

A Digital Twin-Based Marine Buoy Communication System for Real-Time Ocean Monitoring and Telemetry Applications

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Abstract - Marine monitoring systems play a vital role in oceanographic research, maritime navigation, environmental assessment, weather forecasting, and disaster management. Reliable acquisition and transmission of ocean data from offshore regions remain challenging due to harsh environmental conditions, communication constraints, and the high cost associated with field testing and deployment. This paper presents a Digital Twin-based Marine Buoy Communication System, developed using a Hardware-in-the-Loop (HIL) framework to validate marine telemetry applications. The proposed system combines a Unity-based virtual marine environment, a Python middleware communication layer, an ESP32 embedded controller, and a cellular communication module to establish an end-to-end telemetry platform that simulates real-world buoy operations.

The Unity simulation environment serves as a Digital Twin of an offshore buoy and generates oceanographic and environmental parameters, including wave height, temperature, humidity, buoy orientation, and geographical location. These parameters are transmitted through a middleware layer where the data are processed, compressed, and forwarded to the embedded hardware. The ESP32 microcontroller performs telemetry management and communication control, while a SIM7670C LTE/GSM communication module enables long-range wireless data transmission. A Streamlit-based shore station dashboard provides real-time monitoring and visualisation of the generated telemetry information. Experimental validation demonstrated successful transmission of telemetry data across all subsystems with reliable communication performance and real-time monitoring capability. The proposed framework offers a cost-effective and scalable approach for testing marine communication systems without requiring immediate offshore deployment. The developed platform can support future integration of physical oceanographic sensors, cloud-based analytics, satellite communication networks, and intelligent monitoring applications. The results indicate that Hardware-in-the-Loop simulation combined with Digital Twin technology provides an effective solution for accelerating the development and validation of next-generation marine monitoring systems.

Key Words: Hardware-in-loop Simulation, NB-IoT, Marine Buoy, Ocean Monitoring.

1. INTRODUCTION

Oceans of the world occupy more than 70 percent of the Earth's surface. They have various roles such as regulating climate, supporting biodiversity, facilitating maritime transportation, and providing natural resources. Continuously monitoring oceanographic parameters and environmental aspects is required for knowing marine ecosystems, forecasting the weather, supporting fisheries, enabling offshore operations, and ensuring safety at sea. For this reason, marine monitoring systems have become a very important part of modern ocean observation networks.

Marine buoy systems that collect ocean data in real-time are the most popular method among the various platforms available. These systems are sent out to the coastal and offshore areas to collect environmental data such as wave results, water temperature, atmospheric temperature, humidity, wind speed, buoy orientation, and geographical position. The recorded data are then sent to land stations where they are studied for ocean research, environmental monitoring, disaster prediction, and navigation support. Accurate and constant communication between the marine buoys and the monitoring stations is, without a doubt, a very important factor for effective ocean observation.

Firstly, on the one hand, offshore deployments of marine buoy systems require very high investment, specialized equipment, and logistical support. On the other hand, sea roughness, strong winds, waves, saltwater corrosion, and interference of communication are elements that can affect the performance and reliability of the system. The validation of communication protocols, telemetry systems, and monitoring applications sometimes requires highly frequent field trials. All this makes repeated field trials often impractical and expensive.

Therefore, these problems have led to looking for alternatives that help to get efficient testing and validation before actual deployment in marine environments.

Digital Twin Technology or simply Digital Twin has been recently developed as a solution that offers more possibilities for the implementation of new complex systems resulting from the integration of cyber and physical environments. Examples of such systems can be

found in marine buoy applications. Coupling a physical system and its counterpart virtual system results in a Digital Twin. The virtual system replicates not only the physical features of the physical system but also its operational behavior as well as its interactions with the environment.

Nowadays, Digital Twin is used extensively in industries such as manufacturing, transportation, healthcare, smart cities, and industrial automation due to its capability to improve system reliability while reducing development costs.

Simultaneously, Hardware-in-the-Loop (HIL) simulation has come to be recognised as a reasonably successful way of validating embedded systems as well as communication architectures.

HIL simulation blends real hardware units with virtual environments, which permits developers to check actual embedded devices running under simulated conditions. Along the lines of this technique, by allowing real communication hardware to become a part of a virtual simulation environment, it is possible to examine system behavior under typical operating conditions without exposing oneself to the risks and costs of field testing.

The Internet of Things (IoT) has developed so quickly that it has revolutionized marine monitoring systems as well. Nowadays, the IoT-enabled communication technologies support activities such as real-time data acquisition, remote monitoring, connection to the cloud, and the making of intelligent decisions. Low-cost and power-efficient controllers like the ESP32 meet the needs for local processing, whereas cellular communication modules offer a long-range wireless connection that is suitable for remote telemetry.

This paper proposes a Digital Twin-based Marine Buoy Communication System whose design has been a Hardware-in-the-Loop simulation framework. The combined system includes a virtual marine environment provided by Unity 3D, middleware communication services in Python, an embedded ESP32 controller, cellular communication module, and shore monitoring dashboard.

The most important point of this study is its capacity to create a step-by-step, low-cost solution for marine communication systems that is not dependent on oceanic deployment so as to be able to take risks in the marine environment without actually doing the real thing.

On the other hand, the system simulated the transmission of marine telemetry data, the communication reliability, the data processing, and the monitoring functionalities as a full set of features altogether in a controlled environment.

The development of the following:

- A Digital Twin model for marine buoy behaviour and environmental conditions simulation.
- A Hardware-in-the-Loop (HIL) communication framework that integrates virtual components with physical components.
- A telemetry system for marine monitoring using an ESP32 microcontroller.
- Long-range data transmission through the use of cellular IoT communication technology.
- An interactive, real-time visualization and analysis of maritime data shore monitoring dashboard built with Streamlit.
- Realization of a low-cost testing platform that drastically limits the need for expensive offshore field trials.

This paper continues as follows. Section II reviews the related work and existing marine monitoring technologies. Section III highlights the research gap and the objectives of the proposed system. Section IV details the proposed system architecture and methodology. Section V is dedicated to describing the hardware and software implementation aspects. Section VI is focused on presenting experimental results and performance analysis. Finally, Section VII summarizes the paper and points to future research directions.

3. LITERATURE REVIEW

Marine monitoring and communication systems have garnered a lot of attention lately as oceanographers, environmentalists, and pros in the safety and disaster management sectors are all demanding fresh and local data. The research community has been quite active in proposing various buoy-based remote sensing systems equipped with wireless communication technology, embedded platforms, IvT architectures, Digital Twin frameworks, and simulation-based validation methods. This section summarizes the key advances in marine buoy communication systems, IoT-enabled ocean monitoring, Digital Twin technologies, and Hardware-in-the-Loop (HIL) simulation.

A. Marine Buoy Monitoring Systems

The basic purpose of marine buoys is to act as isolated platforms which collect data about the environment and the oceanographic conditions of the area where they are located offshore. Old and traditional buoys were designed with sensors for waves, water temperature, pressure, humidity, salt level, wind speed, and the geographical GPS position. Usually, the information is sent to coastal monitoring stations by means of radio frequency, satellite communication, the cellular phone network, or a combination of these communication methods.

Wireless sensor network-based buoy systems for environmental monitoring applications have been developed by different researchers. Most of the time these systems use distributed sensing nodes connected through a low-power communication technology. The architecture offers efficient data collection and remote monitoring. However, communication reliability, failure of the nodes, power consumption, network scalability, and maintenance costs pose major challenges in the case of large deployments.

Nowadays marine monitoring platforms integrate IoT technologies to enhance their connectivity and operational efficiency. IoT-enabled buoy systems are capable of real-time data acquisition, cloud integration, remote diagnostics, and intelligent data analytics. Such systems ensure continuous monitoring but at the same time minimize manual efforts. One of the biggest challenges, however, lies in validating the communication reliability of IoT-based marine systems prior to their deployment due to the high cost involved in performing tests offshore.

B. Cellular IoT Communication for Marine Applications

Recent advances in cellular communication technologies have enabled the potential of marine telemetry systems to be further leveraged. Various cellular technologies such as GSM, GPRS, LTE, NB-IoT, and LTE-M have been used to provide connectivity over long distances between the marine devices and the shore-based monitoring centers.

Several advantages such as good coverage, medium to low-cost of deployment, minimum requirement of infrastructure, etc. prompt the use of cellular networks for marine communications. Various studies have also demonstrated the successful application of LTE-based communication systems for the transmission of environmental and navigational data from remote locations.

Even if cellular communication is a solid competitor to satellite communication networks, its performance can degrade as a result of signal fluctuations, network unavailability, and time delays in communication when used offshore. Hence, communication validation using real-life scenarios will continue to be a significant research area.

C. Internet of Things in Ocean Monitoring

The invention of Internet of Things (IoT) has revolutionized the traditional monitoring systems through networked devices that are equipped with sensing, processing, and transmission capabilities. Their use in marine environments is highly beneficial for the continuous tracking of oceanic conditions, identification

and monitoring of changes, and the monitoring of different structures like piers, buoys, etc.

A large number of IoT marine monitoring systems have been created by relying upon embedded platform such as Arduino, Raspberry Pi, ESP8266, and ESP32. ESP32 is heavily favored mainly due to its low power consumption, integrated wireless communication, higher processing capability, and low price.

IoT marine systems are built by coupling sensors, communication modules, cloud platforms, and visualization dashboards which are able to provide full monitoring solutions. While these systems guarantee efficient data management and remote accessibility, many works mostly focus on deployment and implementation while ignoring thorough communication validation through realistic simulation environments.

D. Digital Twin Technology

Digital Twin concept has become a powerful framework both for understanding and influencing the behavior of physical systems through resolutions. A Digital Twin transfers information back and forth between the physical and virtual worlds, thus a continuous reflection of the status and behavior of the physical entity is maintained.

Among them, the concept has been applied to areas like manufacturing systems, industrial automation, transportation networks, aerospace systems, smart cities, healthcare applications, and infrastructure management. They help to reduce developmental expenditures as well as operational hazards at the same time they support activities like predictive analytics, performance evaluation, fault detection, and optimization.

In marine engineering, Digital Twins have been used in monitoring of ship's condition, operation of offshore platforms, maritime logistic management, and oceanographic observation systems. According to the literature, Digital Twin can portray even the most complicated marine scenarios, thus giving users a clear picture of system behavior way before physical deployment.

The use of Digital Twin to validate marine buoy communication systems is still at an embryonic stage even though, from a technological standpoint, it has wide adoption. Existing works are limited to aspects such as visualization and monitoring rather than the end-to-end telemetry communication test.

E. Hardware-in-the-Loop Simulation

Hardware-in-the-Loop (HIL) simulation is probably the most well-known testing technique being used in areas such as embedded systems, automotive engineering, aerospace applications, robotics, and industrial control

systems. HIL simulation is a combination of actual hardware with software-generated environments to produce realistic test conditions.

Usually, virtual models and physical controllers form a complementary pair in HIL simulation. Communication devices can be operated in conjunction with other components of the system also interacting with a simulated environment. One can analyze the system performance in real-life scenarios with the help of this technique without going through the expense of physical deployment.

The usage of HIL methods in the development of marine communication systems, however, remains limited. Most marine monitoring studies that can be found in the literature rely on laboratory tests or on field deployments which do not have the flexibility and scalability of integrated Digital Twin and HIL frameworks.

F. Streamlit-Based Monitoring Dashboards

Visualization of data and remote monitoring form the backbone of the modern IoT systems. Web-based dashboards make it possible for the operators to view the status of the system, to analyze telemetry data, and to react to abnormal situations in real time.

Streamlit, due to its ease of use, extensibility, and rapid deployment capabilities, has become one of the most widely used frameworks for building interactive monitoring dashboards. Real-time data visualization has been one of the areas in which Streamlit has been used by the researchers.

By combining telemetry systems with Streamlit dashboards, monitoring centers can be presented with graphical representations of sensor data, device status, and communication performance. Still, a relatively modest number of researchers have incorporated Streamlit dashboards in marine communication validation frameworks that also involve Digital Twin simulation and embedded hardware interaction.

G. Summary of Literature Review

Substantial development has been indicated by the reviewed works in the areas of marine monitoring devices, IoT-enabled telemetry platforms, Digital Twins, and Hardware-in-the-Loop simulation methods. At separate levels, effectiveness has been demonstrated by different studies of these technologies for various monitoring, communication, and system validation purposes.

A combination of Digital Twin simulation, Hardware-in-the-Loop validation, ESP32-based embedded control, cellular IoT communication, and real-time telemetry visualization for marine buoy applications as a comprehensive framework is near to non-existent in the literature. Most solutions put a lot of weight either on in

silico simulation or on expensive field deployment for validation purposes.

In order to cope with these issues, this paper attempts to offer an integrated Digital Twin based Marine Buoy Communication System, one that beyond Virtual Marine Simulation, Embedded Hardware Validation, Cellular Communication, and Real-Time Monitoring, runs within a Hardware-in-the-Loop framework.

4. RESEARCH GAP AND OBJECTIVES

A. Research Gap

New demand for live marine monitoring has led to a surge in the creation of telemetry systems that use wireless communication technologies, Internet of Things (IoT) platforms, and cloud-based monitoring infrastructures as their base. Embedded systems, sensor networks, and long-range communication technologies have been widely accepted for collecting and transmitting oceanographic data. However, although these systems are quite successful at a large scale in environmental monitoring, there are still some limitations in research and implementation that need to be ironed out.

Majority of the existing marine buoy communication systems depend primarily on direct field deployment and offshore testing for validation purposes. Field testing offers true-to-life conditions but it demands a great deal of financial resources, highly specialized equipment, logistics, maintenance, and risks of operations are quite high. Therefore, carrying out multiple tests, experimenting with changes, and redesigning may not be very feasible in terms of time and expenses, especially at the early stages of system development.

Several studies have employed software-based simulations to evaluate communication architectures and monitoring algorithms. While simulation environments offer cost-effective testing opportunities, they often lack interaction with actual embedded hardware components. Consequently, software-only simulations may fail to accurately represent real-world communication behavior, hardware constraints, processing delays, and interface-related issues that emerge during practical implementation.

Recently, as Digital Twin technology has taken root in the area of physical object modeling and monitoring via virtual representations, its marine engineering applications, according to the current literature, are mainly limited to visualization, predictive maintenance, vessel management, and environmental monitoring. Nevertheless, only a few studies have explored how a Digital Twin framework can be used to validate end-to-end marine telemetry communication systems that

include actual hardware devices and wireless communication modules.

Hardware-in-the-Loop (HIL) simulation also enjoys wide usage in automotive systems, industrial automation, robotics, and aerospace engineering for the purpose of embedded system validation. Despite the fact that it has been proven to be an effective tool, its use in marine buoy communication systems remains scarce. The existing marine monitoring research hardly ever combines the virtual marine environments with physical communication hardware to form a comprehensive testing platform.

Another major issue that current literature has revealed is the absence of integrated frameworks that are capable of simultaneous combinations of:

- Simulation of a marine environment that offer realistic conditions.
- Validation of an embedded controller.
- Testing of cellular IoT communication.
- Processing of telemetry data.
- Visualization of the monitoring dashboard in real-time.

The vast majority of the documented systems only manage the aspects that are directly related to marine monitoring and forget to consider complete end-to-end communication validation under realistic operational conditions.

In addition, with the growing use of IoT technologies for marine applications, there is a need for scalable and cost-effective testing methods that could help in risk mitigation of development prior to deployment offshore. Presently, such approaches are often deficient with regards to mechanisms for evaluating communication reliability, telemetry processing efficiency, and monitoring performance all in one validation environment.

A detailed scrutiny of the literature indicates that a very important research gap exists in the development of a full-fledged Digital Twin enabled Hardware-in-the-Loop marine buoy communication framework that fuses virtual simulation, embedded hardware, cellular communication, and real-time monitoring capabilities into a single platform for validation.

This research intends to develop a Digital Twin based Marine Buoy Communication System. This system will be realized through Unity-based marine simulation, ESP32 embedded processing, cellular IoT communication, Python middleware integration, and Streamlit-based telemetry visualization all within a Hardware-in-the-Loop testing environment.

B. Research Objectives

The main focus of this research project is to create, build, and test a marine buoy communication platform that will be affordable and highly functional while not depending on immediate offshore deployment for telemetry communication testing systems.

Below are the precise aims and objectives of the present study:

- To create an environment which is a Digital Twin capable of simulating a marine buoy's behavior and generating oceanographic telemetry data of a representative nature.
- Developing a Hardware-in-the-Loop structure which allows the simulated marine environments to interact physically with the embedded hardware.
- Designing an ESP32-based telemetry processing unit that receives, processes, and transmits the buoy data generated in the simulation.
- Adding a cellular communication module for the transmission of wireless telemetry between the buoy and shore station systems over long distances.
- Formulating a middleware communication architecture in Python for reliable data exchange between simulation and hardware components.
- Creating a Streamlit-based monitoring dashboard for visualization and analysis of telemetry data in real-time.
- Testing the proposed framework to see whether it is helpful in validating marine communication systems in realistic operational conditions.
- Minimizing the expenses involved in development, the complexity of testing, and deployment risks which are linked to conventional marine communication system validation approaches.

C. Novelty of the Proposed Work

The distinguishing feature of the proposed research is the assimilation of several emerging technologies into a single marine communication validation framework. Instead of depending entirely on software simulation or costly field deployment, the suggested method includes the use of:

- Digital Twin for realistically simulating a marine environment.
- Hardware-in-the-Loop for validating embedded hardware.
- Telemetry processing based on ESP32.
- A cellular communication network for the IoT.
- Python as the middleware for data integration.

- Streamlit as the platform for real-time monitoring and visualization.

Hence, the proposed model is a practical and at the same time a scalable solution to the problem of testing marine telemetry systems that also drastically decreases development cost and risks of operation. In fact, it is the combination of virtual simulation and actual communication hardware that makes performance evaluation much closer to the real world as compared to the traditional simulation-only approaches.

This system would serve as a starting point for enhanced marine monitoring platforms that will incorporate the state-of-the-art sensors, AI algorithms, cloud computing infrastructures, edge intelligence, and satellite communication technologies.

5. PROPOSED SYSTEM ARCHITECTURE AND METHODOLOGY

A. Overview of the Proposed System

The proposed Marine Buoy Communication System is designed as an integrated Digital Twin and Hardware-in-the-Loop (HIL) platform for validating marine telemetry communication systems. The framework combines a virtual marine environment, middleware communication services, embedded hardware, wireless communication infrastructure, and a shore-station monitoring dashboard to establish an end-to-end marine communication architecture.

The primary objective of the proposed system is to simulate real-world buoy operations while incorporating actual communication hardware into the validation process. This enables comprehensive testing of telemetry transmission, communication reliability, data processing, and monitoring functions without requiring immediate offshore deployment.

The overall architecture consists of five major subsystems:

1. Unity Digital Twin Environment
2. Python Middleware Communication Layer
3. ESP32 Embedded Controller
4. Cellular Communication Module
5. Streamlit Shore Monitoring Dashboard

Together, these subsystems create a complete communication chain that closely resembles the operational workflow of a real marine buoy deployment.

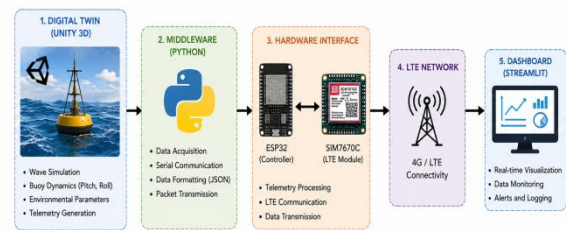


Fig. 1. Overall architecture of the proposed digital twin-based marine buoy communication system.

B. System Architecture

The proposed architecture follows a layered communication model where telemetry information generated by the virtual buoy is processed and transmitted through multiple communication stages before reaching the monitoring station.

The architecture operates according to the following sequence:

Step 1: The Unity Digital Twin simulates marine conditions and generates telemetry parameters.

Step 2: The generated telemetry data are transferred to the Python middleware through serial or socket communication.

Step 3: The middleware formats, validates, and forwards the telemetry packets to the ESP32 controller.

Step 4: The ESP32 processes the received information and prepares communication frames.

Step 5: The cellular communication module transmits telemetry information through the wireless network.

Step 6: The transmitted information is received by the shore station monitoring system.

Step 7: The Streamlit dashboard visualizes telemetry data in real time.

This layered approach ensures modularity, scalability, and ease of future expansion.

C. Unity-Based Digital Twin Environment

The Digital Twin represents a virtual replica of a marine buoy operating within a simulated ocean environment. Unity 3D is utilized for creating realistic marine conditions and generating dynamic telemetry information.

The Digital Twin continuously produces environmental and operational parameters that emulate real-world buoy behavior. These parameters include:

- Wave Height
- Pitch Angle
- Roll Angle
- Temperature
- Humidity

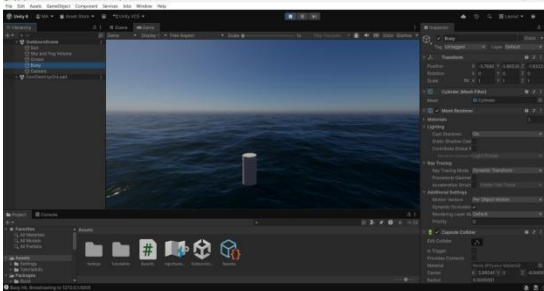
- Latitude
- Longitude
- Buoy Status Information

The virtual environment incorporates animated wave motion and buoy dynamics to simulate realistic ocean conditions. The generated values vary continuously according to predefined simulation models, thereby producing realistic telemetry patterns.

The Digital Twin serves several important functions:

- Simulation of offshore conditions.
- Generation of telemetry information.
- Testing of communication behavior.
- Verification of system performance.
- Reduction of field-testing requirements.

By using a Digital Twin environment, developers can repeatedly evaluate system performance under different operating conditions without incurring deployment costs.



D. Python Middleware Communication Layer

The Python middleware acts as an intermediary communication bridge between the Unity simulation environment and the embedded hardware subsystem. The middleware performs several critical operations including:

- Data acquisition from Unity.
- Telemetry packet formation.
- Data validation.
- Error checking.
- Communication management.
- Data forwarding to hardware.

The middleware continuously listens for telemetry updates generated by the Digital Twin environment. Upon receiving data, the middleware converts the information into a structured format suitable for transmission to the ESP32 controller.

A typical telemetry packet consists of:

Telemetry Packet = {Wave Height, Pitch, Roll, Temperature, Humidity, Latitude, Longitude, Timestamp}

The middleware ensures synchronized communication between software and hardware components while minimizing packet loss and transmission errors.

E. ESP32 Embedded Processing Unit

The ESP32 microcontroller functions as the central processing element within the Hardware-in-the-Loop framework.

The ESP32 was selected because of:

- Low power consumption.
- High processing capability.
- Integrated wireless features.
- Large developer ecosystem.
- Cost-effectiveness.

The controller receives telemetry information from the middleware and performs the following tasks:

- Data parsing.
- Packet verification.
- Communication control.
- Telemetry management.
- Interface handling.

After processing the incoming telemetry data, the ESP32 prepares communication packets for transmission through the cellular communication module.

The ESP32 therefore serves as the hardware representation of an actual marine buoy controller and enables realistic validation of embedded communication processes.

F. Cellular Communication Module

Reliable long-range communication is essential for marine monitoring systems. To address this requirement, the proposed framework utilizes a cellular communication module capable of supporting GSM/LTE communication.

The communication module performs:

- Wireless telemetry transmission.
 - Network connectivity management.
 - Packet forwarding.
 - Communication session maintenance.
- Cellular communication was selected due to:
- Wide-area network availability.
 - Lower cost compared to satellite communication.
 - Ease of deployment.
 - Compatibility with IoT infrastructures.

The module transmits telemetry information generated by the simulated buoy to the shore monitoring station,

thereby replicating actual marine communication operations.

```

Buoy Data ->
{"wave":1.0,"temp":28.6,"hum":84.1,"lat":17.385,"lon":78.4867,Loc:Searching...

Buoy Data ->
{"wave":2.98,"temp":28.5,"hum":84.9,"lat":17.385,"lon":78.4866,Loc:Searching...

Buoy Data ->
{"wave":2.0,"temp":28.3,"hum":84.4,"lat":17.385,"lon":78.4867}

Buoy Data ->
{"wave":2.2,"temp":28.6,"hum":85.2,"lat":17.385,"lon":78.4868}

Buoy Data ->
{"wave":3.0,"temp":28.5,"hum":85.6,"lat":17.385,"lon":78.4867}

Buoy Data ->
{"wave":2.39,"temp":28.5,"hum":85.9,"lat":17.385,"lon":78.4868}
    
```

Unlike conventional software-only simulation approaches, the proposed methodology incorporates actual embedded hardware into the testing environment.

The HIL framework operates according to the following workflow:

1. Virtual buoy generates telemetry data.
2. Middleware receives telemetry parameters.
3. Data are transmitted to ESP32 hardware.
4. ESP32 processes telemetry packets.
5. Cellular module performs wireless transmission.
6. Monitoring dashboard receives updates.
7. Results are visualized and evaluated.

This approach provides realistic testing conditions while eliminating the need for costly marine deployment during early development stages.

G. Streamlit-Based Monitoring Dashboard

The shore station monitoring interface is developed using Streamlit. The dashboard provides a user-friendly platform for visualizing telemetry information in real time.

The dashboard displays:

- Wave height readings.
- Temperature values.
- Humidity measurements.
- Pitch and roll angles.
- Geographic location information.
- Communication status indicators.
- Timestamp information.

The monitoring interface enables operators to continuously observe system behavior and verify communication performance.

Advantages of the Streamlit dashboard include:

- Rapid deployment.
- Interactive visualization.
- Real-time monitoring.
- Easy scalability.
- Platform independence.

The dashboard serves as the final destination of telemetry information within the communication chain.

H. Hardware-in-the-Loop Methodology

Hardware-in-the-Loop simulation forms the foundation of the proposed validation framework.

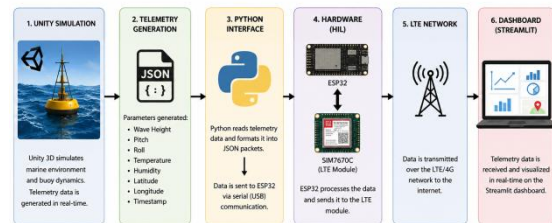


Fig. 2. Hardware-in-the-loop telemetry communication workflow.

I. Advantages of the Proposed Methodology

The proposed architecture offers several advantages over traditional validation approaches:

- Reduced development cost.
- Improved testing flexibility.
- Faster system validation.
- Enhanced communication reliability assessment.
- Safe experimentation environment.
- Scalability for future expansion.
- Integration of real hardware with virtual environments.
- Reduced dependence on offshore testing.

The methodology therefore provides a practical solution for developing and validating marine communication systems before physical deployment.

J. Working Algorithm

The operational algorithm of the proposed system is summarized below:

- Step 1: Initialize Unity Digital Twin environment.
- Step 2: Generate marine telemetry parameters.

Step 3: Transmit telemetry information to Python middleware.

Step 4: Validate and format telemetry packets.

Step 5: Forward telemetry data to ESP32 controller.

Step 6: Process data and prepare communication frames.

Step 7: Transmit packets using cellular communication module.

Step 8: Receive telemetry data at shore station.

Step 9: Display information through Streamlit dashboard.

Step 10: Repeat continuously for real-time monitoring.

The above algorithm ensures continuous telemetry acquisition, processing, transmission, and visualization within the proposed Hardware-in-the-Loop marine communication framework.

6. HARDWARE AND SOFTWARE IMPLEMENTATION

A. Implementation Overview

We built the Marine Buoy Communication System on a Digital Twin simulation and combined it with embedded hardware, cellular communication technology, middleware services, and a web-based monitoring dashboard. The aim of the implementation was to accurately reflect how a marine buoy communication network operates while also being flexible, scalable, and cost-effective.

The entire system has software as well as hardware components connected via a Hardware-in-the-Loop (HIL) architecture. With this setup, it's possible to generate, process, transmit, and display marine telemetry data live.

The major implementation modules include:

- Unity Digital Twin Simulation Environment
- Python Middleware Communication Service
- ESP32 Embedded Controller
- Cellular Communication Module
- Streamlit Monitoring Dashboard
- Telemetry Data Management System

Together, these modules form a complete marine communication validation framework.

B. Hardware Components

The Hardware-in-the-Loop platform integrates real embedded hardware to physically validate communication procedures.

In Table 1 we list the main hardware components used in the system.

Table 1. Hardware Components Used

Component	Function
ESP32	Processing & telemetry
SIM7670C/SIM7000	LTE communication
PC	Simulation & monitoring
USB Interface	Data exchange
Network	Telemetry transfer
Power Supply	Power source

System operation

- ESP32 Development Board

ESP32 is the heart of proposed communication system; it fetches telemetry data from middleware and handles communication activities.

Some of the ESP32 standout features are:

- Dual-core processor
- High processing capability
- Low power consumption
- Integrated Wi-Fi and Bluetooth
- Multiple serial communication interfaces
- Cost-effective implementation

The ESP32 carries out telemetry packet handling, communication control, data validation, and hardware interface management.

- Cellular Communication Module

The SIM7670C/SIM7000 module is in charge of sending the telemetry data through cellular networks.

This module offers:

- LTE connectivity
- GSM support
- Long-range communication
- Low-power operation
- Reliable telemetry transmission

The communication module serves as the wireless bridge between the buoy subsystem and the monitoring station.

C. Software Components

The software infrastructure merges modules for simulation, communication, data processing, and visualization.

- Unity 3D Simulation Platform

Unity 3D platform was used to create the Digital Twin model that simulate the marine buoy and the surrounding ocean conditions.

The simulation environment offers:

- Realistic ocean visualization
- Buoy motion simulation
- Dynamic telemetry generation
- Interactive environment control
- Real-time parameter updates

The Digital Twin is constantly producing environmental data that mimic the real offshore conditions.

- Python Middleware

Python is the middleware that coordinates the operations between the Digital Twin and the embedded hardware.

Its key functions are:

- Data acquisition
- Packet formation
- Communication management
- Serial data transfer
- Error handling
- Data synchronization

Python modules were used to set up a sturdy communication link between Unity and the ESP32 hardware platform.

- Streamlit Dashboard

The monitoring dashboard was created with Streamlit to show the telemetry data in real-time.

It shows:

- Environmental parameters
- Buoy orientation data
- Communication status
- Location information
- Historical telemetry updates

Through this interface, the operator can constantly monitor the performance of the system and confirm the communications are successful.

D. Telemetry Parameters

The system generates and consumes a variety of telemetry parameters which collectively represent the different marine conditions.

Table 2. Telemetry Parameters

Parameter	Function
Wave Height	1-3 meters
Pitch	Longitudinal tilt
Roll	Lateral tilt
Temperature	25-28.5 C
Humidity	83-85%
Latitude	17.3850
Longitude	78.4867
Timestamp	Record time

Such parameters are usually measured by marine monitoring buoys and the current system emulates them.

E. Communication Framework

This communication framework is responsible for facilitating data exchange among simulation software, embedded hardware, and monitoring applications.

The communication workflow is:

- Telemetry parameters are generated in Unity.
- Data is passed to the Python middleware.
- Packet undergoes processing and validation.
- Serial communication with ESP32.
- Cellular communication transmission.
- Reception at monitoring station.
- Visualization through Streamlit dashboard.

This framework supports ceaseless telemetry streams within the system

F. Data Packet Structure

Before being transmitted, telemetry data are encapsulated in communication packets with a certain structure.

An example packet looks like:

Packet = {Timestamp, Wave Height, Pitch, Roll, Temperature, Humidity, Latitude, Longitude}

The standardized packet format makes it easier to maintain the chain of communication, be it for processing, storage or logging.

G. Experimental Setup

The experimental setup was made to check the proper functioning of end-to-end communication under simulated marine environment.

The setup included:

- A personal computer running the Unity Digital Twin.
- Python middleware carrying out telemetry exchange.
- ESP32 development board linked through serial interface.
- Cellular communication module for wireless transmission.
- Streamlit dashboard serving as the shore monitoring station.

While the system was running, the Digital Twin kept generating telemetry data that after being processed were transmitted through the entire communication chain.

Numerous test runs were performed for checking:

- Telemetry generation accuracy.
- Middleware performance.
- Embedded processing functionality.
- Communication reliability.
- Dashboard visualization capability.

The experimental setup was able to emulate the marine buoy communication system workflow.

H. System Integration

The objective of integration was to create a flawless interaction among all software and hardware modules.

The developed architecture depicts:

- Digital Twin integration done successfully.
- Middleware communication reliability.
- ESP32 processing efficiency.
- Cellular transmission stability.
- Real-time visualization on the dashboard.

Integration done well confirms that Hardware-in-the-Loop framework proposed here for marine telemetry is viable.

I. Implementation Advantages

Implemented system has quite a few very practical merits:

- Development environment at low cost.
- Less offshore testing needed.
- Highly realistic communication validation.
- System scalability and expansion can be done easily.
- Rapid prototyping of systems.
- Future sensor integration is supported.
- Works well with advanced analytics platforms.

The implementation proves that Digital Twin, embedded hardware, and IoT communication systems can be merged to form an effective marine monitoring framework.

7. RESULTS AND DISCUSSION

A. Overview

The Marine Buoy Communication System that we have developed was tested to assess whether the Digital Twin-based Hardware-in-the-Loop framework could be realistically implemented. The experimental objectives were focused on telemetry generation, communication reliability, embedded hardware operation, data transmission and real-time visualization.

The tests combined a Unity-based marine simulation environment, a Python middleware communication layer, an ESP32 embedded controller, a cellular communication module, and a Streamlit monitoring dashboard. The main purpose was to check the entire telemetry communication process from start to finish and to prove that marine communication systems can be tested feasibly without an offshore deployment.

The experimental findings demonstrate that all hardware and software components have been successfully integrated into the proposed architecture.

B. Digital Twin Telemetry Generation

The Digital Twin setup in Unity was capable of generating real-time telemetry data that reflected the buoy behavior realistically over time.

As a result, the system was able to produce:

- Wave Height
- Pitch Angle
- Roll Angle
- Temperature
- Humidity
- Latitude
- Longitude
- Timestamp Information

The underwater buoy generated was shown to have waves in motion and the telemetry data continuously changing during the execution so that the marine environment appeared to be realistic.

The Digital Twin software has also been a stable and repeatable source for telemetry data during the Hardware-in-the-Loop experiments.

Observations:

- There was continuous data production.
- Changes in the parameters were according to the realistic behavior of a buoy.

- The simulation was performed efficiently without any "pause".
- Updates in the telemetry were ready for use immediately.

So, the above observations show that the Digital Twin method was appropriate for marine communication testing purposes.

C. Middleware Communication Performance

Between the Digital Twin software and the ESP32 embedded board, the Python middleware has established communication successfully.

The middleware functionalities included the following:

- Acquiring telemetry
- Preparing data packets
- Checking data quality
- Managing communication
- Forwarding data

At the same time, telemetry information was passing from Unity to hardware.

Observations:

- Reliable packet transfer was achieved.
- Data synchronization remained stable.
- No significant packet corruption was observed.
- Continuous communication was maintained.

Thus, the middleware acted perfectly as a link for the virtual and the real parts of Hardware-in-the-Loop Framework.

D. ESP32 Processing Performance

The ESP32 board received the telemetry packages from the middleware and carried out the instructions in the communication process.

Functions performed by the ESP32 include:

- Receipt of packets
- Extraction of data
- Comparison of parameters
- Decommunication
- Forwarding of data

Tests showed that ESP32 could follow the constant telemetry flow from Digital Twin perfectly.

Observations:

There was a stable performance throughout the experiment.

- Packets were correctly interpreted.
- Communication reliability was ensured.

- Incoming telemetry data were continuously processed.

ESP32 proved to be a very suitable low-cost embedded microcontroller for marine telemetry purposes.

E. Cellular Communication Validation

The system aimed at verifying a telemetry communication via a cellular network infrastructure as a major objective. The communication module transmitted telemetry that originated in the Digital Twin, was handled by ESP32 controller, and then successfully relayed telemetered signal over the network.

The communication system showed:

- Successful wireless data transmission.
- Stable network connectivity.
- Reliable telemetry delivery.
- Continuous communication operation.

So, the obtained results show that communications through cellular IoT technologies are quite suitable for marine telemetry in the environment with network coverage.

Observations:

- Communication sessions did not fail.
- Telemetry signals were successfully sent and received.
- The whole communication chain remained intact.
- The performance of the wireless transmission was up to the standards.

Uses of cellular communication modules in marine monitoring systems are proven by this set of data.

F. Streamlit Dashboard Visualization

The Streamlit interface could correctly display the telemetry data derived from the framework we set up.

The user interface showed the following parameters directly on the screen:

- Wave height
- Temperature
- Humidity
- Pitch angle
- Roll angle
- Latitude and longitude
- Timestamp information

Timely updates of the dashboard were ensured by the real-time data stream.

Observations:

- It was indeed possible to visualize data instantaneously.

- The way data were presented was very pleasing to the user.
 - There was no visible break in the telemetry update.
 - Operation of the monitoring function was very good.
- The program was able to create a beach station monitoring operation simulation effectively.

G. Hardware-in-the-Loop Validation Results

The Hardware-in-the-Loop framework brought about the effective mixture of the virtual marine world and real physical embedded hardware.

The research model highlighted the undisturbed communication between various components like:

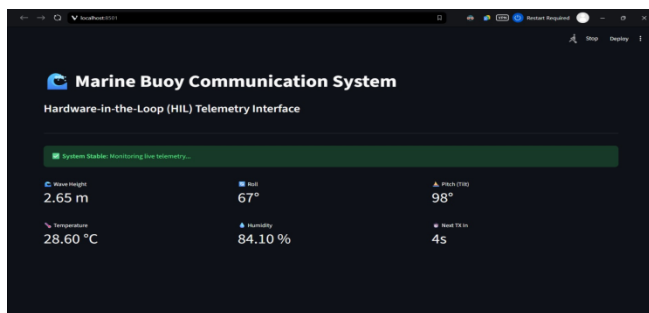
- Unity Digital Twin
- Python Middleware
- ESP32 Controller
- Cellular Communication Module
- Streamlit Dashboard

On the other hand, successful joining together of these elements communicates the capacity of the proposed architecture in representing real marine communication workflows within controlled test environments.

Major benefits of the HIL framework are:

- Genuine communication validation.
- Testing of embedded hardware.
- Regular telemetry transmission.
- Simplification of test procedures.
- Removal of offshore deployment requirement.

This confirms that Hardware-in-the-Loop simulation is a good alternative to quite expensive field-based testing methods.



H. Comparative Analysis

We compared with traditional testing methods, the new approach that has been proposed here shows a great many advantages.

Table 3. Comparison with Traditional Marine Testing Approaches

Parameter	Conventional	Proposed
Offshore Deployment	Required	Not Required
Cost	High	Low
Flexibility	Limited	High
Repeatability	Moderate	Excellent
Testing Risk	High	Low
Hardware Validation	Limited	Supported
Monitoring	Available	Available
Simulation	Limited	Advanced

As one can see from the table, the proposed approach features a whole raft of benefits especially during the development and validation stages of marine communication systems.

I. DISCUSSION

Clearly, the experimental data strongly favor the integration of Digital Twin technology with the Hardware-in-the-Loop simulation for purposes of marine telemetry verification.

The main advantages of the Digital Twin Marine Environment are generating realistic marine telemetry data and avoiding physical ocean deployment. The middleware layer took care of error-free communication between software and hardware. The ESP32 controller was capable of telemetry functions and after that, the cellular communication module extended the telemetry data transmission range wirelessly. At last, the Streamlit dashboard made monitoring so much more pleasant and easier.

Noticing that these separate elements joined together in a novel architecture is what sets apart the proposed framework from the current marine monitoring research, which mostly relies on simulation, embedded hardware, and wireless communication, without any integrated visualization.

Also, the modular structure of the proposed system is possible to be extended by:

- Deployment of physical oceanographic sensors together with
- Cloud-based data storage to which the sensor data will be uploaded
- Implementation of AI based algorithms for recognizable pattern detection and other functionalities.
- Incorporation of satellite communication networks.
- Installation of predictive maintenance systems.

- Further development of advanced marine analytics platforms.

The results from this research indicate the utility of the interface for marine monitoring system development and testing, as well as for validation purposes.

J. Summary of Results

In short, the experimental results support the proposed Marine Buoy Communication System as an operational system.

The first-hand achievements of the system are listed below:

- Marine condition simulation with Digital Twin.
- Telemetry generation and transmission with undoubted reliability.
- Stable communication through middleware.
- ESP32-based processing carried out effectively.
- Cellular communication was fully verified.
- Telemetry visualization in real time.
- Integration of Hardware-in-the-Loop system was successful.
- Economical testing technique.

All the above points basically confirm the proposed framework's efficiency and practicality for marine communication system development and testing.

8. CONCLUSIONS AND FUTURE SCOPE

A. CONCLUSION

Marine monitoring systems are crucial for conducting oceanological studies, performing environmental monitoring, ensuring safety in maritime transportation, disaster management, and supporting offshore industrial activities. However, the design of reliable and cost-effective communication systems for the marine environment remains a complex problem despite various technological developments. The major challenges are linked to offshore installation, adverse environmental conditions, and the demand for communication reliability.

The primary output of the project is the first-ever Marine Buoy Communication System based on Digital Twin, which has been developed through Hardware-in-the-Loop (HIL) framework to validate marine telemetry communication architectures.

This paper addresses the integration of different components of the system into a single testing platform: a Unity-based Digital Twin environment, Python middleware communication services, an ESP32 embedded controller, a cellular communication module, and a Streamlit-based shore monitoring dashboard.

The Digital Twin environment realistically recreates marine environmental conditions and continuously generates marine telemetry parameters such as wave height, pitch, roll, temperature, humidity, latitude, and longitude. These telemetry data were transmitted via the middleware layer to the ESP32 embedded controller where they were analyzed and communication procedures were scheduled. The cellular module was tasked with wireless transmission over long distances, and Streamlit was the real-time communication monitoring and control dashboard.

The components in the communication system conducted end-to-end communication without experiencing any problems as per the experimental study. Telemetry generation was dependable, middleware operations were efficient, embedded processing was robust, wireless communication was effective, and dashboard visualization was executed correctly. And the HIL architecture enabled realistic testing of the communication chain without actually having to go offshore.

This framework reduces (1) the development cost (2) the complexity of testing, (3) the risks of deployment, and (4) the dependence on field trials. Besides, the modular design makes it easy to customize and scale up for other marine monitoring applications.

This combination of Digital Twin and HIL simulation can be an excellent method of accelerating the design, testing, and validation of marine communication systems. The platform described here provides a solid foundation for marine telemetry and smart ocean monitoring technologies R&D.

B. FUTURE SCOPE

While the proposed system allows for running marine communication scenarios within a controlled laboratory environment, there is still a lot of work that can be done to go beyond simulation and make use of the real physical environment.

In the next development phase, considerations can be given to integration of physical oceanographic sensing instruments such as: water temperature sensors, salinity sensors, dissolved oxygen sensors, pressure sensors, wind speed sensors, water quality monitoring sensors.

Implementing these instruments would transform the work from virtual telemetry generation to the use of traditional sensing equipment for collecting environmental data from a marine environment.

Cloud Computing: Future system configurations could encompass cloud computing capabilities for large scale data storage, remote access, and higher level analytics. Cloud platforms will facilitate handling data over extended

time periods and will support collaborative marine research.

Artificial Intelligence/Machine Learning could be leveraged to:

- Dissect ocean condition prediction models
- Perform anomaly detection
- Monitor equipment health
- Support decision making systems
- Offer predictive maintenance strategies.

Such highly intelligent features, if integrated, would greatly enhance the operational capabilities of marine monitoring systems.

Satellite communication is another avenue that can be explored after this work. Even though cellular communication is still the most cost-effective method near the shore and coast areas, satellite communication is one that can take the system to locations offshore beyond any terrestrial network coverage.

Moreover, the proposed concept can be widened to include the following:

- Unmanned marine vessels
- Sophisticated navigational systems
- Offshore energy monitoring
- Maritime security
- Environmental protection
- Coastal disaster early warning

One of the next changes may be the comprehensive designing and testing of multi-buoy communication networks to support distributed ocean observation systems. Such networks will likely facilitate large-scale marine data collection and provide enhanced situational awareness over vast ocean regions.

Edge computing one of the most recent technological advancements is also an option for future research. Edge intelligence is capable of reducing communication latency, limiting bandwidth requirement, and facilitating instant decision-making right at the buoy.

To summarize, this paper puts forward a Digital Twin based Hardware-in-the-Loop concept which might lead to future developments in marine communication, ocean observation, and intelligent maritime monitoring systems. The design presented here can serve as a good foundation for scalable next-generation smart marine infrastructure as well as advanced ocean monitoring applications.

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