TELKOMNIKA Telecommunication Computing Electronics and Control
Vol. 21, No. 3, June 2023, pp. 513~527
ISSN: 1693-6930, DOI: 10.12928/TELKOMNIKA.v21i3.24010

Research advancements in ocean environmental monitoring systems using wireless sensor networks: a review

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Article Info

Article history:

Received May 13, 2022
Revised Nov 05, 2022
Accepted Nov 12, 2022

Keywords:

MEMS sensor
Ocean environment monitoring
Ocean waves
WSN
Wireless sensors

ABSTRACT

The ocean environment monitoring system is of great significance to the researchers because the ocean is the storehouse of natural resources. It is critical to comprehend and assess the ocean's environmental conditions. Several studies have been conducted over the last several decades that use sophisticated information and communication techniques to ensure the ocean ecosystem. Wireless sensor networks (WSNs) are a promising technology to monitor the ocean environment, which delivers significant benefits such as enhanced accuracy and real-time observations. The advancements in sensor technology such as micro electromechanical systems (MEMS), integrated systems, distributed processing, wireless communications, and wireless sensor applications have contributed to the development of WSNs. This paper describes the utilization of WSN and analyzes the previous and existing project works and technologies used for ocean environment monitoring through WSNs, and also includes the MEMS sensor technology used for monitoring various ocean parameters such as ocean wave monitoring, water conductivity, temperature, and depth of ocean.

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1. INTRODUCTION

In the current scenario and due to technological advancements in wireless communication, wireless sensor technology is highly demanding in several sectors. Such types of demand may be fulfilled by using wireless sensor network (WSN). The WSN is a wireless network including distributed independent various sensors designed to monitor physical or environmental parameters. A WSN is made up of a set of interconnected several dedicated and specialized sensor nodes that communicate and exchange information and data by using a specified topology [1]. A WSN has a variety of unique features including power efficiency, scalability, responsiveness, reliability, and mobility. In the recent decade, WSNs have been widely used in various sectors, including water observation [2], agricultural surveillance [3], forest monitoring [4], battlefield and military operations [5], [6], autonomous and smart homes [7], industrial applications [8], ocean environment monitoring for catastrophe prevention [9], [10] and monitoring of various parameters of the ocean [11].

With the exponential growth of social activities and the economy, the ocean ecosystem has steadily been damaged by a growing amount of human activities. In a broad range of day-to-day operations, the ocean environment and underwater monitoring are important activities, so it is required to pay attention to ocean environmental monitoring. Traditionally oceanographic environment monitoring is mostly based on a manual process that includes the collection of a huge amount of seawater and laboratory analysis which involves several stages such as sampling, transport, pre-treatment, and instrument analysis, but this method is very costly and time-consuming, with a minimum resolution both in space and time [12]. A WSN-based methodology will significantly increase access to real-time data spanning long stretches and broad geographical areas for marine environment monitoring and analysis [13]. According to Mohsan *et al.* [14], the WSN-based oceanographic monitoring technique is less expensive and more suitable than the conventional oceanographic monitoring method.

WSNs include several types of sensors, these sensors collect the data from the marine environment by sensing the various physical and chemical parameters such as turbidity, water temperature, salinity, pressure, chlorophyll levels, pH level, oxygen density and then transfer the information to nodes where it gets processed [15]. There are various critical challenges to the design and development of environmental monitoring systems using WSNs, such as communications stability, time synchronization stability and minimization of power consumption are major challenges in the development of environmental monitoring sensor networks [4]. Elgenaidi and Newe [16] have also examined oceanic monitoring research and development by utilizing wireless sensor networks and highlighted the WSN's oceanographic surveillance issues and problems such as energy consumption, data transmission, and security. The research community recognized these problems and challenges and made great efforts to create protocols on various layers to solve them. Such protocols require maintaining accurate network performance with the consideration of numerous aspects like being tolerant of a network failure [17], security in data transmission, and energy constraints [18]. It requires at least four different modules to make the sensor nodes [19]. Primarily, the focus is on developing a sensing module for data acquisition. It can be created by including one or many sensors for sensing the processing module with the sense of one or more environmental constraints. It contains a central processing unit (CPU) that receives the data and performs the storage as well as processing operations. It has an In-charge of the wireless transceiver module that uses several wireless technologies in wireless communications such as ZigBee, Wi-Fi, and radiofrequency. Secondarily, it has a power supply module that is formed by a power management system and consists of batteries. It should deliver stable and continuous power to the rest of the modules. But researchers have some recommendations to develop a sensor system to be integrated with a wireless system for energy-saving and low-cost strategies.

Spencer [20] noted that a sensor must be called a smart sensor with features such as an onboard CPU, compact size, wireless capability, and the promise of low cost and energy saving. Similarly, Spencer *et al.* [21] note that if it contains an onboard microprocessor, a wireless communication device, and sensing capabilities, a sensor can be considered smart. They should also be powered by batteries and have a low cost. Manson *et al.* [22] designed and developed an integrated microsystem for the measurement of ambient humidity, temperature, acceleration, and barometric pressure measurement. In this device, the embedded micro controller unit (MCU) communicates with the sensor bus, which scans the sensors regularly, calibrates and compensates for their data, and uses either a hard-wired system bus or a wireless link to transmit the resulting information to the outside world. Low size and high sensor accuracy for low-power wireless applications were the key concerns of this device. Similarly, Lou *et al.* [23] designed a marine environment monitoring system based on WSN using ZigBee wireless communication technology for monitoring pH and dissolved oxygen (DO). They have utilized CS526 as pH sensor and optical dissolved oxygen technology (OPTOD) as dissolved oxygen sensor and connected with MSP430F149 MCU, the CC2430 is used as ZigBee module. The major advantages of this system are low power consumption of 0–3.6 dBm and an enhanced range of communication up to 30–70 m with power detection capacity.

Since the development of sensor technology, a lot of advancement has been made by researchers on low power consumption and low cost [24]. However, the micro electromechanical system (MEMS) sensor technology also has become proven technology for low power consumption, low cost, and high sensitivity with embedded processing and wireless networking capability for both overwater and underwater applications as compared to other conventional sensor technology [25], [26]. The MEMS-based inertial sensors such as accelerometer and gyroscope can be utilized for wave structure analysis i.e., wave direction, wave height, wave period, and wave velocity with wireless sensor networking [27], [28]. Since the development of MEMS sensor technology, there are few research works have been made on the utilization of MEMS sensor technology with WSN for ocean environment monitoring.

This article presents an extensive overview of research advancements in the field of ocean environmental monitoring and prediction systems using WSN. The remaining part of the paper is arranged accordingly: section 2 examines the monitoring techniques of ocean parameters and characteristics of the ocean environment. Section 3 discusses the advancement in ocean environment monitoring technologies. Section 4 describes the role of MEMS sensor technology in wireless communication. Section 5 discusses the MEMS sensor-based techniques used for ocean environment monitoring systems and at the end of this article, section 6 discusses the conclusion and future scope.

2. MONITORING TECHNIQUES OF OCEAN PARAMETERS AND CHARACTERISTICS

Ocean wave monitoring is a fundamental process that enables data acquisition, understanding of wave behaviors, and design parameters estimation of coastal and offshore infrastructure and plays a major role in the interactions between the atmosphere and the ocean. Many efforts have been made by researchers to predict wave height and severe sea states [29], [30]. The initial approach is using wave models and air-wind interaction for predicting wave height. Various models and methods have been suggested by researchers for the deep-sea or coastal sea with various analytical terms for retrieving the wave parameters and characteristics.

2.1. Wave and ocean environment monitoring

Figure 1 shows the general architecture of the WSN-based wave and ocean environment monitoring system. It involves the base station, sink nodes, multiple sensor nodes, data server, and user interface terminals [31]. The sensor nodes can sense the sea environment parameters e.g., the temperature of the water, humidity, pH level, wave turbulence and transfer the information to sink nodes via wireless communication by utilizing the ZigBee or other communication protocols. The point-to-point approach is considered while developing the communication between the sink node as well as a sensor node. The sink node has the task to gather the information from sensor nodes, and further sends the gathered information to the base station through the general packet radio services (GPRS) wireless network. The received data gets processed and stored by the data server from the base station. Afterward, the internet connects the terminals of user terminals with the data server.

Researchers suggest and work on numerous definite networks, algorithms, protocols, and routing mechanisms for the monitoring of the WSN-based marine environment. Saha and Matsumoto [32] suggested and developed a framework for WSN-based data collection for rescue operations and disaster mitigation. This system is available for data distribution in disaster regions as the protocol is operable at WSN communication with better energy efficiency as well as lower delay. Validation of the simulated experiment was conducted for comparing the performance of several other protocols with the sensor networks for disaster relief operations management (SENDROM) protocol.

Sendra *et al.* [33] proposed another WSN i.e., underwater wireless sensor network (UWSN) using multiple low-cost sensors mounted in the buoy, which keeps it isolated from possible oxidation problems. The buoy is wirelessly connected to the base station using the FlyPort module. Such UWSN needs numerous constraints during its design and development as communication technologies, network topology, sensor node distribution, sensor node mobility models, and sensor node numbers. Roadknight *et al.* [34] suggested data management approaches as multi-layered adaptive and scalable for WSN. Such an algorithm has three decision-making elements as parameter evolution, local rules, and sliding window averaging. Lu *et al.* [35] designed a WSN framework for the applications of environmental monitoring. The main outline of such a network layer is that it was developed by considering multiple factors such as network monitoring unified routing/scheduling, service-aware control platform, and heterogeneity. Barbosa *et al.* [36] illustrated another WSN routing algorithm applicable for the monitoring of marine oil slicks. They suggested the utilization of two different approaches for message routing, multiple relay decision (MRD) and single relay decision (SRD) protocols. Some algorithms are providing much more effective message dissemination than greedy and single-hop methodologies. Although, such a method does not consider network scalability, energy harvesting, and node mobility.

Albaladejo *et al.* [9] illustrated another wireless monitoring system that is standardized as IEEE 802.15.4 for gathering the parameters (temperature and pH) from a fish farm. Such an algorithm utilized the routing (ZigBee) method and the application layer for operating data communication from the source node to the central coordinator. Researchers developed the algorithm to extend the lifetime of the node as the power consumption in the sub-layer procedure. Xu *et al.* [37] suggested an advanced WSN media access control (MAC) protocol that fulfills the requirements of reliability, bandwidth, real-time broadcast, and energy consumption for monitoring the oceanic atmosphere. Although, such an algorithm did not have any real sensor node to validate its performance. Harchi *et al.* [38] presented an algorithm for monitoring the oil slicks based on dynamic clustering. It has features such as metric weights, measurement periods, clustering dynamics, and node numbers to manage climate conditions. The network-clustering algorithm evaluates several constraints and their impact on its stability. Suakanto *et al.* [39] suggested another approach for data processing as a cloud computing-based method in disaster monitoring. This process utilized a transmission technique as FTR-HTTP from the client to the server remotely. Jalali *et al.* [40] suggested the mechanism for energy harvesting as a cooperative hybrid automatic repeat request (C-HARQ) that enhances the feasibility and energy efficiency of solar-powered WSNs. Researchers performed their C-HARQ experiments on a Simulink-based simulator or MATLAB for designing the embedded and network systems. Such experimental shows the superior outcomes of C-HARQ as compared with C-ARQ of relay nodes in energy consumption. Table 1 summarizes the WSN-based projects and systems for ocean environment monitoring.

IoT technology is also becoming a popular technique for ocean environment monitoring. There are various research has been done on ocean environment monitoring using IoT [15]. The massive amount of ocean data was produced recently by the rapid development and implementation of IoT technologies in maritime environment monitoring, and the recent development of big data analytics made it easier to analyze this data. The ocean environment data deals with several substantial issues, mainly the enormous volume of data and considerable poor data, like many other IoT-based data gathering systems. These issues have been the focus of research efforts worldwide. Yang *et al.* [41] suggested a technique or method for rapidly determining the form of data gathered via the Internet of Things (IoT). It is extremely quick to compute the distribution of contour lines properly.

Table 1. WSN-based projects and systems for ocean environment monitoring

Reference / year	Application areas	Sensing parameters	WSN techniques	Buoy	Main features
John *et al.* (2010) [42]	Ocean environmental monitoring	Surface temperature, light intensity	ZigBee	A miniaturized version of sonobuoy	Real-time approach, maintenance-free, dependable, and cost-effective with a high-resolution sampling of ocean factors
O'Connor *et al.* (2011) [43]	River and coastal marine monitoring	Ocean water level using visual sensor	Multi-modal sensor network	–	Investigation under environmental sensing network with a low cost. the shelf nonspecialized camera as their efficiency, wall detection quantity that can be observed in terms of the assessment as flooding risk, tackle data reliability
Pérez *et al.* (2011) [44]	Ocean environmental monitoring	Temperature, pressure, current velocity, salinity, turbidity chlorophyll, and nitrates	GPRS ZigBee	Special buoy	Google Maps and solar energy harvesting are used in a LabVIEW-based user interface
Sendra *et al.* (2015) [33]	Marine environment	Salinity, temperature, turbidity, relative humidity	FlyPort module	Multisensory buoy	Buoy depends on numerous low-cost sensors that can gather information from the weather as well as water
Moreno *et al.* (2017) [45]	Marine-coastal environment monitoring	Temperature, humidity, wind speed, atmospheric pressure	LoRa NET	Multisensory buoy	Simple to operate and minimal power consumption, with a range of several KMs and a cost-effective solution with less infrastructure needed
Lou *et al.* (2020) [23]	Marine environment monitoring	pH and dissolved oxygen (DO)	Zigbee	–	Low power consumption of 0–3.6 dBm and enhanced range of communication up to 30–70 m with power detection capacity
Demetillo *et al.* (2019) [46]	Water quality monitoring in large aquatic areas	Water temperature, dissolved oxygen, and pH monitoring	GSM and Xbee transceiver	Customized buoy	The buoy was remaining stable during the occurrence of the high cyclone, a real-time approach was used, and its solar panel provides continuous power

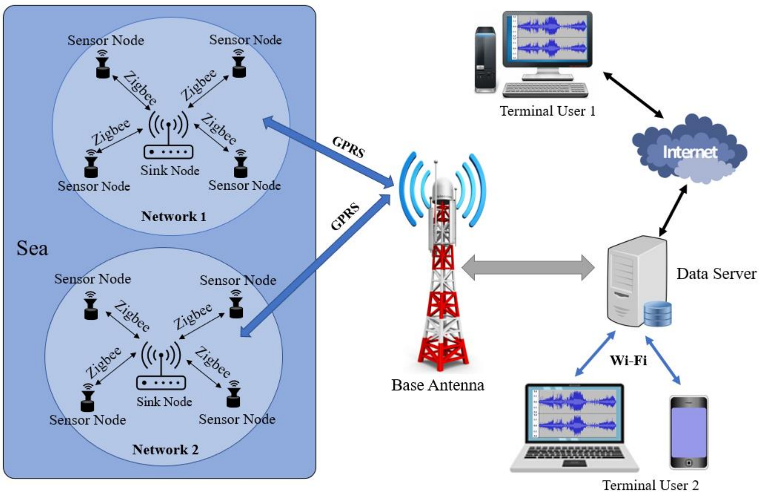


Figure 1. General block diagram of WSN-based sea and wave monitoring system

3. ADVANCEMENTS IN OCEAN ENVIRONMENT MONITORING TECHNOLOGIES

The wireless sensor network-based ocean environment monitoring system can provide better technological equipment and information platforms for the control and monitoring of the marine environment, the conservation of resources, disaster surveillance, marine engineering, offshore development operations, and marine military activities [47]. Wireless sensor networks (WSNs) are appropriate for the monitoring physical and chemical properties of water in remote regions at a low cost and reducing manpower consumption [46]. The WSN is also utilized for underwater applications such as marine shellfish monitoring, coral reef monitoring, fish farms monitoring, water quality monitoring as well as general ocean monitoring such as wave height monitoring. WSN has several advantages, including portability [48] as well as the real-time acquisition and recording of data capabilities [49]. The WSN can be utilized with global system for mobile communication (GSM) for monitoring large aquatic regions and transmitting the sensed parameters to the base station [50]. However, WSN applications and services in the aquatic region are considerably more complicated than land-based WSN applications because of their electronic component, in which water or even moisture should not be penetrated.

Due to day-by-day advancements in WSN technologies, it can be categorized according to the specific data capturing and driven methodology which involves computation methods, analysis, and transmission techniques [51]. The wireless sensor network may either be placed over water or underwater to collect videos, images, voice data, and numeric data. Recently many technologies have been implemented by researchers for ocean environment monitoring such as underwater wireless sensor networks (UWSN) [52], [53], underwater optical wireless sensor networks (UOWSN) [54], and long-range wireless sensor networks (LoRa WSN) [55].

The UWSN is very essential due to its various fields of applications including the gathering of marine data, underwater telemetry, marine pollution monitoring, monitoring of disaster activities such as underwater seismic and earthquakes activities, chemical waste monitoring, oil leakage detection, monitoring of underwater flora and fauna, monitoring the health of marine creatures, underwater military applications such as target detection and tracking [56]. The UWSN consists of movable and stationary nodes that are connected to underwater acoustic communication networks [57]. These nodes might move from one place to another place due to water currents, therefore sensor nodes can collect the data from many different locations [52]. The architecture of the UWSN showing in Figure 2. The UWSN network architecture consists of stationary sensor nodes, AUVs, and surface buoys with radio links that can communicate with each other via acoustic links. Certain stationary nodes are connected with the base station via cables and high-speed radio links, respectively.

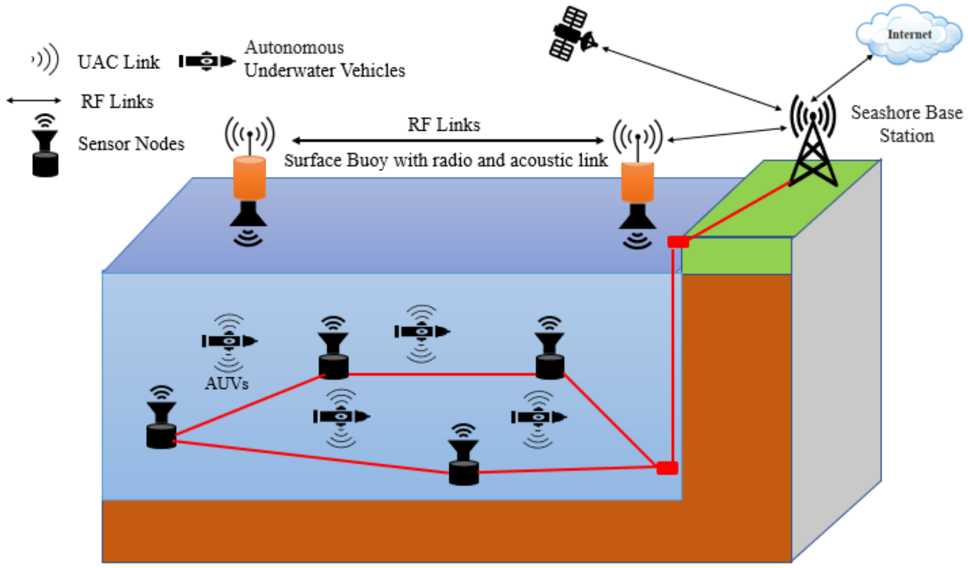


Figure 2. The architecture of the UWSN

The underwater monitoring is generally performed by navigation support such as autonomous underwater vehicles (AUV), underwater sensor nodes, and vehicle surveillance. They usually connect to the surface buoy or sink nodes across the water using acoustic waves and, non-acoustic communication techniques. That can also be utilized in underwater wireless sensor networks, such as radio frequency (RF), underwater free-space optics, and magnetic induction (MI). Magnetic induction may also be utilized for underwater propagation, but it is required a large size of antenna which is impossible in such environmental conditions. Acoustic communication is the most popular technique for underwater communication because acoustic waves become less attenuated and may travel great distances due to their low frequency. Wireless sensor nodes are linked via acoustic waves to form underwater acoustic sensor networks (UASNs). However, the UASNs nodes consume a large amount (ten times more) of energy as compared to sensor nodes deployed for environmental monitoring on land [58].

For improving overall system performance and energy optimization in UWSN, the "energy optimized path unaware layered routing protocol (E-PULRP)" has been developed, that optimizes and reduces the energy consumption in dense WUSN (wireless underground sensor network) [59], in which the network is formed a layered structure surrounding the center sink node. At each layer, communication from the node to the sink takes a multi-hop pathway through the relay node, as a result, the E-PULRP protocol minimizes energy utilization. Another technique for cluster-based energy-efficient UWSN is SEEC: "sparsity-aware energy-efficient clustering protocol for underwater wireless sensor networks". SEEC minimizes and optimizes the energy throughout the entire system by balancing the two algorithms of sparsity search algorithm (SSA) and density search algorithm (DSA) [60]. The clustering techniques in UWSNs still have several concerns and challenges. Because nodes can create many sets of data such as temperature, chemicals, acidity, pH, density, conductivity, and hydrogen. As a result, nodes that generate a lot of traffic should have a greater priority and be more reliable when sending data to the sink. Furthermore, nodes that are near the sink always collect data from other nodes as the hot spot of dead nodes. As a result, after some time nodes should be changed their role as cluster heads.

Khasawneh *et al.* [61] examined and evaluated several routing protocols and most routing protocols are multi-hop localization-free, dependable, and, energy-efficient. As a result, to build a reliable and energy-efficient routing protocol for UWSNs, the routing protocols for UWSNs should be considered impact of node depth, energy utilization, and multi-hop paths. Furthermore, the clustering-based protocol approach for UWSN demonstrates the advantages in terms of network coverage, interconnectivity, and responsiveness to a dynamic environment. Nguyen *et al.* [62] have presented an energy-efficient clustering multi-hop routing protocol (EECMR), which can be used to balance nodes' energy utilization and extend the lifetime of the network. The network area is split into layers, in terms of depth level. The data collected by the nodes is sent over a multi-hop routing network to a sink. The cluster head is chosen based on the node's depth as well as its residual energy. The cluster head collects data packets from all adjacent cluster nodes and sends them to the sink node's top layer. The simulation results show that the EECMR is more effective in terms of node energy usage and network lifetime. Moreover, the energy-efficient Cluster and cooperative-reliability-based routing protocols were widely investigated in [63] for UWSN which improves network link quality and is reliable for energy consumption. The UWSN are based on underwater acoustic sensor networks (UASNs). There are some limitations of conventional underwater acoustic communication, such as low efficiency, low data rate, and high latency due to the low propagation speed (approximately 1500 m/s) and limited bandwidth (kHz) of acoustic waves. But It is a communication technology that can allow three-dimensional ocean underwater monitoring by implementing increasing demand for high-speed data communication, real-time monitoring, and high efficiency of UWSN [64].

The development of the 450–550 nm optical transmission window in 1963 gave rise to a new approach to the development of underwater optical wireless communication technology [65]. However, light waves cannot transmit long distances (up to km) similar to acoustic waves, their wide bandwidth and low latency make them ideal for real-time, high-speed (up to Gb/s), and short-distance (up to 100 m) transmission [66]. Recently various types of optical sources, modulation and multiplexing techniques, photodetectors, and equalization algorithms have been investigated for the development of underwater wireless optical communication (UWOC) systems with better data rates and longer transmission distances [67]. Due to continuous technological advancements in UWOC, it is used in numerous aquatic habitats including rivers, lakes, and oceans [64], [68], [69]. For the smart and next-generation UWOC system development, the underwater optical wireless sensor networks (UOWSN) are to be developed for real-time ocean environmental monitoring. However, theoretical and simulation work on underwater optical wireless sensor networks is limited [70]. Recently, Kong *et al.* [54] and his team have developed the first UOWSN prototype for bidirectional optical wireless communication. It is made up of two sensor nodes as well as an optical hub. The sensor nodes have a transceiver circuit, a pH sensor, and integrated salinity, temperature, and conductivity sensors that allow for real-time underwater environmental monitoring. The optical hub consists of a system-on-chip (SOC) circuit that used on-off (OOK) modulation and demodulation techniques. The data transmission rate of OOK signals have 1.5 Mb/sec. The sensor node and optical hub are placed at 60 cm from each other and during the laboratory experiment 100% packet success rate was achieved between the sensor node and optical hub. But more research is required in the field of ocean environment monitoring technologies to improve data transmission rate, distance, low power consumption, and easy deployment for real-time monitoring.

In the recent advancement in wireless communication technologies, the LoRa communication technology is better for long-distance transmission as compared to other communication technology and it is also appropriate for ocean environment monitoring [71]. A lot of research work has been implemented in the field of LoRa communication technology to improve the ocean monitoring system's performance. Guang Jin *et. al* [72] have designed and developed an ocean environment monitoring system using LoRa wireless sensor network.

They have compared its energy consumption and complexity with the ZigBee sensor network and concluded that this system provides an efficient monitoring service in hazardous ocean conditions and long-range data communication to cover a broader area of up to 800 meters with low power consumption using LoRa technology. Huang *et al.* [73] have practically implemented the ocean environment monitoring system based on LoRa WSN. This system is consisting of a sensor node, gateway, and server platform. The sensor node is integrated with a temperature sensor, a control chip, and a LoRa communication module. The overall system is utilized for the monitoring of the underwater temperature information. Li *et al.* [74] employed a LoRa-enabled WSN prototype for continuous and real-time monitoring of the humidity, temperature, lighting, and noise decibels of high-speed railway stations, and its results may be utilized to analyze the performance study of ocean sensor networks subjected to strong sea waves. They have concluded about the features of LoRa technology are long-range communication, low power consumption, and low cost. The LoRa technology can also be utilized for tracking and monitoring small ships [75], which can be very beneficial for aquaculture activities. The experimental reports show that the LoRa Wireless communication technology can cover a wider range of up to 4 Km for marine environmental monitoring.

Most of these studies are oriented toward extending the life of remote networks and enhancing communication quality between sensor systems, nodes, and gateways. The availability of the LoRa-based ocean WSN for ocean environment monitoring was demonstrated in these experiments, which looked at network architecture, communication quality, and performance. Moreover, there are more research is required in the field of LoRa-based wireless sensor networks for real-time monitoring, low power consumption as well as long-distance communication.

4. ROLE OF MEMS SENSOR TECHNOLOGY WITH WIRELESS COMMUNICATION IN OCEAN ENVIRONMENT MONITORING SYSTEMS

The sensor is a device that detects physical quantity and transforms them into corresponding electrical quantities like voltage, current, capacitance, inductance, and frequency. There are various types of sensors are used to monitor and measure different physical parameters using WSN including water temperature, wind direction, wind speed, pressure, and chemical parameters such as pH, salinity, oxygen density, turbidity, and, chlorophyll levels [31]. The sensor selection depends on deployment region, season, measurement range, accuracy, resolution, and power consumption.

Continuous advancements in MEMS sensor technology provide the opportunity to integrate the low-power WSN with a wireless communication protocol for long-term, continuous, and real-time monitoring [76]. However, for terrestrial applications, the development of MEMS sensor technology, wireless communications, embedded systems, distributed processing, and wireless sensor applications have a major transition in the wireless sensor network for marine environmental monitoring. The MEMS-based inertial sensors such as accelerometer, gyroscope, and magnetic compass can be utilized for wave structure analysis i.e., wave direction, wave height, wave period, and wave velocity with wireless sensor networking.

According to Xu *et al.* [77], the MEMS technology-based sensors are more dependable for wireless communication, and their low-cost fabrication has resulted in a compact size, cheap and efficient production with embedded-processing sensors and wireless networking capability. MEMS technology offers high integration of hardware components (e.g., battery, microprocessor, sensing modules, analog to digital converter (ADC), storage unit) as compared to traditional wired sensors. The MEMS sensor nodes are cheap, but their expense is still too high to make the construction and maintenance of large networks. Perianu *et al.* [78] proposed a WSN-based technology for wave monitoring to track different wave parameters such as wave height, wave direction, and wave velocity. This monitoring system was equipped with IEEE 802.15.4-compatible CC2430 (ZigBee module) along with low-power and low-cost MEMS-based inertial sensors such as accelerometers, gyroscopes, and a digital compass that have been mounted throughout this device. They have investigated using a Ferris wheel contraption which is a technique used in practice to evaluate and calibrate wave monitoring solutions. However, the wave frequency amplitude in real-time cannot be obtained by this system.

A block diagram of an ocean monitoring system using MEMS sensors and a surface buoy is shown in Figure 3 multiple MEMS sensors can be connected to a buoy. A buoy is a floating device that is anchored or allowed to drift with ocean currents. The buoy may either float on the surface or maybe submerged underwater with help of an Anchor. The microcontroller in the buoy gathers information from different MEMS sensors and delivers it to the data acquisition unit. In this unit data is preprocessed such as a format is chosen, invalid data is removed. The data is then passed to a data processing unit where computation takes place and the information regarding the state of the sea is incurred. If abnormal conditions are detected an alert or warning unit is triggered.

Albaladejo *et al.* [79] designed and implemented an oceanographic multisensory shallow-water marine environmental monitoring floating buoy system for monitoring marine pressure, temperature, and atmospheric pressure. This buoy system was developed with a 16-bit MSP430F2618 microcontroller and

CC2520 radio transceiver module that combined with a CC2591 device, to enhance the RF communication coverage area. For the development of the ZigBee, network authors utilize the Z-Stack component of a simple link, which provides a wide range of functionality to the sensor buoy. There were two experimental phases, first was the laboratory test to check the operation of radio modules to achieve maximum range, and the second was the field test in which they verified the power management system (battery charging response and harvesting system), the communication network and mechanical durability of the sensor buoy under marine conditions. Marimon *et al.* [80] developed a WSN based floating platform or buoy by placing wave sensors on it, in a water body and observing the response of different wave conditions and locations. To determine the current wave conditions, wave sensors run with preprocessing techniques. The data from wave sensors were sent to the central node. If the wave sensors have found that the conditions of the local wave exceed the usual conditions, they will report them to the central node. Furthermore, if the data does not exceed this, the existing data will continue to be processed until they detect abnormal conditions.

Similarly, in 2018 Chai and Liu [81] designed a real-time wave parameter monitoring system (buoy) by using a MEMS motion sensor, GPRS wireless transmission technology, and a high-performance STM32F4 series single-chip microcomputer. The frequency and amplitude of ocean waves were monitored by time and frequency domain analysis and the information is transmitted via the GSM module to the cloud server. The main drawback of this buoy system was zero-offsets of the sensor, sensor static noise, sensor hybrid noise [82] and sensor motion response. These specific parameters were not calibrated to retrieve noise performance evaluation and nonlinear distortion. In 2020 Yurovsky and Dulov [83] designed and developed a MEMS sensor (MPU9250) based wave sensing buoy. This buoy was utilized for the measurement of wind speed (1 to 15 m/s), ocean wave height, and wave direction. To minimize the noise performance and nonlinear distortion, they calibrated the sensor buoy at every step. Firstly, they estimated the zero-drift with various sensor orientations, secondly, sensor static noise was estimated for different temperature conditions, and third the motion response of sensor was checked with the sensor rotation at a variable speed with a different orbit radius. Table 2 summarizes the MEMS with buoy-based projects and systems for ocean environment monitoring.

Table 2. MEMS sensor with buoy-based projects and systems for ocean environment monitoring

Reference / year	Application areas	Sensing parameters	Techniques	Buoy	Main features
Aravamudhan and Bhansali (2008) [84]	Ocean monitoring	Pressure	Piezoresistive MEMS	–	The reinforced process leads to greater sensitivity (around 10–15%) and a broader full-scale span (by twice) as compared with the traditional piezoresistive pressure sensor with a single diaphragm
Perianu *et al.* (2008) [78]	Ocean monitoring	Height, direction, speed, and period	MEMS technology	Wave rider buoy system	low-cost, low power with a calibrated wave monitoring solution
Marimon *et al.* (2011) [85]	Wave monitoring	Wave height	MEMS	–	Measuring parameters such as angular deviation and acceleration are utilized as the substitute by minimization of overall data usage as well as system power excluding the quality sacrifice of wave monitoring, data is pre-processed within the wave sensor
Brown and Meadows (2011) [86]	Ocean wave monitoring	Wave height, wave acceleration, and wave direction	MEMS-based inertial wave sensor (IWS) via RS232	Sensor buoy	low-cost, low-powered, and real-time dissemination to data centers with onboard processing
Crandle *et al.* (2016) [87]	Ocean monitoring	Wave height	MEMS	Data buoy	low power consumption, MEMS sensor has onboard processing capability, and data is Pre-processed within the MEMS
Chai and Liu (2018) [81]	Ocean wave monitoring	Wave frequency and amplitude	MEMS	Sensor buoy	low cost and real-time
Zhang *et al.* (2018) [88]	Marine field	Inertial sensors, underwater acoustic sensors, and conductivity temperature-depth sensors	MEMS technology	Ocean buoy	As a marine parameter ocean turbulence plays a significant part in research on ocean energy transfer, population distribution, and marine productivity
García *et al.* (2018) [89]	Marine	Wave height / period, wind, marine current intensity / direction	Multi-sensor floating system	Sensor buoy	Treating the characteristics of static as well as hydrodynamic states under the offshore marine systems, consisting of the materials and anchoring requirements
Liu *et al.* (2020) [90]	Ocean wave monitoring	Wave height	MEMS technology with cross dimensional method Kalman filter	Six-dimensional accelerometer-based buoy	Development of a novel type of parallel six-dimensional accelerometer to enhance the wave buoy's stability with principle error reduction using the Kalman filter technique

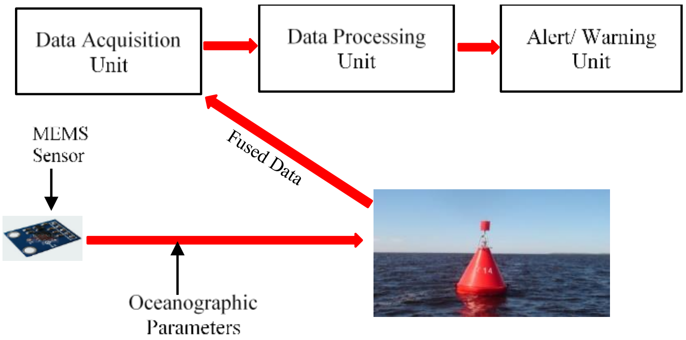


Figure 3. Sea wave monitoring using MEMS sensors

5. MEMS SENSOR-BASED TECHNIQUES FOR OCEAN MONITORING SYSTEMS

The MEMS sensor technology is an intelligent sensing system and integration of microelectronics, actuators, micro-sensors, and mechanical microstructure on a common silicon substrate through integration lithography, etching, thin-film, silicon micromachining and precision machining technologies. With the expanding interest in the marine investigation and the consistent advancement of MEMS innovation. Different types of sensors based on MEMS have been utilized in ocean perceptions.

5.1. MEMS sensor-based inertial sensors

Brown and Meadows [86] designed and developed a low-cost, low-powered MEMS-based inertial wave sensor (IWS) for ocean environment monitoring. This inertial sensor has been attached to a buoy to measure wave height, wave acceleration, and wave direction via RS232. This IWS contains a 3-Axis accelerometer and digital compass. In 2013 Yunjia and Chuan [91] proposed a monitoring system to identify multi-point vibration at offshore platforms by combining the MEMS sensors and WSN, and they identify the multi-point vibration at offshore platforms in the ocean. Sun and Dai [92] proposed a low-power wireless ice-initiated vibration monitoring system that depends on the MEMS dual-axis acceleration sensor (ADXL202), and 3-D Acceleration data was visually displayed and stored. The real vibration observing investigation was performed on the vibration test stage, and the accuracy of the time domain exploratory information was demonstrated from the frequency domain [93]. Moreover, Zhang *et al.* [88] of the “naval submarine institute” gave another strategy for observing sea parameters, for example, ocean target rise, ocean surface tide height, ebb and flow factor, shore seashore separation, and shore seashore slant dependent on MEMS tilt sensor. The technique has been executed through the task “portable multifunctional navigation locator”.

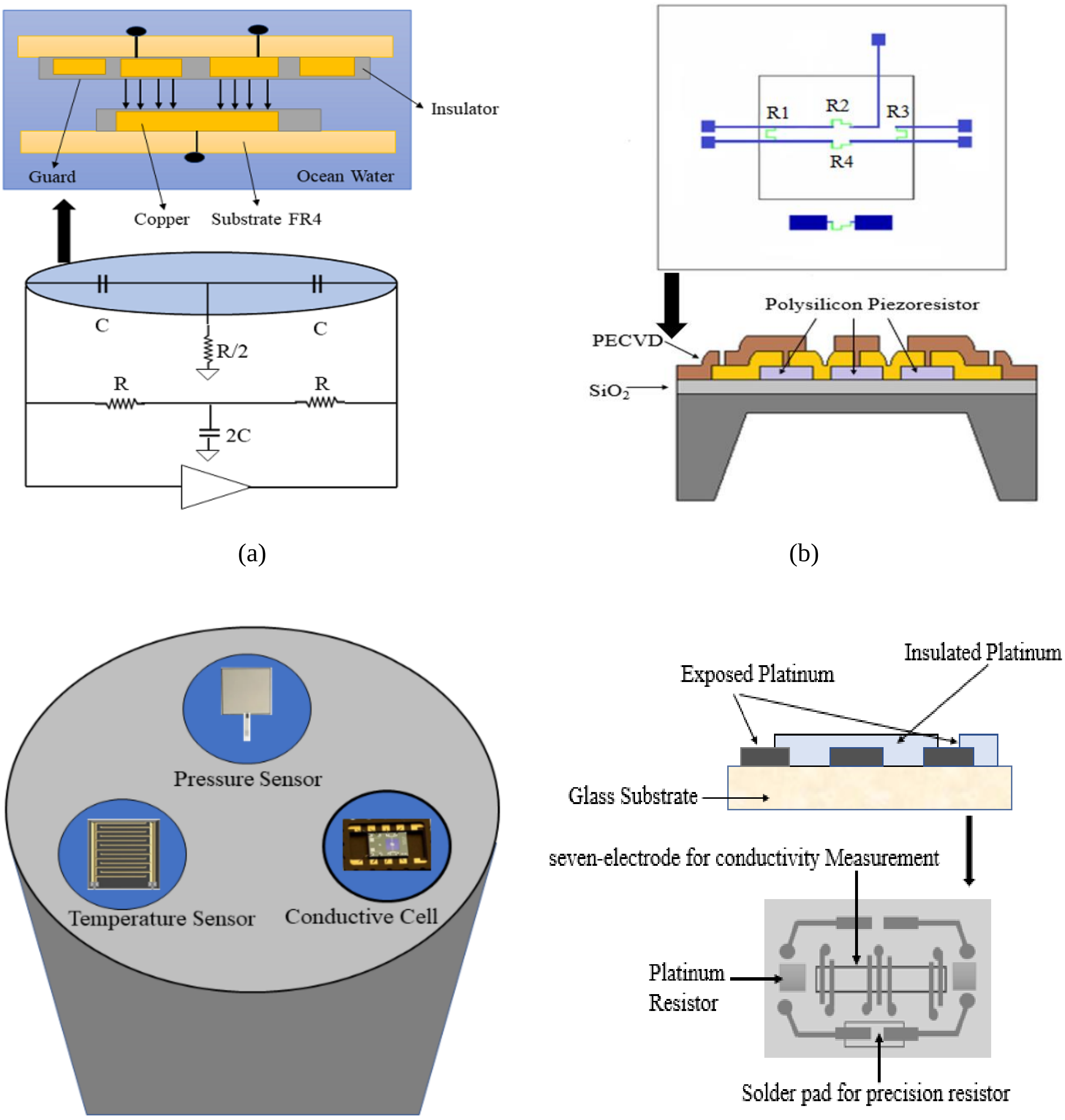
Chaudhury *et al.* [94] utilized MEMS inertial sensors MPU6050 to detect the behavior of ocean waves. They determined and controlled the direction of locomotion by altering pitch and roll by changing the center of mass. Concerning the issue of swaying vibration of the seashore stages brought about by the effect of wind and wave, Boehlert *et al.* [95] utilized MEMS gyroscopes to build a 1DOF rocking vibration test stage for the angular velocity information and they utilize an Integral and complementary filter for tackle the issue of zero drift of the gyro and obtained the time domain and frequency domain curve of single DOF vibration.

5.2. MEMS sensor-based conductivity, temperature and depths (CTD) sensors

Conductivity, temperature, and depth are significant parameters in Ocean wave monitoring research. The CTD sensors are a significant device in the sea wave perceptions field such as the study of physical, chemical, and biological structures of the ocean [96]. The CTD sensors are made by using expensive multi-layer screening or standard micromachining development.

Singh *et al.* [97] designed the structure of a MEMS-based CTD sensor. They have used the parallel-plate capacitor structure (Figure 4(a)) for the conductivity sensor, in which most of the electric field is enclosed between the regions of two charged plates. For the MEMS-based temperature sensor, they utilized a technique of “doping transition metal impurities” to expand the resistivity of the silicon substrate. Thus, the MEMS-based CTD sensor was highly sensitive and accurate. The MEMS-based depth sensor was developed by piezoresistive sensor innovation, its computation principle is depending on the flexibility of the diaphragm structure. The fixed diaphragm structure was utilized as a flexible component to sense the pressure, and afterward, a sensitive network was utilized to change the vibrations onto the diaphragm structure into a corresponding electrical signal. The pressure sensor is designed often built on a flexible membrane as the sensing pressure spring element. When pressure is applied to the sensitive diaphragm which has capacitive coupling then the deflection of the membrane and related stresses (piezo-resistors, strain gauges) are converted into an electric output. The measurement of temperature compared to pressure may easily be translated to depth (Figure 4(b)).

Broadbent *et al.* [98] built up a scaled-down CTD perception system, which was integrated with three inexpensive sensors included with three inexpensive sensors: a piezoelectric sensor, a resistance temperature detector (RTD), and an unique planar four-electrode conduction unit. Every one of them can be quickly and easily supplanted when it is damaged and polluted organically. The conductivity and temperature sensors (RTD) were integrated with a piezoresistive pressure sensor using micro-electro-mechanical (MEMS) technology on a single printed circuit board (PCB) with thin-film material and liquid crystal polymer (LCP). They have compared the performance of PCB MEMS-based CTD Sensors with conventional CTD instruments in natural seawater by taking measurements of conductivity, temperature, and depth (Figure 4(c)). The sensed data was transmitted wirelessly by using lantronix embedded 802.11b wireless networking transceiver system and after the experiment, they have concluded that the relative accuracy of measurement can be reached ± 1.47%, ± 0.546 °C, ± 0.02 bar respectively.



(a) (b)

(c) (d)

Figure 4. Design structures of different MEMS sensor-based conductivity, temperature and depths (CTD) sensors: (a) multifunctional and miniaturized CTD sensor using a parallel-plate arrangement for measuring conductivity [96]; (b) arrangement of single diaphragm piezoresistive pressure sensor for temperature and pressure measurement [97]; (c) structures of a PCB MEMS-based CTD sensor [98]; and (d) miniaturized conductivity and temperature (CT) sensor chip structure [99]

Huang *et al.* [99] has been designed and developed as low power, miniaturized, and high-precision conductivity and temperature (CT) sensor (Figure 4(d)) using microfabrication technology for continuous ocean monitoring. Such a sensor system has seven electrodes for conductivity and salinity measurement of ocean water. These seven electrodes are combined with a platinum resistor temperature bridge to produce an integrated CT sensor. During the calibration of the CT sensor, accuracies are ± 0.03 mS/cm over the range of 25−55 mS/cm and ± 0.01 °C over the range of 4 °C – 34 °C respectively.

6. CONCLUSION

Wireless sensor networks have become the method of choice for monitoring the ocean environment over traditional techniques as a result of the advancement of wireless communication technologies. WSN-based ocean environment monitoring is a highly effective strategy since it comes with many features including real-time monitoring, automated operation, and relatively inexpensive. This article summarized the present and previous ocean environment monitoring research and development status using WSN and described the general architecture of WSN-based ocean environment systems. This paper depicts the comprehensive literature of systems as well as technologies related to WSN and their targeted parameters for ocean environmental monitoring. This article also summarized the MEMS sensor technology used for ocean environment monitoring. The MEMS sensor technology also has become proven technology for low power consumption, low cost, and high sensitivity with embedded processing and wireless networking capability for both overwater and underwater applications as compared to other conventional sensor technology. There are numerous projects available that use the most advanced technologies, such as WSN and MEMS with the buoy, to monitor the quality of water and the ocean environment.

Some of the other efforts are also going on in the domains of current/wave monitoring, and fish farm/coral reef monitoring. Numerous research works are targeted at certain technologies or devices such as data analysis techniques, data transmitting mechanisms, routing protocols, harvesting/energy-saving devices, and buoys for ocean environment monitoring. However, it has the main challenge of different testing places. Nearly half of them are implemented or experimented with under the river or actual marine environments, while another part is under indoor environments with lab experimental setup. Some of them have experimented in lakes and small ponds or outdoor pools, and numerous are tested through simulations on several software tools. Although wireless communication mostly utilizes ZigBee or/and GPRS, some of the systems are used for underwater acoustic communication. There are mainly two aspects of energy management challenges: using alternative renewable energy sources and reducing energy consumption. Reduction in energy consumption needs to develop advanced routing protocols as well as optimization network topologies. However, several researchers deliberated other options for energy harvesting consisting of ocean currents, waves, wind, and solar as alternative renewable energy sources.

ACKNOWLEDGMENTS

The authors are sincerely thankful to the whole administration of Manipal University Jaipur, India for providing all the facilities, constant support, and encouragement for this work. This the research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

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