applied sciences

MDPI

Review

A Comprehensive Review and Analysis of Nanosensors for Structural Health Monitoring in Bridge Maintenance: Innovations, Challenges, and Future Perspectives

Daguang Han [1], Haidar Hosamo [2,*], Chunli Ying [3] and Ruimin Nie [4]

[1] School of Civil Engineering, Southeast University, Nanjing 211189, China; daguanghan@seu.edu.cn
[2] Department of Engineering Sciences, University of Agder, Jon Lilletuns vei 9, 4879 Grimstad, Norway
[3] School of Architecture, Building and Civil Engineering, Loughborough University, Loughborough LE11 3TU, UK
[4] China Design Digital Technology, Shanghai 200000, China
* Correspondence: haidarh@uia.no

Abstract: This paper presents a thorough review and detailed analysis of nanosensors for structural health monitoring (SHM) in the context of bridge maintenance. With rapid advancements in nanotechnology, nanosensors have emerged as promising tools for detecting and assessing the structural integrity of bridges. The objective of this review is to provide a comprehensive understanding of the various types of nanosensors utilized in bridge maintenance, their operating principles, fabrication techniques, and integration strategies. Furthermore, this paper explores the challenges associated with nanosensor deployment, such as signal processing, power supply, and data interpretation. Finally, the review concludes with an outlook on future developments in the field of nanosensors for SHM in bridge maintenance.

Keywords: nanosensors; structural health monitoring; bridge maintenance; operating principles; fabrication techniques

check for updates

Citation: Han, D.; Hosamo, H.; Ying, C.; Nie, R. A Comprehensive Review and Analysis of Nanosensors for Structural Health Monitoring in Bridge Maintenance: Innovations, Challenges, and Future Perspectives. *Appl. Sci.* **2023**, *13*, 11149. https://doi.org/10.3390/app132011149

Academic Editors: Žydrūnas Kavaliauskas and Vitas Valincius

Received: 7 June 2023
Revised: 3 October 2023
Accepted: 9 October 2023
Published: 10 October 2023

Copyright: © 2023 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction

1.1. Background

Bridges play a critical role in transportation infrastructure, facilitating the movement of people, goods, and services [1]. However, over time, bridges are subjected to various environmental factors, heavy loads, and aging processes, which can lead to structural deterioration and compromise their integrity [2]. The maintenance and continuous monitoring of bridge structures are paramount to ensure public safety and prevent catastrophic failures [3].

Traditional methods of bridge inspection and maintenance, such as visual inspection and manual testing, have limitations in terms of accuracy, reliability, and cost-effectiveness [4]. To overcome these challenges, there has been a growing interest in the development and application of advanced technologies, including nanosensors, for structural health monitoring (SHM) in bridge maintenance [5].

Nanosensors, which utilize nanoscale materials and principles, have shown immense potential for real-time, accurate, and remote monitoring of bridge structures [6]. These miniature devices can be embedded or attached to the bridge components to detect and assess various parameters, including strain, deformation, temperature, humidity, corrosion, and vibration. The information gathered from nanosensors can provide valuable insights into the structural behavior, performance, and health condition of bridges [7].

Moreover, nanosensors offer several advantages over conventional sensing techniques. Their small size and lightweight nature enable seamless integration into bridge structures without significantly altering their mechanical properties [8]. Additionally, nanosensors offer high sensitivity, fast response, and multi-parameter detection capabilities, allowing for comprehensive monitoring of bridge conditions [9].

Given the potential of nanosensors in bridge maintenance, it is essential to comprehensively review and analyze the various types of nanosensors available, their fabrication techniques, integration strategies, and the challenges associated with their deployment. This paper aims to provide a detailed exploration of nanosensors for SHM in bridge maintenance, shedding light on the innovations, challenges, and future perspectives in this rapidly evolving field.

1.2. Importance of Structural Health Monitoring in Bridge Maintenance

Effective maintenance of bridges is vital to ensure the safety of transportation infrastructure and the uninterrupted flow of goods and services. Over time, bridges are subjected to numerous external factors, including dynamic loads, harsh environmental conditions, and aging processes, all of which can lead to gradual deterioration and compromise the structural integrity of these critical infrastructure elements [10].

Structural health monitoring (SHM) has emerged as a valuable tool in bridge maintenance, offering a proactive and data-driven approach to assess and manage the condition of bridge structures [11]. Unlike traditional inspection methods that rely on visual observations and periodic assessments, SHM employs continuous monitoring systems to gather real-time data on various structural parameters, enabling early detection of potential issues and facilitating timely intervention [12].

One of the primary advantages of SHM is its ability to provide a comprehensive understanding of a bridge's behavior and condition [13]. By employing a network of sensors strategically placed throughout the bridge, SHM systems can capture critical information, such as strain, deformation, temperature, humidity, corrosion, and vibration. These data points offer valuable insights into the performance and health of the bridge, allowing engineers and maintenance personnel to make informed decisions regarding repair, maintenance, and rehabilitation strategies.

The integration of nanosensors within SHM systems has revolutionized bridge maintenance practices [14]. Nanosensors, utilizing nanoscale materials and innovative sensing principles, offer enhanced sensitivity, accuracy, and versatility in monitoring bridge structures [15]. They can detect minuscule changes in structural parameters, enabling early detection of damage, fatigue, or other signs of deterioration that may not be immediately visible to the naked eye. The real-time and continuous data provided by nanosensors enable proactive maintenance practices, optimizing the allocation of resources and minimizing the potential risks associated with bridge failures.

Furthermore, SHM systems incorporating nanosensors contribute to the development of a more sustainable and cost-effective maintenance approach [16]. By enabling targeted interventions based on actual structural conditions, resources can be allocated more efficiently, reducing unnecessary repairs and maximizing the lifespan of bridges [17]. This approach not only saves time and money but also minimizes disruptions to traffic flow, reducing the inconvenience caused to the public during maintenance activities.

The implementation of SHM systems in bridge maintenance is of paramount importance. By integrating nanosensors into these systems, engineers can continuously monitor the structural health of bridges, enabling early detection of potential issues and facilitating prompt and targeted maintenance interventions. This proactive approach enhances the safety, sustainability, and cost-effectiveness of bridge maintenance practices, ensuring the longevity and reliability of these critical transportation assets. Figure 1 illustrates the significance of structural health monitoring (SHM) in bridge maintenance by highlighting key aspects of importance. The horizontal bars represent various aspects, including enhanced safety, timely intervention, optimized maintenance, improved durability, and sustainable practices. The importance ratings depicted on the x-axis emphasize the significance of SHM in ensuring the safety, reliability, and longevity of bridges. The ratings represented in Figure 1 were determined through a meticulous, multi-faceted methodology designed to amalgamate insights from various authoritative and empirical sources. An assembly of domain experts provided evaluative scores for each SHM aspect, using a specified rating tool to ensure accuracy and consistency. Concurrently, a comprehensive literature review was undertaken, analyzing various case studies, research articles, and reports to synthesize data and findings related to the SHM's pivotal role in bridge maintenance.

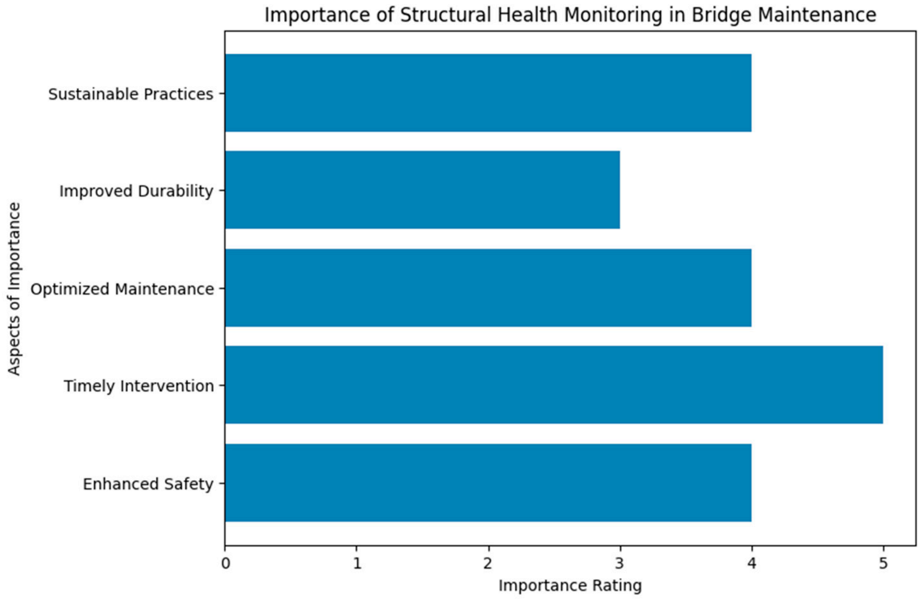

Figure 1. Importance of structural health monitoring in bridge maintenance.

1.3. Nanosensors: An Overview

Nanosensors have emerged as a promising technology for structural health monitoring in bridge maintenance due to their unique properties and capabilities. These miniature devices, typically on the nanometer scale, utilize nanoscale materials and innovative sensing principles to detect and measure various physical and chemical parameters relevant to bridge structures.

The field of nanosensors encompasses a wide range of sensor types, each with its own advantages and applications [18]. Carbon nanotube-based sensors are one such example, known for their exceptional mechanical strength, high electrical conductivity, and sensitivity to strain and deformation [19]. These sensors can be embedded within bridge components to monitor structural changes and provide valuable data on the structural health and integrity of the bridge [20].

Graphene-based sensors have also garnered significant attention in recent years [21]. Graphene, a single layer of carbon atoms arranged in a two-dimensional honeycomb lattice, exhibits remarkable electrical, mechanical, and sensing properties. Graphene-based nanosensors offer high sensitivity, rapid response times, and excellent electrical conductivity, making them suitable for detecting a wide range of physical and chemical parameters, including strain, temperature, humidity, and gas concentrations [22]. There are many other types such as nanowire-based sensors [23], quantum dot-based sensors [22], etc., where each type of nanosensor offers unique properties and capabilities for monitoring structural health and detecting potential issues in bridges.

The fabrication techniques employed to create nanosensors vary depending on the specific sensor type and desired properties [24]. Top-down approaches, such as lithography-based fabrication and chemical etching methods, involve patterning and shaping bulk materials into nanoscale structures [25]. Bottom-up approaches, including chemical vapor deposition (CVD) and molecular self-assembly techniques, involve the growth of nanoscale materials from atomic or molecular building blocks [26]. Hybrid fabrication techniques combine both top-down and bottom-up approaches to achieve precise control over sensor properties [27].

Integrating nanosensors into bridge maintenance systems poses its own set of challenges. Issues such as sensor placement, data communication, power supply, and signal processing need to be addressed for successful implementation [28]. Additionally, calibration, reliability, and the long-term performance of nanosensors in harsh environmental conditions are areas of ongoing research [29]. Nanosensors offer a promising avenue for structural health monitoring in bridge maintenance [30]. Their unique properties and sensitivity make them ideal for detecting and monitoring various parameters critical to bridge integrity. As research and development of nanosensors continue to advance, their integration into bridge maintenance practices holds significant potential for enhancing safety, extending bridge lifespan, and optimizing maintenance strategies.

From the literature above, it appears that the topic of nanosensors for structural health monitoring in the context of bridge maintenance is still relatively nascent and has not been extensively covered in the existing literature. While there may be some papers addressing this topic, the number of publications specifically focusing on nanosensors in bridge maintenance is limited. Therefore, this review paper fills a significant gap in the literature by providing a comprehensive analysis and detailed insights into this emerging field.

2. Methods

In conducting this review paper on nanosensors in bridge maintenance, a systematic approach was employed to gather relevant and reliable information from scholarly sources. The methodology involved a comprehensive search and analysis of documents available in Scopus and Web of Science databases. The following steps were followed in the methodology:

- Literature Search: A thorough search was conducted using keywords and phrases related to nanosensors, bridge maintenance, structural health monitoring, and related topics. The search was limited to the Scopus and Web of Science databases to ensure access to high-quality, peer-reviewed academic literature.
- Inclusion Criteria: The search results were screened based on predefined inclusion criteria. Only research papers, review articles, and conference proceedings published in reputable journals or presented at recognized conferences were considered.
- Document Selection: The titles and abstracts of the search results were reviewed to identify documents relevant to the topic of nanosensors in bridge maintenance. Irrelevant or duplicate documents were excluded during this stage. The selected documents were then obtained in full-text format for detailed analysis.
- Data Extraction and Analysis: The selected documents were thoroughly read and analyzed to extract relevant information. Key findings, methodologies, case studies, and emerging trends were identified and documented. The information gathered from the literature was organized based on the different sections of the review paper.
- Critical Evaluation: The information extracted from the selected documents was critically evaluated to ensure accuracy, reliability, and relevance. The quality and impact of the studies were assessed based on the reputation of the authors, the journals or conferences in which the papers were published, and the rigor of the research methodology employed.
- Synthesis and Writing: The findings, insights, and key points from the selected documents were synthesized and incorporated into the corresponding sections of the review paper. The information was organized in a logical manner to present a comprehensive overview of the topic.
- Iterative Process: The methodology involved an iterative process, where additional searches and document selection were conducted based on the gaps identified during the analysis. This iterative process ensured a comprehensive coverage of the relevant literature and emerging trends in the field.

The methodology described above ensured a systematic and rigorous approach in collecting, analyzing, and synthesizing the information for this review paper. By utilizing reputable databases and employing predefined inclusion criteria, the methodology aimed to ensure the inclusion of high-quality and reliable sources, contributing to the credibility and validity of the findings presented in this paper.

3. Results

The results of the analysis revealed various synthesis methods and fabrication techniques employed in the development of nanosensors for bridge maintenance and will be discussed in the following sections. Figure 2 provides a comprehensive overview, graphically delineating the primary categories of nanosensors, namely carbon nanotube-based sensors, graphene-based sensors, nanowire-based sensors, and quantum dot-based sensors, deployed in the SHM domain. Each category represents a multitude of synthesis methods, fabrication techniques, and specific applications in ensuring the integrity and longevity of bridge structures, which will be explored in detail in the subsequent sections.

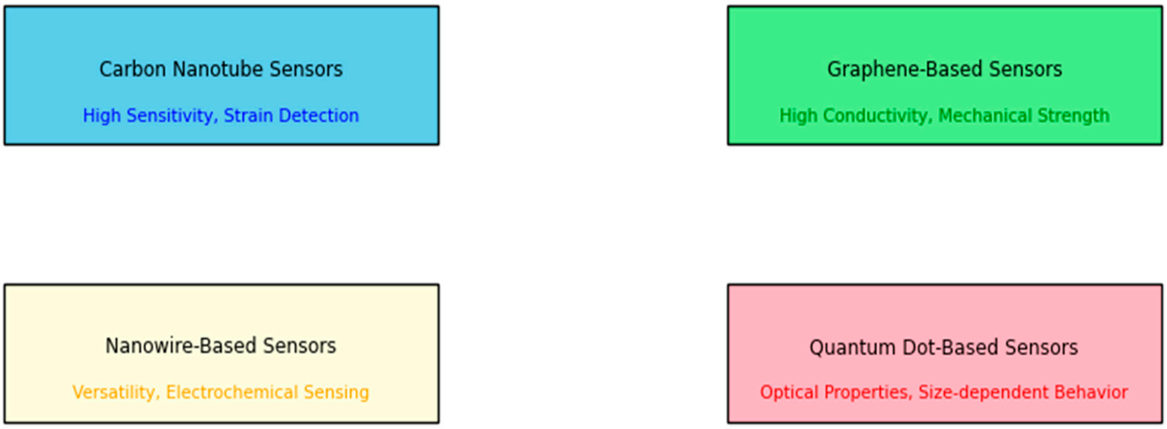

Figure 2. A schematic overview of the primary nanosensor types utilized in bridge SHM, illustrating key characteristics and categories of each sensor type.

With this overarching framework in view, the following sections describe the specifics of each nanosensor type, illustrating their fabrication methods, sensing mechanisms, and pertinent applications in the realm of bridge maintenance and monitoring.

3.1. Carbon Nanotube-Based Sensors

3.1.1. Synthesis Methods and Fabrication Techniques

Carbon nanotube-based sensors have gained considerable attention in the field of bridge maintenance due to their exceptional mechanical properties and sensitivity to strain and deformation [31,32]. Several synthesis methods and fabrication techniques have been developed to create carbon nanotube-based sensors with tailored properties.

One commonly used method for carbon nanotube synthesis is chemical vapor deposition (CVD) [33]. In this approach, carbon-containing gases, such as methane or ethylene, are decomposed on a heated substrate, resulting in the growth of carbon nanotubes [34]. CVD offers control over nanotube diameter, length, and alignment, allowing for customization of sensor properties to meet specific requirements [35].

Another fabrication technique involves the assembly of carbon nanotubes using template-guided growth [36]. In this method, a porous template, such as anodized aluminum oxide or a self-assembled monolayer, is used to guide the growth of carbon nanotubes in desired patterns or arrangements. This technique enables the fabrication of carbon nanotube-based sensors with precise geometries and controlled nanotube alignment.

To enhance the sensing capabilities of carbon nanotube-based sensors, functionalization techniques are employed. Functionalization involves modifying the surface of carbon nanotubes with various molecules or functional groups [37]. These modifications can improve the adhesion of nanotubes to the substrate, enhance their electrical properties, or enable specific interactions with target analytes.

3.1.2. Sensing Mechanisms and Applications

Carbon nanotube-based sensors rely on different sensing mechanisms to detect and measure strain, deformation, and other parameters relevant to bridge maintenance. One commonly utilized mechanism is the piezoresistive effect, where the electrical resistance of carbon nanotubes changes with strain [38,39]. As the nanotubes experience mechanical deformation, the alteration in their structure affects the flow of electrons, resulting in a measurable change in resistance. This change in resistance can be correlated with the applied strain, providing valuable information on the structural behavior of the bridge.

Carbon nanotube-based sensors are also sensitive to other physical parameters, such as temperature and humidity [40,41]. Variations in temperature cause changes in the electrical conductivity of carbon nanotubes, enabling their use as temperature sensors. Additionally, carbon nanotubes' high surface-to-volume ratio makes them susceptible to adsorption and desorption of moisture molecules, allowing them to function as humidity sensors.

The applications of carbon nanotube-based sensors in bridge maintenance are diverse. These sensors can be integrated into bridge components, such as concrete or composites, to monitor strain, deformation, and structural integrity. They can also be attached to critical sections of the bridge to detect and track the development of cracks or other forms of damage. Furthermore, carbon nanotube-based sensors can provide real-time data on temperature and humidity changes, aiding in the identification of potential corrosion or moisture-related issues.

3.2. Graphene-Based Sensors

3.2.1. Fabrication Approaches and Growth Techniques

Graphene, a single layer of carbon atoms arranged in a two-dimensional honeycomb lattice, has garnered significant attention in the field of nanosensors due to its exceptional electrical, mechanical, and sensing properties [42]. Several fabrication approaches and growth techniques have been developed to create graphene-based sensors with precise control over their properties [43].

One common method for graphene fabrication is the mechanical exfoliation technique, also known as the "Scotch tape" method [44]. In this approach, a piece of adhesive tape is used to repeatedly peel off thin layers of graphene from a graphite source. This technique allows the creation of high-quality graphene flakes with a thickness of just one atomic layer. However, the scalability and efficiency of this method are limited. CVD is also another widely used technique for large-scale graphene production.

Other growth techniques, such as epitaxial growth, chemical synthesis, and molecular beam epitaxy, have also been explored to produce graphene with specific properties tailored for sensor applications [45,46]. These techniques offer additional control over graphene's crystal structure, doping levels, and functionalization, allowing for the customization of sensing properties. Figure 3 showcases the various techniques employed in the fabrication and growth of graphene-based sensors. These estimates aim to reflect a general trend in the research field and should be interpreted with caution. Mechanical exfoliation and CVD are observed to be among the most common methods for producing graphene for sensor applications, attributed to their ability to yield high-quality graphene sheets. On the other hand, epitaxial growth, chemical synthesis, and molecular beam epitaxy, while utilized in certain applications, appear less frequently in the surveyed literature. Future work with a systematic meta-analysis approach may provide a more quantified and statistically validated distribution of these techniques.

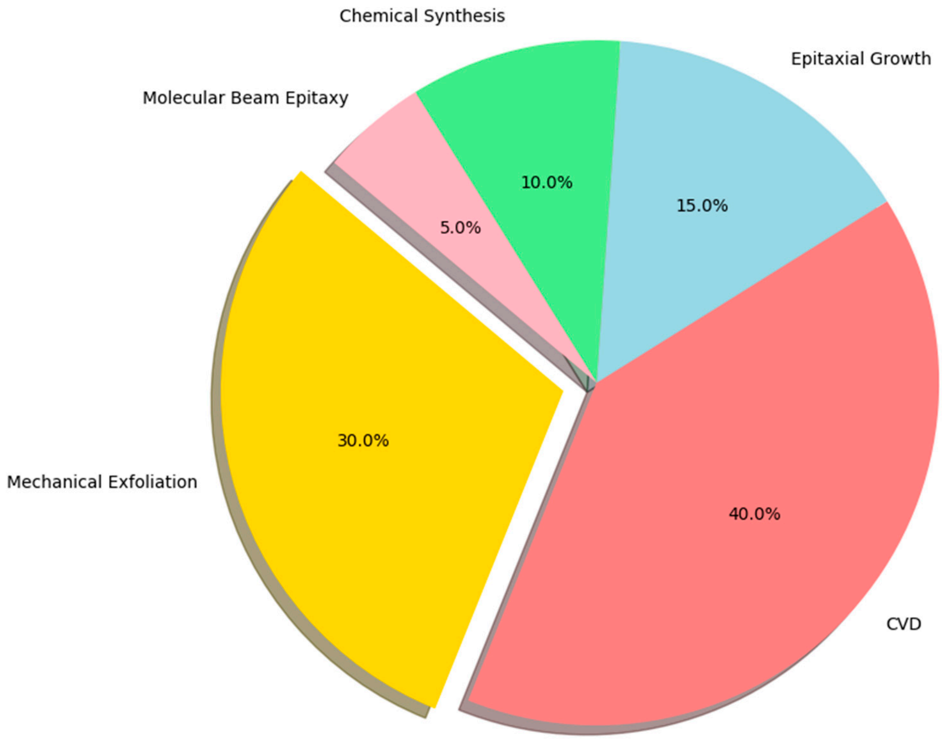

Figure 3. Relative prevalence of various graphene fabrication techniques estimated based on an extensive review of the available literature. It is crucial to note that the specific percentages assigned to each technique—mechanical exfoliation (30%), CVD (40%), epitaxial growth (15%), chemical synthesis (10%), and molecular beam epitaxy (5%)—are approximations derived from the authors' observations across numerous studies and do not represent precise quantitative data from a single source or dataset.

3.2.2. Sensing Properties and Potential Applications

Graphene-based sensors possess remarkable sensing properties due to their unique electrical, mechanical, and surface characteristics. The exceptional electrical conductivity of graphene allows for high sensitivity and low noise in sensing applications. Additionally, graphene's large surface-to-volume ratio and atomic-scale thickness provide an ideal platform for sensing interactions at the nanoscale.

One prominent sensing mechanism in graphene-based sensors is the change in electrical conductivity upon exposure to various analytes [47]. This can be achieved through several sensing mechanisms, including the field-effect transistor (FET) configuration, where the electrical properties of graphene are modulated by the presence of analytes, leading to changes in conductance or resistance [48].

Graphene-based sensors have demonstrated remarkable capabilities in detecting a wide range of physical and chemical parameters relevant to bridge maintenance [49]. Furthermore, graphene's unique surface properties enable the functionalization of graphene-based sensors, allowing selective sensing of specific analytes [50]. Functionalization can be achieved by attaching or coating graphene with various molecules, nanoparticles, or polymers, enhancing the sensor's selectivity and sensitivity towards target substances.

The potential applications of graphene-based sensors in bridge maintenance are vast. They can be integrated into bridge components to monitor structural behavior, detect stress concentrations, and provide real-time data on strain and deformation. Additionally, graphene-based sensors can be utilized for corrosion detection, gas sensing to detect pollutants or leaks, and environmental monitoring to assess temperature and humidity changes.

3.3. Nanowire-Based Sensors

3.3.1. Growth Techniques and Sensor Design

Nanowire-based sensors typically consist of nanoscale wires made from materials such as silicon, zinc oxide, or silver [51]. Several growth techniques and design considerations are employed in the fabrication of nanowire-based sensors.

One common growth technique for nanowire synthesis is the vapor–liquid–solid (VLS) method [52]. In this approach, a vapor-phase precursor is introduced to a heated substrate containing a catalytic metal nanoparticle. The precursor decomposes on the nanoparticle, resulting in the nucleation and growth of nanowires from the liquid catalyst. The VLS method allows for controlled growth of nanowires with desired dimensions, orientations, and crystal structures.

Other growth techniques, including molecular beam epitaxy and electrodeposition, have also been utilized for nanowire fabrication [53]. These techniques offer precise control over nanowire properties, such as diameter, length, and doping levels. Additionally, template-guided growth can be employed, using porous templates or nanoscale patterning to guide the growth of nanowires into specific geometries or arrangements.

The design of nanowire-based sensors involves considerations such as wire material selection, diameter optimization, and integration strategies [54]. Different materials offer varying sensing capabilities, with properties tailored to specific applications. The diameter of the nanowires influences their sensitivity and response time, with smaller diameters providing higher sensitivity. Integration strategies involve positioning the nanowires on appropriate substrates, enabling their incorporation into bridge components or attachment to critical areas for monitoring structural parameters.

3.3.2. Sensing Mechanisms and Performance Evaluation

Nanowire-based sensors operate based on different sensing mechanisms to detect and measure various parameters relevant to bridge maintenance. One common mechanism is the piezoresistive effect, where the electrical resistance of the nanowires changes with mechanical strain or pressure [55]. This change in resistance can be correlated with the applied strain or pressure, providing valuable information on structural behavior and deformation.

Nanowires can also function as field-effect transistors (FETs), where the conductance or current flow through the nanowire is modulated by the presence of target analytes [56]. This enables the detection of chemical species, gases, or biomolecules. Functionalizing the nanowires' surface with specific receptors enhances selectivity and sensitivity in chemical sensing applications.

Performance evaluation of nanowire-based sensors involves assessing their sensitivity, response time, and stability [57]. Sensitivity refers to the ability of the sensor to detect and measure changes in the target parameter. Response time indicates how quickly the sensor reacts to changes in the measured parameter. Stability evaluation involves long-term monitoring of the sensor's performance under various environmental conditions, ensuring its reliability and durability.

Additionally, nanowire-based sensors can be evaluated for their selectivity, cross-sensitivity to other parameters, and limit of detection. Selectivity refers to the sensor's ability to distinguish the target parameter from other interfering factors [58]. Cross-sensitivity is the sensor's response to parameters other than the target, which should be minimized to ensure accurate measurements [59]. The limit of detection defines the lowest concentration or level of the parameter that can be reliably detected by the sensor.

Hence, nanowire-based sensors offer unique sensing capabilities for bridge maintenance. Growth techniques such as the VLS method and molecular beam epitaxy enable the fabrication of nanowires with controlled properties. These sensors operate based on piezoresistive effects, FET configurations, or other sensing mechanisms, allowing detection of parameters such as strain, pressure, or chemical species. Performance evaluation involves assessing sensitivity, response time, stability, selectivity, cross-sensitivity, and limit of detection, ensuring reliability and accuracy.

3.4. Quantum Dot-Based Sensors

3.4.1. Synthesis Approaches and Sensor Integration

Quantum dots are nanoscale semiconductor particles that exhibit quantum confinement effects, resulting in discrete energy levels and tunable optical properties [60]. Several synthesis approaches and sensor integration strategies have been developed for quantum dot-based sensors.

One common method for quantum dot synthesis is colloidal synthesis [61]. In this approach, precursor materials, such as metal chalcogenides or semiconductor nanoparticles, are dissolved in a solvent, and appropriate capping ligands are added. Through controlled chemical reactions, the precursor materials nucleate and grow into quantum dots. The size and composition of the quantum dots can be precisely controlled, allowing for tailoring of their optical properties.

Other techniques, such as epitaxial growth, molecular beam epitaxy, and electrochemical synthesis, have also been employed for quantum dot fabrication. These methods offer additional control over quantum dot properties, including size, shape, and composition. Epitaxial growth techniques enable the growth of quantum dots directly on substrates with high crystalline quality, facilitating their integration into sensor devices [62].

To integrate quantum dots into sensors for bridge maintenance, various strategies can be employed. Quantum dots can be dispersed or embedded within a host matrix, such as polymers or thin films, to form a sensing layer. They can also be functionalized with specific ligands or receptors to enable selective sensing of target analytes. Integration strategies also involve coupling quantum dots with appropriate optical or electrical readout systems for signal detection and analysis.

3.4.2. Optical and Electrical Sensing Principles

Quantum dot-based sensors operate based on optical or electrical sensing principles, taking advantage of the unique properties of quantum dots.

In optical sensing, quantum dots exhibit size-dependent optical properties, including absorption and emission wavelengths [63]. By tuning the size and composition of the quantum dots, their absorption and emission spectra can be tailored to match specific analytes or environmental conditions. Changes in the surrounding environment, such as the presence of target molecules or variations in temperature, can induce shifts in the absorption or emission spectra of the quantum dots, enabling the detection and quantification of the analytes or parameters of interest [64].

Electrical sensing in quantum dot-based sensors relies on the charge transport properties of the quantum dots [65]. By incorporating quantum dots into a conductive matrix or a field-effect transistor (FET) configuration, changes in charge carrier concentration or mobility can be detected. This can be achieved through mechanisms such as modulation of the quantum dots' charge transfer or capacitance in response to analyte interactions or changes in the surrounding environment [66].

The optical or electrical signals generated by the quantum dot-based sensors are typically detected and analyzed using appropriate readout systems [67]. Optical sensing relies on spectroscopic techniques, such as absorption spectroscopy, fluorescence spectroscopy, or luminescence imaging. Electrical sensing involves measuring changes in current, voltage, or resistance using appropriate circuitry and amplification methods.

The applications of quantum dot-based sensors in bridge maintenance are diverse. They can be utilized for the detection of specific analytes, such as gases or chemical species relevant to corrosion or pollutant monitoring. Quantum dots can also be incorporated into strain or deformation sensors, providing optical or electrical readouts for structural health monitoring. Furthermore, their tunable optical properties enable the development of multifunctional sensors capable of detecting multiple parameters simultaneously.

Figure 4 combines two pie charts to provide a comprehensive overview of quantum dot-based sensors in the context of bridge maintenance. The left pie chart illustrates the principles of quantum dot-based sensors, highlighting their optical and electrical sensing capabilities. The chart demonstrates that quantum dots can be utilized for both optical sensing, leveraging their size-dependent optical properties for detecting analytes or environmental conditions, and electrical sensing, relying on the charge transport properties of the quantum dots to detect changes in charge carrier concentration or mobility. The right pie chart focuses on the applications of quantum dot-based sensors in bridge maintenance. It showcases their versatility in bridge monitoring by highlighting three key application areas. These areas include gas/chemical species detection, enabling the identification and quantification of relevant gases or chemicals associated with corrosion or pollution; strain/deformation sensing, providing optical or electrical readouts for monitoring structural health and detecting potential issues in bridge components; and multifunctional sensors, capable of detecting multiple parameters simultaneously, further enhancing the overall monitoring capabilities of bridge maintenance systems.

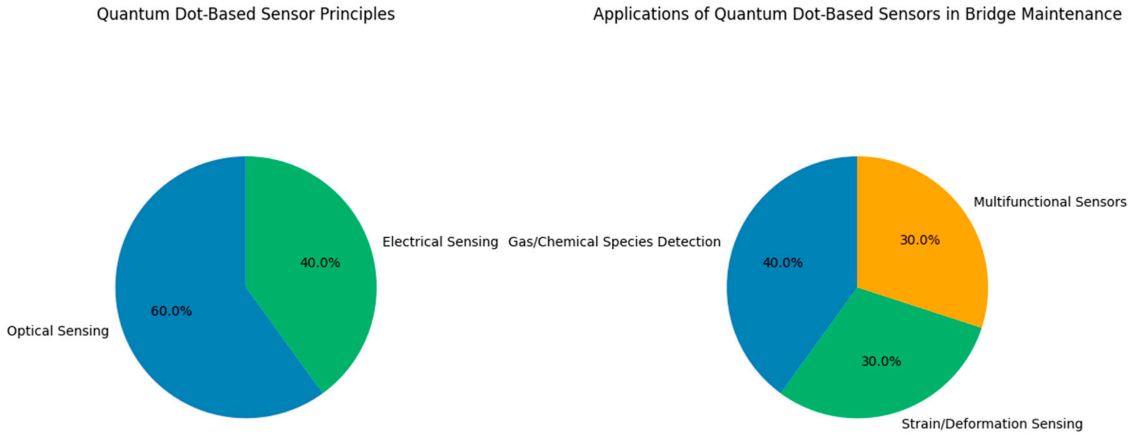

Figure 4. Quantum dot-based sensors in bridge maintenance.

3.5. Fabrication Techniques for Nanosensors

Nanosensors can be fabricated using various techniques, depending on the desired sensor properties and applications. Two common categories of fabrication techniques are top-down and bottom-up approaches. In this section, we will focus on top-down, bottom-up and hybrid approaches.

3.5.1. Top-Down Approaches

Top-down fabrication techniques involve the reduction or modification of larger structures to create nanoscale features (Table 1). These techniques offer precise control over the sensor dimensions, shape, and arrangement.

Table 1. Top-down approaches in nanosensor fabrication.

Technique	Description	Advantages	Disadvantages	Reference
Lithography-Based Fabrication	Involves using a mask or template to selectively expose a photosensitive material, followed by subsequent processing steps to create desired nanoscale features.	Offers high precision and allows the creation of complex sensor geometries and patterns.	Time-consuming and requires specialized equipment. Limitations in scalability and cost-effectiveness for large-scale production.	[68]
Chemical Etching Methods	Selectively removes material from a substrate, using chemical reactions, resulting in the formation of nanoscale features.	Offers flexibility in creating various sensor structures on planar substrates and allows for the formation of nanochannels, nanogaps, or nanostructures.	Control over the selectivity of the etching process and uniformity of etching can be challenging.	[69]

3.5.2. Bottom-Up Approaches

Bottom-up fabrication techniques involve the assembly or growth of nanosensors from atomic or molecular building blocks. These techniques allow for the creation of nanoscale structures by self-organization or controlled deposition of materials as shown in Table 2.

Table 2. Bottom-up approaches in nanosensor fabrication.

Technique	Description	Advantages	Disadvantages	Reference
Chemical Vapor Deposition (CVD)	Involves the growth of thin films or nanostructures by introducing precursor gases into a reaction chamber, where they undergo chemical reactions.	Provides precise control of overgrowth parameters and tailored properties.	Requires specialized equipment and careful optimization of growth conditions.	[70]
Molecular Self-Assembly Techniques	Utilizes spontaneous organization of molecules or nanoparticles into ordered structures driven by intermolecular forces and surface interactions.	Enables precise control over composition and structure of nanosensors.	Stability and robustness of assembled structures need to be considered. Assembly process may be sensitive to pH, temperature, and concentration.	[71]

3.5.3. Hybrid Fabrication Techniques

Hybrid fabrication techniques combine elements of both top-down and bottom-up approaches to create nanosensors [72]. These techniques leverage the advantages of both approaches to achieve precise control over the sensor properties and structures. Table 3 provides some examples of hybrid fabrication techniques used for nanosensor fabrication.

Table 3. Hybrid approaches in nanosensor fabrication.

Fabrication Technique	Description	Reference
Template-Assisted Fabrication	Involves using a template or scaffold as a guide or mold to direct the growth or deposition of nanoscale materials. The template can be created using lithography-based techniques or self-assembly methods. This approach allows for the creation of nanosensors with complex architectures and high reproducibility.	[73]
Directed Self-Assembly	Combines bottom-up self-assembly processes with external forces or templates to control the assembly and arrangement of nanoscale building blocks. External fields, such as electric or magnetic fields, are used to direct the self-assembly of nanoparticles or nanowires into specific patterns or structures. This technique enables the fabrication of nanosensors with precise positioning and controlled orientations.	[74]
Nanopatterning and Nanolithography	Combines traditional nanopatterning or nanolithography methods with self-assembly or growth processes. Nanopatterning techniques, such as electron beam lithography or nanoimprint lithography, are used to create patterns on a substrate. These patterns serve as a template or mask for subsequent deposition or growth of nanoscale materials, resulting in complex and precisely controlled nanosensors with well-defined patterns and structures.	[75]

Hybrid fabrication techniques offer versatility and control in creating nanosensors with specific structures and properties. By combining top-down and bottom-up approaches, these techniques enable the integration of nanoscale features and precise positioning of nanomaterials. They provide opportunities for tailoring the sensor design to meet the requirements of bridge maintenance applications, such as strain monitoring, corrosion detection, or environmental sensing. However, it is important to note that hybrid fabrication techniques may involve additional complexity and require expertise in multiple fabrication methods. Optimization of process parameters and compatibility between different fabrication steps need to be carefully considered to ensure the successful fabrication of functional nanosensors.

3.6. Integration Strategies for Nanosensors in Bridge Maintenance

Nanosensor integration in bridge maintenance encapsulates methodologies that not only concern the effective placement of sensors but also necessitate robust strategies for connectivity, data management, power supply, and system durability under various environmental conditions. The multidisciplinary nature of these integration strategies ensures a symbiotic relationship between the sensor technology and structural health monitoring (SHM) effectiveness.

3.6.1. Sensor Placement and Distribution

One of the key considerations in integrating nanosensors into bridge maintenance is determining the optimal sensor placement and distribution throughout the structure [76]. The placement of sensors should be based on the specific monitoring objectives and the critical areas of the bridge that require continuous monitoring.

Strategic placement of sensors is crucial for capturing relevant data and obtaining a comprehensive understanding of the structural behavior. Sensors can be positioned in critical areas such as load-bearing components, joints, or areas prone to stress concentrations [77]. Distributed sensor networks can be designed to cover a larger area of the bridge and capture data from multiple points.

The number and density of sensors depend on the level of detail required for monitoring [78]. While a higher number of sensors can provide more comprehensive data, it may also increase the complexity of data management and analysis. Therefore, a balance must be struck between the number of sensors, their distribution, and the monitoring objectives.

3.6.2. Connection and Communication Infrastructure

To collect and analyze data from the nanosensors, an efficient connection and communication infrastructure is essential [79]. The sensor data need to be transmitted from the sensors to a central monitoring system for analysis and interpretation.

Various wired or wireless communication technologies can be utilized for data transmission. Wired connections, such as Ethernet or fiber optic cables, can provide reliable and high-bandwidth communication [80]. Wireless communication technologies, such as Wi-Fi, Bluetooth, or cellular networks, offer flexibility and mobility but may have limitations in terms of bandwidth and range [81].

The choice of communication infrastructure depends on factors such as the sensor density, data volume, distance, and power consumption considerations [82]. For large-scale bridge monitoring, a combination of wired and wireless communication systems may be employed to ensure reliable and efficient data transmission.

3.6.3. Data Management and Analysis

Implementing advanced data management and analytical strategies guarantees the conversion of raw data into actionable insights, thereby facilitating informed decision-making.

- Data Pre-Processing and Calibration: Employ automated data pre-processing and calibration to manage noise and ensure accuracy in the data.

- Machine Learning and AI: Integrate machine learning algorithms and AI to derive predictive insights from the data, facilitating preemptive maintenance strategies.
- Visualization Tools: Develop intuitive visualization tools and dashboards that convey real-time and historical data in an accessible manner to various stakeholders.

3.6.4. Environmental and Long-Term Considerations

Consider the impact of various environmental factors (such as corrosion, material degradation, biofouling, etc.) on sensor performance and devise strategies to mitigate these effects to ensure long-term reliability of the SHM system.

- Protective Coatings and Housings: Employ protective coatings and sensor housings that shield them from corrosive and abrasive elements without compromising data quality.
- Long-Term Calibration: Implement methods to ensure that sensors remain calibrated over extended periods and establish procedures for regular recalibration and maintenance.
- Material Compatibility: Ensure that the materials of the sensors are compatible with the bridge materials to prevent adverse reactions that could compromise structural integrity or sensor performance.

3.7. Power Supply Considerations

Nanosensors require a reliable and continuous power supply to operate effectively. The power supply considerations depend on the sensor type, location, and the availability of power sources in the bridge infrastructure.

For embedded nanosensors, power can be supplied through batteries or energy harvesting techniques, such as solar cells or vibrational energy harvesters [83]. Battery-powered sensors offer mobility and independence from external power sources but require periodic maintenance and replacement [84]. Energy harvesting techniques utilize the ambient energy available in the bridge environment, such as vibration or sunlight, to generate power for the sensors.

In some cases, it may be feasible to connect the nanosensors to the existing power infrastructure of the bridge, such as electrical cables or power lines [85]. This option provides a continuous power supply but requires careful planning and coordination with the bridge maintenance and electrical systems.

Consideration should also be given to power management and optimization strategies to prolong the sensor's battery life or reduce power consumption. Techniques such as duty cycling, data compression, or adaptive sampling can be employed to minimize power usage while still capturing relevant data [86].

4. Challenges and Limitations of Nanosensor Deployment

The deployment of nanosensors in bridge maintenance faces certain challenges and limitations that need to be addressed for successful implementation. These challenges primarily relate to signal processing and data interpretation, calibration and sensor reliability, as well as environmental factors and durability. Let us explore these challenges in more detail:

4.1. Signal Processing and Data Interpretation

4.1.1. Unique Challenges in Nanosensor Data Management

Unlike conventional sensors, nanosensors can be sensitive to nanoscale perturbations, resulting in amplified noise or erroneous readings. This sensitivity necessitates the development of specialized signal processing algorithms that can discern actual structural changes from data noise, possibly arising from minute environmental variations or material inconsistencies [87].

4.1.2. High-Dimensional Data

Nanosensors tend to generate high-dimensional data, which can be computationally intensive to process and manage, thereby demanding more robust data management and storage solutions. Machine learning (ML) models and artificial intelligence (AI) algorithms tailored to navigate through this high-dimensional space are pivotal to efficiently extract meaningful insights and predict potential structural deteriorations [88,89].

Developing robust algorithms for real-time data analysis and decision-making is crucial for effective bridge maintenance. Additionally, the interpretation of sensor data should consider the context of the bridge's design, materials, and operating conditions [90,91].

4.2. Calibration and Sensor Reliability

4.2.1. Nanoscale Calibrations

Nanosensors require calibration protocols that account for their nanoscale sensitivity and the quantum effects that may influence their readings. Specialized calibration using nanoscale reference materials and protocols that factor in quantum behaviors, such as quantum tunneling or electron scattering, may be requisite [92].

4.2.2. Real-Time Monitoring and Reliability Assurance

Developing systems for real-time monitoring of the nanosensors themselves is vital to ensure the ongoing reliability of data and to promptly identify and address sensor drift or failure, which might be instigated by factors more subtle and rapid than those affecting conventional sensors [93,94].

4.3. Environmental Factors and Durability

4.3.1. Protecting Nanosensors from Environmental Nano-Particles

Nanosensors, due to their size and sensitivity, can potentially be influenced by airborne nanoparticles or molecular-scale environmental variables, thereby demanding enhanced protective measures, such as specialized nanocoatings, that do not inhibit their sensing capabilities [95,96].

4.3.2. Durability against Nanoscale Wear and Tear

The durability of nanosensors could be compromised by nanoscale wear and tear, not typically encountered by their macro-scale counterparts. Developing materials and deployment strategies that safeguard them against nanoscale erosion, possibly due to interactions with atmospheric molecules or other nanomaterials, is imperative [97].

Incorporating specialized maintenance protocols, which ensure the stability and functionality of nanosensors amid the distinct and complex challenges they encounter, underscores the prerequisite for a comprehensive strategy, bridging nanotechnology and SHM to advance the future of resilient infrastructure [98].

5. Case Studies and Applications

Nanosensors have found a significant application in real-world bridge monitoring scenarios, revealing insights that have broad implications for structural health monitoring (SHM).

The application of graphene in creating self-sensing cementitious composites has opened up new frontiers in bridge health monitoring, as evidenced in another case study that explored the capabilities of graphene-infused ultra-high-performance concrete (UHPC) [99]. Graphene, incorporated into the concrete, enhanced its electrical properties while concurrently bolstering its mechanical attributes. This hybrid material, when subjected to stress, modified its electrical properties, thereby enabling a nuanced self-sensing capability under varying load conditions. The material could adeptly detect and report both tension and compression, providing a continuous stream of data that are crucial for assessing the structural integrity of the bridge.

Finite element simulations played an instrumental role in designing a bridge health monitoring system, adept at recognizing and responding to high-stress conditions in bridge structures. The advantages of using this graphene-based nanosensor are closely tied to its self-sensing capabilities, which not only facilitate continuous monitoring but also significantly contribute towards early detection of potential structural issues, thereby aiding in proactively maintaining and enhancing bridge safety.

These case studies stand as a testament to the potential and efficacy of nanosensors in structural health monitoring, highlighting not only their capability to provide vital, real-time data on structural health, strain, and deformation but also their pivotal role in enabling early detection and intervention in bridge maintenance scenarios.

6. Discussion: Navigating the Expanse of Nanosensors in Structural Health Monitoring

The exploration of nanosensors in the realm of structural health monitoring (SHM) unveils a cascade of advantages that transcend mere miniaturization, proactively embedding enhanced sensitivity and precision into the monitoring matrix. This intrinsic sensitivity of nanosensors offers an unparalleled ability to detect minuscule changes in various parameters such as strain, pressure, and chemical changes, a feature which is paramount in the early detection of potential structural issues in bridge management. With the capacity to discern sub-nanometer displacements or variations, nanosensors facilitate a more granular and accurate understanding of structural behaviors under various loads and conditions, providing a scaffold for predictive maintenance and preemptive interventions.

Navigating through the diverse typologies of nanosensors, it becomes pivotal to underscore their applicability in measuring distinct parameters in the context of bridge SHM. Piezoresistive nanosensors, with their unique property of altering electrical resistance under mechanical strain, become particularly relevant in gauging structural deformations and stress concentrations. Given their high sensitivity and capability to detect minute strain levels, they offer invaluable insights into early-stage deformations and stress accumulations, safeguarding against unforeseen structural failures. Similarly, nanoscale pH sensors, with their exceptional ability to detect changes in chemical composition, become crucial in monitoring corrosion processes in metal structures of the bridge, which may serve as early warning markers for corrosion-induced degradation.

Moreover, diving into the physical and functional characteristics of nanosensors, one discerns the vast arrays of considerations that are quintessential for their optimal deployment in SHM. Characteristics such as dynamic range, frequency range, and acceptable environmental conditions weave into the foundational understanding of a nanosensor operation and its efficacy in specific applications. For instance, the dynamic range, articulating the span between the smallest and largest measurable quantities, signifies the operative spectrum of the sensor, thus influencing its aptitude in capturing and translating diverse magnitudes of the parameter into meaningful data.

Furthermore, side sensitivity, linearity, and power supply requisites of nanosensors weave into the tapestry of their functional viability. A nanosensor's linearity, denoting the proportionality between its input and output, becomes crucial in ensuring that the sensor readings are consistent and scalable across its operational range. Meanwhile, side sensitivity and the environmental robustness of the nanosensors are paramount in safeguarding their performance amidst the plethora of environmental influences, including temperature fluctuations, humidity, and corrosive agents, which are ubiquitous in bridge environments.

Within the universe of structural health monitoring (SHM) of bridges, an amalgamation of common programs and layouts has traditionally anchored the nexus between technology and infrastructure management. Typically, SHM programs contour around a multifaceted structure that assimilates various types of sensors, including nanosensors, to continually assess and analyze the structural integrity and operational status of bridges. These programs meticulously orchestrate sensor layouts to span critical structural components, such as beams, joints, and pillars, thereby ensuring an encompassing capture of pivotal data that delineate both static and dynamic parameters inclusive of stress, strain, vibration, and environmental interactions. The layout essentially stitches a tapestry of information flow that seamlessly melds data from diverse sensor types and locations, culminating in a comprehensive structural profile that is perpetually updated in real time. Thus, these SHM programs architect a vigilant and dynamic monitoring scaffold, securing a persistent gaze on structural behaviors and conditions, and thereby erecting a proactive bridge management paradigm that prioritizes safety, longevity, and optimized maintenance scheduling within its operational framework. This aligns seamlessly with the overarching manuscript, illuminating the cardinal role of nanosensors in enhancing the resolution and depth of insights drawn from SHM programs and layouts.

Navigating through the realm of nanosensors, piezoelectric variants indeed carve out a notable presence, albeit with an acknowledged constraint in the domain of low-frequency parameter measurement. In the context of bridges exposed to perpetual environmental and anthropogenic interactions, such as wind, traffic, and water flow, the excitation frequencies often linger in the lower spectrum. Piezoelectric nanosensors, inherently weaving their functionality around the conversion of mechanical stress into electrical signals, can sometimes find the low-frequency stimulations, such as those engendered by slow-moving heavy traffic or gentle wind breezes, to be suboptimal for precise measurement and data generation. This dichotomy is sculpted by the innate physical and electrical dynamics of piezoelectric materials, which often usher in a diminished sensitivity and signal-to-noise ratio at lower frequencies. Consequently, while the piezoelectric nanosensors fortify SHM through their adept proficiency at monitoring parameters such as vibration and rapid stress variations, there subsists a tacit necessity to pair them with other sensor modalities to weave a more encompassing and accurate SHM narrative, especially when chronicling the impacts and effects of low-frequency stimuli on bridge structures. This integrative approach therefore underscores a symbiotic deployment of diverse sensor types, each compensating for the others' limitations to orchestrate a holistic and high-fidelity SHM framework. This aligns seamlessly within the broader tapestry of this manuscript's discourse, accentuating the imperative of comprehending the intrinsic attributes and limitations of nanosensors, such as piezoelectric types, to strategically curate a multidimensional and reliable SHM platform.

The meticulous selection and deployment of nanosensors, attuned to their physical and functional characteristics, pave the way towards an enriched, precise, and reliable structural health monitoring paradigm. The strategic incorporation of nanosensors, such as piezoresistive and pH sensors, informed by a thorough understanding of their operative characteristics and environmental robustness, empowers a robust and responsive SHM system, which is instrumental in safeguarding structural integrity and longevity amidst the dynamic operational and environmental spectrums that bridges invariably navigate through. Thus, nanosensors, with their multifaceted advantages and considerations, stand poised to revolutionize SHM, intertwining enhanced sensitivity, precision, and reliability into the structural monitoring and maintenance matrix.

7. Future Perspectives and Emerging Trends

The field of nanosensors in bridge maintenance is continuously evolving, with several future perspectives and emerging trends shaping its development. Advancements in sensing materials and nanofabrication techniques, integration of the Internet of Things (IoT) in real-time monitoring, and the utilization of artificial intelligence and machine learning in nanosensor data analysis are key areas driving the innovation and enhancing the capabilities of nanosensors.

7.1. Advancements in Sensing Materials and Nanofabrication Techniques

Advancements in sensing materials and nanofabrication techniques are expected to play a significant role in improving the performance and functionality of nanosensors for bridge maintenance. Researchers are exploring new materials, such as 2D materials, metal–organic frameworks (MOFs), and nanocomposites, that offer unique sensing properties and improved stability [100].

Furthermore, innovations in nanofabrication techniques, such as additive manufacturing (3D printing) and nanoscale assembly processes, enable the creation of complex and customizable nanosensor structures [101]. These techniques allow for the integration of multiple sensing modalities, such as optical, electrical, and mechanical sensing, into a single sensor device, enhancing the range and accuracy of measurements.

7.2. Internet of Things (IoT) Integration for Real-Time Monitoring

The integration of nanosensors into the Internet of Things (IoT)'s framework is a rapidly growing trend in bridge maintenance. By connecting nanosensors to a network infrastructure, real-time data collection, transmission, and analysis can be achieved [102]. IoT integration enables remote monitoring of bridge structures, centralized data management, and seamless communication between sensors and monitoring systems.

IoT-enabled nanosensor networks provide enhanced situational awareness [103], enabling bridge maintenance personnel to monitor multiple parameters simultaneously and respond promptly to any abnormalities. The data collected from the nanosensors can be processed in real-time, facilitating predictive maintenance and enabling the implementation of data-driven decision-making strategies.

8. Conclusions

Nanosensors offer significant potential for revolutionizing bridge maintenance by providing real-time data on structural health, strain, deformation, and environmental conditions. In this review paper, we have explored various aspects of nanosensors in bridge maintenance, including their types, fabrication techniques, integration strategies, challenges, case studies, and future perspectives.

8.1. Summary of Key Findings

Key findings from this review include the following:

- Nanosensors, such as carbon nanotube-based, graphene-based, nanowire-based, and quantum dot-based sensors, offer unique sensing capabilities for bridge maintenance, including strain monitoring, crack detection, corrosion sensing, and environmental monitoring.
- Top-down fabrication techniques, such as lithography-based fabrication and chemical etching methods, provide precise control over sensor dimensions and structures, while bottom-up approaches, such as chemical vapor deposition and molecular self-assembly, enable the growth or assembly of nanosensors from atomic or molecular building blocks.
- Integration strategies for nanosensors in bridge maintenance encompass sensor placement and distribution, connection and communication infrastructure, and power supply considerations. These strategies ensure effective data collection, analysis, and monitoring of bridge structures.
- Challenges and limitations of nanosensor deployment include signal processing and data interpretation, calibration and sensor reliability, as well as environmental factors and durability. Overcoming these challenges requires advanced data analytics, calibration protocols, and robust sensor design.
- Case studies and performance evaluations have demonstrated the effectiveness of nanosensors in bridge monitoring systems and their reliability and accuracy in real-world scenarios. Nanosensors have shown potential in detecting structural anomalies, optimizing maintenance strategies, and improving bridge safety and longevity.

8.2. Recommendations for Future Research

To further advance the field of nanosensors in bridge maintenance, the following areas warrant future research:

- Continued exploration of novel sensing materials and nanofabrication techniques to enhance the performance, stability, and functionality of nanosensors.

- Further development of IoT integration for seamless data transmission, real-time monitoring, and data-driven decision-making in bridge maintenance.
- Advancement in AI and ML algorithms for efficient analysis and interpretation of nanosensor data, enabling predictive maintenance and early anomaly detection.
- Investigation of the long-term durability, reliability, and scalability of nanosensors under diverse environmental conditions and bridge operational parameters.
- Exploration of cost-effective manufacturing processes and large-scale deployment strategies for nanosensors to facilitate their widespread adoption in bridge maintenance.

Author Contributions: The authors, D.H., H.H., C.Y. and R.N., made significant contributions to this review paper. D.H. and H.H. played key roles in the conceptualization, design, and coordination of the paper, conducting extensive literature research and drafting and revising the manuscript. C.Y. contributed to the conceptualization. R.N. provided input on the overall structure. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Acknowledgments: The authors gratefully acknowledge the University of Agder for their technical support throughout this work.

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

References

1. Jeong, Y.; Kim, W.; Lee, I.; Lee, J. Bridge inspection practices and bridge management programs in China, Japan, Korea, and U.S. *J. Struct. Integr. Maint.* **2018**, *3*, 126–135. [CrossRef]
2. Norris, A.; Saafi, M.; Romine, P. Temperature and moisture monitoring in concrete structures using embedded nanotechnology/microelectromechanical systems (MEMS) sensors. *Constr. Build. Mater.* **2008**, *22*, 111–120. [CrossRef]
3. Ko, J.M.; Ni, Y.Q. Technology developments in structural health monitoring of large-scale bridges. *Eng. Struct.* **2005**, *27*, 1715–1725. [CrossRef]
4. Chan, B.; Guan, H.; Hou, L.; Jo, J.; Blumenstein, M.; Wang, J. Defining a conceptual framework for the integration of modelling and advanced imaging for improving the reliability and efficiency of bridge assessments. *J. Civ. Struct. Health Monit.* **2016**, *6*, 703–714. [CrossRef]
5. Martinez-Luengo, M.; Kolios, A.; Wang, L. Structural health monitoring of offshore wind turbines: A review through the Statistical Pattern Recognition Paradigm. *Renew. Sustain. Energy Rev.* **2016**, *64*, 91–105. [CrossRef]
6. Javaid, M.; Haleem, A.; Singh, R.P.; Rab, S.; Suman, R. Exploring the potential of nanosensors: A brief overview. *Sens. Int.* **2021**, *2*, 100130. [CrossRef]
7. Dong, L.; Xu, X.; Sun, K.; Ding, Y.; Ouyang, P.; Wang, P. Sensing analysis based on fano resonance in arch bridge structure. *J. Phys. Commun.* **2018**, *2*, 105010. [CrossRef]
8. Li, J. Nano Sensors and Devices for Space and Terrestrial Applications. In Proceedings of the Space 2005, Long Beach, CA, USA, 30 August–1 September 2005; American Institute of Aeronautics and Astronautics: Reston, VA, USA, 2015. [CrossRef]
9. Qureshi, A.; Kang, W.P.; Davidson, J.L.; Gurbuz, Y. Review on carbon-derived, solid-state, micro and nano sensors for electrochemical sensing applications. *Diam. Relat. Mater.* **2009**, *18*, 1401–1420. [CrossRef]
10. Rizzo, P.; Enshaeian, A. Challenges in Bridge Health Monitoring: A Review. *Sensors* **2021**, *21*, 4336. [CrossRef]
11. Harms, T.; Sedigh, S.; Bastianini, F. Structural Health Monitoring of Bridges Using Wireless Sensor Networks. *IEEE Instrum. Meas. Mag.* **2010**, *13*, 14–18. [CrossRef]
12. Kaya, Y.; Safak, E. Real-time analysis and interpretation of continuous data from structural health monitoring (SHM) systems. *Bull. Earthq. Eng.* **2014**, *13*, 917–934. [CrossRef]
13. Sigurdardottir, D.H.; Glisic, B. On-site validation of fiber-optic methods for structural health monitoring: Streicker Bridge. *J. Civ. Struct. Health Monit.* **2015**, *5*, 529–549. [CrossRef]
14. Drissi-Habti, M.; Betti, R.; Yanev, B. Structural Health Monitoring of Bridge Cables. ASNT NDT Library. 2009. Available online: https://ndtlibrary.asnt.org/2009/StructuralHealthMonitoringofBridgeCables (accessed on 27 May 2023).
15. Farhoud, M. The Use of Nanosensors for Monitoring Civil Structures. 2018. Available online: https://pearl.plymouth.ac.uk/handle/10026.1/14186 (accessed on 27 May 2023).
16. Drissi-Habti, M. Smart Composites for Durable Infrastructures—Importance of Structural Health Monitoring (SHM). In *Advances in FRP Composites in Civil Engineering*; Ye, L., Feng, P., Yue, Q., Eds.; Springer: Berlin, Heidelberg, 2011; pp. 264–267. [CrossRef]
17. Lebental, B.; Ghaddab, B.; Michelis, F. Nanosensors for Embedded Monitoring of Construction Materials: The '2D Conformable' Route. In *Nanotechnology in Construction*; Sobolev, K., Shah, S.P., Eds.; Springer International Publishing: Cham, Switzerland, 2015; pp. 383–388. [CrossRef]
18. Lieber, C.M. Nanoscale Science and Technology: Building a Big Future from Small Things. *MRS Bull.* **2003**, *28*, 486–491. [CrossRef]

19. Tang, R.; Shi, Y.; Hou, Z.; Wei, L. Carbon Nanotube-Based Chemiresistive Sensors. *Sensors* **2017**, *17*, 882. [CrossRef] [PubMed]
20. Abdulhameed, A.; Halin, I.A.; Mohtar, M.N.; Hamidon, M.N. Airflow-assisted dielectrophoresis to reduce the resistance mismatch in carbon nanotube-based temperature sensors. *RSC Adv.* **2021**, *11*, 39311–39318. [CrossRef]
21. Justino, C.I.L.; Gomes, A.R.; Freitas, A.C.; Duarte, A.C.; Rocha-Santos, T.A.P. Graphene based sensors and biosensors. *TrAC Trends Anal. Chem.* **2017**, *91*, 53–66. [CrossRef]
22. Peña-Bahamonde, J.; Nguyen, H.N.; Fanourakis, S.K.; Rodrigues, D.F. Recent advances in graphene-based biosensor technology with applications in life sciences. *J. Nanobiotechnol.* **2018**, *16*, 1–17. [CrossRef]
23. Ramgir, N.S.; Yang, Y.; Zacharias, M. Nanowire-Based Sensors. *Small* **2010**, *6*, 1705–1722. [CrossRef]
24. Abdel-Karim, R.; Reda, Y.; Abdel-Fattah, A. Review—Nanostructured Materials-Based Nanosensors. *J. Electrochem. Soc.* **2020**, *167*, 037554. [CrossRef]
25. Biswas, A.; Bayer, I.S.; Biris, A.S.; Wang, T.; Dervishi, E.; Faupel, F. Advances in top–down and bottom–up surface nanofabrication: Techniques, applications & future prospects. *Adv. Colloid Interface Sci.* **2012**, *170*, 2–27.
26. Khanna, V.K. (Ed.) Bottom-up Nanofabrication. In *Integrated Nanoelectronics: Nanoscale CMOS, Post-CMOS and Allied Nanotechnologies*; NanoScience and Technology; Springer India: New Delhi, India, 2016; pp. 397–417.
27. Teo, B.K.; Sun, X.H. From Top-Down to Bottom-Up to Hybrid Nanotechnologies: Road to Nanodevices. *J. Clust. Sci.* **2006**, *17*, 529–540. [CrossRef]
28. Mustapha, S.; Lu, Y.; Ng, C.-T.; Malinowski, P. Sensor Networks for Structures Health Monitoring: Placement, Implementations, and Challenges—A Review. *Vibration* **2021**, *4*, 551–585. [CrossRef]
29. Li, X.; Zhang, X.; Werschmoeller, D.; Choi, H.; Cheng, X. Embedded micro/nano sensors for harsh engineering environments. In Proceedings of the 2008 IEEE Sensors, Lecce, Italy, 26–29 October 2008; pp. 1273–1276. [CrossRef]
30. Thammadi, S.P.D.; Pisini, S.K. Nanotechnology and building construction: Towards effective stakeholder engagement. *IOP Conf. Ser. Earth Environ. Sci.* **2022**, *1084*, 012074. [CrossRef]
31. Kim, K.-H.; Hong, S.K.; Ha, S.-H.; Li, L.; Lee, H.W.; Kim, J.-M. Enhancement of linearity range of stretchable ultrasensitive metal crack strain sensor via superaligned carbon nanotube-based strain engineering. *Mater. Horiz.* **2020**, *7*, 2662–2672. [CrossRef]
32. Chowdhury, R.; Adhikari, S.; Mitchell, J. Vibrating carbon nanotube based bio-sensors. *Phys. Low Dimens. Syst. Nanostruct.* **2009**, *42*, 104–109. [CrossRef]
33. Zhao, N.; Wu, Q.; Zhang, X.; Yang, T.; Li, D.; Zhang, X.; Ma, C.; Liu, R.; Xin, L.; He, M. Chemical vapor deposition growth of single-walled carbon nanotubes from plastic polymers. *Carbon* **2022**, *187*, 29–34. [CrossRef]
34. Klimin, V.S.; Rezvan, A.A.; Ageev, O.A. Study of the effect of carbon-containing gas pressure on the geometric parameters of an array of carbon nanostructures. *J. Phys. Conf. Ser.* **2018**, *1124*, 022035. [CrossRef]
35. Kohls, A.; Ditty, M.M.; Dehghandehnavi, F.; Zheng, S.-Y. Vertically Aligned Carbon Nanotubes as a Unique Material for Biomedical Applications. *ACS Appl. Mater. Interfaces* **2022**, *14*, 6287–6306. [CrossRef]
36. Corletto, A.; Shapter, J.G. Discontinuous Dewetting, Template-Guided Self-Assembly, and Liquid Bridge-Transfer Printing of High-Resolution Single-Walled Carbon Nanotube Lines for Next-Generation Electrodes and Interconnects. *ACS Appl. Nano Mater.* **2020**, *3*, 8148–8160. [CrossRef]
37. Prajapati, S.K.; Agnihotri, T.; Gomte, S.S.; Jain, A. Surface Modification Strategies for the Carbon Nanotubes. In *Chemically Modified Carbon Nanotubes for Commercial Applications*; John Wiley & Sons, Ltd.: Hoboken, NJ, USA, 2023; pp. 51–74. [CrossRef]
38. Tang, Z.-H.; Li, Y.-Q.; Huang, P.; Wang, H.; Hu, N.; Fu, S.-Y. Comprehensive evaluation of the piezoresistive behavior of carbon nanotube-based composite strain sensors. *Compos. Sci. Technol.* **2021**, *208*, 108761. [CrossRef]
39. Hur, O.-N.; Ha, J.-H.; Park, S.-H. Strain-Sensing Properties of Multi-Walled Carbon Nanotube/Polydimethylsiloxane Composites with Different Aspect Ratio and Filler Contents. *Materials* **2020**, *13*, 2431. [CrossRef]
40. Zhao, B.; Sivasankar, V.S.; Subudhi, S.K.; Dasgupta, A.; Das, S. Printed Carbon Nanotube-Based Humidity Sensors Deployable on Surfaces of Widely Varying Curvatures. *ACS Appl. Nano Mater.* **2023**, *6*, 1459–1474. [CrossRef]
41. Abdulla, S.; Dhakshinamoorthy, J.; Mohan, V.; Ponnuvelu, D.V.; Kallidaikuruchi, V.K.; Thalakkotil, L.M.; Pullithadathil, B. Development of low-cost hybrid multi-walled carbon nanotube-based ammonia gas-sensing strips with an integrated sensor read-out system for clinical breath analyzer applications. *J. Breath Res.* **2019**, *13*, 046005. [CrossRef] [PubMed]
42. Roy, S.; Zhang, X.; Puthirath, A.B.; Meiyazhagan, A.; Bhattacharyya, S.; Rahman, M.M.; Babu, G.; Susarla, S.; Saju, S.K.; Tran, M.K.; et al. Structure, Properties and Applications of Two-Dimensional Hexagonal Boron Nitride. *Adv. Mater.* **2021**, *33*, 2101589. [CrossRef] [PubMed]
43. Iqbal, A.A.; Sakib, N.; Iqbal, A.P.; Nuruzzaman, D.M. Graphene-based nanocomposites and their fabrication, mechanical properties and applications. *Materialia* **2020**, *12*, 100815. [CrossRef]
44. Chen, J.; Duan, M.; Chen, G. Continuous mechanical exfoliation of graphene sheets via three-roll mill. *J. Mater. Chem.* **2012**, *22*, 19625–19628. [CrossRef]
45. Zhu, F.-F.; Chen, W.-J.; Xu, Y.; Gao, C.-L.; Guan, D.-D.; Liu, C.-H.; Qian, D.; Zhang, S.-C.; Ji, J.-F. Epitaxial growth of two-dimensional stanene. *Nat. Mater.* **2015**, *14*, 1020–1025. [CrossRef]
46. Zhan, N.; Olmedo, M.; Wang, G.; Liu, J. Layer-by-layer synthesis of large-area graphene films by thermal cracker enhanced gas source molecular beam epitaxy. *Carbon* **2011**, *49*, 2046–2052. [CrossRef]
47. Yusof, N.M.; Ibrahim, S.; Rozali, S. Advances on graphene-based gas sensors for acetone detection based on its physical and chemical attributes. *J. Mater. Res.* **2022**, *37*, 405–423. [CrossRef]

48. Mathew, R.; Ajayan, J. Material processing, performance and reliability of MoS2 field effect transistor (FET) technology—A critical review. *Mater. Sci. Semicond. Process.* **2023**, *160*, 107397. [CrossRef]
49. Mehmood, A.; Mubarak, N.M.; Khalid, M.; Walvekar, R.; Abdullah, E.C.; Siddiqui, M.T.H.; Baloch, H.A.; Nizamuddin, S.; Mazari, S. Graphene based nanomaterials for strain sensor application—A review. *J. Environ. Chem. Eng.* **2020**, *8*, 103743. [CrossRef]
50. Zhao, G.; Li, X.; Huang, M.; Zhen, Z.; Zhong, Y.; Chen, Q.; Zhao, X.; He, Y.; Hu, R.; Yang, T.; et al. The physics and chemistry of graphene-on-surfaces. *Chem. Soc. Rev.* **2017**, *46*, 4417–4449. [CrossRef] [PubMed]
51. Yang, Y.; Duan, S.; Zhao, H. Advances in constructing silver nanowire-based conductive pathways for flexible and stretchable electronics. *Nanoscale* **2022**, *14*, 11484–11511. [CrossRef] [PubMed]
52. Sunkara, M.K.; Sharma, S.; Miranda, R.; Lian, G.; Dickey, E.C. Bulk synthesis of silicon nanowires using a low-temperature vapor–liquid–solid method. *Appl. Phys. Lett.* **2001**, *79*, 1546–1548. [CrossRef]
53. Desplanque, L.; Bucamp, A.; Troadec, D.; Patriarche, G.; Wallart, X. In-plane InSb nanowires grown by selective area molecular beam epitaxy on semi-insulating substrate. *Nanotechnology* **2018**, *29*, 305705. [CrossRef]
54. Varghese, S.S.; Lonkar, S.; Singh, K.K.; Swaminathan, S.; Abdala, A. Recent advances in graphene based gas sensors. *Sens. Actuators B Chem.* **2015**, *218*, 160–183. [CrossRef]
55. Huang, J.; Wang, H.; Liang, B.; Etim, U.J.; Liu, Y.; Li, Y.; Yan, Z. Oriented freeze-casting fabrication of resilient copper nanowire-based aerogel as robust piezoresistive sensor. *Chem. Eng. J.* **2019**, *364*, 28–36. [CrossRef]
56. Chang, S.M.; Palanisamy, S.; Wu, T.H.; Chen, C.Y.; Cheng, K.H.; Lee, C.Y.; Yuan, S.S.-F.; Wang, Y.-M. Utilization of silicon nanowire field-effect transistors for the detection of a cardiac biomarker, cardiac troponin I and their applications involving animal models. *Sci. Rep.* **2020**, *10*, 22027. [CrossRef]
57. Yang, Y.; Duan, S.; Xiao, W.; Zhao, H. Silver nanowire-based stretchable strain sensors with hierarchical wrinkled structures. *Sens. Actuators A Phys.* **2022**, *343*, 113653. [CrossRef]
58. Ning, H.; Ye, X.; Sada, A.B.; Mao, L.; Daneshmand, M. An Attention Mechanism Inspired Selective Sensing Framework for Physical-Cyber Mapping in Internet of Things. *IEEE Internet Things J.* **2019**, *6*, 9531–9544. [CrossRef]
59. Mele, L.J.; Palestri, P.; Selmi, L. Modeling Selectivity and Cross-sensitivity in membrane-based potentiometric sensors. In Proceedings of the 2020 Joint International EUROSOI Workshop and International Conference on Ultimate Integration on Silicon (EUROSOI-ULIS), Caen, France, 1–30 September 2020; pp. 1–4. [CrossRef]
60. Sivasankarapillai, V.S.; Jose, J.; Shanavas, M.S.; Marathakam, A.; Uddin, M.S.; Mathew, B. Silicon Quantum Dots: Promising Theranostic Probes for the Future. *Curr. Drug Targets* **2019**, *20*, 1255–1263. [CrossRef] [PubMed]
61. Huang, L.; Ye, Z.; Yang, L.; Li, J.; Qin, H.; Peng, X. Synthesis of Colloidal Quantum Dots with an Ultranarrow Photoluminescence Peak. *Chem. Mater.* **2021**, *33*, 1799–1810. [CrossRef]
62. De Arquer, F.P.G.; Talapin, D.V.; Klimov, V.I.; Arakawa, Y.; Bayer, M.; Sargent, E.H. Semiconductor quantum dots: Technological progress and future challenges. *Science* **2021**, *373*, aaz8541. [CrossRef] [PubMed]
63. Aubert, T.; Golovatenko, A.A.; Samoli, M.; Lermusiaux, L.; Zinn, T.; Abécassis, B.; Rodina, A.V.; Hens, Z. General Expression for the Size-Dependent Optical Properties of Quantum Dots. *Nano Lett.* **2022**, *22*, 1778–1785. [CrossRef] [PubMed]
64. Jorns, M.; Pappas, D. A Review of Fluorescent Carbon Dots, Their Synthesis, Physical and Chemical Characteristics, and Applications. *Nanomaterials* **2021**, *11*, 1448. [CrossRef] [PubMed]
65. Cornia, S.; Demontis, V.; Zannier, V.; Sorba, L.; Ghirri, A.; Rossella, F.; Affronte, M. Calibration-Free and High-Sensitivity Microwave Detectors Based on InAs/InP Nanowire Double Quantum Dots. *Adv. Funct. Mater.* **2023**, *33*, 2212517. [CrossRef]
66. Kahmann, S.; Shulga, A.; Loi, M.A. Quantum Dot Light-Emitting Transistors—Powerful Research Tools and Their Future Applications. *Adv. Funct. Mater.* **2019**, *30*, 1904174. [CrossRef]
67. Li, D.; Wang, J. Semiconductor/Carbon Quantum Dot-based Hue Recognition Strategy for Point of Need Testing: A Review. *ChemistryOpen* **2023**, *12*, e202200165. [CrossRef]
68. Domonkos, M.; Kromka, A. Nanosphere Lithography-Based Fabrication of Spherical Nanostructures and Verification of Their Hexagonal Symmetries by Image Analysis. *Symmetry* **2022**, *14*, 2642. [CrossRef]
69. Zhang, B.; Wang, J.; Wang, T.; Su, X.; Yang, S.; Chen, W.; Wang, J.; Sun, J.; Peng, J. High-performance microwave absorption epoxy composites filled with hollow nickel nanoparticles modified graphene via chemical etching method. *Compos. Sci. Technol.* **2019**, *176*, 54–63. [CrossRef]
70. Zhang, J.; Wang, F.; Shenoy, V.B.; Tang, M.; Lou, J. Towards controlled synthesis of 2D crystals by chemical vapor deposition (CVD). *Mater. Today* **2020**, *40*, 132–139. [CrossRef]
71. Zhang, X.; Li, N.; Zhang, S.; Sun, B.; Chen, Q.; He, Z.; Luo, C.; Sun, J. Emerging carrier-free nanosystems based on molecular self-assembly of pure drugs for cancer therapy. *Med. Res. Rev.* **2020**, *40*, 1754–1775. [CrossRef] [PubMed]
72. Seo, M.; Yoo, J.; Jo, M.; Yoon, J. Geometrically Structured Nanomaterials for Nanosensors, NEMS, and Nanosieves. *Adv. Mater.* **2020**, *32*, e190708. [CrossRef] [PubMed]
73. Young, C.; Yi, B.-Y.; Chen, H.-T. Template-assisted fabrication of CuxS–C hybrid-structure-based electrodes for electrochemical applications. *Chem. Eng. J.* **2022**, *428*, 132549. [CrossRef]
74. Li, X.-Z.; Tian, C.-B.; Sun, Q.-F. Coordination-Directed Self-Assembly of Functional Polynuclear Lanthanide Supramolecular Architectures. *Chem. Rev.* **2022**, *122*, 6374–6458. [CrossRef] [PubMed]
75. Yang, Y.-J.; Zhang, D.-L.; Hua, P.-R. Ultra-narrow and ultra-strong nanojet for nanopatterning and nanolithography. *Optik* **2022**, *255*, 168726. [CrossRef]

76. Yang, C. An adaptive sensor placement algorithm for structural health monitoring based on multi-objective iterative optimization using weight factor updating. *Mech. Syst. Signal Process.* **2021**, *151*, 107363. [CrossRef]
77. Hansen, M. Determination and assessment of fatigue stresses on concrete bridges. *Struct. Concr.* **2020**, *21*, 1286–1297. [CrossRef]
78. Jeong, J.-H.; Jo, H.; Laflamme, S.; Li, J.; Downey, A.; Bennett, C.; Collins, W.; Taher, S.A.; Liu, H.; Jung, H.-J. Automatic control of AC bridge-based capacitive strain sensor interface for wireless structural health monitoring. *Measurement* **2022**, *202*, 111789. [CrossRef]
79. Shitharth, S.; Meshram, P.; Kshirsagar, P.R.; Manoharan, H.; Tirth, V.; Sundramurthy, V.P. Impact of Big Data Analysis on Nanosensors for Applied Sciences Using Neural Networks. *J. Nanomater.* **2021**, *2021*, e4927607. [CrossRef]
80. Zeinali, M.; Barenji, R.V. Communication Networks Characteristics Impact on Cyber-Physical Systems. In *Control Engineering in Mechatronics*; Azizi, A., Ed.; Emerging Trends in Mechatronics; Springer Nature: Singapore, 2023; pp. 189–202. [CrossRef]
81. Wilson, A.N.; Kumar, A.; Jha, A.; Cenkeramaddi, L.R. Embedded Sensors, Communication Technologies, Computing Platforms and Machine Learning for UAVs: A Review. *IEEE Sens. J.* **2022**, *22*, 1807–1826. [CrossRef]
82. Abdulzahra, A.M.K.; Al-Qurabat, A.K.M.; Abdulzahra, S.A. Optimizing energy consumption in WSN-based IoT using unequal clustering and sleep scheduling methods. *Internet Things* **2023**, *22*, 100765. [CrossRef]
83. Haroun, A.F.; Le, X.; Gao, S.; Dong, B.; He, T.; Zhang, Z.; Wen, F.; Xu, S.; Lee, C. Progress in micro/nano sensors and nanoenergy for future AIoT-based smart home applications. *Nano Express* **2021**, *2*, 022005. [CrossRef]
84. Boitier, V.; Estibals, B.; Huet, F.; Seguier, L. Battery-Free Power Supply for Wireless Sensor Combining Photovoltaic Cells and Supercapacitors. *Energy Power Eng.* **2023**, *15*, 151–179. [CrossRef]
85. Hiran, K.K.; Khazanchi, D.; Vyas, A.K.; Padmanaban, S. *Machine Learning for Sustainable Development*; Walter de Gruyter GmbH & Co KG: Berlin, Germany, 2021.
86. Giouroukis, D.; Dadiani, A.; Traub, J.; Zeuch, S.; Markl, V. A survey of adaptive sampling and filtering algorithms for the internet of things. In Proceedings of the 14th ACM International Conference on Distributed and Event-Based Systems, Montreal, QC, Canada, 13–17 July 2020; Available online: https://dl.acm.org/doi/abs/10.1145/3401025.3403777 (accessed on 29 May 2023).
87. Leong, Y.X.; Tan, E.X.; Leong, S.X.; Koh, C.S.L.; Nguyen, L.B.T.; Chen, J.R.T.; Xia, K.; Ling, X.Y. Where Nanosensors Meet Machine Learning: Prospects and Challenges in Detecting Disease X. *ACS Nano* **2022**, *16*, 13279–13293. [CrossRef]
88. Zhang, C.; Mousavi, A.A.; Masri, S.F.; Gholipour, G.; Yan, K.; Li, X. Vibration feature extraction using signal processing techniques for structural health monitoring: A review. *Mech. Syst. Signal Process.* **2022**, *177*, 109175. [CrossRef]
89. Qiu, S.; Zhao, H.; Jiang, N.; Wang, Z.; Liu, L.; An, Y.; Zhao, H.; Miao, X.; Liu, R.; Fortino, G. Multi-sensor information fusion based on machine learning for real applications in human activity recognition: State-of-the-art and research challenges. *Inf. Fusion* **2022**, *80*, 241–265. [CrossRef]
90. Ye, C.; Butler, L.; Calka, B.; Iangurazov, M.; Lu, Q.; Gregory, A.; Girolami, M.; Middleton, C. *A Digital Twin of Bridges for Structural Health Monitoring*; DEStech Publications, Inc.: Lancaster, PA, USA, 2019; Available online: https://www.repository.cam.ac.uk/handle/1810/316786 (accessed on 29 May 2023).
91. Hosamo, H.H.; Hosamo, M.H. Digital Twin Technology for Bridge Maintenance Using 3D Laser Scanning: A Review. *Adv. Civ. Eng.* **2022**, *2022*, e2194949. [CrossRef]
92. Tien, T.; Saccomano, S.C.; Martin, P.A.; Armstrong, M.S.; Prud'homme, R.K.; Cash, K.J. Sensors in a Flash! Oxygen Nanosensors for Microbial Metabolic Monitoring Synthesized by Flash Nanoprecipitation. *ACS Sensors* **2022**, *7*, 2606–2614. [CrossRef]
93. Pu, H.; Xu, Y.; Sun, D.-W.; Wei, Q.; Li, X. Optical nanosensors for biofilm detection in the food industry: Principles, applications and challenges. *Crit. Rev. Food Sci. Nutr.* **2021**, *61*, 2107–2124. [CrossRef]
94. Giordano, P.F.; Quqa, S.; Limongelli, M.P. Value of information analysis accounting for data quality. In *Sensors and Smart Structures Technologies for Civil, Mechanical, and Aerospace Systems 2023*; SPIE: Bellingham, WA, USA, 2023; pp. 235–245. [CrossRef]
95. Naderi, A.; Behdad, S.; Fakher, M.; Hosseini-Hashemi, S. Vibration analysis of mass nanosensors with considering the axial-flexural coupling based on the two-phase local/nonlocal elasticity. *Mech. Syst. Signal Process.* **2020**, *145*, 106931. [CrossRef]
96. Singh, A.R.; Desu, P.K.; Nakkala, R.K.; Kondi, V.; Devi, S.; Alam, M.S.; Hamid, H.; Athawale, R.B.; Kesharwani, P. Nanotechnology-based approaches applied to nutraceuticals. *Drug Deliv. Transl. Res.* **2022**, *12*, 485–499. [CrossRef] [PubMed]
97. Theka, T.J.; Motaung, D.E. Chapter 6—Smart and autonomous (self-powered) nanosensor networks. In *Nanotechnology-Based Smart Remote Sensing Networks for Disaster Prevention*; Denizli, A., Alencar, M.S., Nguyen, T.A., Motaung, D.E., Eds.; Micro and Nano Technologies; Elsevier: Amsterdam, The Netherlands, 2022; pp. 105–121. [CrossRef]
98. Alabdulatif, A.; Thilakarathne, N.N.; Lawal, Z.K.; Fahim, K.E.; Zakari, R.Y. Internet of Nano-Things (IoNT): A Comprehensive Review from Architecture to Security and Privacy Challenges. *Sensors* **2023**, *23*, 2807. [CrossRef] [PubMed]
99. Chen, R. Preparation, property determination and bridge health monitoring applications of self-sensing cement nanocomposites. *Alex. Eng. J.* **2023**, *66*, 891–900. [CrossRef]
100. Mubarak, S.; Dhamodharan, D.; Ghoderao, P.N.P.; Byun, H.-S. A systematic review on recent advances of metal–organic frameworks-based nanomaterials for electrochemical energy storage and conversion. *Coord. Chem. Rev.* **2022**, *471*, 214741. [CrossRef]
101. Li, X.; Ming, P.; Ao, S.; Wang, W. Review of additive electrochemical micro-manufacturing technology. *Int. J. Mach. Tools Manuf.* **2022**, *173*, 103848. [CrossRef]

102. Xie, H.; Liu, J. Design of multi-parameter real-time acquisition system of human movement based on nanosensor. *Measurement* **2022**, *194*, 111056. [CrossRef]
103. Alshamrani, M. IoT and artificial intelligence implementations for remote healthcare monitoring systems: A survey. *J. King Saud Univ. Comput. Inf. Sci.* **2022**, *34*, 4687–4701. [CrossRef]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.