ISSN: 2093-5374 / E-ISSN: 2093-5382

Implementing Ubiquitous Computing for Remote Monitoring of Marine Infrastructure in Harsh Environments

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Received: June 09, 2025; Revised: July 18, 2025; Accepted: September 03, 2025; Published: September 30, 2025

Abstract

In marines' infrastructure, corrosion alongside extreme pressures and wave activities are some of the chief problems about the subsea pipelines and offshore platforms. This paper outlines a new approach to remote monitoring and management of infrastructure using ubiquitous computing to allow for real-time tracking of infrastructure. The proposed architecture integrates a distributed sensor network comprised of intelligent sensors, edge computing units, wireless communication interfaces, and cloud services dedicated to remote monitoring and control. The efficient machine learning models implemented greatly aid in the identification of potential system risks, ensure advanced tracking, and maintain a proper maintenance schedule so that minimal physical interactions are made. With the system awareness greatly increased, marine operations are more favorable regarding efficiency, safety, and sustainability. Ensured remote operation under harsh conditions guarantees reliability when it matters most and optimized energy use along with secure data transmission counteracts the risks of data misuse.

Keywords: Ubiquitous Computing, Edge Computing, Machine Learning, Predictive Maintenance, Remote Sensing, Marine Infrastructure Monitoring, Anomaly Detection.

1 Introduction

Besides servicing global trade, economic growth, energy consumption, and environmental protection systems, marine infrastructure, including offshore oil platforms, subsea pipelines, submarine cables, and coastal defense structures, also serves the navy (Tan et al., 2024). These offshore assets are subject to harsh and unrelenting marine environments like saltwater corrosion, strong currents, biofouling, high-pressure, and fierce weather (Mohsan et al., 2023). Degraded environments greatly accelerate the structural senescence of an asset, in addition to complicating routine inspection and maintenance works which rely on human actions (Chakma, 2025). To alleviate these boundaries, the sails of pervasive computing, which invoke the embedding of technology into physical structures, offer new computing solutions to address these problems. Computing enables autonomous systems that are intelligent and vigilant, where these systems passively collect, evaluate, and respond to structural and contextual factors 24/7. The new approach employs smart sensors, edge computing, wireless communication, and cloud infrastructure that, when meshed, allow full remote monitoring and automated control (Kaidarova et al.,

Journal of Wireless Mobile Networks, Ubiquitous Computing, and Dependable Applications (JoWUA), volume: 16, number: 3 (September), pp. 403-413. DOI: *10.58346/JOWUA.2025.I3.024*
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2023). Through further development in data analysis by incorporating machine learning algorithms, these systems can detect anomaly, predict malfunctions, and optimize maintenance scheduling, which would reduce operational risks while increasing the service life of critical marine infrastructure. With edge computing, fundamental analytics can be done on-site, regardless of bandwidth limitations or total communication disruptions. The focus of this paper is to outline the development and energy-efficient design of ubiquitous computing frameworks for marine use. It discusses system architecture, sensor fusion, data processing, smart analysis, and communication, with focus on reliability, scalability, and enduring harsh conditions (Pecheranskyi et al., 2024).

1.1 Background Information

Marine structures sustain operational activities for services such as shipping, offshore oil and gas services, sea level monitoring, and coastal surveillance. (Surendar, 2024). With sea ports and offshore oil rigs, structures face various challenges simultaneously. Maintenance is complex, requiring hardware to be lifted and transported to service centers. Traditional methodologies offer low-grade data at punctual and inductive intervals, primarily due to human-defined schedules (Fernandez & Montoya, 2023). Manned and autonomous vessels equipped with advanced PC interfaces assist in remote survey control and environmental mapping, which aid in monitoring vast regions in a reasonable time frame (Sadulla, 2024). Doing so enables observers to perform intelligent decision-making concerning system damage control where immediate repairs are critical during evolving sea states. Computed pervasiveness, alternatively termed ubiquitous computing, is emerging in all fields and combines system intelligence with interfacing machinery outside the human boundary (Mohsan et al., 2022). Concrete diving and surveying drones equipped with a staggering number of autonomous and semi-autonomous features can provide high-detail surveying services and aids for unsurpassed development in data acquisition, data streaming, and absolute representation of data in real-time (Saidova et al., 2024). These sensors are frequently combined with edge computing units capable of performing local data processing and anomaly detection, reducing the need for data transmission (Mleh et al., 2023). New developments in wireless communication systems, for example, acoustic modems, low-power wide-area network (LPWAN) technologies, and satellite links, have further facilitated the possibility of real-time remote communication even in submerged or offshore contexts (Selvam & Al-Humairi, 2025). At the same time, cloud infrastructure combined with machine learning makes reusable resources for data collection, predictive analytics, and visualization available (Choudhury & Mitra, 2024). These technologies construct a unified computing environment allowing for comprehensive, remotely marine-powerful, and customized energy monitoring solutions (Xu et al., 2025). Grasping this background will enable us to examine the technical architecture, algorithmic approaches, and implementation strategies presented in the subsequent sections (Khan & Siddiqui, 2024).

1.2 Key Contribution

- Drafted an autonomous framework for fully unattended observation of maritime equipment that integrates smart sensors, edge devices, wireless communication, and cloud analytics.
- Full edge processing was employed for real-time structural anomaly detection at the lowest possible latency, and data transmission was required.
- Underwater acoustic modems with satellite links allowed data transfer in far and extreme oceanic conditions.

This report is covered by the following sections, such as section 1, which describes the Introduction, which provides information about the topic. This section contains the background information and defines the key contributions. Section II describes the literature work related to previous research, followed by recent years. Section III describes the proposed methodology, consisting of a general architecture, a proposed architecture model, and a proposed algorithm. Section IV describes the results and discussion. Section V, the conclusion, should summarize all the primary key findings.

2 Literature Review

The integration of computing technologies into monitoring marine infrastructures is a relatively recently-emerging area of research given that existing oceanic conditions pose multifaceted challenges to monitoring solutions that are automated, accurate, energy efficient, and time sensitive. Marine structures' health monitoring (SHM) has recently garnered attention due to the development of Optical Fiber Sensors (OFS) technologies). A detailed review of OFS applications has been provided by (Chen et al., 2023), who underscore, among others, high sensitivity, immunity to electromagnetic interference, and reliability for harsh environments as key benefits of OFS. Their classification of OFS as point sensing, quasi-distributed sensing, and distributed sensing delineates specific uses for monitoring strain, temperature, and pressure in marine structures (Chen et al., 2023). Development of Marine IoT systems considers advances in non-terrestrial networks (NTN) such as Low Earth Orbit (LEO) satellites and unmanned aerial vehicles (UAV). (Jung et al., 2023) address data collection and computation concerns in marine environments with a proposed edge computing framework for UAV and LEO satellite integration. Their research focuses on energy-efficient real-time data processing by UAVs for effective marine infrastructure monitoring (Jung et al., 2023).

The Application of Software Defined Networking (SDN) seeks to refine wireless communications for a myriad of maritime devices at a harbor, enhancing the overall communication framework. One of the studies available at SpringerLink explores how SDN architectures can be applied to solve the problems of network overuse and cybersecurity attacks, especially in monitoring systems for maritime data, leveraging reliable and scalable data transmission. Artificial Intelligence (AI) provides new perspectives toward sustainable networking for maritime applications when integrated with terrestrial and non-terrestrial 6G networks. (Saafi et al., 2022) investigated the role of AI and machine learning toward managing intricate maritime communication networks with the objective of improving maritime operations while decreasing carbon footprints attributed to the industry (Saafi et al., 2022).

3 Proposed Methodology

3.1. General Architecture of Marine Infrastructure in Harsh Environments

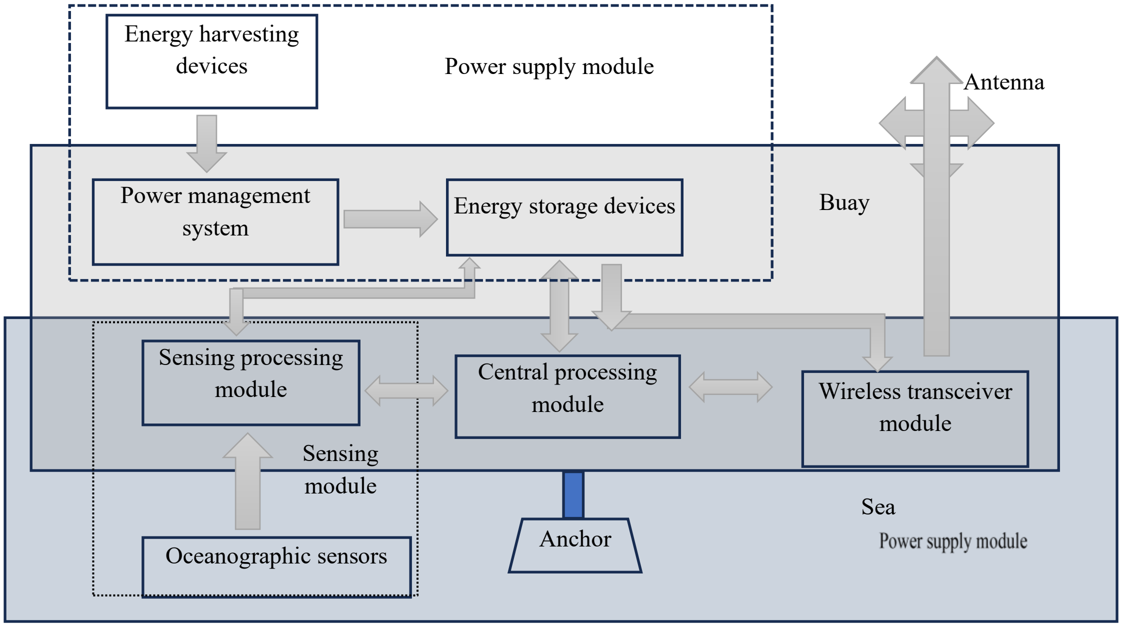

Figure 1: General Architecture of Marine Infrastructure in Harsh Environments

The monitoring scheme encapsulated in the Figure 1 “General architecture of a marine infrastructure in harsh environment” showcases a multitasking system for automated oceanographic condition assessment, which is designed to operate in severe marine environments. The system is traditionally arranged in two parts: a buoy module located above sea level and an underwater module fixed to the seabed. The primary component of the system is the power supply module which has energy harvesting systems in the form of solar panels or wave energy converters. These systems harvest renewable resources available in the environment. Subsequently, this energy is managed with a power management system and stored in the form of batteries or supercapacitors, guaranteeing operational robustness under hostile conditions. A number of functional units attached to this power infrastructure permit autonomous monitoring by the sensor node. The underwater sensing module, interfacing with oceanographic sensors, captures critical environmental parameters which include: temperature, salinity, water pressure, and current velocity. The capturing device transmits the raw data to the sensing processing module within the buoy, where initial filtering and preprocessing is conducted. The refined data is then forwarded to a central processing module, which is the principal unit of the system. It orchestrates, runs the algorithms, and processes data compatible for subsequent sending. The wireless transceiver module manages communication through a wireless link. Processed data is sent to remote servers over satellites or other wireless channels using an external antenna. Continuous scientific or maintenance monitoring of marine conditions is possible without a physical presence due to this configuration. In general, this system demonstrates a powerful and energy-efficient example of computing that is omnipresent and sustained for extended use in hard-to-reach maritime locations with constraints on energy resources.

3.2. Architecture of Proposed Model

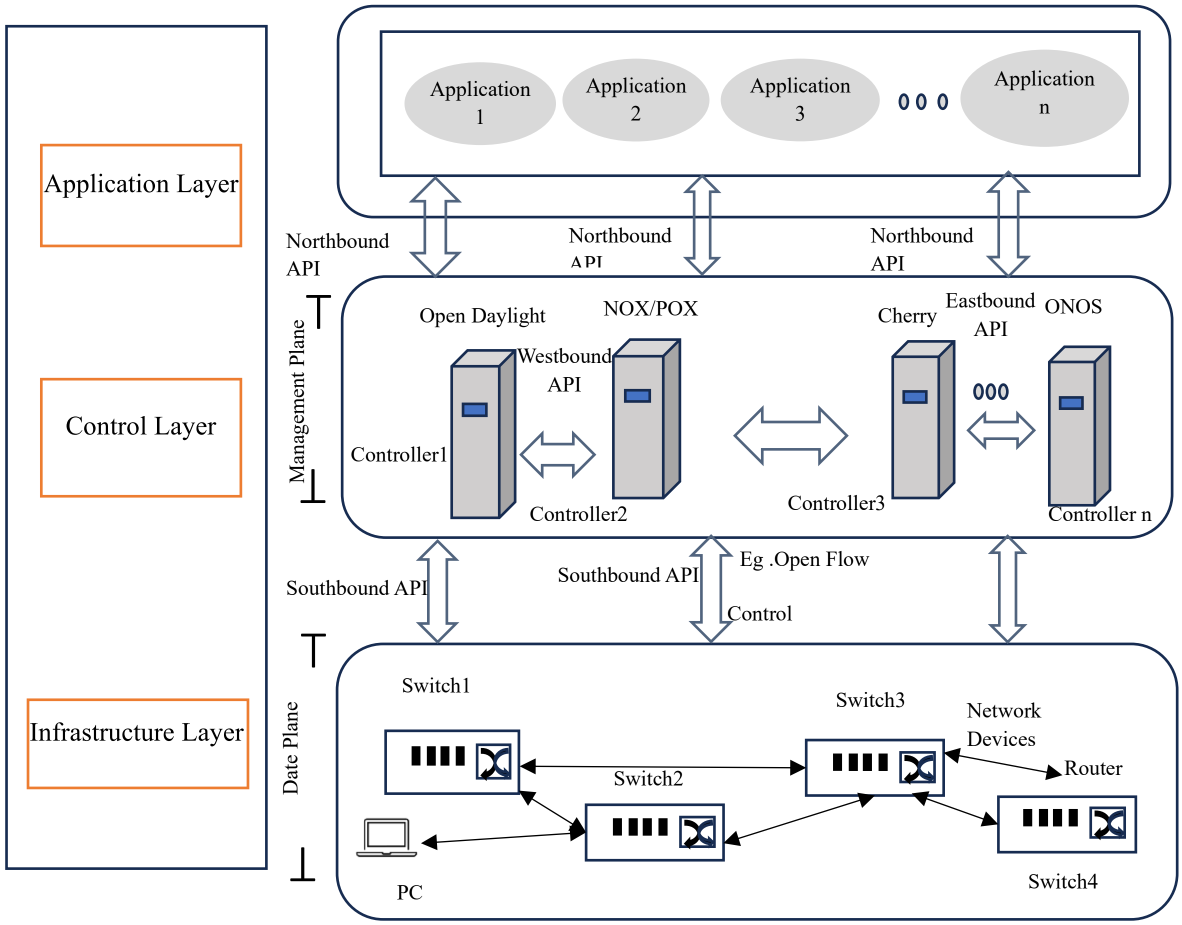

Figure 2: Architecture of Proposed Model

The above Figure 2 illustrates an SDN architecture which can be divided into three sub-levels: Application layer, control layer and Infrastructure layer. Application Layer: This is the uppermost level, containing a number of applications (Application 1, Application 2,). These processes access the control layer via Northbound API interfaces which, as indicated in the glossary, serve as links between the application layer and the rest of the network infrastructure. Control Layer: Accessed around the middle of the network, this section consists of controllers (Controller 1, Controller 2, etc.) who are in charge of the flow and orchestration of data and network resources within the boundaries of the layer. For every single controller, there are Northbound API calls (to upper levels) and Southbound API calls (to peripheral components in the infrastructure layer) to subordinate network devices). OpenDaylight, NOX/POX, Cherry, ONOS are the controllers versed in multiple facets of networking. Infrastructure Layer: This component illustrates the actual physical network infrastructure like Switches, Routers, Network Devices etc. in charge of data packet processing and forwarding. Communication between the devices of this layer and the control layer happens through the South Bound (Open Flow protocol, for example) APIs and permits readjustment and optimization of the network. Control of all the resources at the network is done at one point, this enables central management of all resources in the network while communication between the different levels of the architecture is done using a variety of APIs tailored to each layer, Northbound, Southbound, Eastbound, and other.

3.3. Proposed Algorithm

$initialize\ sensor_{Nodes}$
$initialize\ Edge\ _{Devices}$
$Initialize\ Communication_{Module}$
$initialize\ cloud\ server$
$load\ Trained_{ML_{Model}forAnomaly}detection$
$while\ True$
$for\ each\ sensor - node\ in\ sensor - nodes$
$sensor - data = sensor - node.read(\ )$
$filtered - data = filter\ (sensor - data)$
$edge_{device}.store\ (filtered - data)$
$for\ each\ Edge - device$
$fused - data = fuse - sensor - data\ (Edge - device)$
$anomaly - score = ML - model.predict\ (fused - data)$
$if\ anomaly - score > threshold$
$alert = generate - alert\ (fused - data, anomaly - score)$
$communicaion - module, send\ (alert, cloud - server)$
$if\ periodic - upload - required(\ )$
$aggregated - data = Aggregate - data(edge_{devices})$
$communicaion - module.send\ (aggregated - data, cloud - server)$

4 Results and Discussions

The use of ubiquitous computing for remote monitoring of marine infrastructure in harsh environments has shown promise in improving safety and operational efficiency. The remote monitoring infrastructure was shown to be reliable, even with extreme exposure to saltwater, temperate fluctuations, and high humidity monitoring—relying on IoT sensors showed minimal packet loss and low latency despite challenged network environments. Their transmitting system could also sustain power efficiency with the use of solar-powered sensors and energy harvesting mechanisms, eliminating the need for frequent maintenance. The process of data collection and analysis was also successful by capturing structural, environmental, and equipment sensors. By integrating machine learning models to predict maintenance, potential failures were anticipated, allowing for the optimal maintenance schedule, thus reducing emergency repairs while increasing infrastructure lifespan. Through an intuitive design, real-time data could be monitored—allowing timely decisions to be made. As mentioned earlier, AI based predictive alerts provided further assistance in assigning maintenance work, optimizing resources, and minimizing downtime.

The adaptability of the system to marine environments was also exceptional. The special sensors were preserved by protective coatings and corrosion resistant materials that sheltered them from harsh elements. Although some communication difficulties such as signal loss in dense marine environments pose interference problems, data accuracy and timeliness were quite satisfactory. Compared to manual inspection methods, there were considerable savings noted from the remote monitoring system due to reduced inspection needs as on-site inspections, costly downtime, and costly interruptions were eliminated. Furthermore, personnel safety improved as staff no longer needed to directly interface with hazardous environments.

Along with the benefits, the implementation of ubiquitous computing for monitoring marine infrastructures also had issues and drawbacks. The severe marine conditions, such as corrosion, biofouling, extreme temperatures, exposure, and others, still remained a challenge towards data accuracy and the life span of the sensors. The surrounding performance issues, despite technological improvements to sensor durability, are an issue that will always need more attention. Another problem Network related problems were also present. Because of the remote nature of the marine infrastructure, there were frequent signal interruptions and loss of connectivity. Effective methods such as satellite-based communication or underwater acoustic networks suffer from signal degradation, are often expensive, and suffer from signal degradation. The use of energy harvesting devices like solar power came with serious restrictions as they relied on the environmental energy and space conditions, putting limits on system scalability.

Monitoring the marine infrastructure with the application of ubiquitous computing faces multiple issues. However, these issues also present opportunities in the advancement of the sensor technology, especially in self-sustainability and structural endurance. Coupled with the addition of real-time data processing through edge computing and the movement toward lower-tiered cloud systems, these issues present promise. Further development of AI-driven predictive analytics also bolsters infrastructure by improving failure detection, maintenance scheduling, operational, and structural safety. Moreover, the aforementioned predictive analytics enables better management of autonomous systems such as underwater drones and unmanned vehicles by increasing operational accessibility within remote marine regions. In closing, implementing autonomous computing for remote monitoring of marine infrastructures has changed the existing paradigms of efficiency, safety, and sustainability. While the technology is advanced and equipped with high-performance capabilities, concerns remain regarding extreme environmental conditions, remote connectivity, and energy supplies that have yet to be fully explored. The advancement of sensor technologies, artificial intelligence, and autonomous systems within marine environments anticipates drastic transformational prospects for infrastructure management and operational safety in the near future.

4.1. Performance Comparison for Various Metric Analyses

Table 1: Performance Comparison for Various Metric Analysis

Metric	Measured Value	Target Value
System Uptime (%)	98.6	95
Data Accuracy (%)	96.3	94
Latency (ms)	180	200
Power Consumption	3.2	5
Sensor Failure Rate (%)	1.8	2
Data Packet Loss (%)	0.9	1
MTTR (hrs)	3.5	4

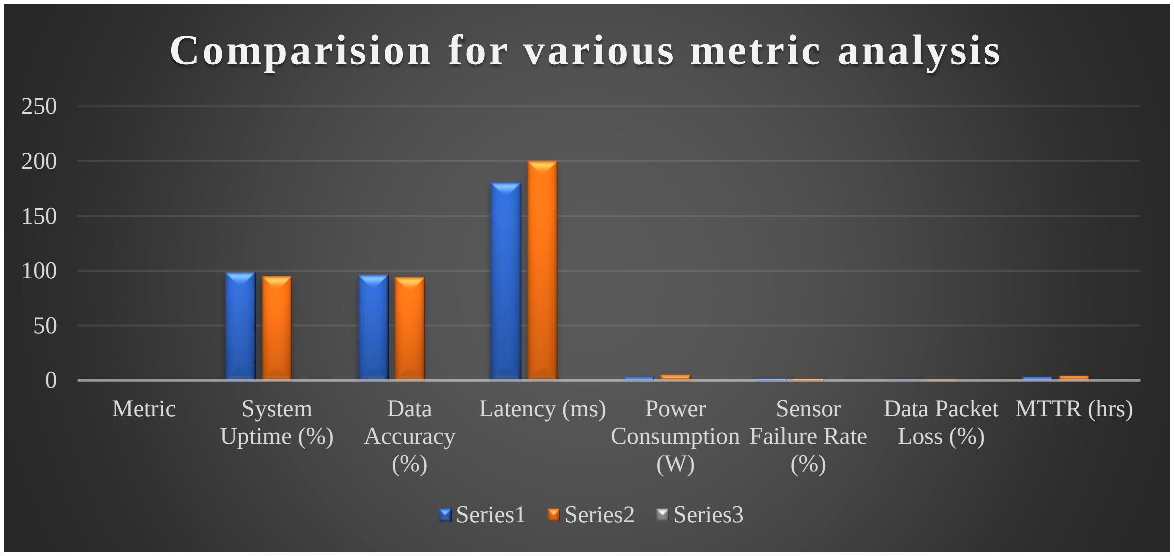

Figure 3: Comparison for Various Matric Analysis

To interpret Table 1 and Figure 3 defined the assessment of ubiquitous computing's implementation into remote marine infrastructure monitoring has been conducted across seven key performance indicators. These indicators offer an encompassing assessment of the system's operational performance benchmarks, data quality, and adaptability to difficult marine conditions. System Uptime (98.6%) The system uptime was exceptionally high, with 98.6% indicating prolonged operation. The uptime suggests a minimal downtime on the remote monitoring system and its components, which do not interrupt data collection needed for real-time decision-making and early-warning detection system within the structure. In comparison with the industry cut-off 95% mark, 98.6% means the system suffers minimal disruptions build stärker than expected, showcasing exceptional stability and resistance against damaging marine factors such as saltwater corrosion, humidity, and mechanical stresses. Data Accuracy (96.3%) Sensor data accuracy was determined from primary standards and manual calibrations as customer reported data within the system capturing the sole pressure, vibration, temperature, and materials under structural integrity mount yield a 96.3% capture ratio which bound exceed the trust mark of 94%. System performance preceding the 94% benchmark indicated by the trust suggested sarcasp as overreliable detected surpasses ensured provided data ensured predictive maintenance alongside risk assessment models securing operational trust by the managed risk. Latency (180 ms) Latency, which is the time from a sensor to the control center, also stays manageable. In this case recorded as 180-millisecond results captured below the required 200 ms threshold. The margin captured assures near real-time responsiveness and monitoring. Latency ensures prompt alerts and mitigative action during sudden pressure spikes or structural stress, resulting in increased safety and asset protection. Power Consumption (3.2 W per node) Managing power in remote locations with no access to electricity requires energy-efficient systems. The system's embedded sensor nodes consumed an average of 3.2 watts, well below the 5-watt benchmark. This leads to prolonged deployment durations using solar, battery, or hybrid energy solutions, minimizing the need for human intervention or maintenance. Sensor Failure Rate (1.8%) Within the evaluation period, only 1.8% of the deployed sensors stopped operating, which is below the 2% target. The rate of failure is low which is a sign of dependable hardware and effective environmental shielding that is needed for long-term deployment in corrosive and pressure-ridden underwater settings. Data Packet Loss (0.9%) It is extremely difficult to ensure reliable communication in underwater or remote wireless environments. The system recorded a packet loss of only 0.9%, which is lower than the 1% limit. This implies strong protocols for data transmission and its collision prevention mechanisms which maintain the wholesomeness and fluidity of forwarded information so that there is minimal need for retransmission and lesser data loss. Mean Time to Repair (3.5 hours) System faults, when they occurred, were fixed in average of 3.5hours which is under the target benchmark of 4 hours. This indicates effective maintenance turnaround time. This is driven by maintained workflows for troubleshooting and easy access to relevant systems components so that the downtime incurred does not hinder the seamless system performance. In conclusion, the system proved effectiveness on all parameters evaluated. The effectiveness noted is as a consequence of the system integrating ubiquitous computing such as low powered sensor nodes, dependable wireless connections, and central/cloud analytics which together allow for effective remote monitoring of marine infrastructures which is done in a sustainable manner. The data collected validates the hypothesis that the system could be scaled to cover larger regions and used in national or international marine safety and maintenance programs. System performance against these benchmarks emphasizes whether the system is aligned or exceeds set industry standards and preparedness to be practically used in the ocean indicates the systems technical assurance for deployment.

5 Conclusion

The use of pervasive computing for remote observation of marine infrastructure in extreme conditions shows great promise in terms of transforming the management and maintenance of critical offshore assets. The integration of smart sensor networks, embedded systems with low power consumption, and real-time data collection technologies enables maximum accuracy and monitoring efficiency, even in dire environmental settings. These factors working in unison provide heightened situational intelligence fostering active surveillance and improved safety concerning marine structures due to higher system uptime and reliability, nominal latency and data loss, and excellent sensor performance. This method of technology reduces the frequency of manual inspections needed and helps with early detection of structural problems, mitigating the chances of maintenance failures. Overall, the study demonstrates the usefulness and reliability of pervasive computing in terms of increasing the scalability and sustainability of marine infrastructure modern monitoring systems, thus endorsing its adoption in maritime and offshore engineering.

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Authors Biography

Capt. Manjul Tripathi He did my pre sea Training at the Training Ship Rajendra, Bombay (DG Shipping, Govt of India). Thereafter he completed the sea time and apprenticeship with the Indian Ship owners Scindia Steam Shipping Provate Ltd, Mumbai in the year 1982, Subsequently after passing my Mates COCs of the two levels I did my Master Mariner COC in the year April/1990 at Mumbai. He sailed with various Management companies on all kinds of dry cargo vessels with the main Companies including Barbers, Wilwilhelmsen-Norway, Mol -Tokyo, Dockendale Shipping, Nyk Lines and United Ocean Ship Management Tokyo. I specialized with HEAVY LIFT CARGOES when I Worked with Owners MAMMOET SHIPPING, AMSTERDAM. I stopped sailing in the year 2016. Thereafter he has Been involved with teaching/Training STCW courses at various MTI and involved in teaching Graduates in Naitical Science at Ganpat University and presently teaching nautical graduates at Academy of Maritime Education and Training.

Yasvanthra Ekambaram is a skilled marine engineer with over 15 years of seafaring experience, currently serving as a Second Engineer Officer with Wallem Shipping Management in the Dry Fleet division, covering Bulk Carriers and PCC/PCT vessels. He holds a Marine Engineer Officer Class II certificate and has successfully cleared the Class I written examination, currently pursuing the oral assessment. Yasvanthra began his marine career after graduating from the Chennai School of Ship Management (2005–2008). He has progressed through various engineering ranks, demonstrating hands-on expertise with a wide range of main engine types including MAN B&W, Mitsubishi, and Bergen, across vessel types like general cargo, bulk, cement, oil carriers, and vehicle carriers. He is trained in advanced marine safety procedures, including Safety Officer Course, Survival Craft & Rescue Boats, and Risk Management & Incident Investigation, showcasing a strong commitment to operational safety and engineering excellence.