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Original Article

Structural Health Monitoring Using Wireless IoT Sensors

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ABSTRACT

Structural Health Monitoring (SHM) has become an important science to help keep civil infrastructure like bridges, buildings, dams, and industrial plants safe, reliable and lasting. Traditional methods of SHM have depended primarily on wired sensor networks and periodic manual inspections that are regularly expensive, labor-intensive and lack real-time responsiveness. The present-day breakthroughs in Wireless Sensor Networks (WSNs) and the Internet of Things (IoT) have made it possible to create intelligent, scalable, and energy-efficient SHM systems that would allow continuous monitoring and remote diagnostics. This paper provides an extensive exploration of Structural Health Monitoring with wireless IoT sensors in terms of system architecture, sensing modalities, communication protocols, data processing methods, and damage detection methods. The intricate literature survey reveals the development of the SHM technologies and outlines the gaps in the research. The suggested methodology will combine low-power wireless sensors, edge computing, and cloud-based analytics to track such structural parameters as strain, vibration, displacement, and temperature. Damage detection and feature extraction mathematical models are discussed and the experimental validation strategies. The findings support the idea that IoT-based SHM systems can greatly improve the accuracy of fault detection, decrease the cost of maintenance, and predictive maintenance. The paper has reached the conclusion that wireless IoT-based SHM is an innovative solution to smart infrastructure management and offers the research perspectives on its future development in terms of scalability and artificial intelligence incorporation.

KEYWORDS

Structural Health Monitoring, Internet Of Things, Wireless Sensor Networks, Smart Infrastructure, Damage Detection, Predictive Maintenance.

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1. INTRODUCTION

1.1. Background

Traditionally, Structural Health Monitoring (SHM) has also been based on regular visual inspection and wired sensing devices to determine the state of civil infrastructure. Human expertise in visual inspection method is also highly relied on and in most cases it is subjective, time consuming and is unable to detect internal or early-stage damage. The wired sensing systems are examples of sensing systems that make use of wired sensors like strain gauges and accelerators, linked by major cabling, and offer precision, but place considerable installation and maintenance demands. These systems have high cost which includes cabling, specialized installation and regular maintenance and make it economically impractical to use in large scale or long term monitoring. Besides the financial implications, conventional SHM proposals have minimal spatial coverage as the quantity of sensors that could be laid out is limited by the complexity of wiring and the budget constraints. Such a limited coverage limits the capability to record the full structural response which may leave vital damage unidentified. Moreover, the majority of traditional systems are not intended to be used in constant real-time monitoring, as they can only be used with regular inspections or offline data gathering. This restricts their ability to identify acute and progressive damage. Wired systems also become extremely vulnerable to impairment of the cables through exposure to the environment or corrosion or mechanical damages that end up destroying data and causing the breakdown of the whole system. These shortcomings demonstrate the necessity of more agile, more economical, and smarter SHM solutions.

1.2. Importance of Structural Health Monitoring

Fig 1 - Importance of Structural Health Monitoring

SHM is an important method of guaranteeing safe, dependable and sustainable civil infrastructure like bridges, buildings, dams and industrial structures. With the age and exposure of the infrastructure systems to the growing environmental and operational pressure, the necessity to ensure continuous and systematic monitoring emerges. SHM gives information on the structural condition which is accurate and timely to make informed decisions and mitigate risk.

1.2.1. Ensuring Structural Safety

The safety of the buildings and their occupants is one of the main goals of SHM. SHM systems could help in early detection of damage like cracks, excessive deformation or stiffness degradation through constant checking of the important structural parameters. The prompt detection of such problems will ensure that the failures occur suddenly and they will be less likely to happen, and this will preserve human lives and properties.

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1.2.2. Extending Service Life of Infrastructure

SHM helps in the lengthening of service life of buildings as it facilitates the condition-based and predictive maintenance plans. SHM data can assist engineers not only in evaluating actual structural performance but also in planning maintenance actions instead of doing it only on a periodic basis or in case of a failure. This preventive strategy will decrease unscheduled repairs, down time as well as postponing expensive structural replacements.

1.2.3. Reducing Maintenance and Operational Costs

The constant tracking will enable the infrastructure owners to plan their maintenance process and to plan their resources more effectively. Early detection of damage prevents expensive repair jobs and emergency operations by SHM since these can be costly. This eventually results in significant maintenance and operational savings, in particular large-scale and critical infrastructure.

1.2.4. Supporting Smart Infrastructure and Decision-Making

SHM systems are a major element of the smart city and infrastructure. The combination of sensing technologies, analytics, and real-time monitoring is beneficial in using data to make decisions that manage infrastructure. SHM increases resilience, reliability, and long-term planning, so this is an essential instrument of the modern civil engineering work.

1.3. Structural Health Monitoring Using Wireless IoT Sensors

SHM with wireless IoT sensors is a marked improvement based on conventional monitoring methods because it allows assessing the structural conditions in a continuous, real-time, and intelligent way. Under this method, wireless sensors that are small and consume less power are installed in strategic points on a structure to monitor such parameters as strain, acceleration, vibration, temperature, and humidity. These sensors create a distributed sensing network that has the capacity of recording structural responses as well as environmental effects. Wireless IoT-based SHM does not require large amounts of cabling as opposed to wired system and hence the complexity of the installation process, the time spent on its deployment is also reduced and the cost of the system is also lowered. IoT technologies will enable the transmission of sensor data wirelessly to edge devices or gateways and then to the cloud platforms to store and analyze it. MQTT and CoAP are lightweight communication protocols that provide efficient transfer of data and conserve energy, and thus the system can be applied in long-term monitoring. Edge processing methods also increase the performance of the system by filtering local data and extracting features, minimizing communication overhead and latency. This hierarchical structure facilitates the ability to implement it at scale wherein more sensors can be added without much effort as more monitoring needs are required. A cloud-based analytics is an important component of the IoT-based SHM system as it provides a visual representation on a real-time, long-term trend analysis, as well as automated detection of damage. State-of-the-art data analytics and machine learning algorithms can detect anomalies and minor alterations in structural behavior, which may reveal early stage damage. Moreover, timely decision making and predictive maintenance plans are supported by real-time alerts and dashboards. In general, wireless SHM systems implemented in the field of wireless Internet of Things offer the flexible, low-cost, and intelligent solution in terms of the modern infrastructure monitoring, safety, reliability, and sustainability in the civil engineering.

2. *LITERATURE SURVEY*

There is a lot of research conducted in the Structural Health Monitoring (SHM) area based on wired and wireless sensing technology. SHM has evolved over the years and is no longer limited to traditional sensor-based systems, but now includes networked systems that utilize wireless communication, Internet of Things (IoT) systems, and advanced analytics on the data they collect. This part is a review of important contributions, development technologies as well as the upcoming trends applicable to SHM systems.

2.1. Conventional SHM Techniques

The traditional SHM systems mostly used wired sensor networks of accelerometers, strain gauges, displacement transducers and piezoelectric sensors to measure structural responses. These systems were highly accurate in measurement, reliable in transmitting data and could offer real live data; hence they could be used in the critical infrastructure bridges, buildings, and dams. Nevertheless, the large cabling that was necessary to install the sensors during deployment increased the cost of deployment and maintenance. Also wired systems were not very scalable or flexible thus incapable of supporting large scale or retrofitted buildings. Physics destruction of cables and reconfiguration complicity also limited their sustainability.

2.2. Wireless Sensor Networks in SHM

With the introduction of Wireless Sensor Networks (WSNs), SHM changed significantly: it became possible to a cquire data in a decentralized manner, not to rely on physical wiring. SHM systems based on WSN include spatially distributed sensor nodes, which are able to sense, process, and transmit data over the air. Many studies have also shown that the WSNs have the potential of saving up to 60 percent of installation and maintenance expenses as compared to the wired systems. In spite of these benefits, there have been common challenges clearly known as limited battery life, wireless interference, loss of data packets, time synchronization, and bandwidth issues. These concerns may have an impact on the reliability of data and the long-term availability of the system, especially in long-term monitoring.

2.3. IoT Integration in SHM

Most recent studies have been on the combination of WSNs and Internet of Things (IoT) infrastructures to provide system intelligence and openness. SHM systems, which are IoT-enabled, also enable transmission of sensor data to cloud servers, to enable real-time visualization, storage and remote analysis. Lightweight communication protocols like MQTT, CoAP and HTTP are sometimes used because they are lightweight and can be adapted to low-power devices. The remote monitoring, automated alert, and predictive maintenance functionality can be achieved through IoT integration, making SHM systems more scalable and user-friendly. Nevertheless, the use of cloud infrastructure creates the issues of latency, network dependency, and cybersecurity.

2.4. Data Analytics and Machine Learning Approaches

Advanced data analytics and machine learning methods have been of particular importance with the growing amount of SHM data. Damage detection, classification and anomaly identification have used the algorithms of Support Vector Machines (SVM), Artificial Neural Networks (ANN), decision trees, and deep learning models. The techniques enhance the capacity to identify small structural shifts that could not be apparent under conventional threshold-based techniques. In particular, deep learning models have demonstrated the ability to process complex and high-dimensional data and automatically detect meaningful features. However, their issues are interpretability of models, complexity of computations, and the need of big labeled datasets.

2.5. Research Gaps

In spite of the significant progress in SHM technologies, there are still a number of gaps in the research. Sustainability of energy in the long run has remained one of the primary issues particularly to battery-powered wireless sensor nodes deployed in distant areas. They are still difficult to achieve reliable wireless communication in difficult environment scenarios and in high sensor densities. SHM systems need network architecture that is robust and data management strategies that are efficient to be deployed on a large scale. Moreover, closely connected to the advent of SHM systems based on IoT and cloud, the concerns of data security and privacy have become important, which has led to the creation of secure communication protocols and access control systems.

3. METHODOLOGY

3.1. System Architecture

The Structural Health Monitoring (SHM) system suggested is based on a layered architecture to guarantee modularity, scalability, and efficient processing of data. The architecture consists of four primary layers, which are Sensor Layer, Edge Processing Layer, Communication Layer and Cloud Analytics Layer. The layers carry out a given purpose in order to facilitate credible data obtaining, transportation, examination, and representation.

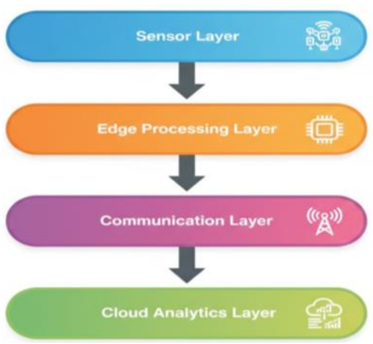

Fig 2 - System Architecture

3.1.1. Sensor Layer

The Sensor Layer is charged with the task of obtaining the raw structural response data on the structure that it is monitor. It is composed of sensors that include accelerators, strain gauges and displacement sensors that are placed in strategic points. These sensors constantly or periodically measure physical parameters that involve the structural behavior and transform them into electrical signals. The acquired data is the basis of the SHM system and in order to have proper monitoring it should be correct and valid.

3.1.2. Edge Processing Layer

EDPL Edge Processing Layer The sensor data is processed locally and transmitted to the higher layers. Microcontrollers or embedded systems are often found in this layer and undertake signal conditioning, noise filtration, data compression, and an initial stage with feature extractions. The system is appropriate in long-term and large-scale SHM applications by minimizing communication overheads, latency, and energy consumption by processing data at the edge.

3.1.3. Communication Layer

Communication Layer provides the effective data transmission of the edge devices to the cloud platform. It uses wireless communication technologies like Wi-Fi, Zigbee, LoRa or a cellular network, depending on the application requirements. Lightweight communications protocols are applied to guarantee an efficient and secure transmission of data like the MQTT, CoAP, or the HTTP protocols. This layer is very important in ensuring the integrity of data and reduce packet loss.

3.1.4. Cloud Analytics Layer

The Cloud Analytics Layer is the one that offers the centralized storage of data, analysis and the visualization. The sensor data sent to the field is stored in cloud servers, where data analytics and machine learning algorithms are implemented to detect the damage, identify anomalies, and analyze trends. Real-time dashboards, alerts, and remote access are also supported by this layer so that stakeholders can observe the structural conditions and make well-informed decisions regarding maintenance.

3.2. Sensor Layer Design

The sensor layer is also a very important element of the envisioned Structural Health Monitoring (SHM) system since it takes the physical parameters that indicate the condition and the behavior of the structure. The sensors that were selected are expected to offer full monitoring of the responses that are mechanical in nature in addition to the environmental factors.

3.2.1. Strain Sensors

Strain sensors are used to measure deformation on structural elements due to applied loads, stress or fatigue. The sensors are commonly mounted on beams, columns, or joints to monitor the shift in the strain distribution, which might be a sign of cracking, yielding, or degradation of the material. Proper strain measurements can be used to determine structural integrity and detect damage in its early stages.

3.2.2. Accelerometers

Accelerometers are used in the measurement of structural vibrations and dynamic responses of acceleration, frequency as well as mode shapes. They are necessary in the identification of the changes in dynamic features due to the damage or linkage loss of elasticity. Vibration-based SHM methods largely rely on acceleration data in order to detect anomalies and monitor the structural health in general.

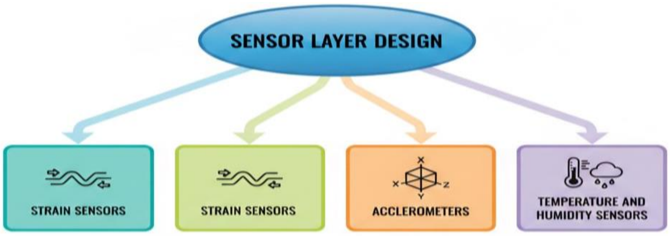

Fig 3 - Sensor Layer Design

3.2.3. Temperature and Humidity Sensors

Environmental sensors are temperature and humidity sensors which may affect the structural behavior and sensor readings. The tempering and creation of the moisture can create an expansion or shrinkage or corrosion of the materials which can make an impact on the structural performance. Observing these parameters can assist in the compensation of the environmental impacts and enhance the competence of the damage recognition algorithms.

3.3. Wireless Communication Protocols

Structural Health Monitoring (SHM) systems require wireless communication as a crucial element because it is used to ensure that there is a high level of data transmission between sensor nodes, and data processing units. Depending on the needs of the application, low-power communication technologies are chosen in order to balance energy consumption, communication distances, and data throughput.

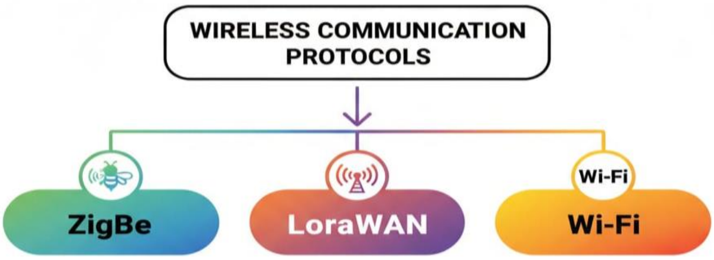

Fig 4 - Wireless Communication Protocols

3.3.1. ZigBee

ZigBee is a low power, low data rate wireless communication standard typically applied in short range sensor network systems. It also promotes mesh networking that increases the reliability and scalability of network because it enables the passage of data across several nodes. ZigBee has a low energy usage and heals itself and thus this makes it suitable in SHM systems that need dense arrays of nodes in which the nodes are spaced in a close relation.

3.3.2. LoRaWAN

LoRaWAN is a low power wide-area network (LPWAN) and long-range technology that relays limited size of data over long distances. It is especially applicable in SHM applications of large structures like bridges or remote infrastructure. LoRaWAN boasts of very high levels of energy consumption and battery life, but it features low data rates and is best suited to periodic sensor data communication and not high frequency measurements.

3.3.3. Wi-Fi

Wi-Fi is supported with high data rates and low latency is presented which makes it appropriate to be made use of in applications entailing real time or high amount of data flow. Wi-Fi finds application in SHM systems within environments that are not constrained by power sources like the buildings that already have network infrastructure in place. It has a disadvantage, however, in that it consumes more power than ZigBee and LoRaWAN, which restricts its application in battery-powered, long-term monitoring projects.

3.4. Data Processing and Feature Extraction

Structural Health Monitoring (SHM) systems Raw sensor data is sometimes noisy and redundant, and requires processing before intelligent analysis can be done. The feature extraction and data processing system convert the raw measurements into representative features representing the dynamic nature of the structure and facilitate the detection of the damage effectively.

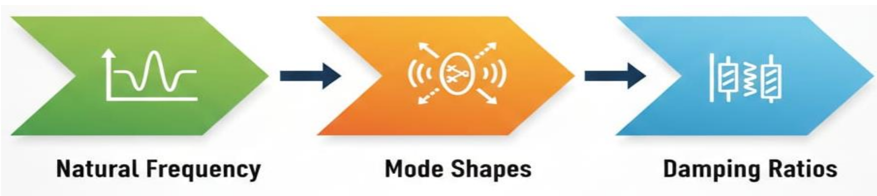

Fig 5 - Data Processing and Feature Extraction

3.4.1. Natural Frequency

Natural frequency is the natural vibration properties of a structure and an important information about the stiffness and mass distribution of the structure. Variations in natural frequencies can be evidence of structural damage in the form of cracks or wear and tear of materials, which modify stiffness. Common methods of frequency-domain analysis, such as Fast fourier Transform (FFT) are employed to identify natural frequencies in vibration data.

3.4.2. Mode Shapes

Mode shapes indicate deformation-patterns of a construction at given natural frequencies. They give spatial data regarding structural behavior and can be used in localization of damage. Comparison between measured mode shapes and either a baseline or reference model can be used to detect variations in structural response which can be used to establish where and how extensive a damage is.

3.4.3. Damping Ratios

Damping ratios are used to measure the dissipation strength of a structure under vibration. Damping characteristics may change with structural damage, joint laxity or material degradation. Estimation of damping ratios as sensor data is done using time-domain and frequency-domain approaches, which are useful properties in estimating the structural condition and diagnosing anomalies.

3.5. Damage Detection Model

Relies on the calculation of a Damage Index (DI), the damage detecting model presupposes the measurement of structural degradation as a quantitative measure using the comparison of the structural response in healthy and damaged states. Under this scheme, the Damage Index is the absolute difference between the measurement of a damaged state and the measurement of a healthy state, that is normalized by the healthy state. Simply put, this model assesses the extent to which a chosen feature of structure has been transformed compared to the state in which it existed before being damaged. The damaged-state measurement The damaged-state measurement is the value of one of the structural parameters (e.g., natural frequency, mode shape amplitude, and damping ratio) that is measured once the structure has possibly been damaged. The healthy-state measurement is the parameter that is measured to provide the baseline of the same parameter measured in a known healthy and intact state of the structure. The Model allows appraising the Damage Index as a normal ratio so that the changes are not determined as absolute changes but on a relatively defined scale. This normalization enables the method to be useful throughout the sensors, structural components and feature magnitudes. A value of Damage Index near zero means that there is minimal departure of the healthy state which implies that the structure has not deteriorated. Conversely, the greater values of Damage Index mean that there are severe deviations, that can be linked to the softening of the stiffness, the start of the crack, the debilitation of the material, or the weakness of connections. The easiness of the Damage Index formulation makes it computationally demanding and applicable to real-time or near real-time application in wireless and IoT based SHM systems. It is capable of being applied to several parameters derived out of sensor data allowing simultaneous quality of the damage to be evaluated in multiple aspects. Moreover, historical information or statistics may also be used to define threshold value so that structural conditions may be classified as healthy, damaged or critical automatically. In general, the suggested damage detection model provides a powerful, scalable, and interpretable framework of detecting structural damage and assisting with timely maintenance decisions.

4. RESULTS AND DISCUSSION

4.1. Performance Metrics

The effectiveness, responsiveness, and capacity of the proposed Structural Health Monitoring (SHM) system are measured with the help of the key metrics. One of the main metrics is the detection accuracy which is the ability of the system to distinguish correctly the presence or absence of structural damage. The significant detection accuracy means that the damage detection model is capable of consistently identifying the condition of healthy and damaged conditions with reference to the extracted features including natural frequency, mode shapes, and damping ratios. Effective detection reduces the occurrence of false alarm and missed detection and that is necessary in ascertaining safety of the structural integrity of the building and assurance of users to the monitoring system. This measure is normally evaluated in comparison of the expectations of the system with known structural conditions acquired in either simulation or controlled experiments. Another valuable performance measure that can be used is latency, which is the time lag between the acquisition of data and the production of the damage detection results. Low latency is of particular concern in SHM applications in that real-time monitoring and early warning systems, where identifying the presence of structural anomalies early enough can save disastrous failures. Latency encompasses delays in sensor data collection, edge processing, wireless communication as well as cloud-based analytics. An effective system design with optimized data processing and communication protocols will reduce latency and is a guarantee of timely delivery of alerts and monitoring updates. Energy use is a very important parameter, particularly in wireless and IoT based SHM, systems that operate along battery powered sensor nodes. Reduced energy use leads directly to increased functional life, and less need to maintain. Usage of energy depends on the sensing frequency, complexity of the data processing, communication protocols and the intervals of transmission. The proposed system should offer a balance between performance and sustainability by including low-power sensors, efficient edge processing and energy-conscious communication strategies. The measurement of energy usage is used to establish the feasibility of the system when used in the long term and large scale structural monitoring purposes.

4.2. Comparative Analysis

The comparative study draws the attention to the performance variations that exist between Conventional Structural Health Monitoring (SHM) systems and IoT-based SHM systems on essential parameters. The values are percentages that stand as relative effectiveness or efficiency of each approach.

Table 1: Comparative Analysis

Parameter	Conventional SHM (%)	IoT-Based SHM (%)
Installation Cost	85%	35%
Real-Time Monitoring	30%	95%
Scalability	40%	90%
Maintenance Efficiency	45%	85%

4.2.1. Installation Cost

The standard SHM systems have a high cost of installation; as the installations are 85 percent, mainly because of a lot of wiring, equipment-intensive systems, and labor-intensive implementation processes. By contrast, disaglo-based SHM systems indicate a low installation cost (35 less) and the wireless sensors and modular architectures make them less costly and simple to deploy in large-scale applications (e.g.).

4.2.2. Real-Time Monitoring

In traditional SHM systems, real-time monitoring is not possible, and its performance measure is 30% because data collection and response may be conducted offline or at a certain period. The IoT-based SHM systems are at the 95 per cent performance through real-time processing, constant data streaming, and instant notifications through cloud-based systems, which is essential in identifying damages early and acting promptly.

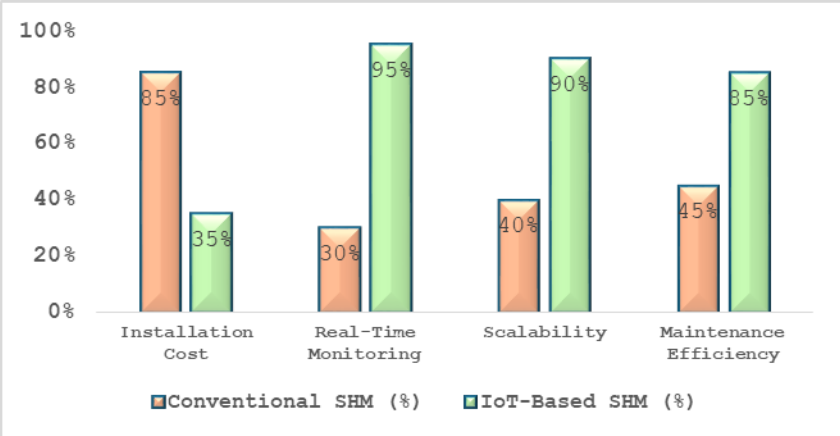

Fig 6 - Comparative Analysis

4.2.3. Scalability

Conventional SHM is relatively not that scalable (the system can only scale by 40%), because to increase the system size, new wiring and hardware changes and additional maintenance efforts are usually needed. IoT SHM systems are highly scaled with 90% scalability as adding more sensor nodes into the network is readily implemented without extreme infrastructure modifications, and this provides both flexibility and large-scale implementations.

4.2.4. Maintenance Efficiency

The efficiency of maintenance in the traditional SHM systems has been measured at 45 percent since the traditional systems are usually relying on manual check-ups and periodical checks, which add more time and cost of operations to the system. The IoT systems used to implement SHM systems demonstrate a 85 percent efficiency by facilitating predictive maintenance via continuous monitoring and insights derived by data analysis and allowing interventions to take place in a timely manner and cut maintenance efforts and costs.

4.3. Discussion

The conclusions of the essemination analysis show clearly that the IoT-based Structural Health Monitoring (SHM) system has better performance regarding a number of key factors, specifically the real-time monitoring and scalability. The proposed system will be able to maintain near real-time monitoring of structural conditions because it utilizes wireless sensor networks and IoT services to make a continuous acquisition of data and subsequently transmit it to the control centre. The ability plays a crucial role in detecting the sudden shifts in structural conduct and providing the timely warning to minimize the possibility of unforeseen breakdowns. The IoT-based methodology provides sustainability of continuous observation and prompt reaction in contrast to the traditional system that involves an uncontrolled frequency of the data sample and its manual analysis. Another important benefit of the SHM system, based on the IoT, is scalability. Accommodate more sensor nodes and also the node of sensor can be easily added without significant change in the current infrastructure. This is because the system is flexible to large and intricate structures like bridges, high-rise buildings and factories. The system can subsequently be extended as the monitoring needs become more complex and provide a monitoring location where new sensors can be integrated to support long term infrastructure management. Introduction of cloud analytics also improves the performance of the systems through the provision of data storage storage as well as offering powerful analytical ability centrally. Cloud based platforms facilitate the long run trend analysis through the storage of historical sensor data, which would be important in studying a long term gradual structural degradation as a result of age, fatigue or environmental influence. High-technology data analytics and machine learning algorithms have the potential to detect small patterns and anomalies otherwise unnoticed with short-term observations. Such trends can be detected early and, therefore, preventive maintenance planning will lower the costs on repairs and increase the life of structural services. In general, the SHM system relying on IoT can be considered more intelligent, flexible, and efficient as opposed to traditional approaches. Its scalable deployment, decision-making based on data, and real-time monitoring are all suitable in the current infrastructure management and smart cities.

5. CONCLUSION

The paper was a full research on Structural Health Monitoring (SHM) via wireless IoT sensors and the limitations of the traditional monitoring systems, as well as the benefits of the new solutions based on the use of the IoT. The combination of wireless sensor networks and IoT platforms has a great positive impact on the efficiency of monitoring as it provides the opportunity to collect and send data continuously, communicate in real-time, and be attacked remotely. The system being proposed instead of the traditional SHM systems wired has lower costs of installation and operation due to reducing the number of cabling used, simplifying installation, and reducing the amount of effort required to maintain the system. When used in conjunction with the edge processing and cloud analytics, the layered system architecture enables it to process large amounts of structural data efficiently and enables the architecture to manage a wide range of infrastructure types, as well as allowing it to scale. Real-time data analytics is very important in enhancing decision making as it gives an up to date insight on the structural behavior and the possibility of damages. The effectiveness of the proposed system in ensuring that efficient and reliable monitoring is done is indicated by the use of performance metrics including detection accuracy, latency, and energy consumption. Moreover, predictive maintenance strategies can be applied since this approach allows uncovering structural degradation at a very early stage, which will result in fewer unexpected failures and an increase in the life of the key infrastructure. Altogether, the SHM framework, implemented based on the IoT, is the strong, smart, and economical tool that meets the increased need to develop smart infrastructure and robust structural systems. The capabilities of the SHM systems can also be improved in the future by developing sophisticated technology in this field. Promisingly, the future of forecasting the extent of the damage lies in the integration of the artificial intelligence-driven damage prediction models that would make use of deep learning and data-based models to enhance the detection precision and automation of the decision-making process. The second significant field is that of the implementation of blockchain-powered data protection processes to guarantee the integrity of data, transparency, and secure access of data in SHM cloud environments. Also, SHM systems, built around digital twins, have a high potential prospective as they can provide artificial reproductions of the real structure, allowing the real-time simulation, the evaluation of the condition, and the prediction of the performance. These will lead to more independent and secure, and intelligent SHM systems and will open the way to the next-generation infrastructure monitoring and management solutions.

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