Journal of
Marine Science and Engineering

MDPI

Review

Recent Advances, Future Trends, Applications and Challenges of Internet of Underwater Things (IoUT): A Comprehensive Review

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Abstract: Oceans cover more than 70% of the Earth's surface. For various reasons, almost 95% of these areas remain unexplored. Underwater wireless communication (UWC) has widespread applications, including real-time aquatic data collection, naval surveillance, natural disaster prevention, archaeological expeditions, oil and gas exploration, shipwreck exploration, maritime security, and the monitoring of aquatic species and water contamination. The promising concept of the Internet of Underwater Things (IoUT) is having a great influence in several areas, for example, in small research facilities and average-sized harbors, as well as in huge unexplored areas of ocean. The IoUT has emerged as an innovative technology with the potential to develop a smart ocean. The IoUT framework integrates different underwater communication techniques such as optical, magnetic induction, and acoustic signals. It is capable of revolutionizing industrial projects, scientific research, and business. The key enabler technology for the IoUT is the underwater wireless sensor network (UWSN); however, at present, this is characterized by limitations in reliability, long propagation delays, high energy consumption, a dynamic topology, and limited bandwidth. This study examines the literature to identify potential challenges and risks, as well as mitigating solutions, associated with the IoUT. Our findings reveal that the key contributing elements to the challenges facing the IoUT are underwater communications, energy storage, latency, mobility, a lack of standardization, transmission media, transmission range, and energy constraints. Furthermore, we discuss several IoUT applications while highlighting potential future research directions.

Keywords: Internet of Underwater Things; autonomous underwater vehicles; underwater wireless communication; underwater wireless sensor network; challenges; mitigative solutions

Citation: Mohsan, S.A.H.; Li, Y.; Sadiq, M.; Liang, J.; Khan, M.A. Recent Advances, Future Trends, Applications and Challenges of Internet of Underwater Things (IoUT): A Comprehensive Review. *J. Mar. Sci. Eng.* **2023**, *11*, 124. https://doi.org/10.3390/jmse11010124

Academic Editor: Alessandro Ridolfi

Received: 14 December 2022
Revised: 21 December 2022
Accepted: 31 December 2022
Published: 6 January 2023

1. Introduction

Generally, large water bodies may be divided into small seas and vast oceans, which together cover about 71% of the earth's surface. Most ocean areas have not been fully explored yet. It is of paramount significance to explore these oceanic areas. In this regard, the IoUT has emerged as a promising technology to support underwater discovery and exploration [1]. The IoUT is considered a remarkable revolution in communication and computing. It is a smart network of underwater objects such as sensor nodes, cluster heads, cameras, autonomous underwater vehicles (AUVs), remotely operated vehicles (ROVs), autonomous surface vehicles (ASVs), buoys, ships, etc. which supports various maritime applications. The IoUT objects are fixed at one position or can move from one position to another to collect information. This information is then transmitted through digitally linked underwater objects, including the gateway or water surface buoys. These smart objects can sense, process, and transmit data to the intended destination. IoUT systems are generally used to measure specific chemical, biological, or physical ocean parameters such as water quality, pH, turbidity, humidity, pressure, and temperature to provide real-time and historical data. These objects can also be used to find hidden treasure, oil and gas spills, minerals, metals, and corals. Moreover, other devices, such as mobile gateways, base stations, satellites, etc., are used to extend the communication range of the IoUT. However, there are several critical concerns regarding the design, development, and implementation of IoUT systems. The major challenges are communication, battery charging, energy storage, reliability, security, mobility, and dynamic node topology. In the last few years, several research studies have been devoted to the IoUT, some of which [2–5] have reported some of its features. The IoUT has a wide range of applications, including environmental protection, ocean observation, early warning generation, deep-sea exploration, underwater communication, submarine tracking, oil spill detection, search and rescue, marine transportation, naval network surveillance, and tactical surveillance. For these applications, networks of permanent cabled observation systems are being deployed in the ocean. In particular, underwater observatory systems are deployed for long term real-time observation and monitoring of natural phenomena such as offshore seismicity and tsunamis. Similar to wireless networks in terms of their architectural components and applications, these cabled networks can also monitor seabed movements, water circulation, salinity, pH, temperature, etc. However, in this review, we will only focus on wireless networks. Even though there are some similarities between the Internet of Things (IoT) and the IoUT, such as their structure and operations, the latter is facing different technological challenges in terms of communication media, computational restrictions, channel characteristics, channel type, energy resources, etc. The channel characteristics define the technical factors which impact the IoUT, such as node mobility, pressure, turbulence, propagation speed, etc., while channel types represent the type of medium utilized in the IoUT, such as magnetic induction (MI), optical, acoustic, or radio frequency (RF) waves. Figure 1 presents an overview of an IoUT system based on sensor nodes which enable the use of smart applications in a data center via EM or acoustic links.

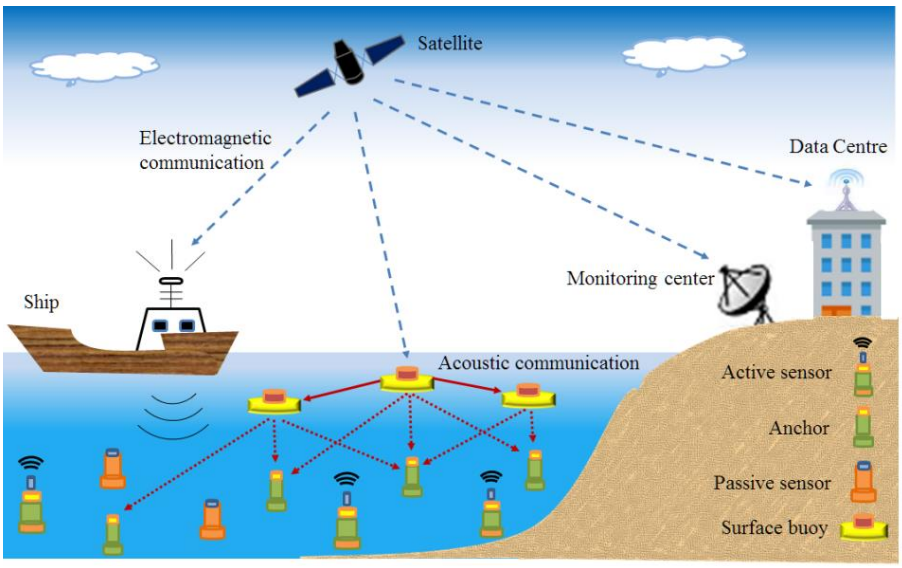

Figure 1. Illustration of an IoUT network.

An underwater wireless sensor network (UWSN), which has a distinct network architecture, is regarded is the key enabler network for the IoUT. Figure 2 presents the network architecture of an UWSN, comprising main elements, i.e., sensors, placed in shallow or deep water. The purpose of the sensors is to gather data and transfer it to elements such as buoys, ships, ASVs, or AUVs via acoustic signals, which, in turn, transfer the data to a remote monitoring center via radio signals. The monitoring center then carries out analyses of the obtained oceanic data. By using these smart devices, UWSNs support various applications such as ecological monitoring, seismic predictions, marine species tracking, disaster prevention, and water quality monitoring [4]. However, this approach is facing several critical concerns, including long propagation delays, limited bandwidth, and ultra-low reliability. Several studies [6] have highlighted further challenges, such as dynamic node topologies, communication, reliability, battery charging, delays, and real-time monitoring, etc. Table 1 summarizes the characteristics of (and issues facing) the IoUT. To overcome these issues, two data acquisition strategies have been proposed [7,8]. One method is to deploy flexible AUVs to collect data from IoUT nodes, while the second employs multi-hop transfer approaches. In [9], the authors propose an energy-efficient data collection strategy using AUVs. This strategy could substantially enhance the life span of the IoUT, as it offers high age of information (AoI) [10]. Similarly, data privacy and security is another critical concern faced by IoUT systems, as malicious node could be used to attack digital infrastructure and steal sensitive information. Several studies [6,11] have identified data confidentiality and authenticity as major challenges in IoUT systems. Thus, research should address privacy-preserving and enhanced security mechanisms to ensure reliable and secure communication across the IoUT network. In their study, Gopinath et al. [6] addressed privacy and security issues in the IoUT, proposing an encryption scheme to support secure data transmission.

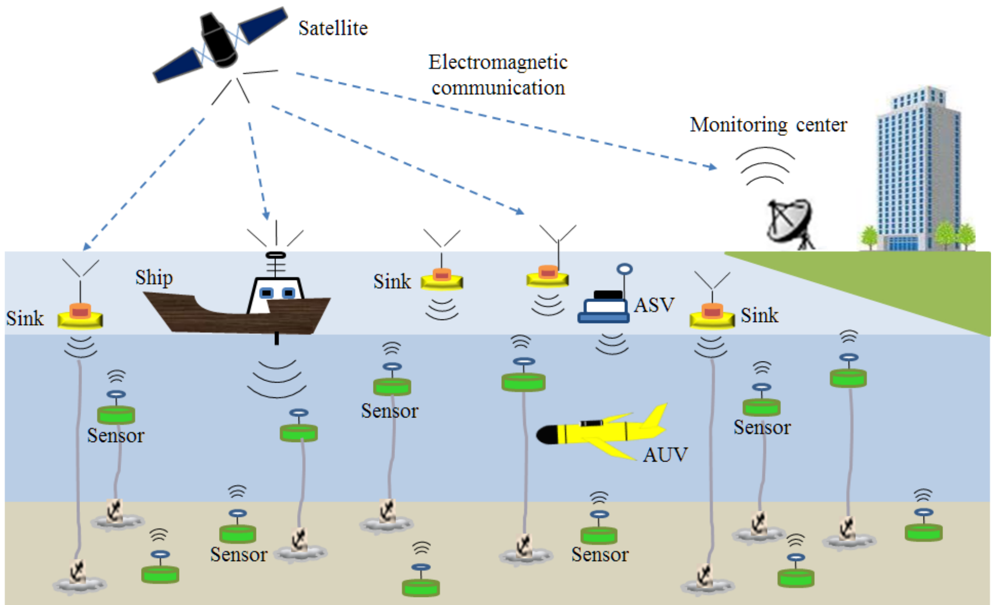

Figure 2. Network architecture of an UWSN.

In the literature, several methods have been proposed to explore and monitor the ocean environment, and various testbed designs have been proposed for the successful implementation of the IoUT [13–15]. Some projects based on software-defined networks have been implemented [16,17]. In Horizon 2020, scientists developed lightweight, cost-efficient acoustic devices and robotic structures for use with the IoUT [18]. SK Telecom, in collaboration with Hoseo University, South Korea, designed an underwater data transfer system using sound waves [19]. This project was implemented to support a novel IoUT monitoring system. Several naval forces have designed military IoUT (MIoUT) systems to ensure connectivity among AUVs, ships, and submarines. Furthermore, the research team from Senses Lab [20] has focused on IoUT system design. Researchers are also focusing on IoT communication protocols for underwater drones. In [1], the author proposed a novel architecture for the IoUT and discussed its principle and key differences with the IoT. That study also addresses the applications of and challenges facing the IoUT. Furthermore, Argo, a global collaborative project, has been successfully implemented to monitor yearly fluctuations in ocean parameters and climate change [21]. It includes buoys which can measure water pressure, temperature, and conductivity. Celik et al. [22] created a hybrid optoacoustic network intended to overcome underwater networking issues. Several other studies have focused on underwater communication to ensure robustness and enhanced energy efficiency and network capacity. Privacy and security concerns are also critical in IoUT systems. IoUT objects are vulnerable to denial-of-service attacks, wormholes, reconnaissance, Sybil, spoofing, jamming, flooding, and eavesdropping. Yisa et al. [23] briefly discussed security and privacy challenges in UWSN and IoUT. The authors of [24] outlined key enabling technologies, protocols, and localization for UWSNs and the IoUT. In [25], the authors comprehensively discussed the benefits of and challenges facing the IoUT and proposed mitigative solutions. In Table 2, we have summarized different studies on the IoUT. The complete layout of this study is shown in Figure 3.

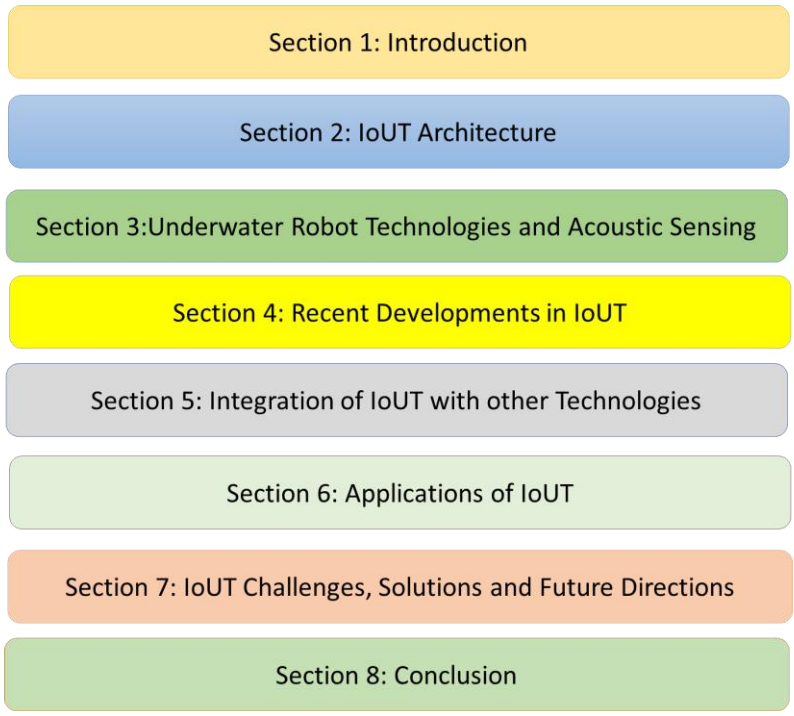

Figure 3. Organization of this study.

Table 1. IoUT Characteristics and Issues [12].

Characteristics and Issues	IoUT
Deployment	Mostly three dimensional
Transmission source	Acoustic signals
Transmission distance	~10 km
Transmission rate	~10's of kbps
Propagation speed	1500 m/s
Mobility	Controlled with AUVs, uncontrolled with water current
Reliability	Low
Delay	Long
Energy consumption	High
Device expense	High
Bandwidth	Low
Localization techniques	Expensive

Table 2. Research Contributions on IoUT.

Reference	Year	Research Contribution
[26]	2015	This article introduces a routing protocol, the "energy efficient enhanced channel-aware routing protocol" (ECARP), for use with UWSNs in the IoUT. The protocol would help to substantially reduce the cost of communications and enhance the network capacity.
[27]	2016	This study proposes a smart system using the IoUT and big data to analyze data received by portable sensors regarding water pH, conductivity, salinity, and temperature.
[5]	2017	This study discusses the differences between (terrestrial) WSNs and UWSNs. It also outlines channel models for the IoUT and their challenges and applications.
[28]	2018	This article addresses routing protocols for the IoUT, discussing the challenges they face and the relationships among them.
[29]	2018	This article focuses on IoUT system design and the challenges faced. It proposes a new prototype, "Smart IoUT 1.0", which can sense and gather ocean data.
[30]	2019	This study addresses the use of the IoT by underwater monitoring and environmental protection applications. It also discusses the application of big data, opportunities, and associated challenges.
[6]	2019	This article introduces a cloud-based platform for the real-time control and monitoring of smart cities via the IoUT. The proposed system ensures reduced energy consumption and enhanced data transmission.
[23]	2020	A systematic study which outlines future research directions to preserve security and privacy in UWSNs and the IoUT.
[25]	2020	This study comprehensively discusses the opportunities, as well as the challenges and associated solutions, of the IoUT in order to assist scientists and industrial players in exploring these areas.
[31]	2020	This study outlines technological developments in communication, localization, consumer electronics, and the IoUT. It also addresses critical challenges facing the design and implementation of the IoUT.
[32]	2021	In this review study, researchers discuss channel models for the IoUT. They survey different models including the ray-theoretical model, the parabolic equation model, parabolic equations, multipath expansion, and the fast-field model.
[33]	2021	This study discusses the IoUT, Big Marine Data (BMD), and the relationship between the two. It also outlines tools, techniques, and state-of-the-art applications of the IoUT. Moreover, it examines current machine learning (ML) approaches for BMD analysis.

2. IoUT Architecture

The IoUT is comprised of sensing and communication entities. These entities are generally referred to as sinks and nodes.

- Endpoint nodes are devices including sensors, cameras, hydrophones, actuators, and radio or acoustic tags.
- Mid-layer nodes are devices such as modems, gateways, repeaters, and relays.
- Sink nodes are located on buoys, ships, satellites, and at on-shore base stations. Generally, IoUT systems are based on several heterogeneous objects; hence, it is very important to introduce a flexible, layered system. Every layer has distinct capabilities in terms of scalability and operation. IoUT architecture is usually based on three layers, as presented in Figure 4.
- Perception layer: This layer is the lowest layer in the IoUT system architecture. It is based on devices such as monitoring stations, UAVs, surface links, GPS sensors, and energy harvesting elements. The basic tasks of actuators and sensors are to collect data and initiate actuation. The key functions of this layer are to obtain water parameters, to perform water quality monitoring, and to collect information about underwater objects or aquatic species.
- Network layer: This layer obtains data from the perception layer and processes it. It is based on wired and wireless links, remotely operated stations, a cloud platform, and the internet. It performs bi-directional data packet handling through internet protocols and data routing.
- Application layer: This layer is responsible for analyzing data using GUI-empowered front-end services. Its main objective is to identify sensors, i.e., their location, id, number, and type. Data collection includes sensing, tracking, storing and streaming information.

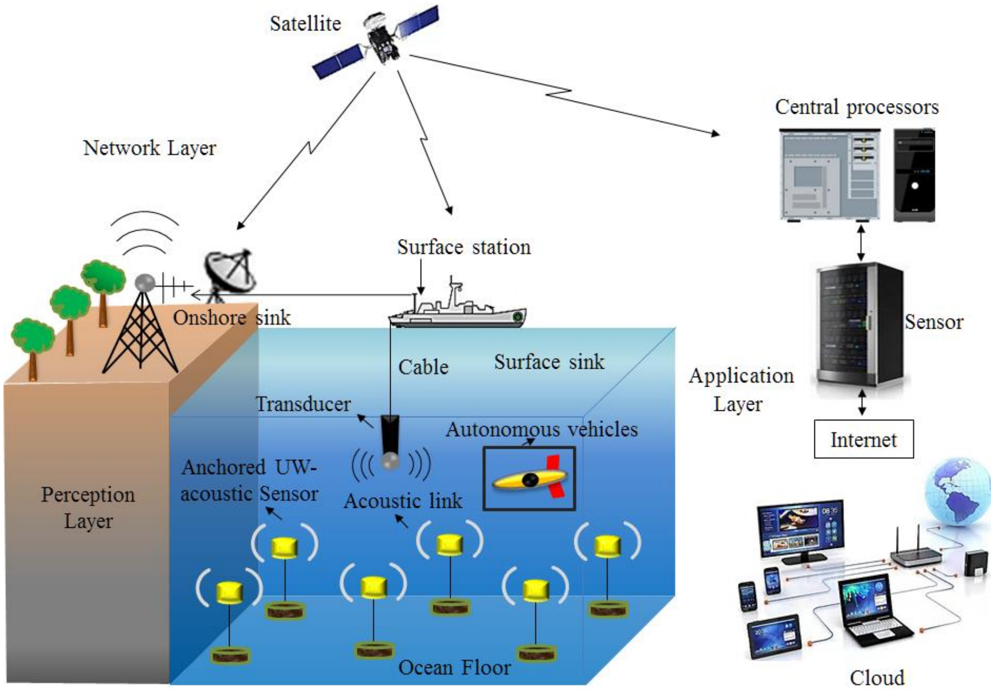

Figure 4. Standard IoUT architecture.

In [1], the authors proposed an IoUT system architecture based on perception, network, and application layers. Furthermore, Qiu et al. [34] proposed an IoUT architecture comprised of five layers, i.e., application, network, fusion, communication, and sensing layers. In this proposed architecture, the authors also added fog computing, cloud computing, and artificial intelligence (AI) features.

In [6], the authors proposed a cloud-based IoUT architecture that addresses security aspects. The authors discussed the incorporation of AI and ML solutions to handle object target and detection, secure data transfer, and quality of service (QoS). In another study [35], the authors proposed an IoUT architecture and ML-aided solutions to sense, transfer, and process data. We have summarized various IoUT architectures discussed in the literature. We have highlighted architecture layers and research contributions. In order to design a solid architecture for the IoUT, tracking, communication, and networking techniques must be considered. Table 3 illustrates several research contributions dedicated to IoUT architecture.

Table 3. Research on IoUT Architecture.

Reference	System Architecture, Layers	Research Contribution
[1]	Perception, network and application layer	The first ever IoUT architecture was proposed in this study. It also provides technical perspectives of the proposed architecture.
[6]	Cloud-based IoUT architecture	The proposed system addresses abovewater security challenges. It uses cloud-based monitoring centers to outperform traditional IoUT base stations. It is based on a monitoring center, sensors, sinks etc.
[21]	Software-Defined Opto-Acoustic Network Architecture	A hybrid opto-acoustic IoUT architecture is presented in this study. The proposed system provides the benefits of both acoustic and optical components.
[34]	Sensing, communication, fusion, networking and application layer	This study discusses system architecture along with fog computing, cloud computing, and AI.
[35]	Future maritime network architecture	The article suggests a maritime network architecture using the ML algorithm for data sensing, transmission, and processing.

Table 3. *Cont.*

Reference	System Architecture, Layers	Research Contribution
[36]	Perception, network and application layer	This study proposes a deep learning approach for image compression in real-time for the IoUT.
[37]	Named Data Networking (NDN) architecture	In this work, the authors propose a Named Data Networking (NDN) architecture to aid in the effective, secure, and simplified deployment of the IoUT.
[38]	Software-defined networking (SDN) architecture	A new software defined networking (SDN) architecture is proposed in this study which ensures reliable connectivity between network objects for QoS enhancement.

3. Underwater Robot Technologies and Acoustic Sensing

In recent years, underwater robot sensing technologies have received much attention in the fields of marine engineering and resource exploration [39]. Underwater robots rely on the capacity of the sensor technology to carry out several real-world tasks. Many countries have contributed to designing underwater robots. Each of the designed robotic platforms for underwater environment exploration requires a variety of sensors to obtain environmental information. Therefore, the development of sensor technologies has an important influence on underwater exploration. Acoustic sensing technology is frequently used in underwater environments, such as in pipeline monitoring, ship maintenance, marine engineering, and underwater robot localization and navigation. Based on sonar data, warships can quickly identify threats like torpedoes, submarines, and anti-submarine planes in military applications. In this section, we discuss some underwater technologies and sensing techniques.

3.1. Underwater Robots

Several types of underwater robots use IoUT systems, as shown in Figure 5. The "bluefin" Autonomous Underwater Vehicle (AUV), created by the US Navy, is capable of autonomous underwater navigation and object detection, while the "Peace 1" and "Peace 2" underwater robots developed in Russia are the only manned submersibles in the world which are capable of collaborative underwater exploration.

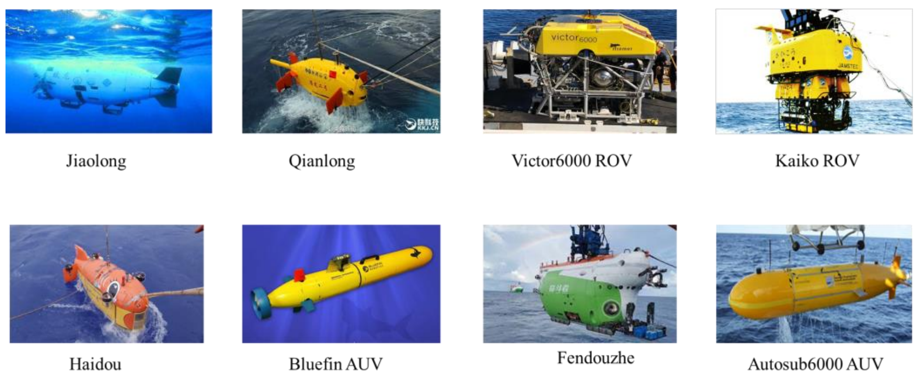

Figure 5. IoUT Robot Technologies.

3.2. Tools and Technologies for System Implementation in the IoUT

The "Deep C" AUV, an underwater vehicle designed in Germany and capable of descending to depts of 4000 m, can operate for 60 h in the deep sea, while the "VICTOR 6000", a cable-operated underwater robot developed in France, can capture a high-quality underwater optical images. The fully automatic "Autosub 6000" submarine designed in Britain has batteries and sensors to allow it to travel on its own. The "Kaiko" ROV, a deep ocean underwater robot developed in Japan, has made 296 dives and is equipped with a variety of underwater sensors.

Meanwhile, a lot of research on robot submarines has been undertaken in China; for example, the Shenyang Institute of Automation (SIA) developed the "Qianlong" and "Haidou" underwater robots. These are equipped with sonar, cameras, and lights and have performed different manipulation tasks at different depths, from the sea surface to the seabed. Furthermore, the China Ship Scientific Research Center, SIA, and other institutions developed the Jiaolong and Fendouzhe manned underwater submarines for deep sea exploration.

3.3. Underwater Acoustic Sensors

Underwater acoustic sensors can generally be divided into acoustic positioning sensors and acoustic ranging/imaging sensors.

3.3.1. Underwater Acoustic Positioning Sensors

Underwater acoustic positioning sensors can be used to find the position of a measured object, such as an underwater robot. Underwater acoustic positioning systems can be divided into the following three categories contingent on the length of the baseline: short baseline (SBL), ultrashort baseline (USBL), and long baseline (LBL).

USBL: The USBL determines the range and angle from the transceiver to the subsea beacon in order to determine the position of the latter. The transceiver, which has many transducers, measures angles. Typically, the transceiver head has three or more transducers spaced ten centimeters or less apart from each other.

SBL: The SBL system generally contains more than three transducers spaced at a distance of 20–50 m. By enlarging the distance, the measurement accuracy can be improved. However, the main drawback of these sensors is that they are difficult to calibrate. The SBL system typically has three transducers spaced at a distance of 20–50 m from each other. The measuring accuracy can be enhanced by extending the distances. The difficulty of calibrating these sensors, however, is their fundamental flaw. SBL systems are useful for tracking underwater targets from boats or ships anchored or at sea because they do not require equipment or transponders fixed on the seafloor.

LBL: LBL consists of a group of acoustic transponders placed on the ocean floor with known relative positions. With them, it is possible to localize robots within the range of the acoustic signal using at least three acoustic beacons with baseline lengths of between 100 m and 20 km. An underwater acoustic network must be deployed and collected regularly; therefore, the system becomes expensive to set up and maintain. The LBL sensor can attain high measurement precision and remains unaffected by water depth.

3.3.2. Underwater Acoustic Ranging/Imaging Sensors

Underwater acoustic ranging/imaging sensors consist of single beam sonar, multi-beam sonar, and side-scan sonar.

Single-Beam Sonar: The short-pulse acoustic signal from a transducer is picked up by the single-beam sonar, which calculates the depth of a submerged item based on the travel time. Due to its low cost and simplicity, single-beam sonar is frequently utilized in marine engineering and resource exploitation. On the other hand, it is unable to produce measurement findings with high precision and does not have broad coverage.

Multibeam Sonar: A multibeam sonar combines several single-beam sonars and can determine with high precision the direction and depth of a submarine object based on the travel time. The effectiveness of sea exploration is substantially increased by the ability of multibeam systems to cover a broader area of the bottom of the sea with greater speed and precision than single-beam sonars.

Side-Scan Sonar: Side-scan sonars are made up of submodules such as a control unit, towed body, cable, and recorder. They perform object searches and tracking in addition to topographic, geological, and mineral studies. A side scan sonar emits directed acoustic pulse signals with a vertical beam angle that is significantly larger than the horizontal beam angle. An object on the ocean floor can be located by examining the received acoustic image data. Side-scan sonar cannot measure the depth of a submarine precisely and can only roughly estimate its direction.

4. Recent Developments in the IoUT

In this section, we discuss some recent advancements in the IoUT in terms of communication, the role of AUVs in the IoUT, sea gliders, and satellite oceanography.

4.1. Communication in IoUT

Communication among the underwater objects of the IoUT is difficult because of the ocean's dynamic, harsh, and turbid nature. The main communication techniques used in the IoUT are MI, acoustics, optical, and RF waves. Generally, acoustic waves are vulnerable to high propagation delay, fading, narrow bandwidths, and high attenuation [33]. The major challenge for acoustic-aided underwater communication is high latency. RF-aided underwater communication is an alternative, as it can withstand turbulence. However, it has a limited distance range for 30–300 Hz frequencies. Using these lower frequencies, it is possible to achieve reliable communication. The conductivity of RF in seawater is very high. Therefore, it is difficult to establish a link via a very high frequency or ultra-high frequency at depths of greater than 10 m. Another critical concern is the large antenna size, leading to high cost and energy consumption.

On the other hand, optical-aided underwater communication ensures high data rates and lower latency. The channel performance is the major difference between RF and optical channels in the IoUT. An insulating material such as dielectric is used for optical channel propagation. Scattering and attenuation are low in the case of short-range communication. Thus, optical communication is reliable for communication up to 10 m and suitable for distances up to 100 m. Visible light communication (VLC) at wavelengths ranging from 450–550 nm is also used in the IoUT. It is effective at distances of up to 100 m, achieving a 500 Mbps data rate. It is very effective for short-range communication. Optical-aided IoUT is cost-efficient and easy to implementat, as it requires only a laser diode and photodiodes. Laser-aided IoUT offers high performance and improved energy efficiency. However, it is restricted by LOS requirements. Moreover, MI is also used to achieve a highly stable channel [40]. It is mostly used underground in seabeds. It can achieve a maximum distance of 10 m. MI can tackle latency issues and offers high transfer speed compared to acoustic approaches. Furthermore, MI-aided underwater communication can be secured by using small coils with non-visible and non-audible waves, which makes it suitable for naval and military applications. The communication technologies associated with the IoUT are summarized in Table 4.

Table 4. Communication Technologies used in the IoUT [41].

Characteristics	MI	Optical	RF	Acoustic
Transmission power	10^{-8} watts (W)	Megawatts (MW)	Megawatts (MW)	>10 W
Communication range, purpose	Deep-sea underground communication	Short range	Surface water communication	Long range
Bandwidth	MHz	≤150 MHz	MHz	1–100 kHz
Channel dependency	Conductivity	Scattering, turbidity, attenuation	Conductivity	Salinity, Doppler spread, Pressure, temperature
Antenna size	0.1 s	0.1 s	0.5 s	0.1 s
Frequency band	-	5×10^{14} Hz	30–300 Hz	10–15 kHz
Data rate	Mbps	Gbps	Mbps	Kbps
Communication range	10–100 m	10–100 m	10 m	km
Channel speed	3×10^8 m/s	3×10^8 m/s	3×10^8 m/s	1500 m/s

4.2. Role of AUV in IoUT

AUVs have emerged as key enablers of the IoUT which can meet the rapidly expanding demands of underwater observations. AUVs have the potential for mobility and energy storage. For example, AUVs have greater battery endurance than sensor nodes. AUVs can be used to link sensors to other devices or the internet. Below, we outline the role of AUVs based on reported studies.

4.2.1. Data Collection

Due to the dynamic and harsh underwater environment, it is challenging to develop energy-efficient routing protocols. Traditional approaches have high power consumption and an imbalance in energy consumption. In this regard, the authors of [42] stated that AUVs could substantially reduce both data collection time and latency.

4.2.2. Localization

Node localization is an important factor for the successful implementation of the IoUT and UWSN, as these technologies rely on location awareness. Node localization becomes extremely difficult due to underwater mobility, water stratification, and the absence of GPS sensors [43]. Localization is very important for optical-aided IoUT to ensure the provision of various services such as link connectivity, data tagging, routing, and navigation. In order to support localization, AUVs can be used to dive into the water to obtain location information. They offer high accuracy compared to traditional localization methods.

4.2.3. Void Challenges

Voids can significantly degrade the reliability and performance of any underwater network. They create difficulties in link connectivity and data delivery. AUVs can be used to overcome these problems. For instance, AUVs can be used to predict the routing voids to be repaired in any network [44]. AUVs can intelligently find critical repair tasks in any network using the Routing Void Prediction and Repairing (RVPR) algorithm [44].

4.2.4. Topology Optimization

The rapid mobility of underwater nodes severely impacts the network topology. Thus, it is critical to optimize network topologies in UWSN and the IoUT to reduce latency. In [45], the authors proposed a topology optimization strategy using AUVs. The proposed mechanism improves the robustness and adaptability of the network topology. Tests of the proposed mechanism show low energy consumption, low latency, and high reliability.

4.2.5. Multi-AUV-Aided Data Collection for Mission Critical IoUT

Two types of AUVs, i.e., V-AUV and H-AUV, are shown in Figure 6. H-AUVs travel horizontally to gather oceanic data from IoUT objects located on the seabed and forward that data to V-AUVs which, in turn, move vertically to forward the data received from the H-AUVs to a surface station. This smart strategy can reduce the frequent diving and floating mobility of H-AUVs by reducing energy consumption while providing uninterrupted data collection.

4.3. Sea Gliders

Internet-enabled devices provide an adequate communication link between nodes. These devices can be floating buoys, ROVs, AUVs, or moving gliders for underwater communication. Wave gliders [46] represent the IoUT nodes that gather data either on the sea surface or underwater via various sensors such as depth sensors, compasses, and hydrophones. For instance, a hydrophone array mounted on each glider is utilized to record underwater sounds. Sea gliders can provide oceanic parameter measurements over long ranges. The data gathered by the gliders is then forwarded to the data center using relay nodes such as satellites. The information is then extracted and distributed among certain users. The mobility of gliders is via electrically driven propellers. Sea-gliders can cover thousands of miles within the underwater medium for several months to achieve persistent observation, as sufficient power can be supplied from solar panels. These objects are used for GPS purposes and oceanographic data collection. The internal sensors in any sea-glider system determine the vehicle direction, while external sensors are used to scan the water for data collection. Furthermore, some sea gliders, such as acoustic wave gliders (AWG), are cost-efficient and can be expanded to the global ocean as a controlled station.

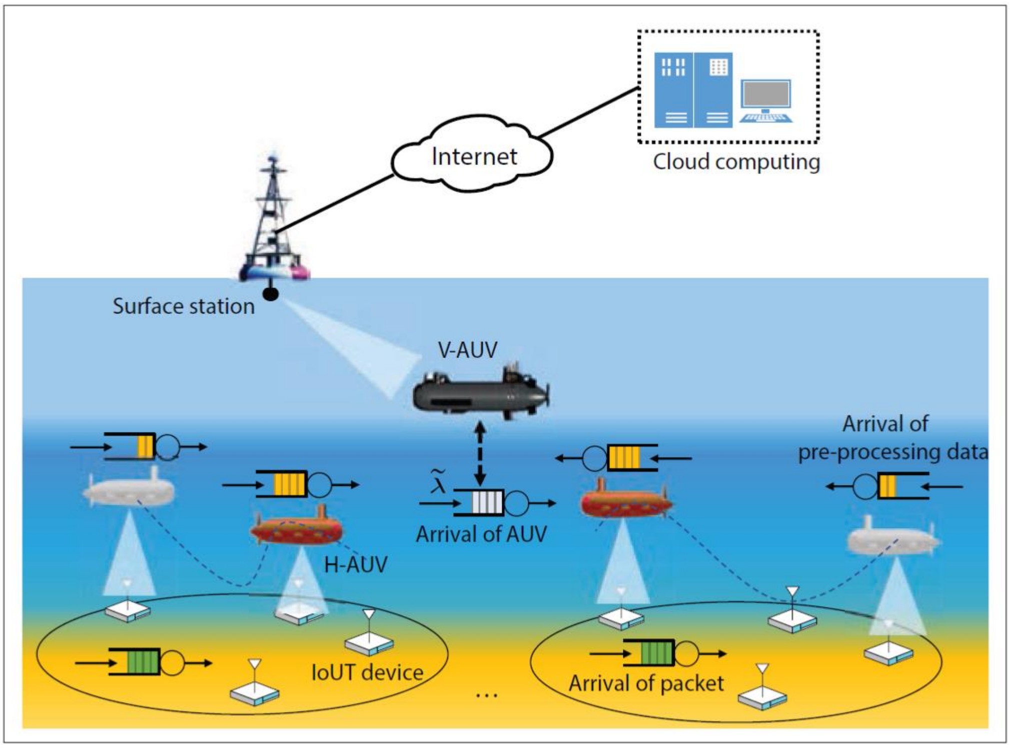

Figure 6. Multiple AUV-aided data collection [35].

4.4. Cabled Underwater Observatory Systems

Several cabled underwater observatory systems have been installed, such as the European Multidisciplinary Seafloor and water column Observatory (EMSO), Dense Oceanfloor Network System for Earthquakes and Tsunamis (DONET) in Japan, Ocean Networks Canada (OCN), and the Monterey Accelerated Research System (MARS) in USA [47]. All of these systems are based on sea-floor cables for both electrical power supply and data communication, offering expanded real-time monitoring related to hydrosphere, biosphere, and geosphere interactions. These are high-technology architectures hosting sensing devices to monitor seabed movements, water circulation, salinity, pH, temperature, etc. Thus, they can monitor both environmental sensing data and underwater acoustic data. These platforms also support services to the industrial sector and are a foundation of multidisciplinary ocean research. In this way, they provide opportunities for research and development as well as technological breakthroughs. These systems offer stability but not flexibility, i.e., they are expensive and difficult to move around.

As shown in Figure 7, MARS utilizes a 52 km underwater power and optical fiber to carry electric power and data to a node that is placed 891 m below the Monterey Bay surface which is linked to the shore through a cable [48]. Other nodes can be attached to this main hub, while further experiments can be performed on each node. DONET is a submarine real-time underwater observatory platform intended to observe tsunamis and earthquakes using 20 sets of submarine cabled instruments located 15–20 km apart with five science node interfaces [49]. OCN is based on two underwater observatories, i.e., the NEPTUNE (800 km) and the VENUS (50 km), along with seven shore stations and four community observatories [50]. It aims to offer live stream data from key sites off the coast of British

Columbia through the internet to users around the globe. OCN ensures environmental protection through these cabled observatories, big data management, interactive sensors, and remote-control systems.

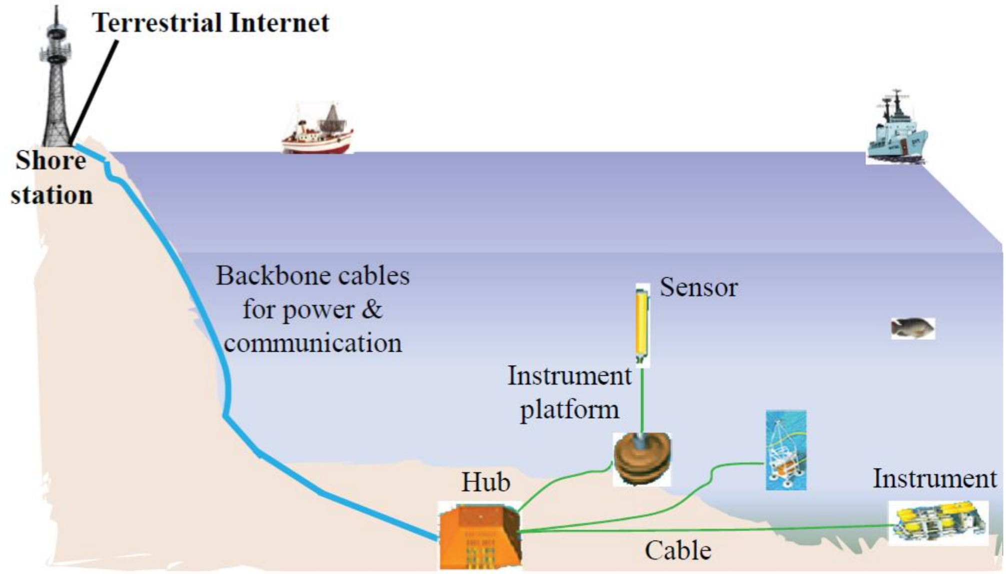

Figure 7. Overview of the MARS architecture [48].

Similarly, EMSO is a European scale network of multidisciplinary ocean observatories, comprising regional facilities located at key sites from the northeast to the Atlantic, via the Mediterranean, to the Black Sea. It provides consistent measurements of different physical and biochemical parameters related to the marine ecosystem, climate change, and natural hazards [51]. Furthermore, China is also actively preparing its China National Scientific Seafloor Observatory (CNSSO) with the Xiaoqushan Seafloor Observatory in the East China Sea [52].

4.5. Satellite Oceanography

In the IoUT, satellites are the most efficient means of communication; they play a vital role in sharing oceanic data with the base station. Moreover, they operate as a communication medium between offshore BS and underwater media to transmit information for further analysis. Satellites are used to measure ocean surface temperatures and weather patterns and to capture images. They can also determine the effect of earthquakes, floods, and tsunamis in disaster-stricken areas. The IoUT for remote sensing and smart satellites can be used for ocean observations and disaster prediction, making it possible to issue warnings to evacuate a potential disaster area. IoUT-empowered systems can analyze data about coastal inhabitants and coral reefs using satellite oceanography.

5. Integration of the IoUT with Other Technologies

This section discusses the integration of the IoUT with different technologies such as edge computing, data analysis, blockchain, optical wireless communication (OWC), and intelligent reflecting surfaces (IRS).

5.1. Edge Computing in IoUT

Edge computing was introduced in the IoT to replace cloud computing. In this technology, edge users perform computing tasks, so data transmission and communication appear to be less complicated tasks. Edge computing-empowered sparse data transfer seems to be absolute for the IoUT, as it faces a harsh and hostile underwater medium. In the IoUT, it is referred to as an elastic computing mechanism, where computing is performed by edge devices such as underwater end nodes. In the absence of edge computing, the process is performed by clouds, computers, or servers, which are insufficient for the IoUT. Edge computing has the potential to perform data collection, processing, and communication. The advantages of edge computing are high data rate, low latency, and quick decision-making capability [53]. In [54], the authors proposed an IoUT using edge computing, providing reliability, scalability, and reduced latency. In another study [55], the authors proposed an edge-IoUT architecture which offers good energy consumption and packet delivery performance.

5.2. Data Analysis in the IoUT

Rapid advancements and deployments of marine technologies to monitor and explore the underwater environment have led to the creation of extensive quantities of data, or big marine data (BMD). BMD are considered heterogeneous information collected from underwater platforms. This can be chemical, biological, or environmental data gathered from different sources, such as sensors, tags, drones, or cameras.

The distinctive features of marine big data, including incompleteness, complexity, and multi-source, surpass the storage and recovery capabilities of traditional systems. The existing literature on big data focuses primarily on how huge quantities of data can be detected and utilized more efficiently and reliably. The main problems reported in different studies are infrastructure, storage, security, analysis, etc. Researchers are working to find possible solutions to these concerns. In [56], the authors discussed big data and its ocean data management implications. They suggested a solution to establish collaboration between marine experts and data scientists. In another work [57], the authors proposed a support vector regression model to handle non-stationary, fluctuating, multi-noise, and abnormal data. In [33], the authors discussed applications, tools, challenges, and future directions for the IoUT and BMD.

5.3. OWC in IoUT

The main concern with using multiple IoUT objects is efficient communication. IoUT networks require high data rates, reliability, reduced latency, and high QoS. Existing IoUT networks use RF, acoustic, and optical waves for communication. Each technology has its pros and cons. RF waves are suitable for use on the water surface due to their high absorption. In contrast, acoustic waves suffer from high latency and low data rates. In contrast, optical waves can ensure high data rates in underwater communications. The optical band is suitable for high density and reliable IoUT networks. OWC offers unique benefits, i.e., high speed, low latency, secure communication, and low power consumption. OWC can efficiently sense, monitor, and distribute data in IoUT communications. Besides these benefits, OWC has some critical shortcomings; notably, suspended particles, temperature fluctuations, and heavy winds can degrade its performance. Moreover, misalignment is also a crucial problem in OWC communication [58]. Several studies have reported OWC-based IoUTs for underwater solid-state lightning [59] and self-powering and internet delivery to IoUT devices [60].

5.4. Blockchain in IoUT

In the IoUT, smart objects must be securely interconnected in order to avoid malicious security attacks. The research community has implemented blockchain technology in the IoUT due to software/hardware vulnerabilities, immature standardizations, and several security and privacy concerns. Blockchain is a decentralized and distributed technology which is capable of handling security challenges in the IoUT. It can securely and efficiently store IoUT data without any dependency on a third party. Blockchain entities can easily verify IoUT data and securely process them before adding them to the blockchain, removing third-party involvement in data processing. Thus, blockchains can offer functional resilience, immutability, and transparency and can reduce fraudulent activities. In [61], Hammi et al. introduced a robust, transparent, and energy-efficient blockchain-based IoUT mechanism. The proposed mechanism can substantially reduce energy consumption and end-to-end delay and can improve delivery rates. In [62], the authors introduced a lightweight blockchain-aided IoUT architecture to overcome data routing and scalability challenges, along with ensuring the legitimacy and privacy of IoUT data. Their research contribution validated the hypothesis that blockchain could enhance the security and QoS of IoUT networks. However, tackling IoUT big marine data (BMD) is still challenging.

5.5. Intelligent Reflecting Surfaces in IoUT

IRS is a novel paradigm in wireless communication which ensures the smart, secure, and reconfigurable propagation of radio waves. It refers to an array composed of multiple scattering elements to control the frequency, amplitude, and phase of any incident signal. IRS offers unique solutions to overcome interference and fading issues, along with enhanced spectral efficiency, reduced cost, low energy consumption, avoidance of antenna noise and self-interference, improved reliability and capacity [63], reduced complexity, low weight, and conformal geometry. It can easily be integrated in any environment.

In an underwater environment, acoustic wave propagation is possible at larger transmission distances. However, it suffers from suspended particles, uneven surfaces, and scattering, leading to reduced data rates and high path loss; IRS can be used to mitigate these challenging issues. Figure 8 presents an IoUT scenario employing IRS. IRS scattering elements can be useful to steer a signal in any intended direction, thus overcoming the multipath effect. IRS can be placed on any ship, AUV, or float below the water surface or can be connected to a ground station by wired media. IRS can be designed in a spherical shape to reflect impinging signals in all directions; this is a promising research direction for future breakthroughs.

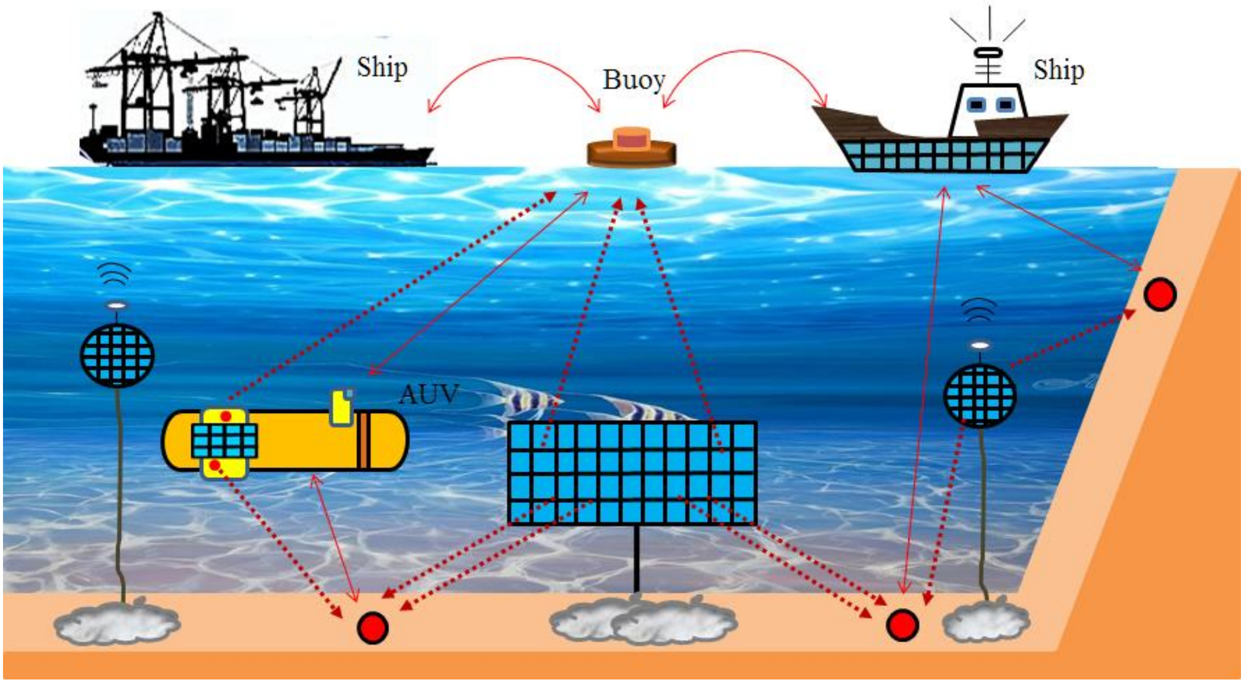

Figure 8. IoUT assisted by intelligent reflecting surfaces.

6. Applications of the IoUT

The research community has explored the IoUT in several application scenarios [37,38]. In [5], Kao et al. classified IoUT applications into five different areas, as shown in Figure 9. Moreover, the IoUT has shown its potential in water quality monitoring, remote sensing, pollution detection, oil and gas spill detection, tsunami prediction, aquatic research, and archeological expeditions. Next, we discuss these and other applications in detail.

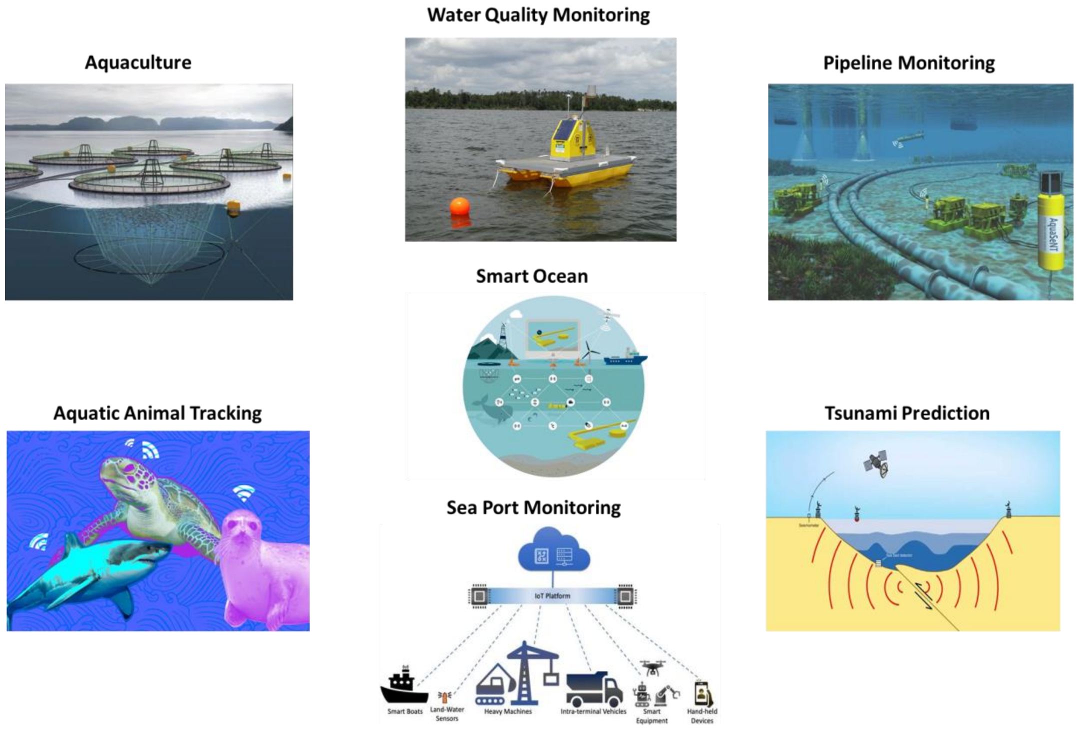

Figure 9. Applications of the IoUT (modified from [5]).

6.1. *Aquatic Animal Tracking*

Aquatic animal tracking can help significantly in efforts to preserve marine species. Generally, endangered and extinct animals are dangerous for humans. The disappearance of marine species can harm the ocean ecosystem and food chain. Previously, marine experts used to have to catch animals to retrieve data from attached tags. However, the IoUT has the potential to overcome this challenge. IoUT systems use acoustic tags, which have better performance as compared to radio waves. Ocean buoys are linked with these tags and forward the received information by using satellite communication. However, marine scientists and industrial experts should be careful to use this technology without harming the ecosystem and marine species. In addition, IoUT objects such as mobile transceivers can also be used on aquatic animals for accurate and real-time tracking. As these animals travel in oceans, the integrated transceivers can collect data on their movement and record data regarding other species in their proximity. These data include information about geographic location, pressure, temperature, heart rate, and speed and can be used for intelligent decision-making policies for the conservation of marine species. Similarly, pop-up satellite tags have also emerged as a promising technology. These tags detach from marine species after a certain duration and float to the ocean surface where marine experts and conservationists can easily collect them to retrieve data.

6.2. *Environmental Monitoring*

Human activities severely damage the marine environment. Consequently, environmental monitoring via IoUT and UWSN, e.g., of water quality, chemical pollution, biological changes, climate changes, thermal pollution, and oil and gas spill monitoring, has become a promising research domain [64]. Among these environmental challenges, water pollution is critical, as it can cause several diseases in animals and humans. Climate change has alarmed marine experts and brought about a need for extensive environmental monitoring. Timely prediction of water pollution can help in taking precautionary measures against any possible critical concerns. The conventional approach to monitor the marine environment is expensive and time-consuming.

In contrast, UWSN and the IoUT offer real-time monitoring, autonomous missions, easy installation, and low cost. Smart environment systems are being developed mainly to monitor water conditions [27]. In [65], the authors reviewed several studies on water pollution monitoring. Similarly, the authors of [66] briefly discussed WSN approaches for ocean monitoring, describing several projects, techniques, and algorithms. That study also addressed challenges and opportunities in the field of marine environmental monitoring. In another recent study [30], the authors discussed the potential application of the IoT and Big Data in marine environment monitoring.

Water Quality Monitoring

Water is an important element; its characteristics can decide the survival of plants and living creatures, including humans and animals. However, ocean ecosystems and other water resources face shortages and pollution issues. At present, the lack of sufficient measures to protect water resources is a critical challenge around the globe. Water quality suffers from waste discharge and the release of deadly chemicals [67,68]. Thus, it is crucial to preserve water quality and protect water resources by monitoring [69]. There is a need to introduce effective management practices for sensing and collecting water information to preserve water sustainability [29,64]. For this purpose, sensing devices are placed in water to collect data, which are then forwarded to host nodes. Biological, chemical, temperature, and pressure sensing devices are used to determine water quality parameters. Such devices can also measure pH, turbidity, salinity, conductivity, oxygen level, etc. These measurements can help marine experts and regulatory bodies to take immediate actions to preserve water quality. In this regard, the IoUT is an indispensable tool to control water quality via the use of smart devices, processing units, and sensors. IoUT objects substantially reduce labor, installation, and maintenance expenses by introducing autonomous missions for water quality monitoring. A recent study focused on efficient resource utilization such as energy harvesting and data transmission optimization [70] in WSN to monitor water quality. In [71], the authors discussed the role of artificial intelligence and big data analysis to control and monitor the quality and situation of the oceanic environment. In [71], the authors demonstrated underwater sensor-based IoT systems for water quality monitoring. A water quality system based on the use of a surface buoy, battery, antenna, sensors, etc., is illustrated in Figure 10. The proposed system is used to measure pH, oxygen level, salinity, temperature, and water depth.

6.3. Military

The military of any country ensures its safety against possible underwater or terrestrial attacks. Global regulations are in place to avoid interference in the ocean territories of each country with a coastal border in order to avoid any conflict. There is a global responsibility to protect ocean transportation, secure harbors, safe routes, and the safety of underwater communication and species. The IoUT is now of paramount significance in naval missions, including submarine tracking, mine detection, underwater navigation, and surveillance. In [73], Kao et al. discussed different challenges and applications of the IoUT in this regard.

Similarly, the authors of [74] designed an underwater mine detection system. They carried out analysis in terms of the security, speed, fuel consumption, and detection accuracy of their proposed system. Furthermore, a UWSN system is proposed in [75] to enhance surveillance coverage.

6.4. Powering Underwater Devices [59,60]

Batteries are widely used to power underwater devices. However, the batteries used on underwater objects such as AUVs need recharging and replacing, which is a laborious, non-scalable, and expensive task. Moreover, underwater charging is inefficient and difficult due to the dynamic mobility of nodes. IoUT sensors depend heavily upon batteries, which means they must be gathered, recharged, or removed from time to time. Due to the rapid advancements of the IoUT and its functionalities, the corresponding labor and cost will be increased. Thus, researchers are finding alternative approaches to recharge batteries using optical, acoustic, and ME resources. Optical, ultrasonic, acoustic, and EM resources to overcome charging issues in IoUT are discussed in [76–79]. Recharging through EM waves require strict alignment between transceiver coils. In contrast, low attenuation makes acoustic waves better than EM induction. Thus, the ultrasonic approach is feasible for charging underwater nodes distributed over wide distances. In [77], researchers demonstrated a charging platform employing an ultrasonic connection for the IoUT that can be charged using acoustic waves, thereby removing the need for batteries. As shown in Figure 11, it was the first battery-less system to succeed in charging sensor nodes using ultrasonic energy transfer. Researchers have also focused on other wireless power transfer (WPT) methods to recharge underwater devices, such as simultaneous light wave information and power transfer (SLIPT). This has been shown to be a cost-efficient approach to recharge remote sensors. In [79,80], the authors proposed powering solutions for IoUT objects to overcome energy issues. In some recent studies [81–83], different undersea energy harvesting methods are discussed in detail.

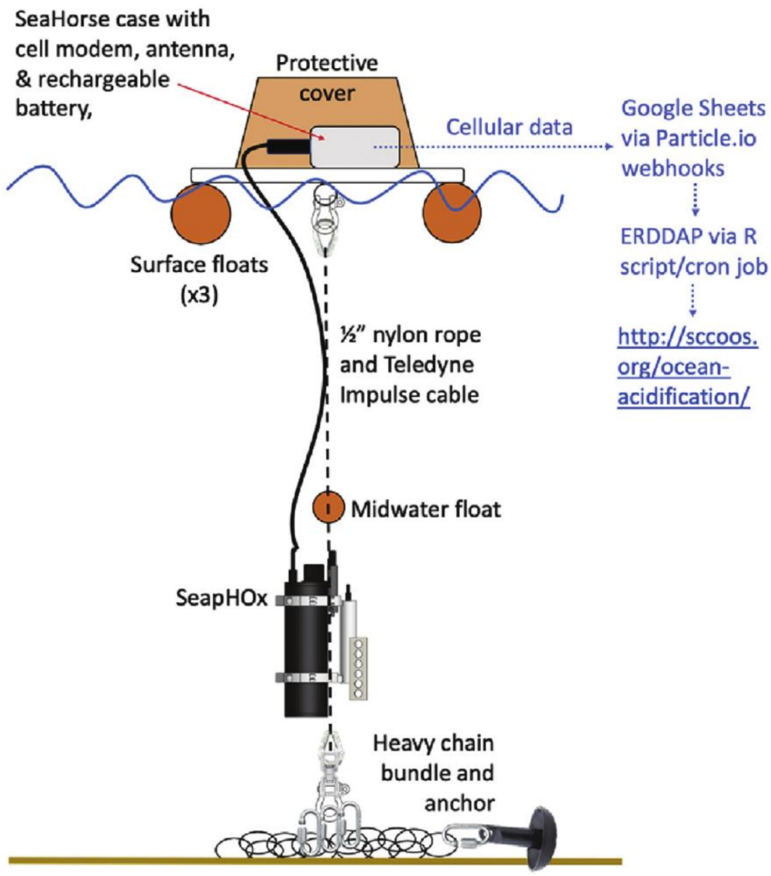

Figure 10. Water quality monitoring system [72].

6.5. Underwater Pipeline Monitoring

The economic benefits of underwater pipelines to deliver gas, oil, and water have led multiple companies to introduce novel designs for oil and gas detection [84], fracture control [85], safety assurance against fracture [86], secure underwater pipeline architectures, and the decommissioning of these facilities in an environmentally sound manner [87]. An efficient monitoring system can effectively support the inspection process for pipelines. Sensors and AUVs can be utilized together for the inspection of oil and gas spills. Such sensors are integrated onto the inner and outer sides of pipelines. The inner sensors can measure pressure and speed, while outer sensors can be fixed or float freely. Localization methods are used to determine the location of these sensors. AUVs are also used to obtain pipeline data; however, locating sensors and AUV navigation remain substantial challenges [88]. Divers can also find pipelines to repair them; however, they face stress and risk due to high pressure, water currents, and low visibility. In this regard, an Underwater Augmented Reality (UWAR) system [89] could be useful for tracing the location of and repairing pipelines. Advanced augmented reality (AR) features have the potential to support divers by enhancing visibility. Acoustic tags are also used when visibility becomes a major concern in dark zones. Additionally, divers can use OWC systems and acoustic phones to transmit important information in the form of audio texts in the marine environment. In [90], the authors presented various architectures of sensor networks for pipeline monitoring and briefly highlighted the pros and cons of each approach.

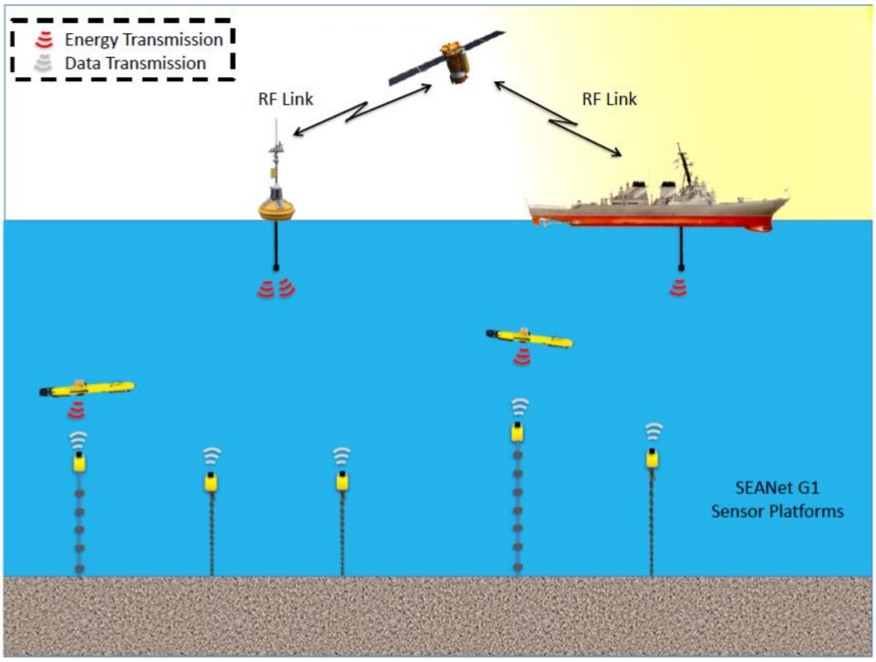

Figure 11. A battery-less IoUT system [77].

6.6. Smart Ocean

The smart ocean concept [34] has gained significant attention from industrial bodies, research groups, and government bodies. The term smart ocean may be utilized to describe underwater operations such as smart ocean pollution monitoring, the smart marine industry, smart cleanup operations, the smart ports market, smart ocean renewable energy, smart deep sea observation, smart underwater navigation, smart underwater resource exploration, the smart blue economy, smart underwater tourism, smart disaster warning, smart surveillance, and smart underwater intrusion detection. It helps ocean researchers to understand dynamic and harsh ocean environments, efficiently use ocean resources, ensure secure and reliable ocean transportation, monitor ocean resources, and, more broadly, to secure the ocean, as well as serving as a regional resilience monitoring network [91]. The IoUT is a key enabler of smart ocean systems. Smart ocean also depends on IoUT-related research domains such as ocean standardization, underwater wireless communication, underwater networking, cooperative computing, and security. Wang et al. [92] described the fabrication, hardware design, and experimental simulation and testing of a robotic IoUT architecture to contribute to smart ocean infrastructure. Similarly, the authors of [93] demonstrated a secure and efficient data collection, transfer, and storage method based on the IoT for smart ocean applications. Several studies have been reported on IoUT-empowered smart ocean developments contributing to protecting marine life, enhanced marine safety, building partnerships among coastal communities, and clean marine shipping.

6.7. AUV-Assisted Underwater Observation [94]

The demand for secure, low-cost, and user-friendly instrumentation is a limiting factor in ocean observation [95]. Most available marine observation equipment is hard to deploy and monitor, costly to operate, and needs specific technical skills. In this regard, AUVs are capable of allowing the IoUT to meet the rapidly growing demands of ocean exploration and underwater observation. It is envisaged that AUVs will play a vital role in this regard due to their unique features of mobility and energy storage. For example, AUVs have an extended life span compared to sensor nodes, allowing them to support extended underwater missions. AUVs have several applications, such as underwater pipeline monitoring, commercial fisheries, oil and mineral extraction, communication, de-mining, and securing port facilities. AUVs outfitted with sensing devices can examine underwater resources and collect data for collaborative monitoring missions. These missions include strategic inspection, disaster anticipation, and offshore investigations. In [96], the authors stated that the trajectory planning of AUVs is the main element influencing the efficiency of routing in the IoUT. Notwithstanding their benefits, the energy constraints of AUVs for mobility make it difficult to achieve high levels of data exchange due to harsh underwater conditions and the instability of acoustic channels.

6.8. Disaster Prevention

Given the damages caused by floods and tsunamis, disaster prediction has become an important application of the IoUT. It has huge significance in preserving both animals and humans against any possible calamity. The IoUT has gained attention in efforts to prevent such calamities through the provision of warning services, early disaster prediction, earthquake and tsunami detection, and seismic monitoring. Several projects have been implemented for ocean observation [49,97]. The DONET real-time seafloor observatory was developed to monitor earthquakes, geodetics, and tsunamis in Japan in real time [97]. In [98], the authors introduced Spain's real-time flood monitoring platform. The proposed system is energy efficient and robust. Furthermore, the authors of [99] proposed an efficient mechanism based on seismic pressure sensors for tsunami detection. Another study [100] was dedicated to humanitarian applications. That study discussed disaster mitigation, global warming, and accessibility to scientific data. The IoUT can be helpful in humanitarian applications such as search and rescue and other catastrophic incidents. Underwater humanitarian applications are illustrated in Figure 12. The IoUT can be used for cost-effective ocean missions and efficient underwater communication via robust underwater sensors, fault-tolerant devices, and eco-friendly floats.

6.9. Aquaculture

In efforts to fulfill future demands for seafood, aquaculture is currently one of the most rapidly growing food industries in the world. For example, the industry is expanding through the introduction of smart aquaculture farms of seaweed and shellfish, which are becoming a major source of income in several countries. However, due to the rapidly growing number of aquaculture farms, environmental damage due to vessels navigating the coast is increasing and morale in the fishing industry is suffering. Thus, it is essential to ensure the reliable navigation of vessels, the protection of fishery property, and enhanced operational efficiency of fisheries. Another concern is finding the location of aquaculture farms in the ocean. To this end, researchers are using satellite oceanography and aerial images [101–104] to investigate the status of aquaculture farms for their management, planning, and security, and to obtain fish telemetry data and increase location awareness.

The IoUT for aquaculture represents a modern integrated architecture empowered by communication techniques such as smart information processing, reliable telecommunication, and smart sensors which can gather and process data, predict future trends, and provide early warnings of changes to protect marine species. With the advancements in the IoUT, this approach has become an integral part of aquaculture in several countries. IoUT nodes are placed in different regions of aquaculture farms in order to gather data.

However, forwarding these data from IoUT sensors to a remote data processing center comes with high installation and maintenance costs. IoUT sensors can be used to digitally observe the distances between ships and aquaculture farms to ensure safety. IoUT-aided wireless communication can be used for water quality monitoring, thereby supporting intensive aquaculture farming. However, it has some negative impacts due to its unstable performance, high cost, and redundant functions; as such, further research is needed to develop cost-efficient strategies. The IoUT has shown its potential in aquaculture and fishing for environmental monitoring, such as temperature and water quality monitoring. It offers several advantages in terms of reduced management of aquaculture farms, minor losses, better environmental outcomes, cost reduction, better quality of sea products, and the smart design of aquaculture farms. A theoretical smart aquaculture system is shown in Figure 13.

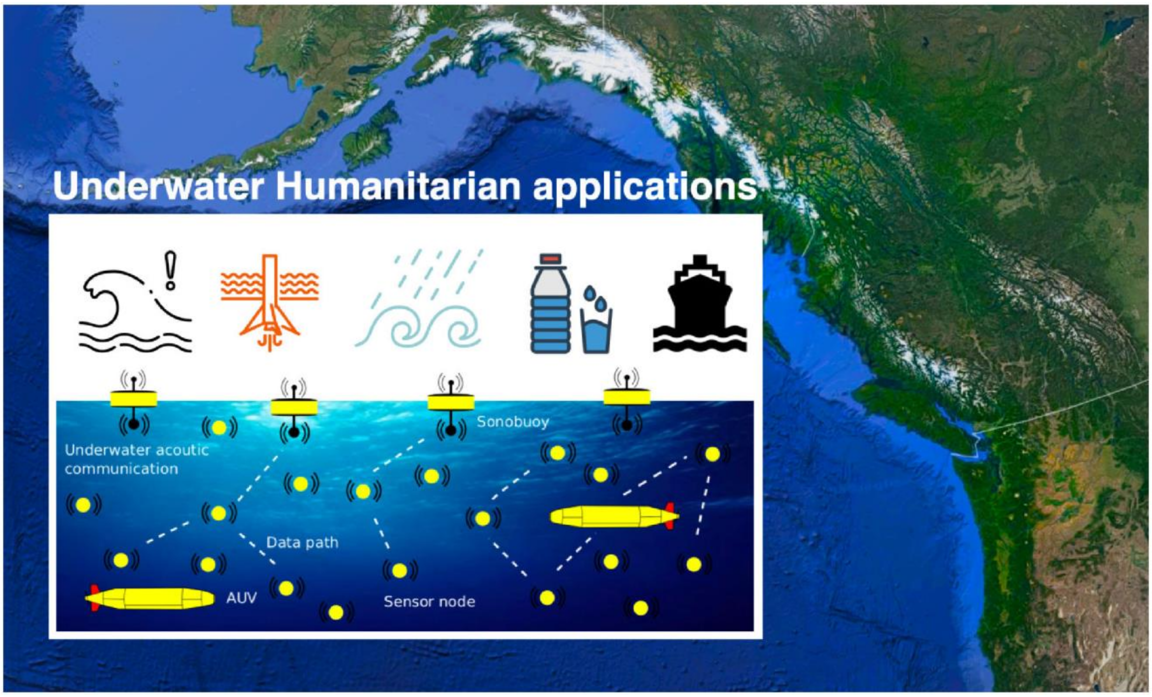

Figure 12. Example of underwater humanitarian applications [100].

6.10. Harbor Monitoring

With enhanced globalization, harbors and ports have become integral to world trade and ocean transport. As ports are expanding, there is a need for manageable, secure, highly efficient, and safe services. In this regard, underwater surface networks, along with autonomous vehicles such as ASVs and AUVs, can greatly aid in monitoring harbors. Underwater networks include satellites, ships, airplanes, drones, AUVs, and ASVs. Stationary platforms such as surface buoys and offshore monitoring centers also contribute to reliable harbor inspection. A large number of sensing devices have been placed throughout the ocean to monitor vast areas. Wired links and metal pieces are used to place these sensors at various depths to measure ocean parameters. The measured data are sent to surface sinks, which forward the data to an onshore processing facility via radio waves. These sensors are used to carry out different missions such as detecting intruder submarines and generating alert messages to AUVs. Acoustic sensors are also significant for harbor monitoring and surveillance. Acoustic sensors can be placed on piers, quays, and seabeds to detect moving vehicles. Optical sensing technologies are also used to detect potential targets by illuminating them with optical beams. Light detection and ranging (LiDAR) [106–108] technology also plays a vital role in surveying approaching ships in order to detect any illegal or explosive material. Underwater laser imaging technology also contributes to detecting suspicious object and alerting command centers. Underwater robots are used to capture images and videos and forward them to multimedia centers via acoustic sensors. The collected data are useful for tactical and coastal surveillance. In [109], the authors proposed imaging technologies, such as infrared (IR) sensors that can be used for underwater surveillance to monitor suspicious incursions that are difficult to trace. Recently, cloud computing has emerged as a suitable, cost-efficient option to perform these inspection tasks. As vast quantities of data are collected by underwater sensors, making them difficult to store locally, cloud storage is used. These data can be easily accessed by harbor monitoring staff, ship owners, surveillance ships, defense personnel, and ferry passengers, as necessary. Such information can be helpful for ocean traffic monitoring and to avoid collisions between ships.

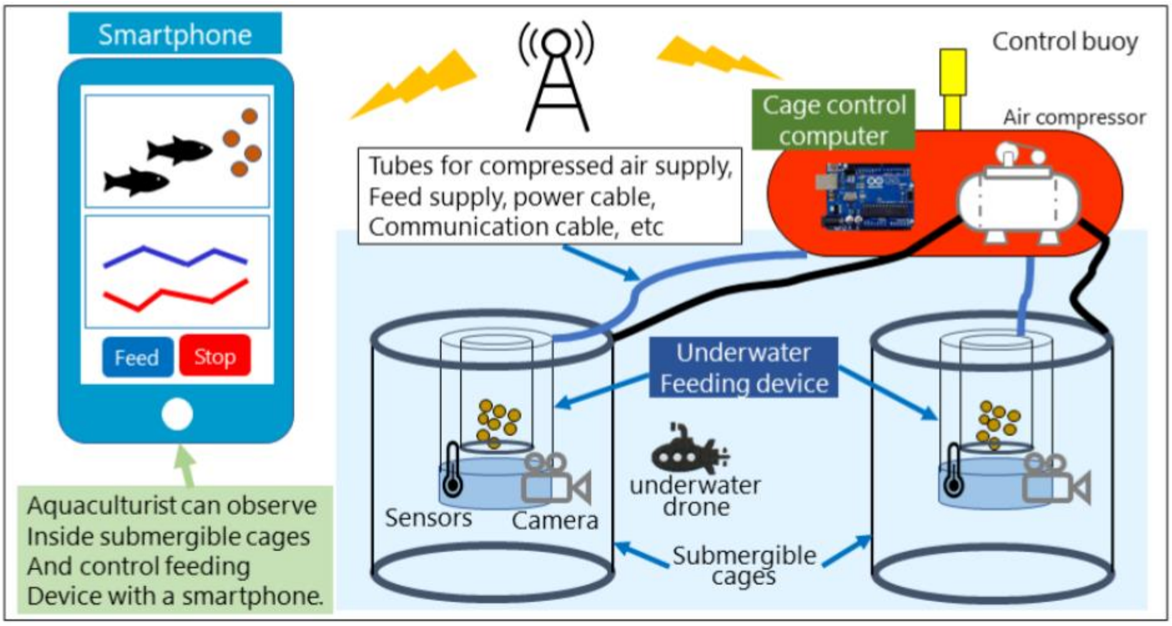

Figure 13. A theoretical smart aquaculture system [105].

7. IoUT Challenges, Solutions, and Future Research Directions

The research studies described herein have highlighted several challenges facing the IoUT. These challenges are mainly due to the differences between terrestrial wireless sensor networks (TWSNs) and UWSNs. Firstly, UWSNs rely on acoustic waves. Secondly, the speed of acoustic channels is lower than that of radio communication due to narrow bandwidth, which makes end-to-end delay a critical issue for UWSNs. Thirdly, UWSN has a longer transmission distance than TWSN, giving rise to interference.

Moreover, the IoUT also faces critical issues in terms of the dynamic topology of the ocean, energy efficiency, the unstable underwater environment, and low link reliability. Table 5 summarizes the differences between TWSNs and UWSNs. Several studies [1,5,110–112] have highlighted issues such as reliability, dynamic topology, the dynamic underwater environment, energy consumption, narrow bandwidth, channel overhead, data transmission, handover prediction, and long propagation delay. Below, we outline several critical challenges facing the IoUT.

7.1. Communication

Different technologies are used for communication in underwater environments, such as optical, RF, and acoustic waves. The use of EM waves including radio waves predominates in communication technologies outside water, as they provide high bandwidth, low power, and longer transmission range. In contrast, EM waves suffer from absorption and limited transmission range in seawater. To be used under water, EM waves need a great deal of power and large antennas. Acoustic waves show better performance under water, achieving transmission distances of over a hundred kilometers. Acoustic waves are also used to achieve omnidirectional communication. However, this approach suffers from low data rates, path loss, noise, multipath, Doppler spread, and high propagation delay.

Table 5. Differences between TWSNs and UWSNs.

Parameters	TWSNs	UWSNs
Link reliability	Dependent to application	Low
Nodes mobility	Dependent to application	High
Recharging	Dependent to application	Difficulty
Transmission speed	~250 kbps	~10 kbps
Transmission range	10–100 m	100 m–10 km
Propagation speed	300,000,000 m/s	1200–1500 m/s
Transmission media	RF waves	Acoustic waves
Power source	Solar, battery	Battery
Propagation delay	Low	High
Device mobility	Static and mobile	Static and mobile
Location error rate	Low	High
Signal bandwidth	High	Low
Anchor	GPS-based	AUV
Noise interference	Low	High
Efficiency	High	Low
Dynamic topology operation	Low	High
Energy consumption	Low	Very high

Optical waves have some distinctive properties and features compared to acoustic or RF waves. Their use is limited to short distances, but they offer higher data rates, i.e., in Gbps. OWC systems have cost-efficient architectures and are simple to deploy. A recent study investigated the multipath attenuation effect in an optical communication-based IoUT network [113]. Hybrid communication technologies for IoUT networks represent a promising field of research. Such technology could enhance the reliability, battery life, and transmission speeds of IoUT systems. Table 6 summarizes the differences between various underwater communication technologies.

Table 6. Differences between underwater communication technologies.

Characteristics	MI	Optical	RF	Acoustic
Magnetic induction	Mb/s	10^1 m	High data rate	Short transmission distance
Visible light communication (VLC)	100 Mb/s	10^2 m	Low cost and high data rate	High scattering
Radio waves	Mb/s	10^2 m	Low consumption and high data rate	Multipath interference, short transmission distance
Channel dependency	Conductivity	Scattering, turbidity, attenuation	Conductivity	Salinity, Doppler spread, Pressure, temperature
Acoustic waves	kb/s	10^3 m	Short distance and low attenuation	Interference, low data rate

7.2. *Energy Storage and Consumption*

Energy storage and utility are critical concerns in TWSN, UWSN, and the IoUT. In the IoUT, acoustic and optical communication channels require significantly more power than RF communication. IoUT nodes are designed with limited memory space, computational capacity, and battery power. These nodes require a lot of power to collect, process, and transfer data. Moreover, energy harvesting is difficult due to the impossibility of using solar power in the IoUT environment. Due to the natural behavior of the IoUT environment, it is difficult to maintain or recharge such systems. This has the potential to reduce battery life and cause data loss. Conventional batteries are unable to satisfy these demands and require regular servicing. As traditional energy sources and optimization methods cannot satisfy the energy requirements of IoUT, energy-efficient algorithms are needed to enhance the lifetime of networks. Energy sources are usually limited for IoUT nodes. Such sensors are equipped with batteries with limited energy capacities [114]. In an underwater environment, it is risky to recharge or replace batteries. Consequently, low battery endurance can result in node failure, and underwater missions may be delayed or stopped. Thus, researchers are looking for alternative solutions for energy harvesting in IoUT networks. To overcome these energy challenges, wireless power transfer techniques or solar energy [62] can be used to prolong the lifespans of IoUT networks. Additionally, researchers have suggested deploying battery-less nodes, WPT, and autonomous recharging methods to overcome the aforementioned energy problems.

7.3. Mobility and Reliability

Generally, IoUT networks include static and dynamic nodes. Static nodes have a fixed location while dynamic nodes can move from one position to another. However, the motion of water particles, sediment formation, internal waves, and water currents severely influence the location and topology of underwater sensor nodes. These mobility challenges are more critical in shallow water than in deep water. Such challenges tend to result in higher latencies and broken connectivity, leading to delays, data transmission errors, or the failure of the network. Thus, researchers are focusing on novel mobility models to tackle these challenges.

7.4. Transmission Medium

Communication technologies such as EM waves, acoustic, radio, and optical waves each have distinct characteristics in terms of underwater transmission distance. For instance, acoustic signals are mostly preferred for longer transmission ranges in underwater settings. However, acoustic signals are useful for low data rate applications. Meanwhile, optical waves are emerging as a promising alternative due to their enhanced data rates. However, optical waves also suffer from low transmission range and strict line-of-sight (LOS) requirements. The aforementioned factors show that the transmission range for IoUT networks must be considered for any particular application scenario. For example, optical communication can be considered for applications with high data rates and low latency for short distances. On the other hand, acoustic communication can be used for long-range applications with higher latency and lower data rates.

7.5. Latency

Latency is a critical concern for the successful implementation of IoUT. Currently, IoUT systems mostly use acoustic signals with low transmission speeds for underwater communication, in contrast to the terrestrial IoT. This has a severe impact on the real-time deployment of the IoUT. In contrast, optical communication systems can ensure real-time deployment of the IoUT due to the lower latencies that they offer. However, optical modems for the IoUT require considerable further study.

7.6. Sparse and High-Maintenance Sensing Devices in the IoUT

IoUT sensing devices are sparsely distributed, and environmental conditions severely impact their performance. The nature of the ocean and sparse deployment result in high maintenance costs for IoUT networks. Explicitly, maintenance should tackle the challenges of erosion, corrosion, sediments, and pollution. A compelling approach to lower the maintenance costs of IoUT networks is to introduce self-manageable capabilities [115] such as self-evaluation, self-adjustment, self-configuration, self-storage, self-charging, and autonomous reports to operating bodies. In this regard, machine learning (ML)-aided solutions for self-management and decision-making solutions are emerging research topics.

7.7. The IoUT for Humanitarian Applications

Current humanitarian applications in the underwater environment are based on limited UWSN architectures. One crucial challenge in this domain is developing an IoUT system which can intelligently and autonomously collect underwater data for smart predictions about tsunamis or earthquakes. In this regard, the DARPA's Strategic Technology Office has started an Ocean of Things funding program to develop analytical solutions for large-scale and high-resolution underwater sensing [100]. These data analysis methods can process and evaluate data as required. This program also includes the design and deployment of underwater floats to sense and record ocean parameters such as pH, pressure, temperature, dissolved oxygen, etc. These floats have communication and energy harvesting features along with data collection capabilities. Moreover, they have the potential to significantly improve performance in terms of sampling rate, mobility control, reduced biofouling, and energy consumption. Apart from these advantages, several issues must be considered for in humanitarian applications of the IoUT, including data aggregation and routing, energy efficiency, smart deployment, stable connectivity, and enhanced coverage. Opportunistic or routing and void-control solutions can be adopted to control and enhance the network performance. To overcome the daunting challenge of connectivity, topology control algorithms [116] to move underwater nodes from shadow zones to deeper areas can be used. Such depth control solutions can support reliable network connectivity and enhanced coverage. In this way, earthquakes or tsunamis can be detected in a timely manner to prevent catastrophic incidents. Moreover, marine experts should develop novel mechanisms for packet reduction in the IoUT, as this could substantially reduce energy consumption, thereby prolonging the lifespan of IoUT networks for underwater humanitarian applications.

7.8. IoUT Security and Privacy Issues

In general, acoustic communication and long propagation delays make UWSNs weak. Moreover, it seems difficult to use current access control, privacy, and security methods for UWSNs. Thus, it is important to design novel security mechanisms [58,117]. Existing security mechanisms cannot guarantee secure network services due to a lack of standardizations, security features, and privacy strategies [34]. A secure encryption strategy can pave the way for an IoUT with low computational overheads. The IoUT faces several critical concerns, such as flooding, spoofing, blackholes, sinkholes, Sybil, wormholes, and jamming [23]. When faced with such attacks, network data can be stolen, but complete network failure can also occur. In addition, sensitive data can be stolen during communication between nodes through tapping or eavesdropping attacks. In this regard, mutual authentication methods are used to preserve data authenticity and tackle eavesdropping. Furthermore, blockchain-aided solutions [118,119] and encryption techniques can also be implemented to ensure data availability, integrity, authenticity, and confidentiality. In our opinion, the development of robust and strong security mechanisms for the IoUT is a promising research direction. These security mechanisms can integrate high-level security architectures and confidentiality, integrity, availability, and quality of service (QoS) features to protect IoUT nodes from possible threats like denial-of-service (DoS), routing, spoofing, and jamming.

Similarly, data privacy is another primary concern for the IoUT, as it is based on sensitive data in naval and military operations, e.g., identity and position sharing and submarine tracking. In such circumstances, it is difficult to implement the privacy techniques used with the terrestrial IoT, such as k-anonymity, 1-diversity, t-closeness, and differential privacy. Therefore, preserving privacy in the IoUT is critical [120].

7.9. Reliable Multihop Transmission Control Protocol

In the case of mission-critical IoUT, as much data as possible should be sent in a multihop manner, as the interference, noise, and fading in the underwater environment will severely degrade communication reliability. Consequently, it is hard to satisfy the desiderata of the required IoUT mission. Thus, it is crucially important to take data rate and security into account in order to conceive high reliability in multihop transmission control protocols to support large-scale heterogeneous networks. Artificial intelligence [121], machine learning, and reinforcement learning and related approaches [122–124] are good solutions to tackle large-scale control decision optimization issues in complex environments.

7.10. Lack of Standardization

In order to achieve interoperability, the IoUT needs to be subject to stringent regulations and standardization. Currently, there is a lack of standardization in the IoUT, and the heterogeneity of IoUT objects, technologies, and applications is a major issue. This issue needs to be overcome to meet the interoperability requirements of IoUT network entities. Academics and regulatory bodies should introduce proper standardizations for IoUT objects, applications, and services which also ensure privacy and the security of sensitive data.

Acoustic Protocol for the IoUT

For decades, the global standards defined for cellular networks and WiFi have facilitated data exchange via radio waves. However, these standards cannot be implemented in underwater mediums, and there is a clear lack of research on standardizations for the underwater environment. Scientists from the NATO Centre for Maritime Research and Experimentation (CMRE) introduced the first standard for underwater acoustic communication, named JANUS [125]. It was the intention that this project should serve not only NATO or the military but also that it could be adopted internationally. It is unique, as it can benefit governments, industry, and academia. It is a common standard based on acoustic communication to connect underwater systems. JANUS prescribes specifications such as message format and signal encoding, allowing third parties to use it to construct transmitters or receivers for underwater communication. This protocol also provides easy adoptability by legacy devices, freedom to use sophisticated decoders and receivers, and enhanced performance. Furthermore, it indicates which reduncies must be added in order to reduce communication errors. In the future, researchers should put more effort into improving the JANUS standard in order to overcome any elements which may be missing.

7.11. Link Misalignment in Optical IoUT

UOWC supports high data rate links in underwater environments for optical IoUT (O-IoUT). O-IoUT technologies have been used in several underwater applications such as underwater navigation, diver-to-diver communication, environmental monitoring, search and rescue, underwater habitat tracking, maritime archeology, and ocean exploration. O-IoUT uses LDs or LEDs to achieve efficient underwater communication. Usually, blue or green LDs are used due to the low absorption of this light; such an approach can be used for communication over considerable distances. An optimal source has a narrow divergence angle and follows the LOS path, as shown in Figure 14. However, high-speed optical communication is hampered by misalignment between the transmitter and receiver, absorption, high scattering, and channel impairments. This approach supports high-speed communication only in LOS scenarios achieved by precise synchronization and smart alignment. It is worth mentioning that even a small misalignment caused by wind disturbance or the turbid nature of water can reduce the data rate, lower the SNR, and degrade the BER performance of the system [126]. Different techniques such as spatial diversity and pre-amplification can be used to overcome these SNR and BER challenges. It is essential to overcome the issue of misalignment between transceivers to ensure efficient underwater communication.

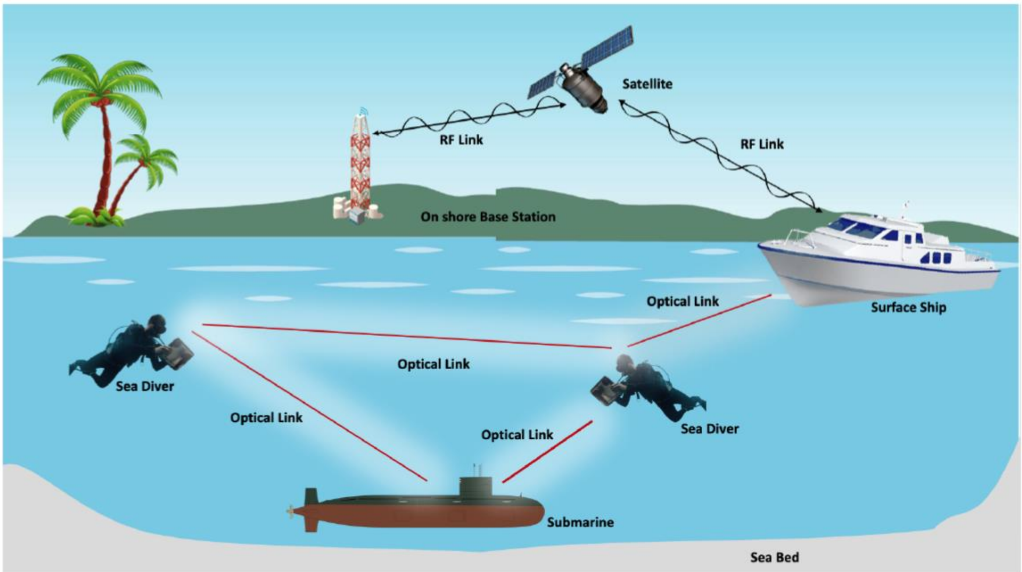

Figure 14. Line-of-sight OWC for optical IoUT [126].

7.12. Localization

In the underwater environment, the localization of nodes critical, as it is the foundation of ocean monitoring and target tracking. When deploying an underwater network, resilience to mobility must be considered. In ROVs and AUVs, mobility is controlled and supervised. However, uncontrolled mobility due to dispersion and water currents severely influences floating underwater sensor nodes [127,128]. The design of an UWSN and predictions of its performance require the precise modeling of the mobility of the component nodes, as such mobility in underwater environments is not completely random. Currently, most node localization algorithms consider fixed node location and calm seas. However, underwater nodes drift due to the motion of currents. Customized mobility models such as tidal mobidlity and meandering l can be used to model node mobility. The meandering model is suitable for deep waters, while the tidal model is well suited for offshore locations. However, more sophisticated models based on temporal and spatial correlation of mobility patterns are yet to be explored. Furthermore, geographic-aided routing protocols are better suited under these circumstances, as they have been shown to be more efficient and scalable for UWSNs, serving to reliably detect the current location of nodes. Similarly, node dynamic prediction algorithms can also be used to overcome localization issues.

7.13. Relay Placement in the IoUT

Relay nodes are important for transmitting data from a source to a sink and enhancing network coverage. In the literature, relay nodes have been utilized to achieve long-distance MI-aided underwater communication, as MI is a promising solution for IoUT communication. In [129], the authors proposed a strategy using relays for MI-aided IoUT networks to monitor the seafloor. In contrast to MI-based waveguides, the active relaying system needs additional power to process and transmit the received signal. Thus, determining the optimal placement of an appopriate relaying system is a challenging task for both terrestrial and underwater systems.

7.14. Unreliable Channel Conditions [41]

Unlike the terrestrial IoT, IoUT nodes communicate through MI, RF, optical, and acoustic channels [130–132]. This results in high levels of error data, significant power needs, and long propagation delays. Additionally, the nature of each approach to communication varies. For instance, the bandwidths of acoustic channels are small compared to those of RFs. Furthermore, due to the open features of IoUT networks, malicious nodes can easily disrupt or hack communications or steal sensitive data. In IoUT networks, channel noise, e.g., ambient and environmental noise, can severely affect the performance of IoUT communication. Ambient noise refers to background noise generated from various sources such as sea animals, underwater objects, or wind, while environmental noise refers to noise generated by human beings via naval, fishing, or shipping activities.

8. Conclusions

Ongoing advancements in IoT technology, and the influence of this technology on coastal and large oceanic areas have brought about a proliferation of intelligent devices, both in terrestrial and underwater applications. These technical advancements have spawned the novel concept of IoUT systems made up of cameras, sensors, underwater drones, hydrophones, etc. The IoUT offers viable opportunities for underwater communication, data acquisition, physical oceanography studies, military surveillance, and scientific research in several areas. This study summarizes the available literature on the IoUT, highlighting possible applications, potential challenges, mitigating techniques, and future research directions. IoUT hardware architecture, security, key enabling technologies, and real-time applications require more study. Our most important recommendation to the scientific community is that they make more contributions leading to ground-breaking discoveries in this thriving interdisciplinary field of study.

Author Contributions: Conceptualization, S.A.H.M. and Y.L.; methodology, S.A.H.M.; formal analysis, S.A.H.M.; investigation, S.A.H.M. and M.A.K.; resources, S.A.H.M.; data curation, Y.L. and M.A.K.; writing—original draft preparation, S.A.H.M. and Y.L.; writing—review and editing, S.A.H.M., Y.L. and M.A.K.; visualization, M.S.; supervision, Y.L.; project administration, M.S. and J.L.; funding acquisition, M.S. and J.L. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by the funding of the Guangdong Provincial Research Platform and Project under No. 2022KQNCX233, the Foundation of State Key Laboratory of Public Big Data under No. PBD2022-14, the Science and Technology Ph.D. Research Startup Project under Grant No. SZIIT2022KJ001, and the Shenzhen University Stability Support Program under No. 20220820003203001.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: We declare that all the authors have informed consent.

Data Availability Statement: Not applicable.

Acknowledgments: We really appreciate the support of the National Natural Science Foundation of China under grant 62261009, Ministry of Education Key Laboratory of Cognitive Radio and Information Processing (CRKL200106).

Conflicts of Interest: The authors declare no conflict of interest.

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