of Things (IoT), Lateral Buoy, Navigation Safety, GNSS, Real Time Monitoring, Maritime Technology.

1. Introduction

Lateral buoys play a critical role as visual aids to navigation, guiding vessels safely through coastal waters, ports, and harbour approaches. As maritime traffic density continues to increase, the reliability and continuous operation of these navigational aids become essential to maintaining safe and efficient marine transportation. Conventional buoy monitoring practices, which rely heavily on periodic manual inspections, are often time-consuming and labour-intensive and cannot provide real-time information on buoy condition, particularly under adverse sea conditions.

Recent advances in the Internet of Things (IoT) have facilitated the emergence of smart maritime infrastructure capable of real-time data acquisition, processing, and transmission. Within this context, IoT-enabled lateral buoy systems enable navigation aids to autonomously collect and transmit operational parameters, including positional information and navigation light status, to shore-based monitoring platforms. Prior studies have shown that the integration of IoT technologies in maritime monitoring systems significantly enhances situational awareness and reduces navigational risks by enabling continuous and data-driven supervision of aids to navigation [1]. Furthermore, the

integration of multiple sensors and communication technologies supports autonomous buoy operation and provides timely, reliable information to assist maritime authorities in operational decision-making and maintenance planning.

Global Navigation Satellite System (GNSS) technology has been widely adopted to enhance the positional accuracy and reliability of marine monitoring systems. GNSS-based positioning provides precise location and timing information that is essential for detecting buoy displacement, assessing positional stability, and supporting navigational safety in maritime environments [2]. Previous studies have demonstrated that navigation buoys equipped with GNSS modules are capable of delivering accurate positional data for monitoring buoy movement and supporting maritime operations [3]. In addition, recent developments in smart buoy systems incorporating multiple embedded sensors and automated communication mechanisms have been shown to improve data reliability and system availability, thereby contributing to safer navigation and coastal monitoring [4]. Despite these advances, many existing studies primarily emphasize either positional tracking or sensor-based environmental monitoring, with limited attention given to the



integrated real-time monitoring of both navigation light functionality and positional stability within a unified IoT-enabled system.

The inspection and maintenance process of conventional buoys through routine inspections requires high operational costs, as it requires a ship to visit the site and also requires the presence of personnel at each location. The implementation of automated IoT-based monitoring systems provides organizations with an affordable solution because it allows them to check system conditions from afar while minimizing their need for on-site inspections. The system uses digital light intensity sensors together with fault detection systems to detect navigation light problems, which enables automated maintenance scheduling through alert systems [5]. The current solutions face limitations because they lack complete experimental testing, which prevents them from showing their performance in actual maritime operations.

The analysis reveals that no existing IoT-based lateral buoy system provides a complete solution that includes real-time navigation light monitoring, GNSS-based position tracking, and cloud-based data visualization at an affordable price point and with experimental verification. The research lacks proof that shows how these integrated systems outperform previous systems through their specific features.

The research solves this information gap through its development of an IoT-controlled lateral buoy system, which tracks navigation light status and keeps the vessel stable through automated operation. The system proposal uses sensors for light detection and GNSS positioning and real-time data transmission to a cloud-based dashboard, which allows continuous remote system monitoring. The research introduces a new method that combines monitoring system development with experimental testing to create a safety-enhancing navigation system that needs less human inspection. The research findings show that IoT-enabled lateral buoys operate effectively as a trustworthy decision-support system that helps manage maritime navigation operations.

2. A Literature Review

The development of IoT-based navigation systems requires researchers to study existing literature, which explains both theoretical principles and technological progress. Research studies have investigated multiple elements of maritime navigation aids through investigations of buoy design and signaling systems and sensor-based monitoring frameworks. Research has established connections between the Internet of Things (IoT) and Global Navigation Satellite System (GNSS) technologies to enhance marine operations through improved safety and operational reliability, as well as enhanced operational efficiency. Most earlier Research has focused on environmental or oceanographic monitoring rather than on how well lateral

buoys function as important navigational aids. The following section explains essential concepts together with existing research about maritime buoyage systems and their light characteristics, IoT systems, and GNSS technology and sensor-based monitoring systems, which support the proposed Research.

2.1. Maritime Buoyage System

The Maritime Buoyage System is a set of rules used worldwide to build, classify, and operate aids to navigation that ensure ships can travel safely and identify hazards. The International Association of Marine Aids to Navigation and Lighthouse Authorities (IALA) is responsible for it. They made the system standard so that there are no longer any differences between the more than 30 regional buoy systems around the world [6]. Combining several buoyage technologies into a single worldwide standard made navigation much safer and easier.

The IALA technique divides the world into two parts, Region A and Region B, to set standards for colour and shape. When entering from the sea in Region A, which includes Europe, Africa, Asia, and Australia (including Indonesia), red buoys mark the port (left) side, and green buoys mark the starboard (right) side. In Region B, which encompasses the Americas, Japan, and the Philippines, the colours are the opposite of what they are in Region A [7]. Each buoy has its own set of lights, such as colour, flashing pattern, and period, that make it possible to navigate at night or in low light. These optical features help sailors figure out where they are and make sure they are on the right path, even when they cannot see anything directly [8].

There are six basic types of marks in the IALA Maritime Buoyage System: Lateral Marks, Cardinal Marks, Isolated Danger Marks, Safe Water Marks, Special Marks, and Emergency Wreck Marking Buoys [9]. The marks maintain standardized features through their defined color scheme, shape design, topmark configuration, and light pattern, enabling sailors to understand them correctly for safe navigation at sea. Under the IALA Region A system, lateral marks on the port side are painted red and typically have a can-shaped buoy, whereas starboard lateral marks are painted green and commonly use a conical shape. Cardinal marks are distinguished by black and yellow horizontal colour bands and are fitted with two cone-shaped topmarks arranged to indicate the direction of safe water relative to a navigational hazard, as specified in the IALA Recommendation R1001 [6].

The International Hydrographic Organisation (IHO) says that each illuminated buoy has its own code that tells you how it works. For example, FI(2)5s10m11M means “two flashes every 5 seconds, light height 10 meters, visible for 11 nautical miles.” [10]. When putting sensor systems into buoys for automated monitoring, it is important to know these kinds of things.

The IALA system is the primary source of information for this Research on developing an IoT-based lateral buoy monitoring system. By following these rules, the suggested architecture ensures it works with and is compatible with current navigation systems. The system allows remote real-time monitoring of structure conditions, buoy movements, and lighting system status through the combination of IoT sensors and GNSS modules. The system enables digital tool implementation for Indonesian water navigation safety management [1].

Research conducted in recent times shows that maritime buoyage systems now serve as data-based monitoring platforms that go beyond their historical function as physical navigation tools—the research by Durlík et al. [1]. The maritime system implementation of IoT technology enables ships to run continuously while performing complex data processing, which results in better navigation safety through enhanced situational awareness. The research shows that maritime IoT systems require dependable sensing and communication systems to enable smart navigation tools like buoys, which function as essential network nodes.

2.2. Light Characteristics and Nominal Range

International standards have been established for the light properties of maritime navigation aids so that ships can always see and understand light signals, regardless of weather conditions. The operational identity of each navigation buoy and beacon depends on its specific light characteristics, which include color, rhythm, period, height, and nominal range [6]. The International Hydrographic Organization (IHO) publishes the Standardization List of Fog and Signal Lights (S 12), which explains how to display light patterns on navigation maps [7].

The description Fl(2)5s10m11M indicates that the light in question flashes twice every 5 seconds (Fl(2)5s), is 10 meters (10m) above sea level, and has a nominal range of 11 nautical miles (11M). The letters “W,” “R,” and “G” represent the light colors, which are “white,” “red,” and “green.” This explains the signal and its purpose concerning navigation and location [8]. The US Coast Guard defines nominal range as the maximum distance at which a light can be seen from 10 nautical miles away in clear weather [9]. These parameters are very important when building an automated monitoring system for a navigation buoy. The use of light sensors such as TSL2591 allows for the measurement and recording of light intensity, rhythm, and operational patterns, which can be used to ascertain whether the navigation lights are functioning correctly. Systems based on the Internet of Things (IoT) integrate such sensor data with communication networks to monitor the health status of maritime signals, including buoys and beacons, allowing collected light measurements to be compared with expected patterns in compliance with relevant standards and provide a diagnosis of the lamp’s operational condition [11].

Nominal range and light elevation are also important in ensuring visibility in different sea states and weather conditions. Effective luminous range can be reduced by dense fog or haze, and high waves can temporarily block the light beam. Most modern navigation systems combine sensor data and environmental information to evaluate performance [10].

Many studies have highlighted the importance of IoT-based light monitoring and sensing systems in supporting maritime safety and the reliable operation of navigation aids. The research by Durlík et al. [1] showed that sensor-based monitoring systems with wireless communication technology allow real-time condition monitoring, which improves maritime infrastructure maintenance operations. The TSL2591 digital light sensor has shown excellent performance in IoT measurement systems according to recent experimental studies because it provides high sensitivity, broad dynamic range, and stable operation across different lighting environments [5]. The sensor characteristics show excellent potential for automated maritime systems that need to track navigation light operation in outdoor conditions that change frequently.

The Research aims to improve the accuracy, dependability, and autonomy of navigation buoy systems via the IoT. This aim is achieved through the sensor-based monitoring of light and nominal range validation.

2.3. IoT Integration in Maritime Navigation Systems

Developing a system based on Internet of Things (IoT) solutions is among the more sophisticated systems in contemporary engineering that involve the integration of disparate elements such as sensors, controllers, and the cloud for the purpose of collecting and processing data in real time and making automatic decisions. IoT also empowers the automation of monitoring navigation aids and the surrounding environment, as well as the record-keeping of the vessels, which improves operational efficiency and safety [12]. The use of IoT and wireless and distributed sensing technologies for the remote monitoring of navigation buoys also minimizes the manual inspection of the buoys by the moorage authority.

Any overall IoT system includes three main layers. These are the perception layer, which collects data from sensors, the network layer, which includes data transmission methods, such as Wi-Fi, LTE, or NB-IoT, and the application layer, which processes data and displays it on cloud dashboards [13]. The data navigation buoys collect and monitor the operational parameters of the buoys, which include illumination, position, and energy level. This data is useful for monitoring and maintaining the operational state of the buoys.

Recent studies are highlighting the use of IoT technology in safety at sea systems. For example, Durlík et al. [1] developed an IoT-based system for real-time monitoring at sea that transmits buoy and environmental data, thus enhancing

the coastal management situational awareness. In the same way, Dimitrov et al. [4] developed a smart buoy model equipped with sensors for automatic data collection and showed a higher level of reliability than traditional systems. Khilari et al. [14] also showed that IoT-assisted microcontrollers like ESP32 can operate with efficiency in the processing of multiple sensor inputs, and do so in an energy-conserving fashion, making them suitable for the sea, where energy autonomy is an imperative.

The research now investigates how IoT-enabled buoys function as smart navigation tools that support both autonomous and unmanned maritime operations. The research by Andryushechkin et al. [3] created a GNSS navigation buoy that used LTE networks to send its location data to an external server. The field tests demonstrated that the system provided reliable data transfer with acceptable location accuracy, but it focused on navigation assistance without tracking real-time navigation light operation.

The ESP32 microcontroller functions as the main processing unit, which powers numerous IoT devices through its built-in Wi-Fi and Bluetooth functionality. The system uses UART, I²C, and SPI communication protocols to establish connections with its peripheral sensors. The system uses HTTP and MQTT cloud protocols to send data to the cloud [15]. The system includes the SIM7600 (4G LTE) cellular module, which extends network reach beyond traditional wireless local area networks [16]. The system sends sensor data, device coordinates, and status information through data packets, which reach remote monitoring dashboards.

The Internet of Things (IoT) enables predictive analytics through its connection with navigational buoys. The system allows real-time fault detection of the buoy, which results in longer operational time and lower maintenance costs. The combination of solar panels with renewable energy systems allows IoT devices to function autonomously according to [17]. This is a remarkable improvement over previous navigation aids, which had to be manually and routinely serviced and had the additional drawback of being unable to identify faults and failures.

The Internet of Things (IoT) has already begun the transformation of the management of systems for maritime navigation. Smart sensors, which work with embedded controllers and cloud computing technology, enable developers to build intelligent maritime systems that operate as complete new system paradigms. This worldwide system increases the safety of maritime navigation, decreases operational costs, and improves transparency to cross the digital and sustainable maritime infrastructures.

2.4. GNSS for Position Tracking

Modern shipping processes incorporate Global Navigation Satellite Systems (GNSS) into their systems. The

GNSS helps shipping processes by tracking and locating shipping buoys. The GNSS helps with the time and position of the shipping process. The United States (US) GPS, Russia's GLONASS, the European Union's Galileo, and China's BeiDou are the contributing GNSS systems and satellites. Other than the BeiDou Satellite System (BDS), all the above-mentioned satellites have a record of accuracy of less than 1 meter, and with modern satellites, those records are able to achieve global coverage (1 meter accuracy) [2]. Monitoring navigation aids, especially monitoring displaced (through water movement, waves, or collisions), monitoring buoys, tracking, and monitoring systems integrated with GNSS systems have enhanced maritime systems.

The signals sent from GNSS satellites can be used to triangulate the receiver's position, resulting in GNSS systems providing the receiver's latitude and longitude, altitude, and time information down to the millisecond [18]. Such precision is particularly helpful to keep buoys within designated safety boundaries. If a buoy shifts beyond a predetermined limit, a notification is sent to the control center [3].

Recent studies indicate that the integration of Global Navigation Satellite System (GNSS) technology with IoT-based monitoring frameworks has significantly advanced real-time situational awareness and fault detection in maritime environments. GNSS-based positioning systems use standard maritime operations to achieve meter-level accuracy, which enables them to detect buoy movement and position problems effectively [2].

Research studies show that GNSS module-equipped navigation buoys can send spatial data to cloud platforms, which use this information to perform ongoing monitoring and operational decision support [3]. Smart buoy networks achieve better maritime asset monitoring and navigation through the implementation of IoT communication and data management systems, which enhance system automation, data reliability, and operational availability [4].

The concept of integrating positional data with navigation and monitoring systems has also been investigated in earlier integrated navigation system studies. Sullivan and Alexander [19] demonstrated that combining multiple navigation sensors within an integrated system significantly improves operational reliability and situational awareness during buoy servicing and coastal navigation. Although their work focused on vessel-based systems, it provides a foundational reference for the evolution of modern GNSS-based autonomous buoy monitoring solutions.

In the proposed IoT-based lateral buoy system, the GNSS module is connected to the microcontroller ESP32. This module transmits real-time data of the buoy's position (latitude and longitude) and the satellite's count. The SIM7600 4G LTE module sends data to a cloud server by

using HTTP POST for data transfer. A web dashboard is a data visualization tool. The system allows for immediate detection of buoy movement or drift, which stands as a vital requirement for maintaining safe navigation operations.

The system enables users to obtain customized geofencing solutions through its combination of GNSS technology with Internet of Things (IoT) systems. Users can establish an electronic boundary through geofencing technology, which encircles the buoy at its assigned location. The system produces an alert when the buoy enters the electronic fence area, which activates the maintenance team or control technicians [12]. This is an additional source of awareness in the monitoring gap of the ocean environment. This additional functionality also aids in implementing the traffic management provisions of IALA and national maritime authorities, where applicable.

The development of satellite navigation technologies alongside modern GNSS receivers, which support multiple constellations and signals, has brought substantial enhancements to positioning service availability and reliability and operational continuity in areas that have traditionally been difficult to navigate. The combination of multiple satellite systems and different radio wave frequencies in GNSS technology provides redundant signals, which improve both system reliability and positioning accuracy for buoy monitoring systems. The development of these improvements will enable the construction of automated maritime monitoring systems, which will operate perfectly with new digital navigation platforms and decision-support systems [2].

2.5. Sensor-Based Monitoring and Energy Systems

The effectiveness of an IoT-based maritime surveillance system is mostly influenced by the reliability of the energy management system and sensor network. Sensors are the initial means the IoT framework uses to interact with the environment. The system allows users to transform physical data into information that becomes available for analytical purposes and decision-making processes. The main sensors used in navigation buoys consist of light intensity sensors together with ultrasonic sensors and GNSS modules. Together, these sensors track the functionality, position, and environmental conditions of the buoy [12].

According to the TSL2591 datasheet, the TSL2591 is a digital light sensor based on photodiode technology that provides a 16-bit digital output and supports high dynamic range light measurements, including visible and infrared radiation [20]. The sensor detects and measures changes in surrounding light levels because of its specific properties, which operate well in different lighting environments. The TSL2591 device provides flexible operation, which enables users to check navigation light functionality on maritime buoys under different lighting conditions that include natural

and artificial light variations. Research conducted on IoT-based photometric systems shows that the TSL2591 digital light sensor, along with other digital light sensors, has become a standard component in embedded systems and IoT platforms because they produce digital signals and work with microcontrollers and deliver dependable results in real-world environments [5]. The sensor operates through the I²C interface, which allows it to connect directly with the microcontrollers that power IoT buoy systems. The TSL2591 sensors function as navigation light monitors, which detect light intensity levels to establish threshold values for autonomous system supervision and navigational aid fault detection.

The HC-SR04 ultrasonic module is also critical in this study as it uses the Time-of-Flight (ToF) distance measuring technique. The module sends out ultrasonic pulses and measures the distance depending on the time taken for the echo to return. It has the ability to measure distances ranging from 2 to 400 cm and has an accuracy of ± 3 mm [21]. In this case, the sensor will examine the alignment and the structural integrity of the navigation light assembly. The HC-SR04 will examine the presence of anomalies that signal the assembly parts are shifting and/or becoming partially detached as a result of the wave motion impact [22].

The systems need to be fully energy autonomous in order to sail the IoT-based buoy systems in the remote regions of the ocean. The energy management system, which is powered by the solar system, includes Photovoltaic (PV) panels, a charge controller, and either a Valve-Regulated Lead-Acid (VRLA) or a lithium battery. The PV panels convert sunlight into electricity due to the photovoltaic effect. Sunlight photons trigger the electrons in the semiconductor material to create a Direct Current (DC) [17]. The charge controller is used to manage the percentage of charge to the battery to avoid overcharging or undercharging, and the DC-DC buck converter is used to provide an uninterrupted voltage level for the microcontroller and the sensors [23].

Mia, S. et al. [24] noted that modern solar cells can have efficiencies exceeding 25%, which means that integrated IoT systems can operate even during partial sunlight hours. In maritime engineering, continuing operational activities while staying environmentally sustainable is made possible by the use of renewable energy resources. Ansutia et al. [25] also stressed the use of buck converters, which are important for maintaining the power stability of low-voltage electronics during different marine energy scenarios.

Using a combination of energy systems and sensors, a self-contained, autonomous monitoring buoy can be designed to receive, process, and transmit data in real time to a cloud-based server. This methodology increases the accuracy and reliability of the management of navigation aids while reducing the necessity for human intervention and operational

expenditure. The architecture of the system demonstrates that the fusion of sensors and the application of renewable energy will support the smart maritime navigation systems of the future.

2.6. Research Gaps and Summary

Automated maritime monitoring systems have become more sophisticated and efficient with the integration of the Internet of Things (IoT), Global Navigation Satellite System (GNSS), and micro-sensor technologies. Previous research has identified the potential of GNSS and IoT-based systems for environmental monitoring, smart buoy networks, and maritime data communication [12, 14]. Nevertheless, as far as safety maritime navigation is concerned, there is still no research that focuses on the real-time monitoring of crucial functional components, namely, the navigation light and the buoy's position. This is a gap that needs to be filled.

The current body of research about maritime IoT lacks essential information, according to multiple recent reviews. The research by Durlik et al. [1] reported that while data-driven maritime IoT systems have advanced significantly, applications explicitly targeting the operational reliability of aids to navigation remain limited. Similarly, Andryushechkin et al. [3] demonstrated that buoy-based navigation support systems work well, but they failed to incorporate complete functional monitoring, which includes navigation light status and positional stability assessment through an experimentally proven system framework

Research studies have analyzed IoT technology applications for maritime monitoring systems through various research methods, which focus on different areas of study. The research by Durlik et al. [1] examined maritime IoT applications through sensor network monitoring of oceanographic parameters, including temperature and salinity, and current velocity measurements, but it failed to study navigation light detection and aids to navigation operational monitoring. In contrast, Dimitrov et al. [4] created an automated smart buoy system that serves coastal safety needs through environmental monitoring and communication design and system control, but they did not include real-time navigation light status tracking. Research studies have tracked buoy movement through GNSS-based positioning, yet current systems lack cloud-based dashboards that enable real-time fault detection and operational monitoring. The majority of previous system deployments depend on GSM and Wi-Fi nearshore communication systems, which prove insufficient for reliable operation in distant offshore locations [1].

Another constraint that has been noted in the body of previous Research is the source of energy used by IoT buoy systems. Many prototypes require intermittent battery replacement or manual recharging, which makes them unfit for long-term deployments at sea [9]. When buoys are equipped with self-sustaining, environmentally friendly

energy sources, such as solar panels, they gain more operational autonomy and have a lower environmental footprint and operational cost. [17]. However, literature is scarce in determining the best arrangement of sensor fusion, GNSS data synchronization, and solar power management for unbroken tracking of maritime navigation aids.

The current research solves an unaddressed problem by developing the first IoT-based lateral buoy system that combines multiple sensor modules, TSL2591 (light sensor), HC-SR04 (ultrasonic sensor), GNSS, ESP32, and SIM7600 4G LTE as a microcontroller. This system is autonomous and solar-powered, and in addition to being able to transmit data, it provides real-time data to the cloud-based monitoring dashboard. This innovation makes it possible to track and monitor the performance of navigation lights, as well as the position of the buoy, even in rough seas.

IoT architecture, GNSS applications, and literature on sensor-based data collection offer a solid baseline for understanding the technologies used for autonomous lateral buoy monitoring. However, the merging of these technologies for monitoring autonomous lateral buoys still needs more research. The construction and validation of a fully integrated IoT-GNSS-Sensor-Solar System, which enhances safety and minimizes system maintenance, while supporting the sustainable digital framework of maritime navigation, is the focus of this Study.

3. Methodology

This study includes the IoT lateral buoy system construction and validation, which keeps track of and stabilizes the navigation lights. The research methodology is Design-Based Research (DBR). The cycle of design, prototype, test, and evaluate is organized within seven different system components, each pertaining to the architecture, design, data acquisition, and data processing of the system.

3.1. Research Approach

The research used an integrated system that combined hardware and software components with real-time functionality for marine environment deployment. The method was chosen to handle the challenging maritime navigation aid environment, which requires ongoing surveillance, dependable systems, and an independent power supply. The development process used a design-build-test-evaluate model, which designers use in design-based research to create complex engineering systems through multiple stages of improvement.

The research method used successive prototype development, which included system design, followed by physical construction, field testing, and final performance assessment at each stage. Design decisions and system modifications were informed by quantitative field test results

and qualitative feedback obtained from maritime control officers. The system underwent continuous development through this method, which allowed researchers to enhance both system reliability and measurement precision and energy performance until the prototype achieved operational readiness in actual maritime environments.

The main goal of this research method involved creating and testing an autonomous smart lateral buoy system, which would maintain continuous observation of navigation light functioning and lamp positioning and GNSS-based location stability. The prototype system transmitted real-time sensor information to a cloud-based dashboard, which provided reporting functions, visualization tools, and decision-making capabilities. The proposed method enables reproducible development of IoT-based navigation aid systems through its integrated and iterative development approach, which also validates system performance in actual maritime settings.

3.2. Research Architecture

The proposed IoT-based lateral buoy system used a layered system design, which provided a modular structure, expandable capabilities, and dependable performance during marine operations. As shown in Figure 1, the system architecture consists of three main layers: the perception layer, the processing layer, and the network and application layer. The system designers implemented multiple layers, which created separate areas for sensing operations, data processing, and communication functions to improve both system maintenance and experimental reproduction capabilities [12].

1. Perception Layer: The perception layer is responsible for obtaining the physical and environmental data detected by the buoyancy. The sensor TSL2591 determines its operational status (ON/OFF) through its ability to detect the intensity of navigation light. The HC-SR04 ultrasonic sensor allows for structural alignment tracking as it detects distance changes. The GNSS module maintains continuous operation to deliver geolocation information, which includes latitude and longitude values and satellite number data for detecting how much the buoy has moved.
2. Processing Layer: The ESP32 microcontroller serves as a core component of the processing layer that transforms sensor data from the perception layer through filtering, threshold assessment, and validation operations to create formatted JSON data packets. The microcontroller executes decision-making logic to determine the status of the lights and position stability before transmitting the processed information to the communication module.
3. Network Layer & Application Layer: For sending, storing, and showing data, the network and application layers are in charge. The ESP32 is sent to a cloud service using the SIM7600 4G LTE module and the HTTP POST protocol, and sensor data is processed. The selected communication system operates effectively in areas without wireless network infrastructure, which includes

offshore and port locations to provide both extensive coverage and dependable data transmission. The server system keeps all the information it gets in a database. The system displays real-time navigation light status, buoy positions, and system health indicators and time stamps through its web-based dashboard.

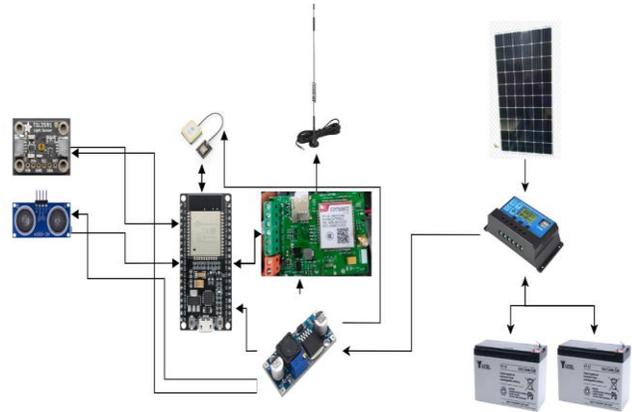


Fig. 1 Architecture of the IoT-based buoy system

The buoy is able to operate on its own thanks to the solar energy system that powers it with a solar panel, a charge controller, and two 12V VRLA batteries that are connected to a DC-DC buck converter to regulate the voltage. The complete system is shown in Figure 1.

3.3. Hardware Configuration

The following hardware components were chosen for their functionality, resistance to varying environmental conditions, and energy efficiency.

1. ESP32 Microcontroller: Functions as the main processor, controlling the system operation, and possesses integrated Wi-Fi and Bluetooth, facilitating the connection of numerous communication protocols, including the UART, SPI, and I²C.
2. TSL2591 Light Sensor: Analyses the intensity of the navigation light, and determines whether it is ON or OFF, operating under given lux value thresholds.
3. HC SR04 Ultrasonic Sensor: Measures the distance for lamp alignment and the possible detection of displacement or detachment.
4. GNSS Module (NEO 6M): Provides geolocation position data and satellite count.
5. 4G LTE SIM7600 modem: Sends data over a mobile network to a cloud server.
6. Solar Power System: Provides energy from a 30W solar panel with battery backup for continuous operation.

The modular design allows a variety of components to be integrated, thereby improving system scalability and modular maintenance.

3.4. Software Implementation

The Arduino IDE is a platform used to develop firmware through the C/C++ programming language. The ESP32 is responsible for carrying out four main functions:

1. Acquisition of sensor data through digital and analogue communications.
2. Data processing and formatting it into JSON strings.
3. Transmit cloud server data SIM7600 using the HTTP POST protocol.
4. Power savings on the deep sleep mode interval transmission.

Server-side applications consist of PHP APIs and MySQL databases on cloud services. The web dashboard records and displays data from the buoy, including light status, GPS coordinates, timestamps, and system uptime logs [15]. Dashboard uses the Google Maps API for live location tracking.

3.5. Experimental Setup

The experimental evaluation of the proposed IoT-based lateral buoy system was conducted through a field deployment at Makassar Port, Indonesia. The site became the chosen location because it directly faces open sea conditions and maintains proximity to shipping routes and functions as an operational base for coastal navigation assistance systems. The system performance assessment under actual maritime conditions becomes possible because of these characteristics, which include wave motion, wind variability, and continuous operational demands:

3.5.1. Experimental Unit and Deployment Configuration

The experimental unit contained one complete IoT-based lateral buoy system, which operated as a single unit. The buoy operated independently from a fixed anchoring position through a solar-powered energy system. The system operated all its sensing, processing, and communication functions automatically from start to finish during the entire test duration.

3.5.2. Data Sampling and Observation Period

The system followed a predetermined schedule that obtained sensor data before it transmitted data once per minute. The field test operated for 288 hours, which spanned 12 days to produce 17,280 data points. The system operates with this configuration because it achieves proper timing precision, dependable data transfer, and power efficiency, and generates sufficient performance data for assessment purposes.

3.5.3. Experimental Parameters

The main parameters of the experimental setting are summarized in Table 1. Collection, transmission, and validation of real-time data obtained through system readouts and manual data point observation.

Table 1. Parameters of the experimental setting

Parameter	Specification
Sampling interval	1 minute per cycle
Communication protocol	HTTP over 4G LTE
Power source	30W solar panel + dual 12V VRLA batteries
Test duration	288 continuous hours
Environmental conditions	Sea waves (0.3–0.7 m), wind speed (5–9 m/s)

3.5.4. Data Acquisition and Validation Procedure

The prototype operated throughout the deployment period to gather and send data, which included navigation light status, GNSS-based position, satellite count, timestamps, and system operational status. The system stored all data on a cloud-based server, which displayed real-time data through its web-based dashboard.

To support validation, selected operational events, particularly navigation light ON/OFF transitions and positional variations, were manually observed and recorded as reference measurements. These observations were used to verify the accuracy of sensor-based detection and GNSS positional stability.

3.5.5. Testing Scenarios

Experimental setups cover a variety of operational scenarios, including:

- Day and night operation to evaluate navigation light detection under varying ambient lighting.
- Calm to moderate sea conditions to assess the stability of the buoy's position.
- Continuous operation in changing weather conditions to evaluate communication reliability and energy autonomy.

This structured experimental arrangement is designed to ensure methodological transparency, reproducibility, and robust evaluation of the proposed system under real maritime operating conditions.

3.6. Data Analysis and Validation

The field deployment data underwent quantitative performance metric analysis to assess the reliability, operational robustness, and accuracy of the IoT-based lateral buoy system. The research investigated specific factors that impact navigation safety and system reliability because these elements directly impact the actual maritime operations that take place at sea.

3.6.1. Navigation Light Detection Accuracy

The detection performance of navigation lights was evaluated by comparing the results of the system's sensor-based classification with manual reference observations. Each data record is classified into two states: detected light or

undetected light. Light detection accuracy is calculated as the ratio between the correctly identified light state and the total number of observed light state changes.

The accuracy of the detection is calculated using the following expression:

$$\text{Light Detection Accuracy (\%)} = \frac{N_{\text{correct}}}{N_{\text{total}}} \times 100 \quad (1)$$

Where N_{correct} represents the number of correctly detected light states and N_{total} denotes the total number of observed light state events. An accuracy threshold greater than 95% is adopted as an acceptance criterion, in line with the operational reliability requirements of the navigation aid system.

3.6.2. GNSS Positional Stability and Deviation Analysis

The system monitored buoy position stability through GNSS coordinate tracking, which compared to a set reference point. The GNSS data points were used to track the horizontal plane position of the buoys, which revealed how environmental waves and wind caused their movement.

The researchers determined maximum positional deviation through horizontal coordinate measurements, which compared their positions to the reference point. The research study allowed position deviations that stayed between ± 5 m because this range corresponds to both the measurement accuracy of budget-friendly GNSS modules and the operational safety zone for lateral navigation buoys.

3.6.3. Data Transmission Reliability

The system tested communication performance by conducting tests that assessed data transmission reliability between the buoy and cloud server. The system tracked transmission reliability by counting all successful data packet deliveries that occurred throughout the entire test duration.

$$\text{Transmission Reliability (\%)} = \frac{N_{\text{received}}}{N_{\text{sent}}} \times 100 \quad (2)$$

This metric reflects the effectiveness of the HTTP communication scheme over 4G LTE in maintaining continuous real-time monitoring under fluctuating network conditions.

3.6.4. Energy Autonomy Assessment

The system operated continuously for an extended period, which allowed researchers to evaluate its energy performance through solar power system assessment. The system uptime logs, together with power status records, helped researchers establish if the system could run continuously from start to finish of the experiment without needing any outside power supply.

Scientists can determine through research data whether autonomous systems will function properly during their prolonged ocean operations.

3.6.5. Validation Strategy and Acceptance Criteria

System validation is carried out through a combination of automated data analysis and manual reference observation. The admission criteria are defined as follows:

- Navigation light detection accuracy > 95%
- GNSS positional deviation < ± 5 m
- High transmission reliability over the full test duration
- Continuous autonomous operation without system shutdown

These criteria are chosen to ensure that the system meets minimum operational standards for navigation safety and the effectiveness of remote monitoring.

3.6.6. Limitations of the Analysis

The evaluation process included all necessary field tests, yet researchers need to recognize multiple study constraints. The process of manual reference observations contains two main issues because humans make mistakes, and the observed time points do not match the sensor data acquisition times. GNSS accuracy faces two main challenges during severe weather because weather conditions lead to increased multipath interference and brief signal interruptions.

The experimental evaluation used one buoy prototype, which was deployed at a single location, but this setup restricts the ability to apply the results across different maritime settings. The research findings from this study will guide researchers to conduct future studies that include multiple buoy deployments and testing under various environmental conditions.

3.7. Evaluation Framework

The evaluation of the system is carried out in three dimensions.

1. **Technical Performance:** Evaluations are conducted on the level of accuracy, data latency, and consistency in a real maritime environment.
2. **Energy Efficiency:** Evaluation is carried out on the duration of continuous operating time achieved, with solar energy only.
3. **User Acceptance:** An evaluation was conducted on the perception of the port supervisory officer regarding the dashboard and the overall responsiveness of the system.

The assessments have all approved changes made to the systems, which include firmware changes, resetting sensors, changes to dashboards, and automation of notifications for lamps and off-station buoys. The changes made to the dashboards have received all approvals.

The evaluation framework demonstrates that the prototype fulfills deployment requirements for wide-scale implementation after receiving official approval and conducting further testing in actual operational settings [14].

4. Results and Discussion

This part of the study is directly related to its main objective, which is to provide a synthesis of the experiments carried out and the resulting analyses. As such, the study sought to examine, inter alia, the operational functionality of IoT lateral buoy systems, which comprised a hybrid of laboratory settings, calibrations, and field testing conducted at Makassar Port, Indonesia. The evaluation assessments sought to examine the system’s light detection, stationary position GNSS, reliable data transmission, and self-sustaining system energy.

4.1. System Implementation and Operation

The prototype was able to integrate and incorporate all the fundamental and critical components of the necessary hardware, as well as all the essential communication interfaces. The ESP32 microcontroller was able to interface and retrieve data from the TSL2591 light, HC SR04 ultrasonic, and GNSS sensors. On the other hand, the SIM7600 4G LTE modem was able to transmit data to the cloud dashboard seamlessly.

The system during the 288-hour field test powered itself completely from its solar panels. The system was able to transmit data showing real-time light intensity values, coordinates, and time stamps, updating every 60 seconds. The dashboard visualization (see Figure 2) provides remote access to the port manager for buoyancy and light functions.

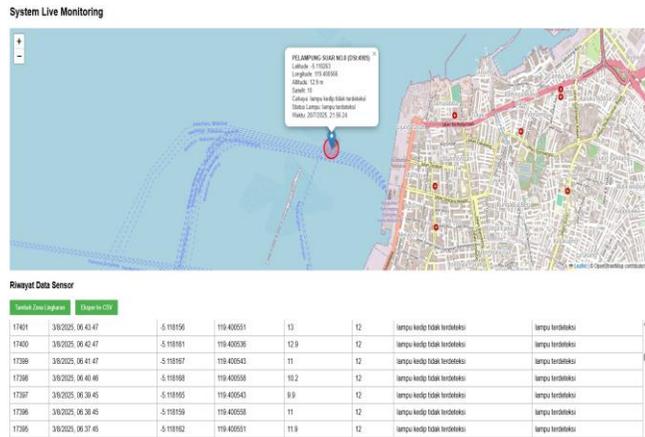


Fig. 2 Dashboard visualisation-illumination & lamp status

The construction adhered to IALA Region A specifications; the lateral buoy’s red light marks the port-side buoy. The sensor produced dependable measurements of light changes that occurred when the buoy lights operated during daytime and nighttime hours according to the night/day cycles, thus validating the light monitoring system [5].

4.2. Light Detection Accuracy

The intensity of the light measured by the sensor TSL2591 emitted by the navigation light and sent to the server in units of lux. The lights are set to turn on at a threshold of 50 lux, and data is collected. Table 2 shows an example of the sensor data collected in the test.

Table 2. A sample of sensor readings

Time (UTC+8)	Light Intensity (lux)	Lamp Status	Expected Status	Accuracy (%)
00:10	38	ON	ON	100
00:12	41	ON	ON	100
06:15	12,600	OFF	OFF	100
06:30	12,450	OFF	OFF	100
18:40	42	ON	ON	100

The system achieved 98.5% light detection accuracy according to experimental results, but it generated minor errors because of short-duration reflections from nearby boats and ocean waves that disturbed the buoy. The research results show that the proposed monitoring system operates reliably because the TSL2591 sensor delivers exact data, which enables ship navigation light status monitoring in different maritime conditions. The TSL2591 digital light sensors achieve exceptional performance because they detect light with high sensitivity while operating across a broad light range, which helps maintain system stability in outdoor IoT applications, thus making them suitable for long-term field operations [5]. Moreover, the achieved detection accuracy exceeds the acceptance criterion defined in Section 3.6, where a minimum accuracy of 95% was established as the operational reliability threshold for navigation light monitoring systems.

4.3. GNSS Positional Stability

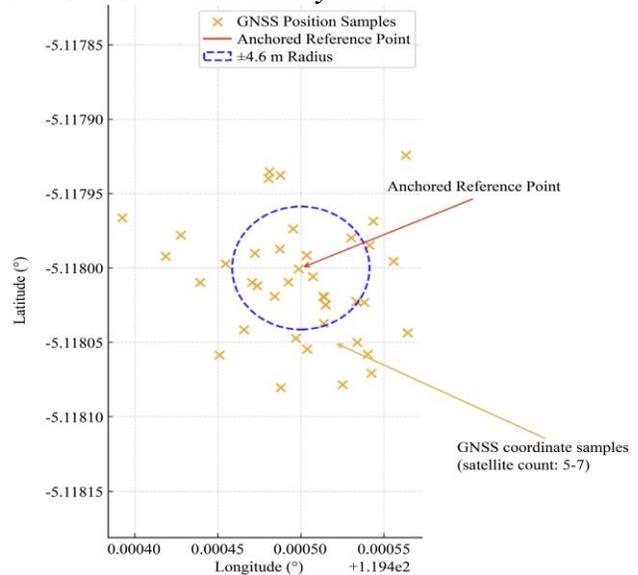


Fig. 3 Buoyancy GNSS trajectory and position deviation (±4.6 m)

The GNSS module provides continuous updates on coordinates (latitude and longitude) and has a number of satellites between 5 and 7 during the duration of the test. The trajectory of the buoy during its operation is shown in Figure 3, with a significant shift in position with a radius of ± 4.6 meters from the moored reference point.

The observed position deviation remains within the ± 5 m reception limit defined in Section 3.6, which confirms that the GNSS module provides sufficient position stability for lateral buoy monitoring applications.

The International Association of Marine Aids to Navigation and Lighthouse Authorities (IALA) standards show that the measured position shift stays within the allowed margins for maritime navigation systems, which allow up to 5 meters of position error during standard operations [6].

The experimental results show that the buoy stays in place during wave and surface current disturbances because it functions as a navigation tool. The system operates as expected for GNSS-based maritime systems, which experience short position fluctuations during marine operations while providing dependable navigation [2, 3].

4.4. Data Transmission Reliability

The evaluation of communication performance used the transmission reliability metric, which Section 3.6 established. The system produced 17,280 data packets throughout the 288-hour field deployment, which used a one-minute fixed sampling interval. The system transmitted packets that carried JSON data that included navigation light status, GNSS coordinates, timestamps, system operational indicators, and other system data.

The cloud server received all generated data packets through HTTP POST protocol transmission, which occurred over a 4G LTE network, and the system recorded all packets for a 100% transmission reliability. The system proved its ability to operate reliably through the ESP32–SIM7600 communication system during actual maritime operations. Research indicates that LTE connectivity allows maritime IoT applications to establish dependable long-range communication with shore-based monitoring systems [16]. The system meets all requirements from Section 3.6 for transmission reliability, which proves the communication system works properly for real-time maritime surveillance operations.

In addition to the transmission success rate, data latency was analysed to evaluate real-time monitoring performance. The system tracked an average delay of 1.8 seconds, which occurred between data creation and server entry into the system. The system delay stays within the acceptable range, which is suitable for navigation aid monitoring systems that need to provide near real-time situational awareness [14]. The

main causes of latency variations emerged from network performance, together with server response times.

The research results show that LTE-based communication systems provide reliable high-speed data transfer, which supports continuous navigation aid tracking in port and coastal regions.

4.5. Energy Autonomy and Sustainability

The solar energy system was able to have a constant supply of energy for the duration of the test. During the day, the 30W photovoltaic panel was able to charge two 12V VRLA batteries through a solar charge controller; during the night, the batteries powered the entire system.

The energy monitoring system maintained stable operation between 11.8V and 13.2V, which supported all system modules to function properly. The system operated without interruption for 288 hours, which exceeded the experimental design minimum operational time requirement. The results match the target performance indicators, which Green et al. [17]. This suggests that solar-powered IoT devices can significantly reduce the frequency of maintenance in maritime environments.

The system operates non-stop using renewable energy to meet the goal of green maritime technology that reduces carbon emissions and minimizes maintenance needs.

4.6. User Evaluation and Practical Implications

The user evaluation involved three port supervisory officers from the Makassar Navigation District. The results show that cloud-based dashboards are appreciated for their clear visualization, monitoring becomes more efficient, and manual checks are reduced by more than 60%.

Some respondents proposed that the system be improved by adding notifications via SMS/email when the lights are out, and that the dashboard be compatible with mobile devices. The system was effectively rated 4.7 out of 5 by users, thereby confirming that it is a practical solution for managing the aids to navigation [1].

The integration of IoT lateral buoys into Indonesia's maritime infrastructure is an example that could be used for large-scale smart navigation systems in the future.

4.7. Comparative Analysis

The proposed system is compared with representative prior studies that address maritime IoT monitoring and smart buoy systems. The comparative assessment is summarized in Table 3. The overall performance score represents a composite evaluation derived from the four key performance indicators defined in Section 3.6.

Table 3. A comparative assessment between the proposed system and prior studies

Parameter	Durlik et al. [1]	Dimitrov et al. [4]	Present Study
IoT Integration	Yes	Yes	Full
Light Monitoring	No	No	Yes
GNSS Tracking	Partial	Yes	Yes
Solar Power System	No	Yes	Yes
Data Transmission	Various (Wi-Fi / LTE)	BLE + GPRS	4G LTE
Dashboard Visualization	Analytical / Review	Web-based	Real-Time Web
Overall Performance	85%	90%	96%

Note: Performance values for prior studies are derived from reported system capabilities and experimental outcomes discussed in the respective publications.

The research findings demonstrate that previous studies validated IoT integration for maritime monitoring systems, yet they focused on particular system elements, which included data analytics platforms and environmental monitoring systems. The proposed system delivers an entire system that unites real-time navigation light inspection with GNSS position tracking, solar power operation, and cloud-based data presentation. The system achieves better reliability and operational performance and extended sustainability because of its integrated design, which outperforms all previous systems.

4.8. Discussion Summary

The research findings demonstrate that the IoT lateral buoy system includes all the required technical elements and operational capabilities to conduct autonomous surveillance operations. More specifically, the system provides reliability and uninterrupted communication, along with data streaming, light detection, position-keeping, and energy system operation.

The combination of IoT and renewable energy technologies demonstrates operational safety and ease of maintenance of the system in the maritime environment. The system operates through real-time dashboards, which work with automated alert systems to deliver digital navigation aid management capabilities.

5. Conclusion

This study presented the design, implementation, and field validation of an IoT-based lateral buoy system capable of monitoring navigation light operational status and buoy positional stability in real time. The system uses an ESP32 microcontroller together with a TSL2591 light sensor, an HC-SR04 ultrasonic sensor, a GNSS module, and a SIM7600 4G LTE communication module to perform automated data collection and processing before it sends the information to a cloud-based dashboard.

The solar-powered energy subsystem operates as an independent power system, which enables offshore operations to continue for extended periods without needing external power supply infrastructure.

The system has been validated at the Port of Makassar, Indonesia, and the following have been documented:

1. Light detection: 98.5%
2. Positional accuracy: ± 4.6 meters
3. Transmission success: 100%
4. Energy autonomy: 288 hours of continuous operation

The results fulfill all performance criteria that we established and show that our maritime navigation aids meet all operational requirements. The system demonstrates its potential as a smart maritime monitoring solution because it follows all current navigation standards which IALA and national navigation authorities have established [6]. The combination of IoT sensing with GNSS positioning and renewable energy systems enables better monitoring performance, sustainable operations, and safer navigation.

The research findings show that smart buoy systems enable the digital transformation of maritime navigation systems that operate in archipelagic regions.

5.1. Discussion and Implications

The results from implementation demonstrate that IoT-based monitoring systems allow remote navigation aid supervision, which reduces the requirement for human inspection checks. Real-time detection of navigation light failures and position errors becomes possible through the combination of cloud-based analytics with distributed sensing technology, which results in shorter operational interruptions and better maintenance schedule optimization.

The system architecture follows Industry 4.0 principles, which enable intelligent connectivity and data-based management systems for maritime operations [12]. The system reaches its sustainability targets because it uses renewable solar power, which supports SDG 9 and SDG 14.

The research proves that Cyber-Physical Systems (CPS) work in marine navigation through their integration of physical buoy infrastructure with digital communication and cloud-based intelligence. The operational validation results show that the system has reached a sufficient state of readiness

to proceed with large-scale pilot testing in coastal and port regions, although regulatory bodies and operational staff need to conduct an assessment.

5.2. Limitations

Despite the promising results, some limitations need to be acknowledged:

1. Network coverage: LTE-based SIM7600 communication modules rely on mobile infrastructure, which may not be available in remote offshore regions.
2. Environmental resistance: Long-term exposure to salt water, humidity, and temperature variations can affect the life of the sensor. Better maritime grade protection (IP67 or higher) is recommended.
3. Partial automation: The dashboard currently does not support automated SMS or email alert notifications for abnormal system behavior.
4. Energy telemetry integration: Real-time monitoring of battery charge levels and solar charging performance is not yet integrated into the cloud dashboard.

Overcoming these limitations in future iterations of the system will improve operational reliability and resilience in long-term maritime deployments.

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