Journal of
Marine Science and Engineering

Review

Review on Sensors for Sustainable and Safe Maritime Mobility

Giovanni Briguglio and Vincenzo Crupi *

Department of Engineering, University of Messina, 98166 Messina, Italy; giovanni.briguglio1@studenti.unime.it
* Correspondence: crupi.vincenzo@unime.it

Abstract: The increasingly stringent requirements—in terms of limiting pollutants and the constant need to make maritime transport safer—generated the necessity to foresee different solutions that are original. According to the European Maritime Safety Agency, the total number of reported marine casualties and incidents is 21.173 over the period 2014–2021, with a yearly average of 2.647 casualties and incidents. According to the same source, 495 cases of pollution were reported in the period from 2014 to 2021. Marine pollution by ships' fuel and other pollutants is linked to 64.2% of all pollution. It is mandatory to offer a new kind of ship that can exploit new technologies to increase safety for people and onboard goods. It has been found that existing marine structures for maritime mobility do not have essential sensors for avoiding emergency situations such as flooding, oil spills, or health situations requiring efficient monitoring. In addition, there is a lack of legislation defining the insertion of unmanned vehicles into the actual marine infrastructure. This review highlighted the strengths and weaknesses of sensors in the maritime sector, intensifying areas of improvement for future challenges, such as sensor energy efficiency, data processing, sensor fusion methodologies, and accurate sea state description with environmental monitoring by means of unmanned vehicles.

Keywords: offshore structures; navigation safety; structural health monitoring; water and air pollution monitoring; green ships

check for updates

Citation: Briguglio, G.; Crupi, V. Review on Sensors for Sustainable and Safe Maritime Mobility. *J. Mar. Sci. Eng.* **2024**, *12*, 353. https://doi.org/10.3390/jmse12020353

Academic Editor: Rafael Morales

Received: 30 December 2023
Revised: 10 February 2024
Accepted: 14 February 2024
Published: 19 February 2024

1. Introduction

Shipping is responsible for 11 billion tons of annually delivered goods (Trade and Development, 2021). According to (United Nations Conference on Trade and Development) UNCTAD, a growth of container ships was recorded during the last year in several regions: 5.6% in Africa, 3% in Latin America and the Caribbean, and 3% in Asia, the most crowed area in the world for container ships. The greenhouse emissions from the world shipping sector are going in the wrong direction because there was an emission increase of 4.7%, according to data collected during 2020–2021 (UNCTAD), which is mainly coming from the following ship categories: container ships, dry bulk carriers, and general cargo vessels. Ship collisions are still significant in several specific categories and contribute to the majority of sea accidents [1]. According to the same source, groundings and fires are the most common critical events for ships. General cargo ships, tugs, and oil tankers are the most frequent categories involved in sea accidents [2]. There is an obvious need to underline mitigation actions for increasing onboard security. Maritime transport contributes significantly to air pollution along shipping routes and next to the ports, increasing the risk of health issues [3]. Nowadays, the average life of a ship is nearly 22 years, and shipowners usually choose to keep their ships active rather than decommissioning them. This is due to the uncertainty of the future in relation to the last significant changes that affected the world in recent years. The pandemic period changed a lot of static paradigms and visions about several aspects of the actual world, such as the coming era of renewable energies with interlinked limitations involving the utilization of the classical fossil fuels, the spread of new digitalization process that involves innovative usage of machine learning, and convolutional neural networks. All these events raised doubts among shipowners, but, at the same time, this was a beginning for future innovations and changes in the marine world. Currently, innovative sensors could be a solution for helping ships to be safer and more eco-sustainable. Environmental monitoring is essential for detecting anomalies in air or water condition parameters [4]. The spread of the Internet of things (IoT) could be a path to follow in order to create a more efficient environment for the working sensors [5]. Sensors give the industry the chance to improve the capacity of controlling events that are linked to the common usage of ships. This review puts forward several sensor applications in order to point out strengths and weaknesses, focusing on areas of improvement such as efficiency issues linked to harsh environmental applications. It is very common to observe sensors employed for submarine applications where battery range is the primary problem. The development of self-powered sensors might be interesting for autonomous underwater vehicle (AUV) missions. More sophisticated sensors could help AUVs solve actual orientation problems in the depths of the abyss where technologies such as GNSS are not available. In addition, the evolution of sensor technologies could support the spread of autonomous vehicles, which needs more attention when integrating them with traditional existing ships to avoid work conflicts. It is mandatory that legislation follows the spread of unmanned vehicles into the maritime sector in order to avoid mismatching situations with human-manned vehicles. The advantage of employing AUVs to obtain data about water and air quality is possibly very significant for continuously simplifying human activities. AUVs are systems that exploit sensors to operate in forbidden places for humans, and they need improvements in terms of energy efficiency and underwater orientation. Different from other reviews existing in the scientific literature that just focused on specific topics [6–9], the novelty here is that this review sees sensors by means of a holistic approach, which explores multiple applications in the maritime sector. This illustrates the fact that it is necessary to know the possible interactions between sensors of different maritime structures (marine vehicles and offshore structures) in order to generate and transmit effectively a huge amount of data, detected by several sensors, to a digital architecture for further post-processing analyses.

Aim of the Paper

The aim of this review is to offer a scenario involving sensors in several fields of maritime applications (maritime vehicles and offshore structures) in order to point out their possible synergies and weaknesses with other architectures. This review lays the foundations for the next era of sea digitalization, which is required in order to increase maritime safety and pollution reduction. For example, the recent updates into the European guidelines 2023/2776 of 12 October 2023, concerning the emission monitoring of greenhouse effects relating to the maritime transportation sector, sets the requirement of every ship docking into the UE ports to be fully monitored according to emissions issues. In order to accomplish this task, it is mandatory that ships/ports develop proper monitoring systems to take into account actual emissions situations in real-time. In this case, knowing the sensors' possible interactions with other environments is essential to developing future embedded systems. Knowing the actual state of development is also essential to conducting proper research to overcome actual sensor technology limits. If overcome, this will guarantee an innovative future in the digitalization of the sea.

2. Methodology

The methodology applied for performing this work was based on detailed research on Google Scholar. The conducted research gave priority to recent articles (5 years), but at the same time, it reported some older articles for giving a description of the sensor's background in some fields. All cited articles have been found by means of keywords indicated in the keywords section, adding the word sensors in front of them. Nearly 30% of the found articles have not been considered for lacking technical information or subject mismatching. It is relevant to point out that in the last 11 years, more articles concerning sensors in the maritime sector have been published than in the period from 1971 to 2013. This trend shows an increasing interest in the subjects analyzed in this review, such as remote sensing, marine environment monitoring, autonomous underwater vehicles, underwater acoustics, and sensor networks. Figure 1 shows the contribution of different countries in terms of scientific papers on the topic of sensors for maritime applications. This analysis is based on the Scopus database. It is possible to observe a relevant influence of the United States and China, which are the countries with the highest gross domestic product (GDP), on this topic, which is strategic for shipping.

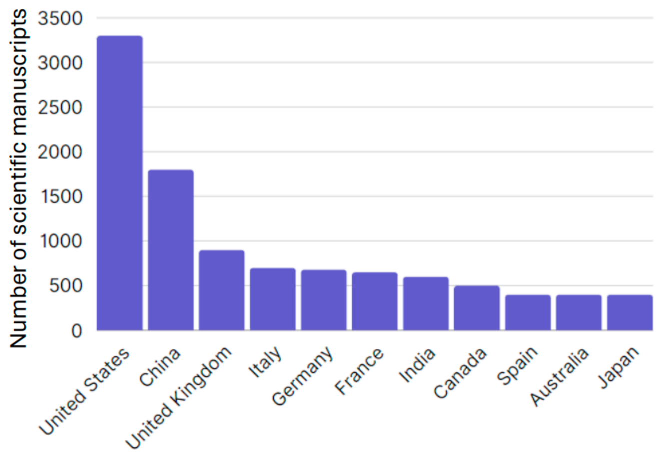


Figure 1. Scientific contribution of different countries to the topic of sensors for maritime applications in the last 40 years.

Another possible hypothesis could link the proximity of first-position nations to the sea. The most widespread sensor applications in the maritime field are shown in the Figure 2. According to the NOAA Office of Ocean Exploration and Research, the ocean covers nearly 70% of Earth's surface, and the majority is unknown. This could explain why there is a great interest in the development of sensors for Oceanography. The harsh nature of the ocean could be an interesting habitat to test, in an extreme way, structures for other kinds of applications. For example, this vision is shared by Saga Architects, who think of the ocean as an environment for testing structures for aerospace purposes. In some circumstances, astronauts could benefit from training procedures in specific underwater assembled habitats before going to space.

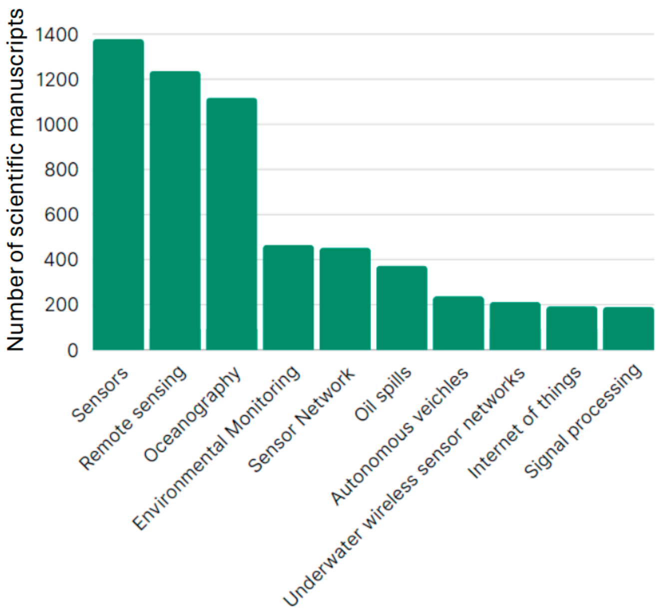


Figure 2. Scientific contribution to several fields of applications, including the keywords "sensors and maritime" from the current year to 1971.

3. Sensor Applications for Structural Health Monitoring of Marine Structures

The sensors have been applied in the shipping industry for 50 years, but in their first years of application, their purpose was just to analyze problems related to the ship's structure rather than improve and discover new methods for structural monitoring systems. However, there are some exceptions that are about studies on sensor development for the shipping sector. A monitoring system was equipped on a high-speed catamaran to analyze its mechanical response in the marine environment [10]. The catamaran owns wireless and fiber optic sensors for strain monitoring. Several wireless sensors were installed onboard with some tri-axial accelerometers. An application like the previous one shows the fact that wireless sensor solutions could be useful in cases where the positioning of onboard devices is hard. For example, wireless sensors might be a possibility for military ships with complex structures. Future investigation must be conducted on wireless sensors in order to study the long-term effects of heat and vibration during a ship's activity and on the quality of the wireless signal. Another notable application on military ships is shown in [11], which is equipped with a network of fiber-optic sensors for structural monitoring of an RV Triton vessel during trials in severe sea states. The vessel hosted 35 temperature-compensated fiber-optic strain sensors for measuring the still water and the slamming loads. The vessel was also equipped with a control unit that was used to collect data about wind velocity, wave height and direction, engine parameters, and data from 200 local strain gauges. The study shows the effectiveness of Bragg grating fiber optic strain gauges for monitoring ships. Another research [12] explained how ship structural data harvesting by means of accelerometers and strain gauges is crucial to establishing essential parameters for preventing faults and describing future actions for maintenance. In addition to failure procedures, their feasibility, and consequences, further analyses using the appropriate sensors might be applied to prevent corrosion, crack initiation, and propagation in various ship parts. A recent study by [13] involved insights into experimental tests of ingenious tourist submarines. A new type of exo-structure, which was orthogonally exposed to the flow, was equipped on a submarine for tourist activities. The onboard sensors are crucial in making considerations about the needed power and the relative thrust. The application of fiber optic sensors with a focus on Bragg grating strain sensors to a composite hull of the Skjold class Fast Patrol Boat is reported in the study [14], which points out evidence of the strength of this type of strain sensors to very common events of the marine environment, such as corrosion and electromagnetic fields. Another key point in sensor applications is not only finding the right place to position sensors but also identifying the appropriate strategies for processing data. The main goal is always to forecast critical situations that can lead the hull to uncomfortable events. Processed data from structural health monitoring (SHM) sensors might be used in the first part of the vessel's activities for monitoring the hull and confirming the design. With the usage of the hull and the connected components, the monitoring system is essential to estimate the fatigue life and for planning the maintenance operations. A crucial application is also monitoring and eventually verifying stress distribution when ships operate in harbors under static conditions. The online data monitoring could identify loads and the hull's response during sea trials. Data recorded may be used in comparison with Finite Element Analysis (FEA) to validate the numerical models.

Nowadays, a general methodology for damage detection has not been developed. Damage identification by means of vibration-based technologies is an interesting technique that could cooperate with a distributed fiber optic strain-sensor system. The main problem linked to the application of Fiber Bragg gratings is choosing the appropriate methodology for being aware of the Bragg wavelength for the chosen sensors. There are several procedures for accomplishing this task, such as scanning fiber filters, unbalanced fibred interferometers in combination with wavelength division multiplexers, wavelength-swept lasers, and CCD arrays combined with some dispersive elements. Bragg gratings strain sensors are suitable for several applications for hull monitoring, especially as they do not remove noise from the raw data. Table 1 shows the main applications of sensors for SHM. Figure 3 shows the most commonly used sensors in the SHM of ships.

Table 1. Applications for SHM sensors.

Aim of the Study	Analysis Technique	References
Monitoring fast Patrol boat	Bragg grating sensors	[15]
Mitigating post-processing troubles after strain measurements	Carbon nanotube polymer strain sensor	[16]
Evaluating multidirectional strain properties	Carbon nanotube sensors	[17]
SHM of nonconductive composites	Carbon nanotube sensors	[18]
SHM of HSV-2 Swift catamaran	Strain gages	[19]
SHM of HNOMS Otra Vessel	Strain and temperature sensors	[20]
Infinite Finite Element Method (iFEM) applications	Fiber Bragg Sensors	[21,22]
Health monitoring of materials and joints	Thermography	[23–26]
Health monitoring of composite joints	Fiber Bragg Sensors	[27]
Health monitoring of full-scale bi-material joint	Acoustic emission	[28]

Figure 3. Most commonly used sensors in the SHM of ships.

Another technique used in structural health monitoring of ship structures is acoustic emission (AE) technology [19], which is a valid technique to guarantee general control of structures for crack detections and damage evolution. An application of AE for strain monitoring on a structural element of the USCGC BERTHOLF, the first Legend-class maritime security cutter of the United States Coast Guard, is shown in [29]. Offshore structures cover a wide range of applications for drilling and mining operations in a harsh environment like the ocean. An offshore structure has several crucial aspects that distinguish it from other types of structures: it is constantly subjected to different types of conditions coming from the environment (mechanical loads, corrosion, vibrations). The most common types of offshore structures are the Tension Leg Platform (TLP), jacket and jack-up, and gravity style offshore. The most common loads on offshore structures are wave loads that depend on structures' geometries and wind loads. Wind loads are usually evaluated in offshore structures using land-based models. To guarantee safety on this type of structure is crucial for the development of an SHM system for real-time monitoring and damage detection. The sensors play an important role in guaranteeing data according to sea-state conditions, structural motions, and operation status. The first full-scale measurement system for offshore platforms was adopted by the BTM company in 1987 [9], then, several projects have been developed to monitor offshore structures with the main goal of verifying the design and providing a set of data for further research. Table 2 shows an overall view of notable applications of SHM applied to offshore structures.

Table 2. Applications of SHM sensors applied to offshore structures.

Aim of the Study	Analysis Technique	References
Waves interactions with offshore structures	Wave buoy	[30]
Measuring waves properties	X-band radar	[31]
Monitoring wind turbine support structure (tripod)	Fiber Bragg grating sensors	[32]
Monitoring TLP (tension-leg-platform) of floating offshore wind turbines	Inclinometers Bi-axial sensors and top tension meters	[33]
Ropes monitoring for offshore structures	Polymer Fiber Optics	[34]
Mooring lines monitoring	In-line load cells, inclinometers, strain gauges	[35]
Structural Health Monitoring of Tendons in a Multibody Floating Offshore Wind Turbine	Accelerometers	[36]
Measuring tension of mooring lines of a moored platform in waves	Optical sensors	[37]
Recording the geometry varieties of multi-component mooring lines	Water depth inclination sensor	[38]

Table 3 shows an overall view of notable applications of sensors for waves investigation into offshore structures. Other researchers used different SHM methods for damage detection in offshore structures: a modal strain energy method [39] and the bicoherence function of measured structural acceleration [40]. Surprisingly, the effects of full-scale measurements have not been closely examined. A new method was proposed in [41] for detecting damage on a floating structure using a sensor network and correlation coefficients, which are useful to investigate the structure's condition during its lifetime. This method uses a sensor network for monitoring responses coming from a previous study [42] and offers a new method for data organization and manipulation with data post-processing.

Table 3. Common sensors for waves investigation applied into offshore structures [9].

Analysis Technique	Field of Application	Technical Features	Costs
Wave buoy	Weight height Weight period Weight direction	−20–20 m 1.5–33 s 0–360°	Deployment 30,000 $ Maintenance 170,000 $ per year Repair 25,000 $
X-band Radar	Weight height Weight period Weight direction	0.5–20 m 3.5–40 s 0–360°	Up to $900 million
Air Gap Sensor	Weight height Weight period	0–60 m 0–20 s	-

4. Sensor Application for Vibration and Noise Measurement of Ships

In this new era of smart ships, it is crucial to enhance the managing properties of mechanical equipment such as main engines, air compressors, and diesel generators. The working parameters, like vibration and sound, are essential to guarantee onboard comfort. In the literature, there are several methods based on vibrational signals for machinery fault feature extraction [43]. A way to measure underwater noise using only onboard sensors is shown in [44]. Data collected in the study could help the design phase of new ships for predicting underwater noise during this early-stage condition. Another study [45] presents how boat noise can influence marine habitats according to different engine types, highlighting how human noises could mask communication in organisms and cause orientation confusion. The ports can act to decrease underwater noise coming from ships, as shown in [46], which offers a series of actions to achieve this important goal. A self-powered vibration sensor based on a bouncing-ball triboelectric nanogenerator (BB-TENG) was proposed in [47]. The great advantage of this sensor type is that it can convert vibration energy into electricity and can supply a further temperature sensor. A prominent study [48] based on making diagnoses of machinery analyzed the validity of psychoacoustic metrics as a tool for recognizing mechanical failures. Another interesting study [49] on vibration monitoring in the shipping industry is the vibration assessment monitoring point with the integrated recovery of energy (VAMPIRE) prototype. A wireless, self-powered accelerometer was developed that could measure vibrations in United States Navy (USN) and United States Coast Guard Cutter (USCGC) ships. This new type of accelerometer is a self-powered device that exploits a transformer that works with the energy coming from the magnetic fields of an electromechanical load. A new type of magnetostrictive sensor, which exploits patch deformation by shaft torsional vibration into electric voltage output, was proposed in [50], where this system was applied to an LPG carrier. A comparison with a standard strain gauge with a telemetry system can be made by analyzing the following work about vibration measurement on a ship's shafts [51]. Figure 4 shows the traditional strain gauge system with the employed battery and a receiving antenna, which is fixed and can detect the signal by means of wireless communication.

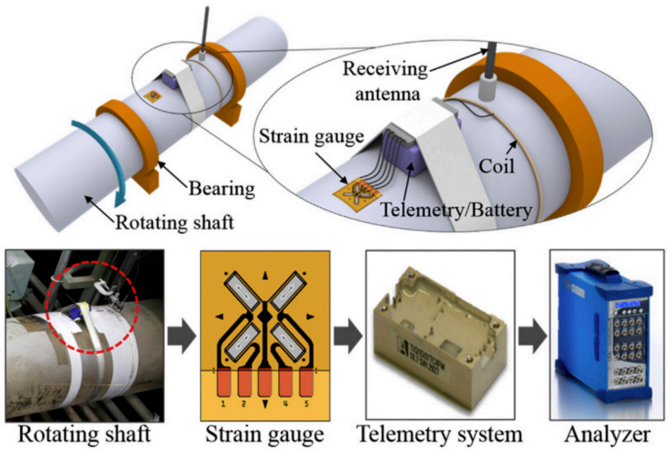


Figure 4. Traditional strain gauges system with added battery [50].

The main innovation of the previous study is implementing a magneto strictive torsional vibration sensor (MTVSs) that could be mounted on rotating shafts without a battery and without shaft interruptions, as shown in Figure 5 After the testing phase, it is important to point out that the MTVS system has sufficient sensitivity to measure torsional vibration information in shafts.

An innovative use of vibration sensors is linked to the ice type and thickness identification methods [52]. Ice type and thickness classification was a task always accomplished by synthetic aperture radar (SAR) images; a new methodology was proposed [52] for identifying several types of ice with the linked thickness using accelerometers and gyroscopes working with two cameras from the ice image recognition system (SIIRS). Vibration sensors are installed in the bow of an icebreaker ship in six different locations. Each sensor owns an (inertial measurement unit) IMU module with an accelerometer and a triaxial gyroscope. A wireless communication module with a Lora low-power SX1268 chip is used in order to send data from sensors to the gateway. All collected data have been implemented on a machine learning algorithm to recognize the ice type and its thickness.

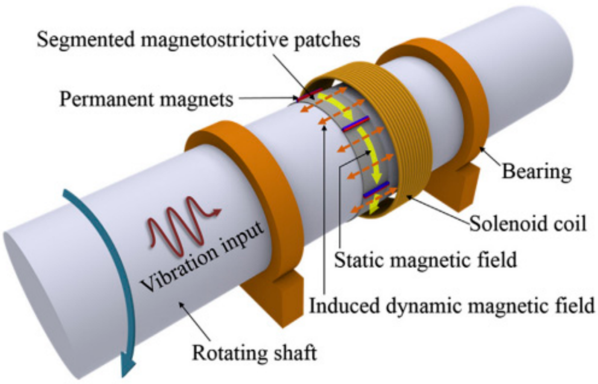


Figure 5. Magneto strictive patch sensor for measuring torsional vibrations in a rotating shaft [50].

5. Sensor Application for Environmental Measurements

The shipping sector's emissions have a central role in the global pollution scene. The most common pollutants coming from ship's plumes are particulate $PM_{2.5}$, sulphur oxides SO_x, and nitrogen oxides (NO_x) [53,54]. Sulfur oxides contribute to the acidification of the ground and the marine environment, in addition to leading to premature death [55]. For the previous reasons, the International Maritime Organization updated new regulations on ship emissions to force the development of recent applications of low-carbon marine fuels. Suddenly, it is crucial that a proper emissions monitoring system is ready for the new upcoming changes.

In this paragraph, several ways to monitor ship emissions will be presented, from UAV to airborne monitoring systems and other applications for water pollution monitoring. Regarding evidence of a multi-sensor network application for water monitoring, the following essay discusses remotely controlled boats for water quality [56]. The boat (Figure 6), which was realized on a frame structure utilizing PVC pipes, is equipped with several probes that are able to measure several water properties, such as electrical conductivity, pH, total dissolved solids, and temperature of the water tested. GPS is mounted on the boat and gives the chance to control the position of the boat and, consequently, the area to analyze. An ultrasonic sensor (HCSR-04) is used in order to detect objects. Water temperatures are measured with a waterproof temperature sensor. The boat is also equipped with a conductivity sensor and pH sensor.

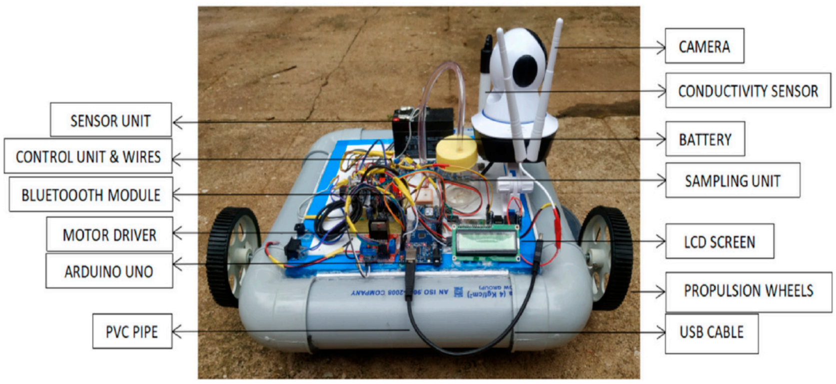


Figure 6. Smart water monitoring prototype-boat [56].

Regarding air quality monitoring, it is essential to point out a recent study [57] that assesses shipping emissions near the Melbourne cruise ship terminal. Some researchers deployed seven units of KOALA air quality monitor sensors capable of measuring PM and CO concentrations in real-time, transmitting this data to a cloud database. During the measurement period (98 days), the team detected information about PM pollutants from nearly 3000 ships' arrivals/departures from Beacon Cove (Melbourne). The effects of disease causes that are linked to long-term PM emissions are known. Instead, there could be interesting short-term effects of emissions in an urban area. The residential areas are the most interesting parts regarding ship's pollution. Due to this, in recent years, the coastal areas have been controlled in order to check air quality parameters periodically. A study [54] proposed a three-dimensional eulerian method for simulating atmospheric transport and transformation of pollutants in the North Sea region. This study demonstrated that in the northern part of Germany, Denmark, and southern Sweden, the sulfate concentration may be increased by 50%, caused by burning sulfur-rich bunker oil in ship engines. Sensors play a crucial role in detecting real-time data for managing phenomena like this and mitigating possible spikes of concentrations that are harmful to health. Another study [58] proposed a paradigm for constructing a ship emission monitoring sensor web (SEMSW). The goal of the previous research is to develop a feasible model to give satisfying answers to new regulations of maritime institutions and shipping companies in terms of emissions. In order to have a global and accurate vision of the emissions of a control area, it is necessary to build solid monitoring platforms. In this case, sensors play a crucial role in the development of this type of technology. There are several types of sensors (Figure 7) involved in this application: airborne sensors, ocean sensors, land sensors, and satellite sensors. This system has great possibilities to collaborate with existing physical and web-based infrastructures. The cited system might be able to recognize ships that are not compliant with standards, sending them alerts to make mitigation actions. The area analyzed will have some platform for monitoring emissions that can communicate with an onshore server in real time for post-processing analyses.

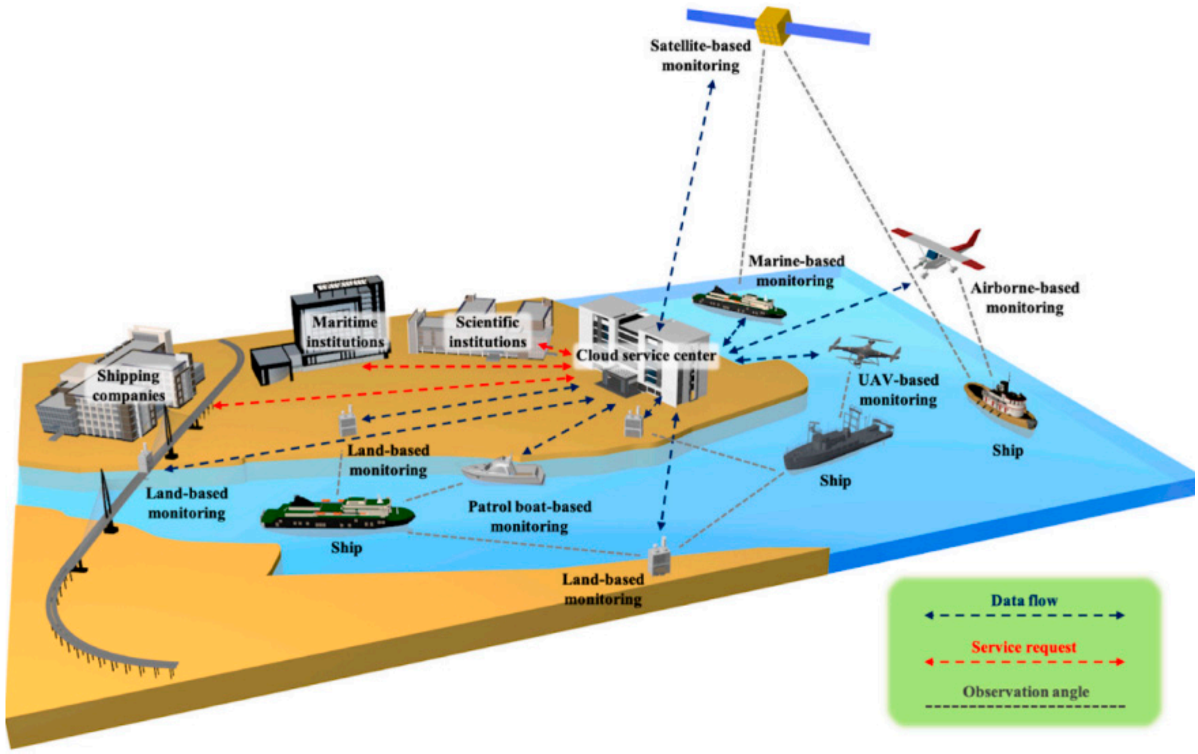


Figure 7. Different ship emission monitoring platforms [58].

Table 4 points out additional applications of sensors for environmental monitoring.

Table 4. Common applications for environmental sensors.

Aim of the Study	Analysis Technique	References
Detection of catalytic fines into fuel oil	Low-field nuclear magnetic resonance (NMR) sensor	[59]
Monitoring ship's emissions by means of UAV	Mini-sniffing sensor	[60]
Airborne and in situ shipping emissions monitoring	SO_2 and CO_2 sensor	[61,62]
Van-based laboratory for static measurement of shipping emissions	CO, CO_2, SO_2, NO, NO_2 sensor	[63]
Single particle mass spectrometry for long-distance monitoring from the coast	Sniffing sensors	[64]
Marine environmental monitoring by means of UAVs, USVs (Unmanned surface vehicles), USs (Underwater Gliders), UGs (Underwater Gliders)	RGB Cameras, Multispectral, and Hyperspectral sensors	[65]

Tables 5–7 show some technical features of common environmental sensors coming from [63–65].

Table 5. Technical specifications of UAV sensors for maritime applications.

Analysis Technique	Field of Application	Range of Application
RGB	Fluid flow tracking, aerial photogrammetry	400–700 nm
LiDAR	Terrain mapping, erosion studies	905 nm
Hyperspectral	Water quality, classification studies	900–1700 nm
Multispectral	Vegetation mapping, water quality	400–700 nm, 655 nm 725 nm, 800 nm

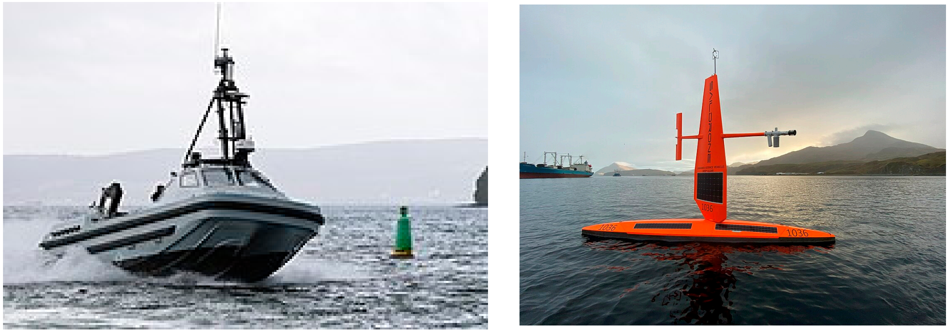
Table 6. Example of sensor applications for air monitoring.

Analysis Technique	Field of Application	Technical Features
APNA 360 Horiba	NO, NO_2, NO_x measurements	Measuring range: 0–1000 ppb Detection Threshold: 0.5 ppb
CO12M Environment S.A.	CO measurements	Measuring range: 0–50 ppm
Thermo Environmental Instruments, model 43 C	SO_2 measurements	Measuring ranges: From 0–0.5 to 100 ppm
VA 3100, Horiba	CO_2 measurements	Measuring range: 0–100 ppm
HMP45A Vaisala Pt 1000 IEC 751 1/3 Class B	Environmental temperature measurement	Measurement range: $-40 \div 60$ °C
CUBIC Laser Particle Sensor PM2012SE-A/PM2012SE-B	Detecting particle concentration size between 0.3 and 10 μm in the air and real-time output PM1.0, PM2.5, PM10 in μg/m^3 directly via mathematical algorithm and scientific calibration.	Measurement particle 0.3–10 μm Measurement range 0~5000 μg/m^3 Accuracy PM1.0/PM2.5: 0~100 μg/m^3, ±10 μg/m^3; 101 μg/m^3~500 μg/m^3, ±10% of reading PM10: 0~100 μg/m^3, ±25 μg/m^3; 101~500 μg/m^3, ±25% of reading (GRIMM, 25 ± 2 °C, 50 ± 10%RH)

Table 7. Summary of sensors for water monitoring exploiting USV (Unmanned surface vehicle) platforms [66–70].

Analysis Technique	Field of Application	Cost	Technical Features
Analog pH Sensor/Meter Kit For Arduino	pH measurement	29.50 $	-
Analog Turbidity Sensor for Arduino	Turbidity measurement	9.90 $	-
Temperature Waterproof DS18B20 Sensor Kit	Water temperature measurement	7.50 $	-
EM506 (GPS)	Position	39.95 $	-
Telesky pH Sensor	pH measurement	-	Range: 0–14 Working Voltage (5 V) Accuracy (%) ±0.7
WAAAX TDS Sensor	Total Dissolved solids measurements	-	Range: 0–1000 ppm Working Voltage (3.3–5 V) Accuracy (%) ±5
EIXPSY Turbidity Sensor	Turbidity measurement	-	Range: 0–4000 NTU (turbidity unit) Working Voltage (5 V) Accuracy (%) ±0.75
DS5-DS5X Multi Probe	Ambient light, ammonia, chloride, chlorophyll, rhodamine WT, conductivity, depth, dissolved oxygen, nitrate, ORP, pH, temperature, total dissolved gas, turbidity, blue-green algae measurements	14,000–17,000 $	-
RBR Temperature Sensor	Aged glass thermistors for temperature monitoring of water	-	Accuracy: ±0.002 °C
RBR Dissolved O_2 Sensor	Optic dynamic luminescence quenching for O_2 detection	-	±0.002 µM
Nortek Signature 500 Acoustic Doppler current profiler (ADCP)	Current profiling, wave height measurements	-	±0.1 cm/s (velocity resolution)
U-BLOX GPS	Position	-	Accuracy: Position 2.5 m Velocity 0.1 m/s Heading 0.5°

A way to develop this new concept is by integrating satellite remote sensing with unmanned vehicle capabilities. Satellite remote sensing has high spatial coverage but low resolution, while unmanned vehicles could have higher mobility and may be used for monitoring specific open areas. In addition to UAV vehicles, there are also unmanned surface vehicles (USVs), unmanned ships (USs), and underwater gliders (UGs). The combination of all these applications could reach the proposed goal. For example, underwater gliders can use a lot of sensors that can monitor several parameters from different phenomena. A typical application of gliders is harvesting oceanographic data, especially from hurricanes; this is a big advantage for further studies on storms [71]. Going into detail about oceanic mixing interactions could improve the possibility of forecasting possible storms. USVs are also a good solution to integrate into the network monitoring system of the ocean because they can exploit wind and solar energy to accomplish their duty. Usually, these vehicles are sailboats equipped with sensors for marine environmental measurements: temperature, sea surface temperature, salinity, ocean color, dissolved oxygen, and seawater pCO_2. In the Figure 8 are shown some examples of USVs and marine drones.



(a) (b)

Figure 8. (**a**) British Harrier autonomous USV; (**b**) sail drone.

There are also unmanned ships that comprise a type of platform that can exploit several types of sensors for ocean digitalization. The most common parameters identified during these types of operations are wave height, wave period, and depth. Other particular applications are linked to the detection of mammal sounds and fish concentrations in specific areas. Another type of marine pollution is based on events of oil spills. Oil spills are critical disasters with immediate negative consequences on the marine environment. These types of disasters can also have long-term residues. It is challenging to separate oil and water once they are mixed because oil does not dissolve into the water. Today, there are several methods for removing oil from water, such as centrifugation processes [72], flotation [73], or the employment of membrane technology [74], but a real challenge is detecting and mapping oil pollution. In recent years, synthetic aperture radar (SAR) has been a valid technology for monitoring oil spills for great properties, especially for the weather illumination capabilities [75]. Several analytical methodologies have been developed based on SAR images to detect oil spills. Nevertheless, quantitative relationships of different SAR sensors' properties for identifying oil spills are still missing. The most common techniques for detecting and mapping oil spills are using cameras in the infrared, visible, near-infrared, and ultraviolet spectra. Optical data are not enough to detect and identify oil spills if the location is not defined well [75]. The main difficulty is to be careful to confuse oil spills with other sea bio-elements [8]. When the area of interest is identified, it is necessary to remove oil species from the sea water. Innovative procedures have been studied in recent years, and it is interesting to highlight recent research [76] that is based on the design of a methodology for monitoring oil pollution and providing an oil-water separation device by means of a semi-permeable membrane. The cited application could be used on an operating ship for detecting oil pollution in specific areas and calculating oil volume during removing operations with the identification of the type of oil. Another way to detect and localize water pollution is based on wireless sensor networks (WSN) [77]. This application exploits sensors installed on microstations and unmanned ships. UV-visible spectrometry sensors are used for harvesting data about total organic carbon (TOC) and nitrate nitrogen (NO3-N). In addition, dissolved oxygen, pH, and conductivity sensors are also present. Unmanned ships are usually powered by solar panels that send energy directly to lithium batteries. The methanol fuel cell could also be taken into consideration the supply of traction power to the entire vessel due to the low velocity that unmanned vessels usually reach. Methanol fuel cells have the advantage of giving the needed energy even if harsh environmental conditions are present where solar panels might have problems. Another interesting application of sensors for identifying pollutants in the sea is based on a remotely operated vehicle (ROV) as in [78], where a robotic platform with an integrated video camera, probes for water analysis, and some hydrophones for measuring underwater noise are shown. The aim of these robotic platforms is to reach places forbidden to humans. Usually, chemical and physical parameters (conductivity, temperature, and depth) are measured by underwater probes. The robotic platform exploits the GPS to have information about its position when operating on the water. Things are a bit more complicated when its activities are some meters into the sea. In this case, localization sensors are used.

6. Sensor Application for Navigation and Onboard Security

With the development of new sensor technologies linked to innovative systems like the IoT, a new concept of smart ships has been considered in recent years. It was recognized in [12] that sensors play a critical role in realizing the concept of smart ships for enhancing safety, maintenance, and ship inspections. A container ship vessel made a journey from Tarragona (Spain) to Livorno (Italy), and during this route, parameters such as temperature and pressures were recorded for various machinery equipment located in the engine room of the ship. Data were collected hourly, so after the journey, the four columns of data were realized just because the journey ended in four hours. All data were then processed for further investigations and to improve the ship's global safety. A large number of ship incidents are linked to collisions among ships, and their impact is severely dangerous from many points of view [1]. These types of accidents are usually due to the lack of a communication system or radar failing operations for detecting small obstacles. One of the most common categories of ships involved in this case are the fishing boats. A significant analysis and discussion on the subject was presented by [79], who proposed a system that includes ultrasonic and vibration sensors, GPS, and GSM modules for realizing a detection system to alert the fishing boats about incoming ships or obstacles. A multi-sensor system application for the maritime sector was due to [80], which realized milliAmpere, an autonomous ferry research platform equipped with sensors for evaluating tracking performances across some environments. The whole sensing system is made up of 10 cameras, a radar, and a lidar. This work evaluated the performances of both detecting and tracking systems for two specific environments, finding specific issues that could be solved by introducing multiple sensors for enhancing, for example, tracking performances. Another crucial subject for safety on ships is based on flooding sensors. This view is supported by [81,82], which considers the influence of decision-making during emergency flooding situations on passenger ships. For this purpose, locally installed flooding sensors are needed. The study showed several sensor configurations and recommended minimum sensor arrangements for similar ship designs. Nowadays, most passenger ships do not have an onboard flooding-sensor solution. These types of sensors are needful for forecasting a flooding situation and improving to help the crew choose the best path to solve the situation. Another study about flooding sensors [82] reports that this type of sensor can be used to improve decision systems on ships with the aid of machine learning algorithms. An input database of flooding simulations could be used to predict ships' activities during flooding times. With the spread of smart hybrid and full electric ships, monitoring batteries is mandatory for accomplishing all current security restrictions. An example of sensor applications in this shipping industry is the National Marine Electronics Association (NMEA) 2000 smart sensor network [83]. The authors focused on making predictive fault-damage analyses about valve-regulated lead–acid (VRLA) batteries installed on a ship. This study puts into evidence the importance of monitoring the inner temperature of the battery pack because it is an essential parameter for detecting aging time.

From the main deck, the crew of the vessel is able to check a lot of parameters from sensors placed in crucial onboard positions. It could be possible to check the operating status of batteries with all needed parameters (inner temperature, environmental temperature, state of charge, discharge current, charging current). A notable example of a ship monitoring system is SeaPerformer [84], which has been implemented on several sea ships. It is based on a modular solution of several servers that have the duty to process and store data. At the same time, they give access to users by means of satellite communication system. Both the main bridge and engine room are equipped with harvesting data units for recording useful signals. One of the purposes of this type of monitoring system is to analyze engine fuel oil consumption to detect engine wear. Another neural network application in the marine field is due to [85], which proposed a process to forecast the temperature of the ship propulsion devices in order to detect damages by giving an alert automatically. Autonomous shipping operations have been under investigation in recent years due to the possibility of using them in critical situations unreachable by humans. Autonomous ships exploit a large number of sensors and auxiliary data from external databases, for example, to feed Artificial Intelligence (AI) Machine Learning Algorithms. In this way, it is possible to reach autonomous situational awareness cases for shipping operations. The vessel could recognize the presence of obstacles and identify the right route using installed sensors. The most common sensors used in this type of application are visual sensors and microphones. Visual sensors are all sensors that can capture an image. Some microphones for outdoor activities are shown in [7]. A prominent example of autonomous ships is based on the studies and experiments in [86], where an experimental prototype computer system was developed to grant full control of an unmanned ship model by means of sensors and navigation devices. Autonomous unmanned ships exploit sensors to accomplish several interesting tasks that in the past were devoted to humans, such as automatic mooring and unmooring, selection and optimization of the shipping route from one port to another, and performing anti-collision maneuvers. The possibility of ships capable of making decisions without the final supervision of humans could be an essential skill for optimizing autonomous ship operations, even when considering future large-scale unmanned ships. These techniques are very useful when working with advanced sensors, as demonstrated in [87], which makes reflections about machine learning systems applied to the autonomous shipping world, pointing out present limitations and strategies for overcoming them. Another prospective into the sensor-based field has been reached from [88], where it described the problem of threats of anomalies and cyber-attacks in the marine sensor world. The authors propose a robust model to secure the marine sensor system from cyber-attacks and illegal activities. The cited Light-GMB model can operate with 98.52% of detection accuracy. Another interesting problem regarding the introduction of autonomous ships into the real world inhabited by conventional ships is reported in [89]. The main problem is based on the possibility of understating from the point of view of the autonomous vessel in the event of facing a human-manned ship. The goal should be to reach a state of awareness by means of sensors that can help autonomous ships face all possible situations, including conventional ships. Figure 9 shows the most common sensors for improving security on passenger ships.

Figure 9. Sensors for passenger ships.

Tables 8 and 9 show sensors for navigation security and shaft monitoring.

Table 8. Sensor applications for navigation and onboard security.

Aim of the Study	Analysis Technique	References
Monitoring rotating machines	Powerless non-contact sensors	[90]
Finding the best route considering the influence of sea state	Accelerometers, strain gauges	[91]
Evaluation of sensors' error in function of the variation of the temperature on maritime autonomous surface ships	Microelectromechanical system sensors	[92]

Sensors network could be very useful with the spread of AUVs, which can operate in dangerous areas and accomplish tasks that could be difficult for a human-manned vehicle. The challenge is managing to design an AUV that can accomplish its tasks without the supervision of humans. A linked challenge is granting the underwater vehicle a sensing system that allows it to act safely and efficiently. There are some types of applications where GPS is not available or shows some problems in detecting the position of a maritime vehicle, especially when they are considered submarine applications. In this case, discovering new numerical techniques and innovative sensors for establishing position could be an interesting point for future researchers [93]. Wireless sensors can be a solution for compact design marine applications, but, at the same time, they suffer from limited access to energy resources and could face battery state of charge (SOC) problems. A method based on charging underwater sensor nodes using AUVs is shown in [94]. Charging submarine sensors in this way could improve the transmission feasibility of the signals. Nevertheless, one of the most limiting factors in submarine operations is the underwater orientation. Deep ocean technologies like LIDAR, RADAR, or GPS have some problems involving the attenuation of electromagnetic waves. For this reason, a combination of acoustic and optical sensors is usually used in this type of application [95], which points out a series of orientation problems for submarine sensors and the actual strategies for mitigating them.

Table 9. Examples of sensors for monitoring onboard shafts [90].

Analysis Technique	Technical Specifications	Cost
TMP36 Temperature sensor	Low voltage operation (2.7 V to 5.5 V) Calibrated directly in °C 10 mV/°C scale factor ±2 °C accuracy over temperature Specified −40 °C to +125 °C, operation to +150 °C Less than 50 µA quiescent current Shutdown current 0.5 µA max	15 $
INA 219 CHIP (Current Sensor)	Operational Voltage: 3–5.5 Volts Operating Temperature: −400–1250 °C Maximum Voltage: 6 Volts Bus Voltage Range: 0–26 Volts Current sensing Range: ±3.2 A with ±0.8 mA resolution 0.1 ohm 1% 2 W current sense resistor	18 $
SparkFun Load Cell Amplifier HX711	Operation Voltage: 2.7–5 V Operation Current: <1.5 mA Selectable 10SPS or 80SPS output data rate Simultaneous 50 and 60 Hz supply rejection	11 $
Omega Strain Gauges SGD	Nominal resistance from 120 to 1000 Ω Maximum bridge excitation voltage from 2.5 to 37 V	150–250 $

7. Sensor Application for Green Propulsion Plants of Ships

According to The International Maritime Organization (IMO), the emissions of greenhouse gases have to be reduced by 50% by 2050 to spread the process of decarbonization into the shipping sector. Detailed examination of the decarbonization process by [96] showed that up to today, the alternative fuels available for ships include liquefied natural gas, liquefied petroleum gas, methanol, biodiesel, hydrogen, and ammonia (NH3) [97]. According to a long-term vision, biodiesel, hydrogen fuel, and ammonia fuel will inevitably become the future fuels for ships. As said, in recent years, a lot of investigations have been conducted into exploiting new fuel technologies. An application for the design and the utilization phase of a Direct Methanol fuel cell is presented in [98]. A direct methanol fuel cell (DMFC) is an electrochemical device that converts chemical energy into electrical energy by means of the electrochemical oxidation of methanol. It belongs to the family of proton-exchange membrane fuel cells (PEMFCs) and exploits similar working principles. The main difference is based on the fuel source; indeed, a reformer is not needed to convert methanol into hydrogen before it enters the fuel cell. Several strategies to use bio-methanol as a renewable fuel from waste biomass are shown in [99]. Fuel Cells are a suitable solution for small crafts, but an internal combustion engine that exploits methanol as a fuel is required for high-power density applications like high-speed craft [100]. There are a few examples in the literature of ICE running on methanol, and making advancements in this field of research could be the right solution for the problems cited before. Another solution for marine vessels may be liquefied natural gas (LNG) due to its low emissions and high energy density [101]. LNG requires several specific tanks for storage at low temperatures and could be uncomfortable in some ship applications. Compressed natural gas may be easier to store onboard, but it has to face high-pressure storage (200–250 bar) tanks that require a complex security system in order to avoid accidents. Hydrogen is a good alternative for supplying ships for its high heating value and high combustion efficiency, but it has to deal with storage and leakage problems. Hence, sensors play a crucial role in this phase of development and research because they can give the chance to improve the management of the problem, enhancing the security of the whole system. To better understand the mechanisms of leakage detection and its effects, the effects of ship motion on hydrogen dispersion in an enclosed area were analyzed in [102]. This study shows an experiment to measure the hydrogen concentration inside an enclosed space simulating a ship's oscillating motions. Ship oscillation motions are detected by means of a gyroscope, while hydrogen concentrations are detected by means of a gas sensor. Detecting leakage sensors is essential for designing control and security systems for ships with onboard hydrogen. Hydrogen fuel cells combined with battery packs could be a chance to innovate the sector of costal or inner waters navigation. An example of a hybrid catamaran supplied by a combined system of fuel cells and batteries is shown in [103]. The catamaran could carry 220 passengers at the speed of 20 knots. The displacement is 120 tons, 30 m overall length, and 10 m of breadth. Fuel cells supply the average power to the ship, while batteries are responsible for the dynamic power. The main route is always in the area of the Amalfi coast. It is probably the case that maritime applications that require more power and autonomy do not have to take into account fuel cells but consider a type of combustion engine that exploits fuels such as hydrogen or methanol, which can be produced with renewable processes. New types of internal combustion engines that exploit these new types of fuel were developed in [104,105]. Applications that require internal combustion engines require the possibility of stocking hydrogen in the safest manner. Liquid hydrogen plays an important role in maritime hydrogen transport due to its high storage efficiency. According to this, it is crucial to have a hydrogen monitoring system for monitoring parameters linked to maintaining hydrogen safely in the liquid state. An application of a sensor for detecting the hydrogen liquid level is reported in [106]. This study shows an example of a superconductive magnesium diboride sensor for detecting the level of liquid hydrogen. Another study [107] shows how important monitoring liquid hydrogen temperature is for marine transport applications. It is necessary to maintain a series of parameters like pressure and temperature in a certain range in order to maintain hydrogen to the liquid state. The study [107] presented platinum resistance sensors for marine applications with excellent feasibility for monitoring the temperature of liquid hydrogen.

Sensors in the green ships world will play a crucial role in the context in which they have been introduced, and probably, their impact will be more impressive than other fields. The usage of sensors will be 20 times more frequent than the actual ships, as explained in [108]. Obviously, an important factor is the feasibility of the sensors in order to catch possible faults of the sensors themselves. According to this problem, there are some approaches for mitigating this problem: the first one is the sensor validation technique, which is based on assessing the sensor's working properties and comparing actual data with the previous one. The second approach is called sensor data fusion–recovery, and it is based on multisensory measurements that exploit different single measurements, mixing them to obtain information about one single measurement. Another green boat application is based on the studies of [109] that developed a PEM fuel-cell battery hybrid system for the propulsion system of a tourist boat. In a case like this, it is crucial to have onboard the possibility of managing all essential parameters linked to the propulsion system.

Lithium batteries are appropriate for e-mobility applications because they have good properties in terms of energetic density and weight [110]. Lead–acid batteries are also used in the shipping sector [109] for sustaining fuel cells during the sail. As said before, in regard to applications that foresee the presence of batteries, it is essential to manage their temperatures to avoid disasters. Lithium batteries are very sensitive to temperature and could generate relevant accidents if the temperature is not properly controlled. In addition to this, monitoring temperatures for lithium-ion batteries could improve their performance and prevent aging. Some sensors could be present for monitoring lithium-ion battery temperatures. Two categories of sensors for monitoring them are shown in [111]. The first one is called hard sensors; they manage to monitor the inner temperature of cells. The soft sensors use external temperatures with specific models to forecast the inner temperature of the cells. Regarding fuel cell applications, a lot of parameters have to be managed for safe use, such as pressure, mass flow, and humidity. Gas sensors are used to manage hydrogen leakage [112]. According to several types of fuel cell applications, there are specific gas sensors for the possible gas contamination that could happen [6].

Another important field of analysis for innovative boats with renewable properties focuses on solar boats. In the past, there were two main categories of solar boats: hybrid solar boats, where solar panels were used in addition to a diesel generator to supply onboard electrical loads, and full solar boats, where solar panels were used to supply all onboard electrical loads [113]. Recently, new types of boats that are supplied with only solar panels have been developed. A photovoltaic catamaran for sailing into the rivers, lake, or along the coast is described in [114]. Obviously, the solar panels are associated with battery banks in order to provide the stationary and dynamic power of the boat. Another type of solar boat [115], which also uses wind energy, has the goal to reach the state of autonomous sailing boats. The cited boat has a panoramic camera for recognizing the environment, a sonar, and a pair of hydrophones for obstacle detection. The great trial is collecting all data coming from sensors and using them to feed the navigation module for making an autonomous sailing boat. Experiments like this are the initial steps for a fully autonomous sailing renewable sailing boat. Figure 10 points out the most useful sensors for new upcoming green technologies into hybrid ships.

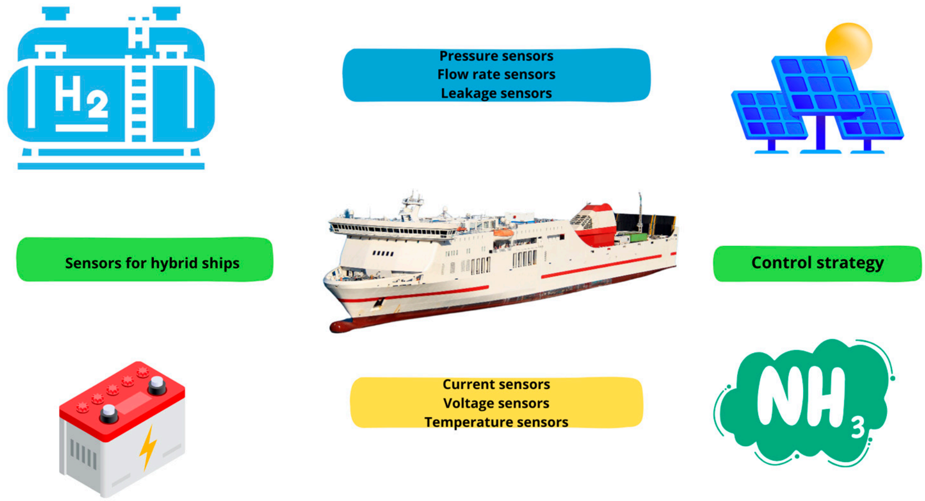


Figure 10. Sensors for upcoming hybrid ships.

8. Discussions and Future Challenges

This review analyzed the actual state of the art of sensors in the maritime industry, pointing out applications for sustainable and safe mobility. With the rising goals of exploiting resources for land-based activities in a more sustainable way and with the unceasing interest in discovering unexplored environments such as the ocean, it is essential to evolve the technology to obtain security and efficiency. This literature review points out several aspects of the sensor world that have to be improved in order to overcome the challenges in the world that we are living in. First of all, it has been recognized that sensors applied to harsh applications, such as submarine applications and offshore structures, suffer from a lack of power due to the batteries' discharging phase. It is crucial for enhancing the safety of the interested marine structures by improving energy recovery technologies for feeding sensor applications like the previous ones. Several wave energy recovery systems applied on little vessels are reported in the literature. These types of technologies, if correctly designed, could help to recover a minimal residue of energy that is not enough to feed the entire power demand of a boat but could be useful for feeding submarine sensors that do not need those power requests.

Studies about vibration energy recovery and wave interaction could be a path to try to solve the problem of continuous power supply of sensors. Several technologies could be developed in a deeper way, such as self-powered sensors; some examples have been cited in this state of the art, too, such as magneto-restrictive sensors.

In the case of submarine vehicles, a crucial point of development is the environmental orientation into the deep ocean; real-time sensor information combined with numerical models could help to make up for lacking evident technologies that could solve this problem in the near future. According to the problem of the insertion of autonomous unmanned ships into the real world of shipping, it is essential to grant developments into communication systems between autonomous ships and traditional ones to avoid accidents exploiting several known scenarios. In this context, the help of machine learning and deep neural networks could be the right path for improving the integration of autonomous ships into the manned ships world.

In addition, a future application in the shipping industry could be the increasing employment of acoustic emission monitoring. This technique is very common in bridges of some other civil infrastructures. It is based on the principle of emitting acoustic alarms due to the elastic energy release during plastic deformations of metals; this gives the chance to study and monitor cracks and fatigue damage in structures. The huge problem interlinked with this technique in shipping applications is the great number of sensors and cables to allow hull monitoring. Future developments may be based on exploiting one optical fiber to integrate a high number of sensors. The great advantage of acoustic emission sensors over strain gauges is that the former can indicate when a crack is present in the artifact and when it is pushing forward, whilst strain gauges can just predict and suddenly operate for these events. Strain gauges could work with acoustic emissions sensors in order to correlate crack growing to specific load conditions. The new path for future ships might be a combination of previous technologies (strain gauges and acoustic emission sensors) integrating wireless data transmission to limit the extent of cabling. Unmanned ships are very common for harvesting data about water and air pollution. It has been shown that they currently base their possibility to operate just on batteries and solar panels. An interesting solution could be the application of methanol into this type of ship in substitution of solar panels. It is obvious that emissions coming from methanol fuel cells have to be monitored in order to assess carbon neutrality, taking into account exclusively renewable methanol. Today, there are some methanol fuel cell applications that take into consideration small amounts of power linked to the weight installed. Moreover, an application like unmanned vehicles could be taken into account. Some steps forward could also be taken in the field of oil spills.

Combining applications of unmanned vehicles with the latest sensor technologies could direct the research to improve the time response to an oil spill disaster and coordinate in real-time the mitigating actions. The whole digitalization of the ocean, in this case, could give quantitative data about a disaster and limit its spread in a shorter time. A useful improvement in the oil spill detection research could be applying sensors for detecting Total Dissolved Solids (TDS) or color sensors for recognizing water droplets in the oil in order to mitigate the phenomenon more easily. In order to improve structural health monitoring of ships' responses, it could be interesting to conduct more research activities on the right positioning of onboard sensors to limit sensor redundancy and costs. In addition, it is obvious that a general methodology for damage detection in marine structures has not been developed. A key point for making forward steps in this field is finding innovative signal processing methods for including more parameters to give more accurate responses about ship-wave interaction. The use of sensors with the new upcoming technologies coming from the IoT world could help to develop a new, accurate way to study the sea state.

Future Views: Internet of Things and the Role of Artificial Intelligence for the Maritime Mobility

It is always difficult to contextualize Artificial Intelligence (AI) into different areas of application because it is necessary to put in evidence the ratio between the strengths and weaknesses of every single case. The impressive skills of this tool are evident, but it is necessary to apply it in a proper way to avoid dubious situations. In the marine sector, a large amount of data every day is collected by numerous recording devices such as sensors, satellites, and unmanned marine vehicles [116]. The Internet of Maritime Things (IoMT) is a customization of the international standard of the Internet of things (IoT) designed for the marine environment [117]. This type of communication system could send data up to 40 km by means of automatically adjusting antennas. The advantages are evident, especially in the short-medium routes compared to LTE technologies. The extended process of harvesting and sending data, based on a proper digital architecture, has to be supported by a suitable classification and managing logic. In these cases, specific AI algorithms could be the right path to follow to avoid excessive data analysis and post-processing sessions. The main risk linked to the establishment of AI is not being fully aware of the event's physical nature. This could negatively influence the quality of harvested data. In the near future, a great goal to accomplish for the digitalization of the ocean is the fulfillment of V2C (Vehicle to Cloud). A cloud-based activity [118] could coordinate tasks among USVs or other categories of unmanned vehicles in order to intensify, for example, harvesting data procedures in situ. Integration between cloud infrastructure and next-generation AI algorithms may be the right path for increasing security in the maritime sector, especially in the costal areas where the previous technology could be integrated with land connectivity platforms (Vehicle to infrastructure, Vehicle to Grid, Vehicle to Device, Vehicle to Network). Vehicle to cloud is particularly usefull for monitoring enviromental impacts: by analyzing data collected from electric vehicles, manufactures could have the chance to optimize energy efficiency, reducing operational costs. At the same time, we can have the possibility of monitoring electric components in real-time and try to make more efficient battery life, minimize energy consumption, and optimize vehicle performances.

9. Conclusions

A holistic view of the sensors in maritime vehicles and offshore structures is proposed in this review. In order to accomplish new regulation tasks in terms of maritime pollution and, at the same time, improve the security of maritime vehicles, it is necessary to develop innovative and efficient digital architectures for generating real-time spatiotemporal data for marine vehicles and structures near and outside ports. Knowing all the possible interactions among sensors and surrounding maritime structures, it is essential to build embedded maritime systems for accomplishing future tasks.

Author Contributions: Conceptualization, G.B. and V.C.; writing—original draft preparation, G.B.; writing—review and editing, G.B. and V.C.; funding acquisition, V.C. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Acknowledgments: This study shows the results of the research activities of the Research Project PNRR Ecosystem "SAMOTHRACE" (SiciliAn MicronanOTecH Research and Innovation Center) (Code: ECS00000022), project funded by the UE—NextGenerationEU.

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

References

1. Antão, P.; Sun, S.; Teixeira, A.P.; Guedes Soares, C. Quantitative Assessment of Ship Collision Risk Influencing Factors from Worldwide Accident and Fleet Data. *Reliab. Eng. Syst. Saf.* **2023**, *234*, 109166. [CrossRef]
2. Eliopoulou, E.; Alissafaki, A.; Papanikolaou, A. Statistical Analysis of Accidents and Review of Safety Level of Passenger Ships. *J. Mar. Sci. Eng.* **2023**, *11*, 410. [CrossRef]
3. Mueller, N.; Westerby, M.; Nieuwenhuijsen, M. Health Impact Assessments of Shipping and Port-Sourced Air Pollution on a Global Scale: A Scoping Literature Review. *Environ. Res.* **2023**, *216*, 114460. [CrossRef] [PubMed]
4. Parra, L.; Viciano-Tudela, S.; Carrasco, D.; Sendra, S.; Lloret, J. Low-Cost Microcontroller-Based Multiparametric Probe for Coastal Area Monitoring. *Sensors* **2023**, *23*, 1871. [CrossRef] [PubMed]
5. Kishore Sonti, V.J.K.; Sundari, G.; Bernatin, T. Ecological Observing Using Sensor and IoT to Protect the Global Warming in WSN. In Proceedings of the 2023 International Conference on Recent Trends in Electronics and Communication (ICRTEC), Virtual, 10–11 February 2023.
6. Mehrpooya, M.; Ganjali, M.R.; Mousavi, S.A.; Hedayat, N.; Allahyarzadeh, A. Comprehensive Review of Fuel-Cell-Type Sensors for Gas Detection. *Ind. Eng. Chem. Res.* **2023**, *62*, 2387–2409. [CrossRef]
7. Thombre, S.; Zhao, Z.; Ramm-Schmidt, H.; Vallet Garcia, J.M.; Malkamaki, T.; Nikolskiy, S.; Hammarberg, T.; Nuortie, H.; Bhuiyan, M.Z.H.; Sarkka, S.; et al. Sensors and AI Techniques for Situational Awareness in Autonomous Ships: A Review. *IEEE Trans. Intell. Transp. Syst.* **2022**, *23*, 64–83. [CrossRef]
8. Fingas, M.; Brown, C. A Review of Oil Spill Remote Sensing. *Sensors* **2017**, *18*, 91. [CrossRef] [PubMed]
9. Wang, P.; Tian, X.; Peng, T.; Luo, Y. A Review of the State-of-the-Art Developments in the Field Monitoring of Offshore Structures. *Ocean Eng.* **2018**, *147*, 148–164. [CrossRef]
10. Swartz, R.A.; Zimmerman, A.T.; Lynch, J.P.; Rosario, J.; Brady, T.; Salvino, L.; Law, K.H. Hybrid Wireless Hull Monitoring System for Naval Combat Vessels. *Struct. Infrastruct. Eng.* **2012**, *8*, 621–638. [CrossRef]
11. Kiddy, J.S.; Baldwin, C.S.; Salter, T.; Chen, P.C. Structural Load Monitoring of the RV Triton Using Fiber Optic Sensors. In *Smart Structures and Materials 2002: Industrial and Commercial Applications of Smart Structures Technologies*; McGowan, A.-M.R., Ed.; SPIE: St. Bellingham, WA, USA, 2002; pp. 462–472.
12. Raptodimos, Y.; Lazakis, I.; Theotokatos, G.; Varelas, T.; Drikos, L. Ship Sensors Data Collection & Analysis for Condition Monitoring of Ship Structures & Machinery Systems. In Proceedings of the Smart Ships Technology 2016, London, UK, 26–27 January 2016; RINA: Genoa, Italy, 2016; pp. 77–86.
13. Parunov, J.; Pedišić-Buča, M.; Gatin, I.; Ćatipović, I. Hydrodynamic Tests of Innovative Tourist Submarine. *J. Mar. Sci. Eng.* **2023**, *11*, 1199. [CrossRef]
14. Wang, G.; Pran, K.; Sagvolden, G.; Havsgård, G.B.; Jensen, A.E.; Johnson, G.A.; Vohra, S.T. Ship Hull Structure Monitoring Using Fibre Optic Sensors. *Smart Mater. Struct.* **2001**, *10*, 472–478. [CrossRef]

15. Mieloszyk, M.; Majewska, K.; Ostachowicz, W. Application of Embedded Fibre Bragg Grating Sensors for Structural Health Monitoring of Complex Composite Structures for Marine Applications. *Mar. Struct.* **2021**, *76*, 102903. [CrossRef]
16. Kang, I.; Schulz, M.J.; Kim, J.H.; Shanov, V.; Shi, D. A Carbon Nanotube Strain Sensor for Structural Health Monitoring. *Smart Mater. Struct.* **2006**, *15*, 737–748. [CrossRef]
17. Xu, T.; Qiu, Q.; Lu, S.; Ma, K.; Wang, X. Multi-Direction Health Monitoring with Carbon Nanotube Film Strain Sensor. *Int. J. Distrib. Sens. Netw.* **2019**, *15*, 155014771982968. [CrossRef]
18. Alexopoulos, N.D.; Bartholome, C.; Poulin, P.; Marioli-Riga, Z. Structural Health Monitoring of Glass Fiber Reinforced Composites Using Embedded Carbon Nanotube (CNT) Fibers. *Compos. Sci. Technol.* **2010**, *70*, 260–271. [CrossRef]
19. Sabra, K.G.; Huston, S. Passive Structural Health Monitoring of a High-Speed Naval Ship from Ambient Vibrations. *J. Acoust. Soc. Am.* **2011**, *129*, 2991–2999. [CrossRef]
20. Torkildsen, H.E.; Grøvlen, Å.; Skaugen, A.; Wang, G.; Jensen, A.E.; Pran, K.; Sagvolden, G. *Development and Applications of Full-Scale Ship Hull Health Monitoring Systems for the Royal Norwegian Navy*; RTO: Neuilly-sur-Seine, France, 2005.
21. Kefal, A.; Mayang, J.B.; Oterkus, E.; Yildiz, M. Three Dimensional Shape and Stress Monitoring of Bulk Carriers Based on iFEM Methodology. *Ocean Eng.* **2018**, *147*, 256–267. [CrossRef]
22. Kefal, A.; Oterkus, E. Displacement and Stress Monitoring of a Chemical Tanker Based on Inverse Finite Element Method. *Ocean Eng.* **2016**, *112*, 33–46. [CrossRef]
23. Bucci, V.; Corigliano, P.; Crupi, V.; Epasto, G.; Guglielmino, E.; Marinò, A. Experimental Investigation on Iroko Wood Used in Shipbuilding. *Proc. Inst. Mech. Eng. C J. Mech. Eng. Sci.* **2017**, *231*, 128–139. [CrossRef]
24. Fan, J.; Guo, X.; Wu, C.; Crupi, V.; Guglielmino, E. Influence of Heat Treatments on Mechanical Behavior of FV520B Steel. *Exp. Tech.* **2015**, *39*, 55–64. [CrossRef]
25. Tighe, R.C.; Dulieu-Barton, J.M.; Quinn, S. Infrared Techniques for Practical Defect Identification in Bonded Joints in Liquefied Natural Gas Carriers. *Exp. Tech.* **2018**, *42*, 121–128. [CrossRef]
26. Crupi, V.; Chiofalo, G.; Guglielmino, E. Using Infrared Thermography in Low-Cycle Fatigue Studies of Welded Joints. *Weld. J.* **2010**, *89*, 195–200.
27. Li, H.C.H.; Herszberg, I.; Davis, C.E.; Mouritz, A.P.; Galea, S.C. Health Monitoring of Marine Composite Structural Joints Using Fibre Optic Sensors. *Compos. Struct.* **2006**, *75*, 321–327. [CrossRef]
28. Saeedifar, M.; Saleh, M.N.; Krairi, A.; de Freitas, S.T.; Zarouchas, D. Structural Integrity Assessment of a Full-Scale Adhesively-Bonded Bi-Material Joint for Maritime Applications. *Thin-Walled Struct.* **2023**, *184*, 110487. [CrossRef]
29. Rogers, L.M. *Application of Acoustic Emission Technology for Health Monitoring of Ship Structures*; Ship Structure Committee: Washington, DC, USA, 2014.
30. Edwards, R.; Prislin, I.; Johnson, T.; Campman, C.; Leverette, S.; Halkyard, J. Review of 17 Real-Time, Environment, Response, and Integrity Monitoring Systems on Floating Production Platforms in the Deep Waters of the Gulf of Mexico. In Proceedings of the Offshore Technology Conference, Houston, TX, USA, 8 April 2005.
31. Gerner, M.B.; Perryman, S.R.; Geyer, J.F.; von Aschwege, J.T. Marine Monitoring of Gulf of Mexico Deepwater Floating Systems. In Proceedings of the All Days, OTC, Houston, TX, USA, 30 April 2007.
32. Mieloszyk, M.; Ostachowicz, W. An Application of Structural Health Monitoring System Based on FBG Sensors to Offshore Wind Turbine Support Structure Model. *Mar. Struct.* **2017**, *51*, 65–86. [CrossRef]
33. Chung, W.C.; Pestana, G.R.; Kim, M. Structural Health Monitoring for TLP-FOWT (Floating Offshore Wind Turbine) Tendon Using Sensors. *Appl. Ocean Res.* **2021**, *113*, 102740. [CrossRef]
34. Gordelier, T.; Thies, P.R.; Rinaldi, G.; Johanning, L. Investigating Polymer Fibre Optics for Condition Monitoring of Synthetic Mooring Lines. *J. Mar. Sci. Eng.* **2020**, *8*, 103. [CrossRef]
35. Gordon, R.B.; Brown, M.G.; Allen, E.M. Mooring Integrity Management: A State-of-the-Art Review. In Proceedings of the Offshore Technology Conference, OTC, Houston, TX, USA, 5–8 May 2014.
36. Sakaris, C.S.; Yang, Y.; Bashir, M.; Michailides, C.; Wang, J.; Sakellariou, J.S.; Li, C. Structural Health Monitoring of Tendons in a Multibody Floating Offshore Wind Turbine under Varying Environmental and Operating Conditions. *Renew. Energy* **2021**, *179*, 1897–1914. [CrossRef]
37. Nguyen, T.T.D.; Park, J.W.; Nguyen, V.M.; Yoon, H.K.; Jung, J.C.; Lee, M.M.S. Experimental Study on Application of an Optical Sensor to Measure Mooring-Line Tension in Waves. *J. Ocean Eng. Technol.* **2022**, *36*, 153–160. [CrossRef]
38. Wu, W.; Feng, J.; Xie, B.; Tang, D.; Yue, Q.; Xie, R. Development and Sensing Properties Study of Underwater Assembled Water Depth-Inclination Sensors for a Multi-Component Mooring System, Using a Self-Contained Technique. *Sensors* **2016**, *16*, 1925. [CrossRef] [PubMed]
39. Wang, S. Damage Detection in Offshore Platform Structures from Limited Modal Data. *Appl. Ocean Res.* **2013**, *41*, 48–56. [CrossRef]
40. Hillis, A.J.; Courtney, C.R.P. Structural Health Monitoring of Fixed Offshore Structures Using the Bicoherence Function of Ambient Vibration Measurements. *J. Sound Vib.* **2011**, *330*, 1141–1152. [CrossRef]
41. Tseranidis, S.; Theodoridis, L.; Loukogeorgaki, E.; Angelides, D.C. Investigation of the Condition and the Behavior of a Modular Floating Structure by Harnessing Monitoring Data. *Mar. Struct.* **2016**, *50*, 224–242. [CrossRef]
42. Chung, J.S.; International Society of Offshore and Polar Engineers. *The Proceedings of the Twenty-Third (2013) International Offshore and Polar Engineering Conference: Anchorage, AK, USA, 30 June–5 July 2013: ISOPE-2013 Anchorage*; International Society of Offshore and Polar Engineers: Mountain View, CA, USA, 2013; ISBN 9781880653999.

43. Chu, C.; Zuo-Xi, Z.; Xin-Rong, K.E.; Yun-Zhi, G. The Research of Machinery Fault Feature Extraction Methods Based on Vibration Signal. *IFAC-Pap.* **2018**, *51*, 346–352. [CrossRef]
44. Gilroy, L. Ship Noise Management and the ORCA Class of Ships. *Mar. Pollut. Bull.* **2022**, *174*, 113196. [CrossRef]
45. McCormick, M.I.; Allan, B.J.M.; Harding, H.; Simpson, S.D. Boat Noise Impacts Risk Assessment in a Coral Reef Fish but Effects Depend on Engine Type. *Sci. Rep.* **2018**, *8*, 3847. [CrossRef]
46. Virto, L.R.; Dumez, H.; Romero, C.; Bailly, D. How Can Ports Act to Reduce Underwater Noise from Shipping? Identifying Effective Management Frameworks. *Mar. Pollut. Bull.* **2022**, *174*, 113136. [CrossRef]
47. Du, T.; Zuo, X.; Dong, F.; Li, S.; Mtui, A.E.; Zou, Y.; Zhang, P.; Zhao, J.; Zhang, Y.; Sun, P.; et al. A Self-Powered and Highly Accurate Vibration Sensor Based on Bouncing-Ball Triboelectric Nanogenerator for Intelligent Ship Machinery Monitoring. *Micromachines* **2021**, *12*, 218. [CrossRef]
48. Poveda-Martínez, P.; Ramis-Soriano, J. A Comparison between Psychoacoustic Parameters and Condition Indicators for Machinery Fault Diagnosis Using Vibration Signals. *Appl. Acoust.* **2020**, *166*, 107364. [CrossRef]
49. Gerhard, K.L. Non-Intrusive Vibration Monitoring in US Naval and US Coast Guard Ships. Master's Thesis, Massachusetts Institute of Technology, Cambridge, MA, USA, 2013.
50. Lee, J.K.; Seung, H.M.; Park, C.I.; Lee, J.K.; Lim, D.H.; Kim, Y.Y. Magnetostrictive Patch Sensor System for Battery-Less Real-Time Measurement of Torsional Vibrations of Rotating Shafts. *J. Sound Vib.* **2018**, *414*, 245–258. [CrossRef]
51. Han, H.; Lee, K.; Park, S. Estimate of the Fatigue Life of the Propulsion Shaft from Torsional Vibration Measurement and the Linear Damage Summation Law in Ships. *Ocean Eng.* **2015**, *107*, 212–221. [CrossRef]
52. Zhao, Y.; Sun, Z.; Li, W.; Tian, K.; Zhan, Z.; Shan, P.; Li, L. Sea Ice Type and Thickness Identification Based on Vibration Sensor Networks and Machine Learning. *IEEE Trans. Instrum. Meas.* **2023**, *72*, 2512111. [CrossRef]
53. Liu, H.; Fu, M.; Jin, X.; Shang, Y.; Shindell, D.; Faluvegi, G.; Shindell, C.; He, K. Health and Climate Impacts of Ocean-Going Vessels in East Asia. *Nat. Clim. Chang.* **2016**, *6*, 1037–1041. [CrossRef]
54. Matthias, V.; Bewersdorff, I.; Aulinger, A.; Quante, M. The Contribution of Ship Emissions to Air Pollution in the North Sea Regions. *Environ. Pollut.* **2010**, *158*, 2241–2250. [CrossRef]
55. Sofiev, M.; Winebrake, J.J.; Johansson, L.; Carr, E.W.; Prank, M.; Soares, J.; Vira, J.; Kouznetsov, R.; Jalkanen, J.-P.; Corbett, J.J. Cleaner Fuels for Ships Provide Public Health Benefits with Climate Tradeoffs. *Nat. Commun.* **2018**, *9*, 406. [CrossRef]
56. Dsouza, V.L.; Dsouza, S.F.; Sarosh, M.; Kukkilaya, S.; Chilimbi, V.; Fernandes, S.R. Remotely Controlled Boat for Water Quality Monitoring and Sampling. *Mater. Today Proc.* **2021**, *47*, 2391–2400. [CrossRef]
57. Jayaratne, R.; Kuhn, T.; Christensen, B.; Liu, X.; Zing, I.; Lamont, R.; Dunbabin, M.; Maddox, J.; Fisher, G.; Morawska, L. Using a Network of Low-Cost Particle Sensors to Assess the Impact of Ship Emissions on a Residential Community. *Aerosol Air Qual. Res.* **2020**, *20*, 2754–2764. [CrossRef]
58. Zhou, F.; Fan, Y.; Zou, J.; An, B. Ship Emission Monitoring Sensor Web for Research and Application. *Ocean Eng.* **2022**, *249*, 110980. [CrossRef]
59. Sørensen, M.K.; Vinding, M.S.; Bakharev, O.N.; Nesgaard, T.; Jensen, O.; Nielsen, N.C. NMR Sensor for Onboard Ship Detection of Catalytic Fines in Marine Fuel Oils. *Anal. Chem.* **2014**, *86*, 7205–7208. [CrossRef]
60. Deng, M.; Peng, S.; Xie, X.; Jiang, Z.; Hu, J.; Qi, Z. A Diffused Mini-Sniffing Sensor for Monitoring SO_2 Emissions Compliance of Navigating Ships. *Sensors* **2022**, *22*, 5198. [CrossRef]
61. Beecken, J.; Mellqvist, J.; Salo, K.; Ekholm, J.; Jalkanen, J.-P. Airborne Emission Measurements of SO_2, NOx and Particles from Individual Ships Using a Sniffer Technique. *Atmos. Meas. Tech.* **2014**, *7*, 1957–1968. [CrossRef]
62. Kattner, L.; Mathieu-Üffing, B.; Burrows, J.P.; Richter, A.; Schmolke, S.; Seyler, A.; Wittrock, F. Monitoring Compliance with Sulfur Content Regulations of Shipping Fuel by in Situ Measurements of Ship Emissions. *Atmos. Chem. Phys.* **2015**, *15*, 10087–10092. [CrossRef]
63. Pirjola, L.; Pajunoja, A.; Walden, J.; Jalkanen, J.-P.; Rönkkö, T.; Kousa, A.; Koskentalo, T. Mobile Measurements of Ship Emissions in Two Harbour Areas in Finland. *Atmos. Meas. Tech.* **2014**, *7*, 149–161. [CrossRef]
64. Passig, J.; Schade, J.; Irsig, R.; Li, L.; Li, X.; Zhou, Z.; Adam, T.; Zimmermann, R. Detection of Ship Plumes from Residual Fuel Operation in Emission Control Areas Using Single-Particle Mass Spectrometry. *Atmos. Meas. Tech.* **2021**, *14*, 4171–4185. [CrossRef]
65. Yuan, S.; Li, Y.; Bao, F.; Xu, H.; Yang, Y.; Yan, Q.; Zhong, S.; Yin, H.; Xu, J.; Huang, Z.; et al. Marine Environmental Monitoring with Unmanned Vehicle Platforms: Present Applications and Future Prospects. *Sci. Total Environ.* **2023**, *858*, 159741. [CrossRef]
66. Jo, W.; Hoashi, Y.; Paredes Aguilar, L.L.; Postigo-Malaga, M.; Garcia-Bravo, J.M.; Min, B.-C. A Low-Cost and Small USV Platform for Water Quality Monitoring. *HardwareX* **2019**, *6*, e00076. [CrossRef]
67. Cao, H.; Guo, Z.; Wang, S.; Cheng, H.; Zhan, C. Intelligent Wide-Area Water Quality Monitoring and Analysis System Exploiting Unmanned Surface Vehicles and Ensemble Learning. *Water* **2020**, *12*, 681. [CrossRef]
68. Yaakob, O.; Mohamed, Z.; Hanafiah, M.S.; Suprayogi, D.; Abdul Ghani, M.; Adnan, F.; Mukti, M.; Din, J. Development of Unmanned Surface Vehicle (USV) for Sea Patrol and Environmental Monitoring. In Proceedings of the International Conference on Marine Technology, Kuala Terengganu, Malaysia, 20–22 October 2012.
69. Cryer, S.; Carvalho, F.; Wood, T.; Strong, J.A.; Brown, P.; Loucaides, S.; Young, A.; Sanders, R.; Evans, C. Evaluating the Sensor-Equipped Autonomous Surface Vehicle C-Worker 4 as a Tool for Identifying Coastal Ocean Acidification and Changes in Carbonate Chemistry. *J. Mar. Sci. Eng.* **2020**, *8*, 939. [CrossRef]

70. Chang, H.-C.; Hsu, Y.-L.; Hung, S.-S.; Ou, G.-R.; Wu, J.-R.; Hsu, C. Autonomous Water Quality Monitoring and Water Surface Cleaning for Unmanned Surface Vehicle. *Sensors* **2021**, *21*, 1102. [CrossRef] [PubMed]
71. Glenn, S.M.; Miles, T.N.; Seroka, G.N.; Xu, Y.; Forney, R.K.; Yu, F.; Roarty, H.; Schofield, O.; Kohut, J. Stratified Coastal Ocean Interactions with Tropical Cyclones. *Nat. Commun.* **2016**, *7*, 10887. [CrossRef] [PubMed]
72. da Silva, D.C.; dos Santos Lucas, C.R.; de Moraes Juviniano, H.B.; de Alencar Moura, M.C.P.; Dantas Neto, A.A.; de Castro Dantas, T.N. Novel Produced Water Treatment Using Microemulsion Systems to Remove Oil Contents. *J. Water Process Eng.* **2020**, *33*, 101006. [CrossRef]
73. Lee, J.; Cho, W.-C.; Poo, K.-M.; Choi, S.; Kim, T.-N.; Son, E.-B.; Choi, Y.-J.; Kim, Y.M.; Chae, K.-J. Refractory Oil Wastewater Treatment by Dissolved Air Flotation, Electrochemical Advanced Oxidation Process, and Magnetic Biochar Integrated System. *J. Water Process Eng.* **2020**, *36*, 101358. [CrossRef]
74. Zhang, N.; Yang, X.; Wang, Y.; Qi, Y.; Zhang, Y.; Luo, J.; Cui, P.; Jiang, W. A Review on Oil/Water Emulsion Separation Membrane Material. *J. Environ. Chem. Eng.* **2022**, *10*, 107257. [CrossRef]
75. Jafarzadeh, H.; Mahdianpari, M.; Homayouni, S.; Mohammadimanesh, F.; Dabboor, M. Oil Spill Detection from Synthetic Aperture Radar Earth Observations: A Meta-Analysis and Comprehensive Review. *GIsci. Remote Sens.* **2021**, *58*, 1022–1051. [CrossRef]
76. Budiman, F.; Ismardi, A.; Hardinah, T.; Muhammad, R.; Nurwijayadi; Hartaman, A.; Nurhidayat, A.; Sasto, I.H.S.; Sutapa, I.D.A. Strengthening Oil Pollution Monitoring System in Aquatic Environment through Development of IoT-Based Oil-Water Separator Device. *Ecohydrol. Hydrobiol.* **2023**, *in press*. [CrossRef]
77. Ma, J.; Meng, F.; Zhou, Y.; Wang, Y.; Shi, P. Intelligent Water Pollution Source Identification and Localization in Wireless Sensor Networks. In Proceedings of the 2018 2nd IEEE Advanced Information Management, Communicates, Electronic and Automation Control Conference (IMCEC), Xi'an, China, 25–27 May 2018; IEEE: Piscataway, NJ, USA, 2018; pp. 1300–1305.
78. Hidalgo, F.; Mendoza, J.; Cuellar, F. ROV-Based Acquisition System for Water Quality Measuring. In Proceedings of the OCEANS 2015—MTS/IEEE, Washington, DC, USA, 9–22 October 2015; IEEE: Piscataway, NJ, USA, 2015; pp. 1–5.
79. Subash, T.D.; Pradeep, A.S.; Rajan Joseph, A.; Jacob, A.; Jayaraj, P.S. Intelligent Collision Avoidance System for Fishing Boat. *Mater. Today Proc.* **2020**, *24*, 2457–2463. [CrossRef]
80. Helgesen, Ø.K.; Vasstein, K.; Brekke, E.F.; Stahl, A. Heterogeneous Multi-Sensor Tracking for an Autonomous Surface Vehicle in a Littoral Environment. *Ocean Eng.* **2022**, *252*, 111168. [CrossRef]
81. Takkinen, E.; Ruponen, P.; Pennanen, P. Required Flooding Sensor Arrangement for Reliable Automatic Damage Detection. In Proceedings of the Smart Ship Technology, London, UK, 24–25 January 2017.
82. Braidotti, L.; Valčić, M.; Prpić-Oršić, J. Exploring a Flooding-Sensors-Agnostic Prediction of the Damage Consequences Based on Machine Learning. *J. Mar. Sci. Eng.* **2021**, *9*, 271. [CrossRef]
83. García, E.; Quiles, E.; Correcher, A.; Morant, F. Marine NMEA 2000 Smart Sensors for Ship Batteries Supervision and Predictive Fault Diagnosis. *Sensors* **2019**, *19*, 4480. [CrossRef]
84. Dudojc, B.; Mindykowski, J. New Approach to Analysis of Selected Measurement and Monitoring Systems Solutions in Ship Technology. *Sensors* **2019**, *19*, 1775. [CrossRef]
85. Li, T.; Hua, M.; Yin, Q. The Temperature Forecast of Ship Propulsion Devices from Sensor Data. *Information* **2019**, *10*, 316. [CrossRef]
86. Szelangiewicz, T.; Żelazny, K.; Antosik, A.; Szelangiewicz, M. Application of Measurement Sensors and Navigation Devices in Experimental Research of the Computer System for the Control of an Unmanned Ship Model. *Sensors* **2021**, *21*, 1312. [CrossRef]
87. Wright, R.G. Intelligent Autonomous Ship Navigation Using Multi-Sensor Modalities. *TransNav Int. J. Mar. Navig. Saf. Sea Transp.* **2019**, *13*, 503–510. [CrossRef]
88. Tiwari, D.; Bhati, B.S.; Nagpal, B.; Sankhwar, S.; Al-Turjman, F. An Enhanced Intelligent Model: To Protect Marine IoT Sensor Environment Using Ensemble Machine Learning Approach. *Ocean Eng.* **2021**, *242*, 110180. [CrossRef]
89. Rødseth, Ø.J.; Wennersberg, L.A.L.; Nordahl, H. Improving Safety of Interactions between Conventional and Autonomous Ships. *Ocean Eng.* **2023**, *284*, 115206. [CrossRef]
90. Lee, Y.C.; Hoang, V.A. Battery-Free and Real-Time Wireless Sensor System on Marine Propulsion Shaft Using a Wireless Power Transfer Module. *Sensors* **2023**, *23*, 558. [CrossRef]
91. Vettor, R.; Szlapczynska, J.; Szlapczynski, R.; Tycholiz, W.; Soares, C.G. Towards Improving Optimised Ship Weather Routing. *Pol. Marit. Res.* **2020**, *27*, 60–69. [CrossRef]
92. Lee, H.-J.; Park, D.-J. Analysis of Thermal Characteristics of MEMS Sensors for Measuring the Rolling Period of Maritime Autonomous Surface Ships. *J. Mar. Sci. Eng.* **2022**, *10*, 859. [CrossRef]
93. Sahoo, A.; Dwivedy, S.K.; Robi, P.S. Advancements in the Field of Autonomous Underwater Vehicle. *Ocean Eng.* **2019**, *181*, 145–160. [CrossRef]
94. Cui, Y.; Zhu, P.; Lei, G.; Chen, P.; Yang, G. Energy-Efficient Multiple Autonomous Underwater Vehicle Path Planning Scheme in Underwater Sensor Networks. *Electronics* **2023**, *12*, 3321. [CrossRef]
95. Huy, D.Q.; Sadjoli, N.; Azam, A.B.; Elhadidi, B.; Cai, Y.; Seet, G. Object Perception in Underwater Environments: A Survey on Sensors and Sensing Methodologies. *Ocean Eng.* **2023**, *267*, 113202. [CrossRef]
96. Wang, Y.; Cao, Q.; Liu, L.; Wu, Y.; Liu, H.; Gu, Z.; Zhu, C. A Review of Low and Zero Carbon Fuel Technologies: Achieving Ship Carbon Reduction Targets. *Sustain. Energy Technol. Assess.* **2022**, *54*, 102762. [CrossRef]

97. Kim, K.; Roh, G.; Kim, W.; Chun, K. A Preliminary Study on an Alternative Ship Propulsion System Fueled by Ammonia: Environmental and Economic Assessments. *J. Mar. Sci. Eng.* **2020**, *8*, 183. [CrossRef]
98. Ahmed, A.A.; Al Labadidi, M.; Hamada, A.T.; Orhan, M.F. Design and Utilization of a Direct Methanol Fuel Cell. *Membranes* **2022**, *12*, 1266. [CrossRef]
99. Gautam, P.; Neha; Upadhyay, S.N.; Dubey, S.K. Bio-Methanol as a Renewable Fuel from Waste Biomass: Current Trends and Future Perspective. *Fuel* **2020**, *273*, 117783. [CrossRef]
100. Acanfora, M.; Altosole, M.; Balsamo, F.; Campora, U.; Scamardella, F. A Methanol Fueled Marine Engine Simulator for Fast Craft Applications. In *HSMV 2023: Proceedings of the 13th Symposium on High Speed Marine Vehicles*; IOS Press: Amsterdam, The Netherlands, 2023.
101. Padolecchia, D.; Utzeri, S.; Marinò, A.; Bucci, V. Feasibility Study for the Fuel Switch of a Fast Ferry. In *HSMV 2023*; IOS Press: Amsterdam, The Netherlands, 2023.
102. Kim, B.; Hwang, K.-I. Experimental Analysis of the Effects of Ship Motion on Hydrogen Dispersion in an Enclosed Area. *Int. J. Hydrogen Energy* **2023**, *48*, 31779–31789. [CrossRef]
103. Coppola, T.; De Luca, F.; Gambardella, S.; Mancini, S.; Micoli, L.; Pensa, C.; Sorrentino, V. Feasibility Study of a Zero-Emission Passenger Catamaran Ferry Operating in Italian Coastal Island. In *HSMV 2023: Proceedings of the 13th Symposium on High Speed Marine Vehicles*; IOS Press: Amsterdam, The Netherlands, 2023.
104. Teoh, Y.H.; How, H.G.; Le, T.D.; Nguyen, H.T.; Loo, D.L.; Rashid, T.; Sher, F. A Review on Production and Implementation of Hydrogen as a Green Fuel in Internal Combustion Engines. *Fuel* **2023**, *333*, 126525. [CrossRef]
105. Gainey, B.; Yan, Z.; Gandolfo, J.; Lawler, B. Methanol and Wet Ethanol as Interchangeable Fuels for Internal Combustion Engines: LCA, TEA, and Experimental Comparison. *Fuel* **2023**, *333*, 126257. [CrossRef]
106. Takeda, M.; Matsuno, Y.; Kodama, I.; Kumakura, H.; Weisend, J.G.; Barclay, J.; Breon, S.; Demko, J.; DiPirro, M.; Kelley, J.P.; et al. Characteristics of Mgb_2 Sensor for Detecting Level of Liquid Hydrogen. *AIP Conf. Proc.* **2008**, *985*, 933–939.
107. Nakano, A.; Shimazaki, T.; Sekiya, M.; Shiozawa, H.; Ohtsuka, K.; Aoyagi, A.; Iwakiri, T.; Mikami, Z.; Sato, M.; Sugino, Y.; et al. Research and Development of Liquid Hydrogen (LH2) Temperature Monitoring System for Marine Applications. *Int. J. Hydrogen Energy* **2021**, *46*, 15649–15659. [CrossRef]
108. Logan, K.P. Intelligent Diagnostic Requirements of Future All-Electric Ship Integrated Power System. *IEEE Trans. Ind. Appl.* **2007**, *43*, 139–149. [CrossRef]
109. Choi, C.H.; Yu, S.; Han, I.-S.; Kho, B.-K.; Kang, D.-G.; Lee, H.Y.; Seo, M.-S.; Kong, J.-W.; Kim, G.; Ahn, J.-W.; et al. Development and Demonstration of PEM Fuel-Cell-Battery Hybrid System for Propulsion of Tourist Boat. *Int. J. Hydrogen Energy* **2016**, *41*, 3591–3599. [CrossRef]
110. Koumentakos, A. Developments in Electric and Green Marine Ships. *Appl. Syst. Innov.* **2019**, *2*, 34. [CrossRef]
111. Jinasena, A.; Spitthoff, L.; Wahl, M.S.; Lamb, J.J.; Shearing, P.R.; Strømman, A.H.; Burheim, O.S. Online Internal Temperature Sensors in Lithium-Ion Batteries: State-of-the-Art and Future Trends. *Front. Chem. Eng.* **2022**, *4*, 804704. [CrossRef]
112. Wang, H.; Morando, S.; Gaillard, A.; Hissel, D. Sensor Development and Optimization for a Proton Exchange Membrane Fuel Cell System in Automotive Applications. *J. Power Sources* **2021**, *487*, 229415. [CrossRef]
113. Kurniawan, A. A Review of Solar-Powered Boat. Development. *IPTEK J. Technol. Sci.* **2016**, *27*, 1–8. [CrossRef]
114. Spagnolo, G.S.; Papalillo, D.; Martocchia, A.; Makary, G. Solar-Electric Boat. *J. Transp. Technol.* **2012**, *02*, 144–149. [CrossRef]
115. Plumet, F.; Pêtrès, C.; Romero-Ramirez, M.A.; Gas, B.; Ieng, S.H. Toward an Autonomous Sailing Boat. *IEEE J. Ocean Eng.* **2015**, *40*, 397–407. [CrossRef]
116. Park, S.; Yang, C.-S.; Kim, J. Design of Vessel Data Lakehouse with Big Data and AI Analysis Technology for Vessel Monitoring System. *Electronics* **2023**, *12*, 1943. [CrossRef]
117. Song, Y.; Shin, H.; Koo, S.; Baek, S.; Seo, J.; Kang, H.; Kim, Y. Internet of Maritime Things Platform for Remote Marine Water Quality Monitoring. *IEEE Internet Things J.* **2022**, *9*, 14355–14365. [CrossRef]
118. Wang, Z.; Yang, S.; Xiang, X.; Vasilijević, A.; Mišković, N.; Nađ, Đ. Cloud-Based Mission Control of USV Fleet: Architecture, Implementation and Experiments. *Control Eng. Pract.* **2021**, *106*, 104657. [CrossRef]