A Survey of Structural Health Monitoring Advances Based on Internet of Things (IoT) Sensors

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***Abstract*—Structural Health Monitoring (SHM) is a technique that ensures the safety and reliability of structures through continuous and real-time monitoring. IoT-based sensors have become a popular solution for implementing SHM systems, and research in this area is essential for improving the accuracy and reliability of SHM systems. A review of the current state-of-the-art is necessary to identify the challenges and opportunities for further development of SHM systems based on IoT sensors. This study presents a survey to comprehensively review of SHM, focusing on IoT sensors. Secondly, the categorization of the current civil structural monitoring methods is established, and the advantages and disadvantages of the methods are addressed. Thirdly, an analysis is performed, and the result is compared to civil structural monitoring methods. Finally, key features of the methods are discussed and summarized, and at last, some directions for future studies are presented.**

Keywords—Structural health monitoring; civil structures; internet of things; sensors; survey

I. Introduction

Structural monitoring is especially critical for aging infrastructure, which can suffer from wear and tear over time [1, 2]. By detecting early signs of damage or deterioration, it is possible to implement repairs or replacements before more extensive damage occurs [3, 4]. This can help prevent catastrophic failures and ensure the safety of the public and infrastructure workers. Structural Health Monitoring (SHM) is a method that facilitates the continuous and real-time monitoring of various structures such as bridges, buildings, and pipelines [5, 6]. SHM systems employ different sensors and technologies to detect structural damages or defects. This allows for timely repair or maintenance, thus avoiding catastrophic failures [7]. In civil engineering, SHM plays a critical role in ensuring the safety and reliability of important infrastructure.

Advancements in SHM systems have the potential to enhance the longevity, safety, and sustainability of structures, resulting in significant social and economic benefits [8]. Consequently, SHM has become a significant research area in this field and other civil structures [4, 9]. The goal of structural monitoring is to identify early signs of damage or deterioration and assess the structural integrity of the infrastructure to ensure safety and longevity [10, 11]. Many techniques and technologies are used in civil structural monitoring, including sensors, cameras, and other monitoring equipment [12, 13]. The data collected from these devices is often analyzed using machine learning algorithms to identify patterns and detect anomalies [14].

The integration of Internet of Things (IoT) technology with SHM systems allows for remote and real-time monitoring of structures, providing valuable data that can be analyzed to detect any damage or defects [15]. IoT-based SHM systems use various sensors and devices that can detect environmental conditions, vibrations, and strains in the structures, allowing for timely maintenance or repair before a failure occurs [16]. This approach has the potential to significantly improve the accuracy and reliability of SHM systems, making it an exciting and promising area of research in the field of civil engineering.

This study presents a comprehensive overview of SHM using IoT sensors. Section II deals with the categorization of the current civil structural monitoring methods is established, and the advantages and disadvantages of the methods are addressed. In Section III, an analysis is performed, and the result is compared to civil structural monitoring methods. Section IV presents key features of the methods are discussed and summarized, and finally conclusion of this paper and some directions for future studies are presented in Section V and Section VI, respectively.

The uniqueness of this paper, when compared to the review of the literature, lies in its multifaceted approach to Structural Health Monitoring (SHM) with a specific focus on IoT sensors. While the existing literature provides some insights into SHM, this study goes beyond by not only offering a comprehensive overview but also categorizing the current civil structural monitoring methods. By addressing the advantages and disadvantages of these methods and conducting a detailed comparative analysis, this paper provides a more in-depth understanding of the state-of-the-art in SHM based on IoT sensors. Furthermore, the paper concludes by presenting key features and directions for future research, adding a forward-looking dimension that sets it apart from a mere literature review.

II. Related Works

This section presents a review of previous studies on structural health monitoring with the covering of IoT-based sensors. Tokognon et al. [15] presented a comprehensive survey of the existing literature on Structural Health Monitoring (SHM) frameworks based on the Internet of Things (IoT). The authors discuss the importance of SHM and how IoT technologies can be used to enhance SHM systems. They review the various IoT-based sensors and devices that can be used for SHM and the different techniques for data collection and analysis. The authors also identify the challenges and limitations of IoT-based SHM systems and the potential solutions to address them. Overall, this paper provides a valuable resource for researchers and practitioners working on IoT-based SHM systems, highlighting the current state-of-the-art and future research directions in this field.

Ye et al. [17] provided a comprehensive review of the recent developments in deep learning-based structural health monitoring (SHM) of civil infrastructures. The paper discusses the benefits of using deep learning techniques, such as artificial neural networks and convolutional neural networks, for SHM applications and reviews the different types of deep learning models that have been developed for civil infrastructure monitoring. The authors also provide case studies of deep learning-based SHM in various civil infrastructure projects, demonstrating the potential of these techniques in improving the accuracy and efficiency of SHM. Overall, the paper is a valuable resource for researchers, engineers, and practitioners working in the field of SHM and civil infrastructure, especially those interested in applying deep learning techniques to enhance the reliability and safety of civil structures.

Mishra et al. [18] presented an overview of the use of the Internet of Things (IoT) for structural health monitoring (SHM) of civil engineering structures. The authors discuss the benefits and challenges associated with using IoT technologies for SHM, including improved data collection, analysis, and communication. The paper also provides case studies of IoT-based SHM in different civil engineering structures, demonstrating the potential benefits of these technologies in improving the safety and reliability of civil engineering structures. Overall, the paper is a useful resource for researchers, engineers, and practitioners working in the field of civil engineering and structural health monitoring.

A survey of the recent developments in fiber-optic sensing technologies was presented for structural health monitoring (SHM) of civil infrastructure by Wu et al. [19]. The paper discusses the benefits of fiber-optic sensors, including their sensitivity, durability, and resistance to electromagnetic interference, and reviews different types of fiber-optic sensors that have been developed for SHM applications. The authors also provide case studies of fiber-optic sensor applications in various civil infrastructure projects, demonstrating the potential of these sensors in improving the safety and reliability of civil infrastructure. Overall, the paper is a valuable resource for researchers, engineers, and practitioners working in the field of SHM and civil infrastructure.

Malekloo et al. [20] presented a comprehensive overview of machine learning (ML) techniques for structural health monitoring (SHM) applications, with a focus on emerging technologies and high-dimensional data sources. The paper discusses the benefits of using ML techniques, such as support vector machines and random forests, for SHM applications and reviews different types of ML models that have been developed for civil infrastructure monitoring. The authors also highlight the importance of using emerging technologies, such as unmanned aerial vehicles and wireless sensor networks, to enhance the effectiveness of ML-based SHM. The paper provides case studies of ML-based SHM in various civil infrastructure projects, demonstrating the potential of these techniques in improving the accuracy and efficiency of SHM. Overall, the paper is a valuable resource for researchers, engineers, and practitioners working in the field of SHM and civil infrastructure, especially those interested in applying ML techniques to enhance the reliability and safety of civil structures.

An overview of the subspace system identification (SSI) method was presented for the health monitoring of civil infrastructures by Shokravi et al. [21]. The paper discusses the benefits of using the SSI method for SHM applications, such as its ability to identify system parameters accurately and detect damage in civil infrastructures. The authors provide case studies of SSI-based SHM in various civil infrastructure projects, demonstrating the potential of this method in improving the accuracy and efficiency of SHM. Overall, the paper is a valuable resource for researchers, engineers, and practitioners working in the field of SHM and civil infrastructure, especially those interested in applying the SSI method to enhance the reliability and safety of civil structures.

III. STRUCTURAL HEALTH MONITORING TECHNOLOGIES

Various types of monitoring methods are available, including visual inspections, non-destructive testing, and structural health monitoring using sensors, among others. Each method has its strengths and limitations, and the selection of a monitoring method depends on factors such as the type of structure, its location, and the available resources. Fig. 1 shows the categorization of civil structural monitoring methods.

A. *Visual Inspections*

Visual inspections are one of the most common methods used in civil structural monitoring to assess the condition of a structure [22]. The visual inspection is used computer vision algorithms to extract useful information from the images and videos [41]. This method involves the visual examination of a structure's surface and other visible components to identify signs of damage or degradation. Visual inspections can be conducted by trained professionals or by using automated technologies such as drones equipped with cameras [23, 24]. Table I presents visual inspection methods used for civil structural monitoring.

B. *Structural Health Monitoring (SHM)*

The SHM is a method of continuously monitoring a structure's condition to detect any signs of damage or degradation [5]. SHM involves the use of sensors to measure various parameters such as strain, vibration, temperature, and displacement, which are then analyzed to assess the structure's condition [25]. SHM can help to identify potential problems before they become serious, allowing for timely repairs and maintenance to be performed [26]. Table II presents the Infrared SHM used for civil structural monitoring.

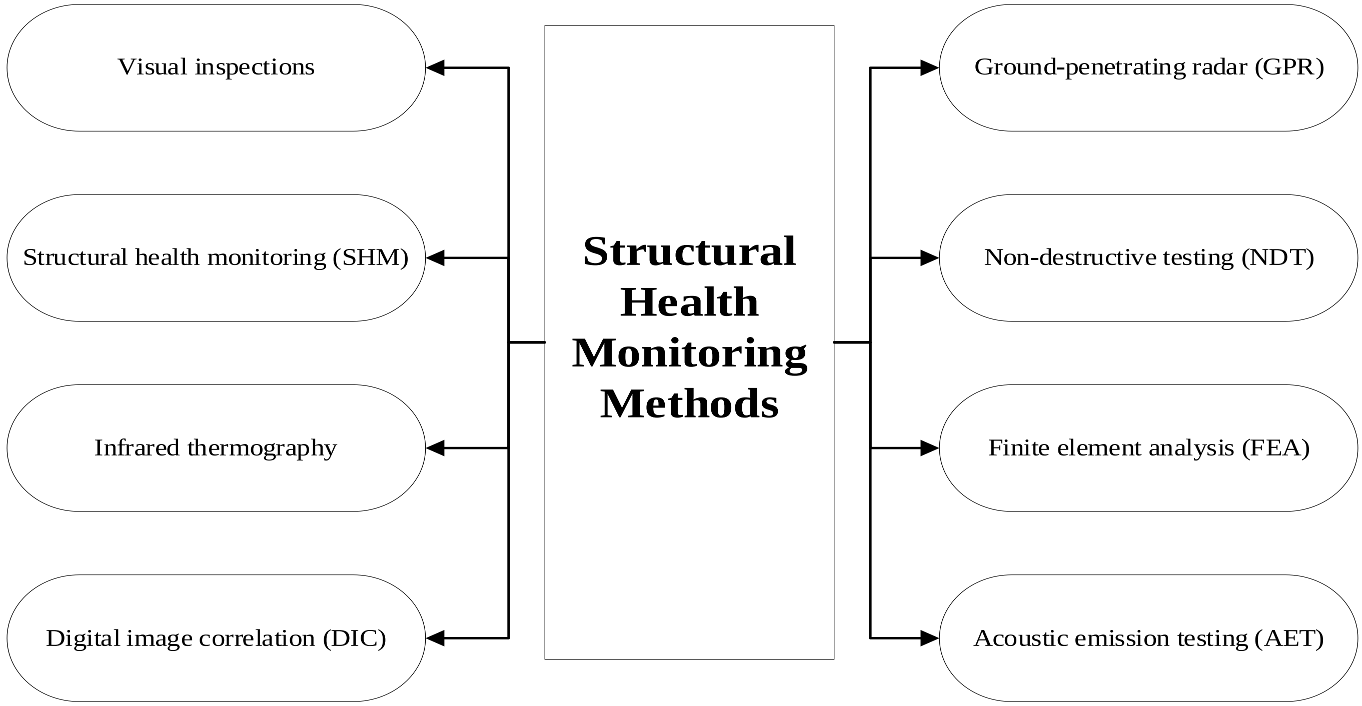

Fig. 1. Categorization of civil structural monitoring methods.

TABLE I. THE VISUAL INSPECTION METHODS USED FOR CIVIL STRUCTURAL MONITORING

Method	Description	Pros	Cons
Bridge inspection using unmanned aerial vehicles (UAVs)	Inspection of bridges using UAVs equipped with high-resolution cameras	Non-intrusive can access hard-to-reach areas	Limited ability to detect internal damage
Crack detection using digital image correlation (DIC)	Detection of cracks and deformations using high-resolution cameras and computer vision algorithms	High accuracy, non-intrusive	Limited to surface damage
Tunnel lining inspection using LiDAR	Inspection of tunnel linings using LiDAR scanners	Rapid data collection, accurate mapping of interior surfaces	Limited ability to detect internal damage
Corrosion detection using electrochemical techniques	Detection of corrosion on metal structures using electrochemical sensors	Highly sensitive can detect early-stage corrosion	Limited to metal structures
Building facade inspection using drones	Inspection of building facades using drones equipped with high-resolution cameras	Non-intrusive can access hard-to-reach areas	Limited to surface damage

TABLE II. THE SHM METHODS USED FOR CIVIL STRUCTURAL MONITORING

Method	Description	Pros	Cons
Fiber optic sensors	Sensors that use light to measure strain and temperature	High accuracy, non-intrusive	Expensive, require specialized installation
Wireless sensor networks	Networks of sensors that communicate wirelessly to a central monitoring system	Real-time monitoring, easy installation	Limited range, may require battery replacement
Piezoelectric sensors	Sensors that measure mechanical stress using electric charge	High sensitivity can detect damage at early stages	Limited to certain types of structures
Acoustic emission sensors	Sensors that detect and analyze acoustic signals emitted by structures	Non-intrusive can detect damage at early stages	Limited to certain types of structures
Electrochemical corrosion sensors	Sensors that detect corrosion on metal structures using electrochemical reactions	Highly sensitive can detect early-stage corrosion	Limited to metal structures

TABLE III. THE INFRARED THERMOGRAPHY METHODS USED FOR CIVIL STRUCTURAL MONITORING

Method	Description	Pros	Cons
Building envelope inspection using Infrared thermography	Inspection of building envelopes to detect heat loss and insulation issues	Non-intrusive can detect hidden damage	Limited to surface damage
Concrete inspection using Infrared thermography	Inspection of concrete structures to detect internal defects such as voids and delamination	Non-intrusive can detect internal damage	Limited to certain types of structures
Bridge inspection using Infrared thermography	Inspection of bridges to detect delamination and corrosion on the surface	Non-intrusive can detect hidden damage	Limited to surface damage
Electrical equipment inspection using Infrared thermography	Inspection of electrical equipment to detect overheating and potential electrical faults	Non-intrusive can detect hidden damage	Limited to electrical equipment

C. Infrared Thermography

Infrared thermography is a method of detecting changes in temperature on a structure's surface to identify potential defects or damage [27, 28]. This method involves the use of infrared cameras to capture thermal images, which can then be analyzed to identify areas of the structure with abnormal temperature patterns [29]. Infrared thermography can be used to identify defects such as water infiltration, heat loss, and insulation issues [30]. Table III presents the Infrared thermography methods used for civil structural monitoring.

D. Digital Image Correlation (DIC)

Digital image correlation (DIC) is a non-destructive testing method that uses digital images to measure the deformation and strain of a structure [31, 32]. This method involves capturing images of the structure at different intervals during loading and then using specialized software to analyze the images and determine the deformation and strain. Table IV presents the DIC methods used for civil structural monitoring.

E. Ground-penetrating Radar (GPR)

Ground-penetrating radar (GPR) is a non-destructive testing method that uses electromagnetic waves to detect and map features within structures and materials [33, 34]. This method involves transmitting a high-frequency electromagnetic pulse into the structure or material and measuring the reflections and diffractions that occur as the pulse travels through it. Table V presents the GPR methods used for civil structural monitoring.

F. Non-destructive Testing (NDT)

Non-destructive testing (NDT) methods are techniques that allow for the assessment of the condition of civil infrastructure without causing damage to the structure [35, 36]. Table VI presents popular existing NDT methods used for civil structural monitoring.

TABLE IV. THE DIC METHODS USED FOR CIVIL STRUCTURAL MONITORING

Method	Description	Pros	Cons
Bridge load testing using digital image correlation	Testing the load-carrying capacity of bridges using DIC	Non-intrusive can provide accurate data	Limited to certain types of structures
Concrete deformation measurement using digital image correlation	Measuring the deformation and strain of concrete structures	Non-intrusive, high accuracy	Limited to surface measurements
Structural deformation measurement using digital image correlation	Measuring the deformation and strain of various types of structures	Non-intrusive can provide accurate data	Limited to surface measurements
Material testing using digital image correlation	Measuring the deformation and strain of materials under different loading conditions	Non-destructive can provide accurate data	Limited to laboratory conditions

TABLE V. THE GPR METHODS USED FOR CIVIL STRUCTURAL MONITORING

Method	Description	Pros	Cons
Concrete inspection using ground-penetrating radar	Inspecting concrete structures for defects such as cracks and voids	Non-destructive can detect internal defects	Limited to certain types of structures
Detection of buried utilities using ground-penetrating radar	Detecting buried utilities such as pipes and cables	Non-destructive can provide accurate data	Limited to certain types of soils and materials
Assessment of pavement thickness using ground-penetrating radar	Measuring the thickness of pavement layers	Non-destructive can provide accurate data	Limited to certain types of pavements
Assessment of bridge decks using ground-penetrating radar	Detecting delamination and reinforcing steel within bridge decks	Non-destructive can provide accurate data	Limited to certain types of bridge decks

TABLE VI. THE NDT METHODS USED FOR CIVIL STRUCTURAL MONITORING

Method	Description	Pros	Cons
Ultrasonic testing	Ultrasonic waves are transmitted into the structure, and the reflections are measured to detect defects such as cracks and voids.	Non-destructive can detect internal defects, highly accurate	Limited to certain types of structures, requires specialized equipment and training
Magnetic particle inspection	A magnetic field is applied to the structure, and magnetic particles are introduced to the surface. Any defects in the structure cause a disruption in the magnetic field, allowing them to be detected.	Non-destructive can detect surface and near-surface defects	Limited to ferromagnetic materials, may not detect small defects
Eddy current testing	An alternating current is applied to the structure, inducing eddy currents which generate a magnetic field. Any defects in the structure cause a disruption in the magnetic field, allowing them to be detected.	Non-destructive can detect surface and near-surface defects highly accurately.	Limited to conductive materials, may not detect small defects

TABLE VII. THE FEA METHODS USED FOR CIVIL STRUCTURAL MONITORING

Method	Description	Pros	Cons
Static analysis	The structure is modeled as a system of linear equations which are solved to determine the stresses and deformations under static loads.	Highly accurate, can model a wide range of structures and loading conditions	Assumes linear behavior of materials, cannot account for dynamic effects
Dynamic analysis	The structure is modeled as a system of differential equations, which are solved to determine the response under dynamic loads such as earthquakes and wind.	It can account for dynamic effects, useful for assessing the risk of failure under extreme loading conditions.	It can be computationally intensive and requires accurate modeling of damping and material behavior
Fatigue analysis	The structure is modeled under cyclic loading conditions to predict the accumulation of damage over time.	Can predict the expected life of a structure under cyclic loading, useful for designing maintenance schedules	Requires accurate modeling of material behavior and loading conditions, may not account for all sources of damage

TABLE VIII. THE AET METHODS USED FOR CIVIL STRUCTURAL MONITORING

Method	Description	Pros	Cons
Passive monitoring	AET sensors are installed on the structure to monitor for acoustic emissions continuously.	It can detect small or incipient damage, is non-invasive, and can monitor large areas.	Limited to detecting events with significant energy release, cannot pinpoint the location of the damage.
Active monitoring	AET is performed while the structure is under load or undergoing testing.	It can detect damage as it occurs and identify the location and extent of damage.	It may require access to the structure and may not be practical for continuous monitoring.
Source location	Multiple AET sensors are used to triangulate the location of acoustic emissions.	Can pinpoint the location of damage, useful for determining the extent of damage	It may require a large number of sensors, limited by the ability to detect signals in noisy environments.

G. Finite Element Analysis (FEA)

Finite element analysis (FEA) is a computational method that uses numerical models to simulate the behavior of civil infrastructure under various loading conditions [37, 38]. Finite element analysis (FEA) is a computational method that uses numerical models to simulate the behavior of civil infrastructure under various loading conditions. Table VII shows some existing FEA methods used for civil structural monitoring.

H. Acoustic Emission Testing (AET)

Acoustic emission testing (AET) is a non-destructive testing (NDT) method that detects acoustic signals produced by the internal deformation of a material or structure [39, 40]. Table VIII presents popular AET methods used for civil structural monitoring.

IV. ANALYSIS OF CIVIL STRUCTURAL MONITORING METHODS

In this study, the analysis of the methods is conducted through a meticulous examination of previous research and a thorough review of the data presented in the original papers. Our approach involves a comprehensive assessment aimed at identifying and elucidating the advantages and disadvantages of these methods. To ensure the accuracy and reliability of our analysis, we rely on the data reported in the original papers as our foundational source, supplemented by our own investigations. These investigations are carried out using standard performance metrics, allowing us to provide a rigorous and objective evaluation of the methods under consideration. This combined approach ensures a robust and well-informed analysis, contributing to the depth and credibility of our research findings. For this analysis qualitative and quantitative analysis are conducted, the detail of each discuss as follows,

A. Qualitative Analysis

The qualitative analysis for the SHM method involves comparing different monitoring methods across several criteria to determine their effectiveness in detecting changes or damage in civil structures. These criteria include cost, ease of implementation, resolution, and range. By analyzing each method based on these criteria and assigning a numerical score, a comprehensive comparison can be made to identify the most suitable method for a specific application. The analysis uses data and information from previous studies and research, allowing for a data-driven approach to evaluating each method.

- Cost: The estimated cost associated with implementing the monitoring method. This includes equipment, labor, and any other expenses associated with the method.
- Ease of implementation: How difficult it is to set up and utilize the monitoring method. This takes into account factors such as the expertise required to operate the equipment, as well as any additional equipment needed to implement the method.
- Resolution: The level of detail that the monitoring method can provide in measuring changes or damage in the structure being monitored.
- Range: The distance from the structure that the monitoring method can effectively measure changes or damage. This takes into account the maximum effective range of the equipment used in the method.

Based on the performance analysis criteria, Table IX presents the performance analysis for civil structural monitoring methods.

According to Table IX, the cost of the different methods ranges from low to high, with visual inspections being the least expensive and SHM, NDT, and FEA being the most expensive. Ease of implementation ranges from easy to difficult, with visual inspections being the easiest and SHM and FEA being the most difficult. Sensitivity, accuracy, and resolution are all high for SHM, NDT, FEA, GPR, and DIC, while visual inspections and infrared thermography have lower values for these parameters. The range of each method varies from short to medium, with most methods being limited to the immediate vicinity of the structure. Overall, the choice of method will depend on the specific needs of the project, including the level of detail required, the available budget, and the location and accessibility of the structure.

B. Quantitative Analysis

The quantitative analysis for Civil Structural Monitoring methods involves comparing different monitoring methods across several criteria to determine their effectiveness in detecting changes or damage in civil structures. For this analysis, image processing, machine learning and deep learning approaches are considered. In the following section, the quantitative analyses are conducted for these methods.

1) Analysis of image processing methods: In this analysis, the most popular image processing methods are analyzed. These methods involve Edge Detection, Thresholding, Morphological Operations, Region-based Segmentation, Contour Analysis, Texture Analysis, Template Matching, Hough Transform and Connected Component Analysis.

For this analysis, popular performance metrics are considered, which include precision, recall and F-score. The precision, recall and F-score values are typically calculated based on the true positive, false positive, and false negative rates. In this study, we collected the values from previously published research works. Fig. 2 demonstrates the analysis of image processing methods.

2) Analysis of traditional machine learning methods: For analysis of traditional machine learning methods, we selected the most used methods in the literature. These methods involve Support Vector Machines (SVM), Random Forests, k-Nearest Neighbors (k-NN), Decision Trees, Naive Bayes, Ensemble methods (AdaBoost), Logistic Regression, and Neural Networks.

Similar to image processing analysis, popular performance metrics are considered, including precision, recall and F-score. Fig. 3 demonstrates the analysis of image processing methods.

TABLE IX. PERFORMANCE ANALYSIS FOR CIVIL STRUCTURAL MONITORING METHODS

Method	Cost	Ease of implementation	Resolution	Range
Visual inspections	Low	Easy	Low	Short
Structural health monitoring (SHM)	High	Difficult	High	Short to medium
Infrared thermography	Medium	Moderate	Medium	Short to medium
Digital image correlation (DIC)	Medium	Moderate	High	Short to medium
Ground-penetrating radar (GPR)	High	Moderate	Medium to high	Short to medium
Non-destructive testing (NDT)	High	Moderate to difficult	High	Short to medium
Finite element analysis (FEA)	High	Difficult	High	Short to medium
Acoustic emission testing (AET)	Medium to high	Moderate to difficult	High	Short to medium

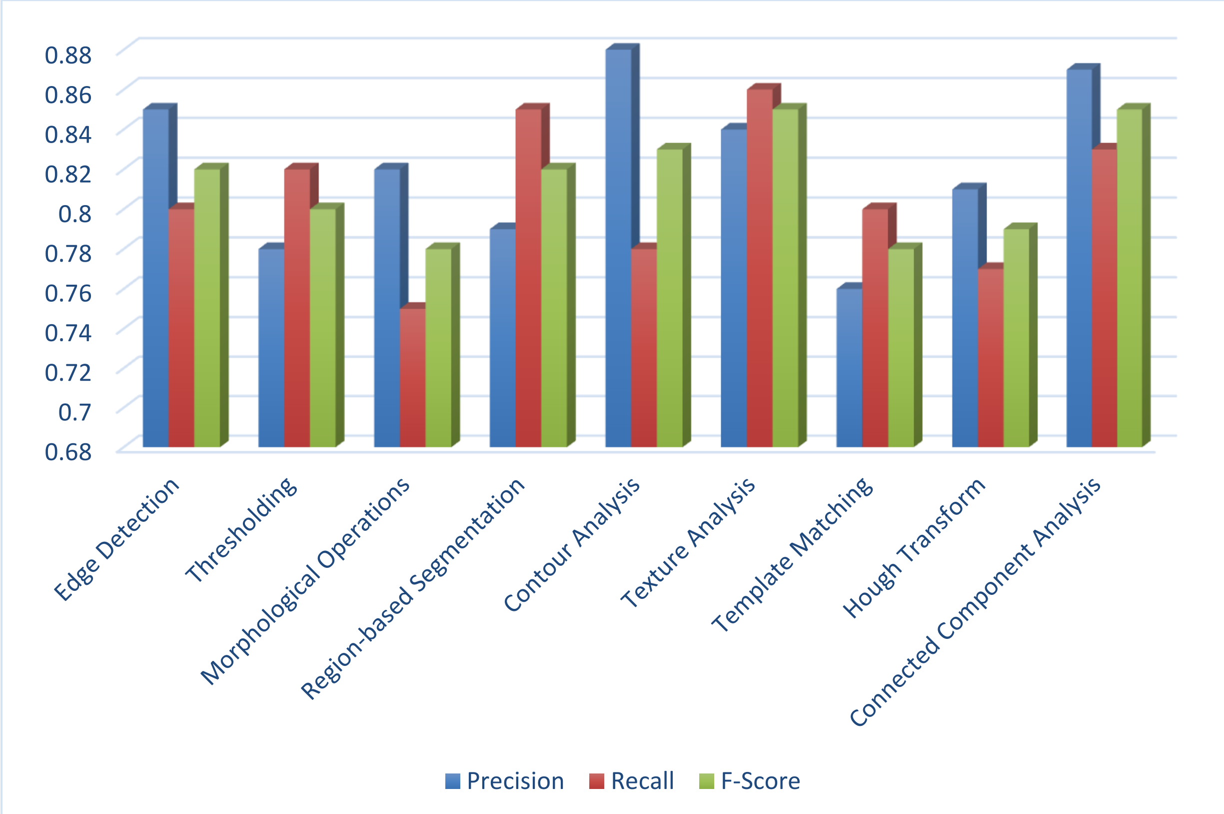

Fig. 2. Quantitative analysis of image processing methods.

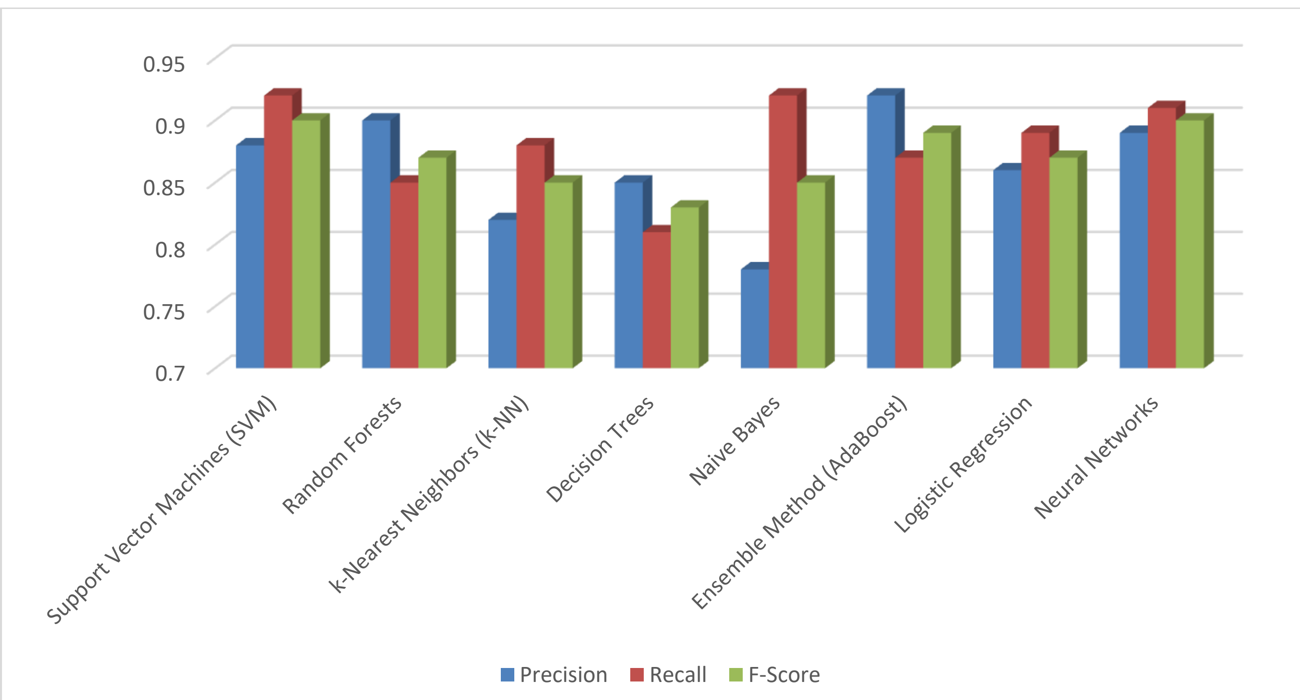

Fig. 3. Quantitative analysis of traditional machine learning methods.

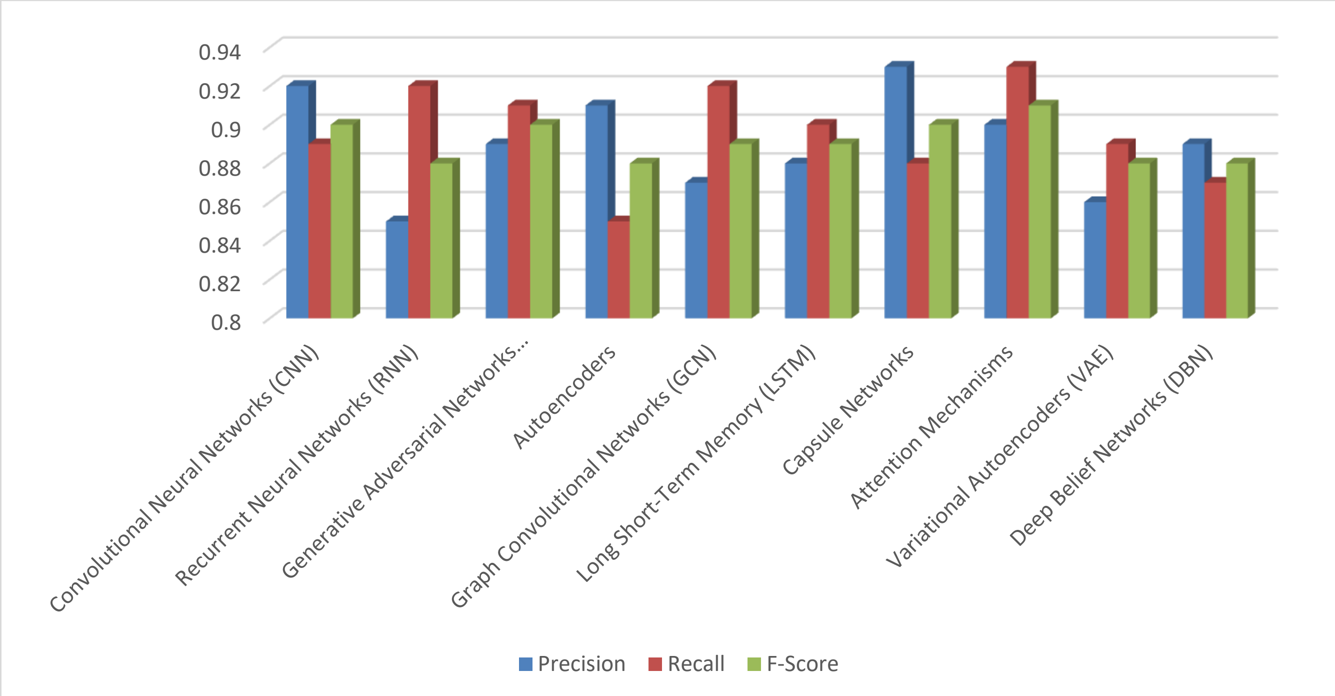

Fig. 4. Quantitative analysis of deep learning methods.

3) Analysis of deep learning methods: For analysis of deep learning methods, we also selected the most used approaches in deep-based structural health monitoring systems. These methods involve Convolutional Neural Networks (CNN), Recurrent Neural Networks (RNN), Generative Adversarial Networks (GAN), Autoencoders, Graph Convolutional Networks (GCN), Long Short-Term Memory (LSTM), Capsule Networks, Attention Mechanisms, Variational Autoencoders (VAE), Deep Belief Networks (DBN).

Similar to image processing and machine learning analysis procedures, popular performance metrics include precision, recall and F-score. Fig. 4 demonstrates the analysis of image processing methods.

4) Comparison of the methods: This section presents a comparison of performance measurements for image processing, machine learning and deep learning methods. Correspondingly, this comparison is conducted in terms of precision, recall and F-score. For this comparison, we calculated the average of precision, recall and F-score for each category of methods. Fig. 5 shows the comparison of the methods.

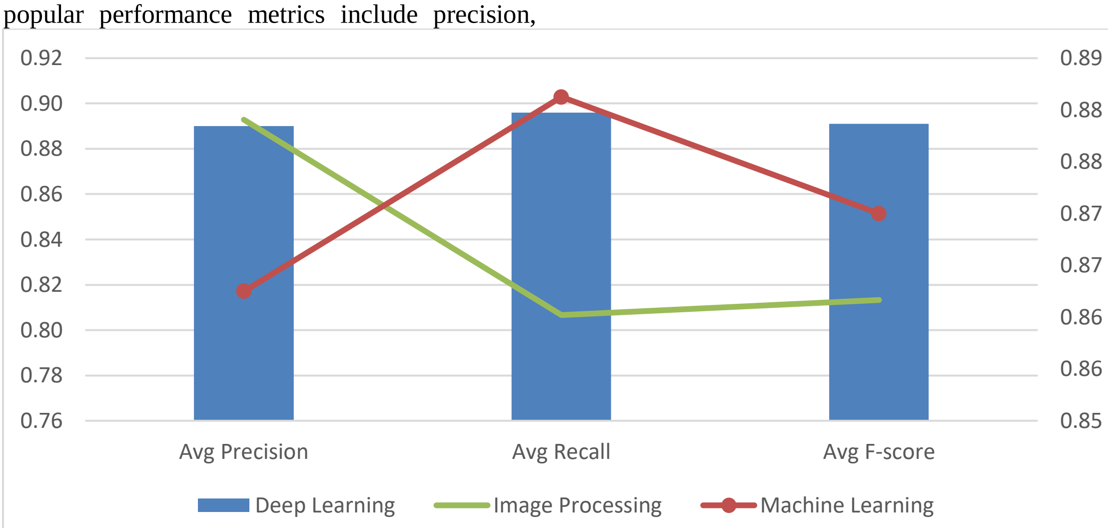

Fig. 5. Average precision, recall and F-score for the methods.

V. Discussion

As discussed above, civil structural monitoring methods refer to techniques and approaches used to detect, monitor, and analyze changes in the behavior and condition of civil structures such as bridges, buildings, and tunnels. In the following, according to the evaluation and analysis section, the key features of the methods used are discussed.

The visual inspection method involves a visual examination of the structure, looking for signs of damage, deterioration, or deformation. It is a cost-effective method that does not require any special equipment, but it is subjective and dependent on the inspector's experience and expertise.

The Infrared thermography method uses thermal imaging cameras to detect changes in surface temperature caused by structural changes. It is non-destructive and can detect changes that are not visible to the naked eye, but it is sensitive to environmental factors such as sunlight and wind.

The DIC method uses two-dimensional images of the structure to detect changes in shape and deformation. It is a non-contact and non-destructive method that provides high-resolution data, but it requires specialized equipment and expertise.

The GPR method uses radar waves to detect changes in the composition and structure of the subsurface materials. It can detect voids, cracks, and other defects that are not visible to the naked eye, but it is dependent on the materials being scanned and can be affected by environmental factors such as moisture.

The FEA method uses computational modeling to simulate the behavior of a structure under different conditions. It is a highly detailed method that provides accurate data on the stresses and strains in the structure, but it requires specialized software and expertise.

The AET method uses sensors to detect high-frequency sounds generated by changes in the structure. It is a non-destructive and sensitive method that can detect changes in real-time, but it can be affected by environmental noise and requires specialized equipment.

VI. Conclusion

This study has offered a comprehensive survey and review of Structural Health Monitoring (SHM) techniques, with a particular emphasis on the integration of IoT sensors. The categorization of existing civil structural monitoring methods has provided a valuable framework for understanding the landscape of monitoring methodologies. By critically assessing the advantages and disadvantages of these methods and conducting a comparative analysis, we have enhanced our insights into the current state-of-the-art in SHM, specifically concerning IoT-based sensors. This paper has underscored the importance of method selection in civil structural monitoring, with each approach having distinct merits and limitations tailored to specific structural requirements and monitoring objectives. The unique contribution of this study lies in its multifaceted approach, combining literature review, categorization, and comparative analysis, to offer a more comprehensive perspective on SHM. there are several promising directions for future research in the field of Structural Health Monitoring. First, the integration of emerging technologies such as machine learning and artificial intelligence into IoT-based monitoring systems could significantly enhance the accuracy and efficiency of SHM techniques. Investigating these innovative approaches holds great potential for advancing the field. Additionally, further exploration of interdisciplinary applications of SHM, such as its utilization in disaster resilience and predictive maintenance, could expand its practical utility. Moreover, research into the development of cost-effective and scalable IoT sensor networks for large-scale infrastructure monitoring is an area that warrants attention. Finally, investigations into the long-term durability and reliability of IoT sensor deployments in real-world scenarios would contribute valuable insights to ensure the sustainability of SHM systems. These future directions have the potential to shape the evolution of Structural Health Monitoring, making it an even more robust and indispensable tool in ensuring the safety and integrity of civil structures.

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