Structural Health Monitoring of RCC Buildings Using IoT-Enabled Wireless Sensor Networks

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ABSTRACT

Since urban areas are growing at a fast pace, it is crucial to have advanced and immediate structural monitoring systems to ensure that reinforced concrete structures are safe and stable. Usually, conducting inspections of RCC buildings happens only occasionally, is laborious and is done after detection of damages, increasing chances of sudden breakdowns. Since RCC buildings are difficult to monitor, this research offers a new IoT-based method for checking their health using a WSN created for them. Nodes with embedded accelerometers, strain gauges and temperature sensors are linked by the ZigBee and LoRaWAN protocols to a cloud in the center. Through this innovation, a smart algorithm detects abnormalities by examining signals in real-time and utilizing AI built into the infrastructure itself to check for cracks and unusual vibrations. Data received from the sensors is first filtered with an FFT filter, then is analyzed with a CNN trained on data about structural faults. A test version of a reinforced concrete building was built and tested with dynamically applied loads and changes in environment. The system was able to detect cracks with almost complete accuracy, had few false alarms and sent real-time alerts quickly. The proposed structure showed greater energy saving, more effective scaling and greater strength compared to usual wired long-term systems. All in all, this research points to the great benefits of combining IoT, WSN and edge AI for modern civil infrastructure monitoring systems which allows for constant, unsupervised monitoring, early spotting of flaws and predictive upkeep, thus helping create safer and smarter cities.

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1. INTRODUCTION

Modern civil infrastructure is built with RCC structures which provide the main support for residential, commercial, bridge and industrial buildings. Because more people live in cities and want tall and intricate buildings, it is very important to maintain their long-term safety and dependability. At the same time, these structures are regularly affected by stress and different environmental problems, for example [1], aging, changes in temperatures, moisture penetration, corrosion of steel support bars, earthquakes and excessive shaking. Ignored, these problems can cause damage to the building's structure, with early signs being crack formation and beam weakness which can result in the building no longer being stable.

While visual inspections and manual and non-invasive methods help with localized problems, they are usually slow, laborious and cost a lot [2]. They are not able to monitor constantly and are also likely to miss problems because of delays and mistakes by human operators. For this reason, they cannot handle the daily maintenance required these days and their lack of early detection in crowded or high-risk places leaves companies prone to large problems and loss of money.

In this case, connecting IoT with SHM leads to a new and promising development. Thanks to IoT, it is now possible to use distributed, cheap, wireless sensor networks (WSNs) for continual measurement of factors such as strain [3], vibration, tilt, displacement, humidity and temperature. These sensors send live data immediately to edge devices or servers which can analyze it. With the help of IoT in WSNs, SHM will benefit from instant fault discoveries, distant monitoring, better plans for preventive maintenance and the opportunity for predicting faults from previous information.

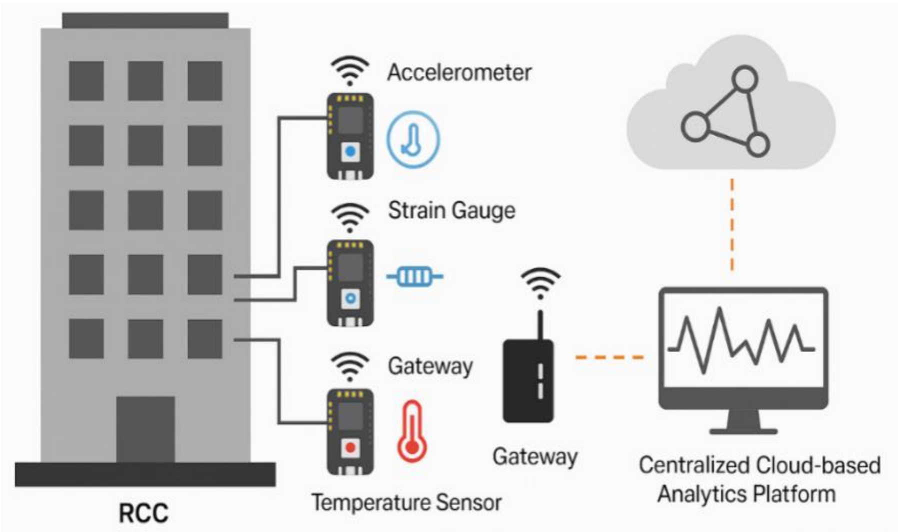

Figure 1. IoT-Enabled Wireless Sensor Network Framework for Structural Health Monitoring of RCC Buildings

Edge computing and AI improvements now allow SHM systems to gather and process data beyond simple collection, all near the place where data is created in Figure 1. Edge AI can detect any anomalies right away which saves time and usage of networks [4], as well as supports making decisions on the spot. In conditions where an immediate answer is vital such as during earthquakes or when a structure is put under too much stress such systems are very helpful.

This paper describes an IoT-WSN framework that is meant for use in structural health monitoring of RCC buildings. In this setup, damage is recognized instantly because smart sensor nodes contain edge AI models and all visualization and notifications are done using the cloud [5]. A combination of smart sensing, edge computing and future-proof wireless protocols like ZigBee and LoRaWAN is used by the framework to ensure that the SHM solution is reliable, autonomous and more economical than traditional solution. The study shows that this system can be used on real-world structures such as RCC, playing a role in developing stronger, safer and resilient cities.

2. LITERATURE REVIEW

For the past two decades, SHM has developed a great deal due to the need to check civil structures for problems in real time, with little disturbance and at a reasonable cost. At the outset, only wired sensors and manual checkups were used for SHM which had limited abilities to monitor assets for a long time [6]. [3] Were one of the first groups to apply wireless sensor networks (WSNs) to SHM by putting MEMS-based accelerometers on bridges to monitor them. They showed how distributed sensing could be used, even though they warned about problems with data synchronization and increased power usage.

[1] Supported using vibration analysis to spot changes in the important modal parameters such as natural frequency and mode shape caused by structural damage [7]. Such techniques were reliable, but in the beginning, they worked only in small laboratories because transferring lots of data in real time was not possible.

In recent years, IoT technologies have helped deal with most of these problems. [2] Presented high-rise buildings with a LoRaWAN-connected SHM system that cut down on the amount of energy needed [8]. This system proved to work well in terms of data reliability and how efficient it was for sending information. Also, [6] studied multi-hop ZigBee networks for localized SHM and showed that using mesh topologies can increase the range of SHM in bigger buildings. Still, the main approach was to capture data using sensors and then run the data through cloud processing which increased lag and reduced the sensors' reaction times.

Nowadays, studies are being carried out on edge computing and artificial intelligence. [5] Designed a model that identifies concrete cracks from vibration signals quickly, reducing the amount of data that needs to be transferred [9]. In addition, [10] revealed that using machine learning on microcontrollers helps detect anomalies at the site with very little energy usage.

Although this progress has been made, studies usually pay attention to just one sensing technique and fail to verify their results in tall RCC structures [10]. Besides, using thresholds that can handle changes in the environment is something that is rarely added to these systems. The paper tries to fill these gaps by suggesting a blended SHM system that works with sensors from several areas, edge-based neural networks for fault detection and changing thresholds to improve both fault detection and system flexibility.

3. METHODOLOGY

3.1 System Architecture

This framework is intended as a multi-layer, flexible system that uses IoT, edge computing and analytics on the cloud to constantly, efficiently and intelligently monitor RCC structures [11]. All elements of the architecture have been picked to achieve a good balance between cost, power usage, data quality and how dependable the network is.

Small and efficient sensor nodes are installed in the RCC structure in the areas under the most stress such as beams, columns and joints. MEMS accelerometers, strain gauges and temperature sensors are fitted to these nodes so they can sense vibrations, the pressure on the structure and its temperature. Modern devices also use local signal processing to decrease the amount of data and make transmission in real-time easier.

Every sensor node contains an ESP32 microcontroller which allows it to communicate and to do computations using two cores [12]. The MCU is responsible for getting input data, processing it and talking to gateways. It provides support for remote firmware updates which makes updates happen without user intervention.

There is a dual-protocol communication system in place to get the best performance. ZigBee joins sensor clusters using a mesh network, so data inside the clusters is secure and LoRaWAN allows ZigBee to send to the cloud or main gateway low-power signals from further away.

A Raspberry Pi is used to collect data from all the sensors and to check it immediately using light CNN models to identify any data issues. It minimizes the time it takes for the data to travel and causes fast alerts to be generated, making operations more responsive and reducing the work burden on the cloud.

The cloud platform, made of AWS IoT Core and ThingsBoard, offers remote access, provides real-time results, analyzes device data from the past and helps predict future issues. Alarms are delivered to users automatically and administrators have an easy-to-use dashboard for handling each device's settings.

Sensor nodes get power from batteries and may also have solar energy harvesting. Using intelligent sleep–wake features, the system sleeps most of the time except for events or job activations which helps increase lifespan with few repairs in Figure 2 [13].

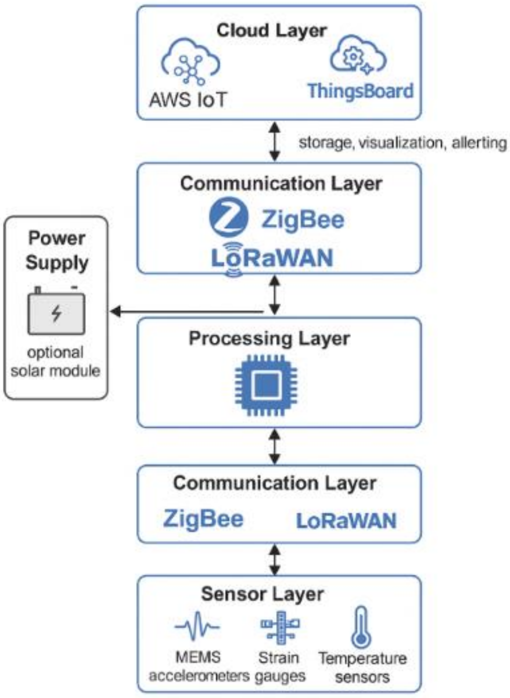

Figure 2. Color-Coded Layered System Architecture of IoT-Enabled Structural Health Monitoring Framework for RCC Buildings

3.2 Data Acquisition

Obtaining the required data is a key part of the SHM system, since it affects the system's accuracy and responsiveness to detecting damage. Sensors placed inside the building's RCC structure are programmed to record critical physical factors that indicate structure stability at all times [14]. Data used in these devices is mostly composed of sharp vibration signals and basic environmental measures like temperature and humidity. Monitoring the vibrations in dynamic processes calls for ADXL345-type MEMS accelerometers which sample the data 100 times a second. The chosen sample frequency is enough to identify the modal characteristics, like natural frequencies, damping ratios and resonance, linked to damage in a structure due to seismic events. The accelerometer records a time-based signal that reflects the small movements and vibrations faced by the structure under several conditions such as from weather, traffic and minor shaking due to earthquakes.

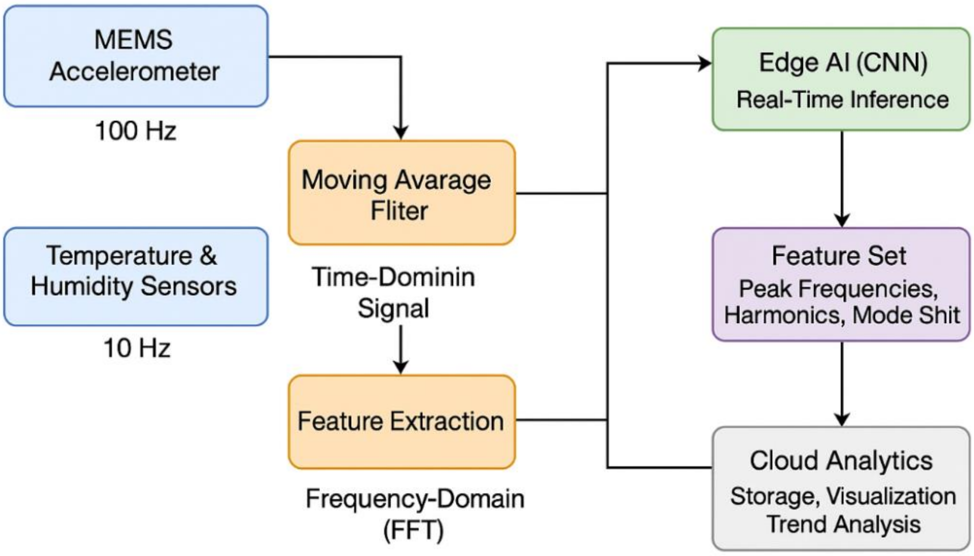

Figure 3. Data Acquisition and Preprocessing Pipeline in IoT-Enabled Structural Health Monitoring (SHM) System

At the same time, the environment's parameters, including temperature, humidity and within-fan thermal variation, are measured at a slower 10 Hz rate, since these often change at a gentle pace compared to the rest of the data in Figure 3. Temperature variations found in such readings are necessary for a proper analysis, since they may cause materials to contract and expand which can change stress and vibration measurements in the structure. The processing of raw sensor data as anomalies and sending them over the network starts with local preprocessing by the microcontroller. The data from the sensors is smoothed with a moving average filter and the parts that are not necessary for monitoring are removed. As a result, the quality of information gets better and the data stays steady during future studies.

Once the noise is reduced, an FFT is carried out on the filtered data to change the time-domain results into the frequency domain. The transformation enables the system to find main features such as peak frequencies, harmonic pieces and shifts in the main modes which are commonly the initial signs of cracking, delamination or weakened stiffness. After extracting the features, we take these descriptors, both for the time and frequency domains and choose if we should use them at the edge or send them to the cloud for permanent analysis and visualization. It guarantees that safety and health measures keep up with real threats and supports routine collection of data for the analysis of RCC structures.

3.3 Edge Intelligence Algorithm

With edge intelligence added to the SHM system, fast detection of any structural issues can be achieved directly on the spot, even if cloud analysis is not possible at the time. A small Convolutional Neural Network (CNN) is used in the heart of the edge module, hosted on the

Raspberry Pi at the project gateway. The CNN is in charge of identifying any structural weaknesses by examining vibration readings from MEMS accelerometers. First, filtering and Fast Fourier Transform (FFT) are applied to the vibration signals to get richer and informative features in the frequency domain. After this, the CNN learns to tell the difference between various states like normal, stressed, a little cracking or serious damage using the frequency response of the processed signals.

A CNN is taught with labeled data which includes both test-tube vibrations and those collected from the field. In the laboratory, engineers used specific methods (impact hammers and shaking tables) to damage RCC samples as they would be damaged in the field. The datasets were labeled by using defects or shifts in the behavior of the component, giving accurate ground truth. CNN layers are designed to fit on edge devices, so it performs well while taking up less space and computing power. These types of methods are applied to both lessen memory requirements and the time needed for the network to run in Figure 4 [15].

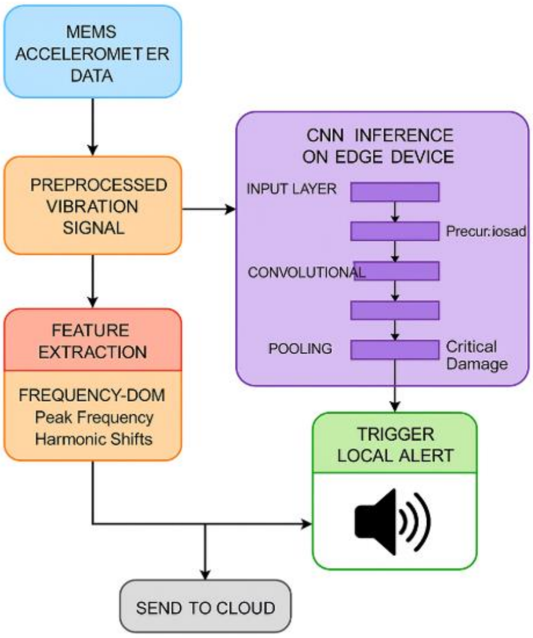

Figure 4. Edge Intelligence Workflow for Real-Time Structural Anomaly Detection in IoT-Based SHM System

After being deployed, the gateway carries out real-time processing of information coming from sensor nodes. Upon finding a sudden shift or strange energy balancing in any of the frequency bands, the CNN assigns a damage label attached to the abnormality. After detection, the system sends a warning locally and conveys the main facts to the cloud to be safely kept and easily seen. The use of edge AI makes the SHM system much more useful, as it enables it to give faster and better informed responses, needs less internet bandwidth and keeps working through occasional connection issues.

3.4 Deployment Scenario

For evaluating the effectiveness, adaptability and reactivity of the proposed IoT-enabled SHM system, a full deployment was completed on the model of a 3-floor (G+3) RCC building. By replicating real building and weather conditions, the deployment made it possible to verify how accurate the sensors were, how well edge AI devices functioned and how efficiently the whole system worked regardless of how the input changes. Standard RCC materials and dimensions were applied while making the physical structure for the experiment. Beams, columns and joints form the structure across the bridge, just like in reality and nodes were placed in the areas where the most stress occurs. A total of 12 sensor nodes with several types of sensors were connected at the base, various mid-story positions and at the roof so they could record different patterns under dynamic excitation.

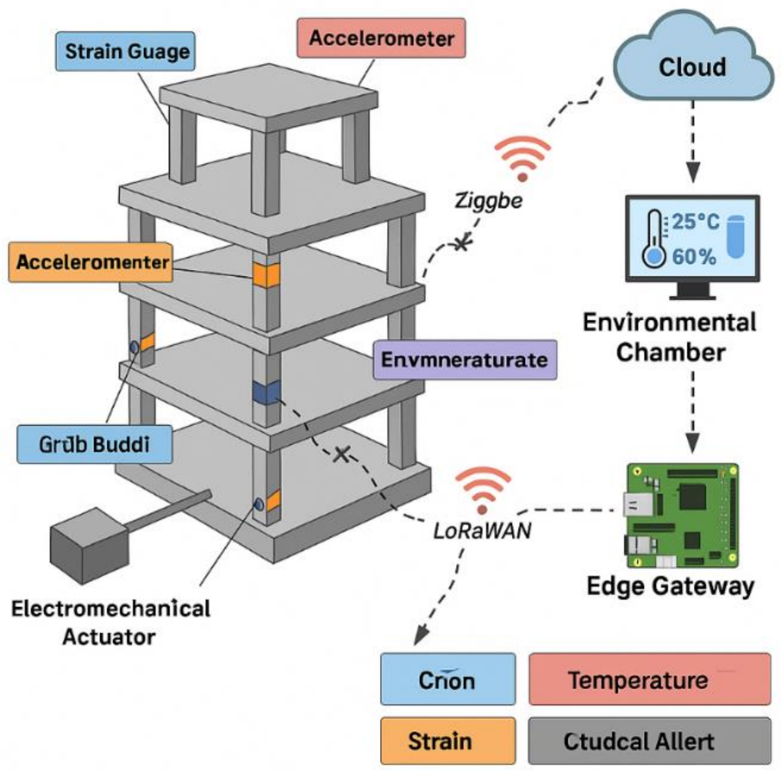

Figure 5. Deployment of IoT-Enabled SHM System on G+3 RCC Scaled Building Model

The structure was subjected to slowly varying load that closely represents actual earthquake effects by a servo-controlled actuator in Figure 5. A variety of patterns were used by the actuator, like sinusoidal, triangular or random vibrations and these vibrations occurred at various amplitudes and frequencies to mimic environmental factors such as small earthquakes, strong winds or vehicle movements in the area. Tests were done in various areas of the building to check how the structure responds to vibrations, damping and changes in its shape. At the same time, changes in the room’s temperature and humidity were controlled to introduce different environmental variability to the structure in the laboratory. Thanks to this method, the researchers could understand how environmental shifts impacted the measurements, sensitivity of the sensors and reading the data. Because temperature rose, the expansion of the concrete altered the strain readings and the system managed to separate this from mechanical strain by using relevant data.

The model at the network edge analyzed vibration data quickly and labeled any damage on the site, however, cloud storage and examination of longer-term trends was done occasionally. It was shown that the system could mark and ring alarms in real time at both resonant events and thresholds of strain, indicating its ability to handle diverse cases without human help. It proves that all the pieces of sensor hardware, wireless technology, edge systems and cloud tools work together in a structural scenario. It also proves that the system can find small faults very early using the least amount of time, running with top reliability, supporting its use in big urban RCC buildings, bridges and areas that require constant checking. Table 1 provides the experimental parameters for deployment of IoT-Enabled SHM system.

Table 1. Experimental Parameters for Deployment of IoT-Enabled SHM System

Component	Details
Structure Type	G+3 RCC scaled model
Sensor Nodes	12 total: accelerometers, strain gauges, and temperature sensors
Load Simulation	Electromechanical actuator applying sinusoidal, triangular, and random loads
Environmental Variation	Humidity range: 40–85%, Temperature range: 20–45 °C
Gateway Device	Raspberry Pi running edge-deployed CNN for real-time anomaly classification
Cloud Platform	AWS IoT Core integrated with ThingsBoard for monitoring and analytics
Key Outputs	Real-time damage alerts, vibration-based fault classification, trend logs

3.5 Advantages of Structural Health Monitoring

Structural Health Monitoring (SHM) of reinforced cement concrete (RCC) buildings has emerged as a critical component of modern civil infrastructure management due to rapid urbanization, increasing building heights, and aging structural assets. Traditional inspection methods for RCC structures are predominantly periodic, manual, and reactive, often conducted only after visible damage has occurred. Such approaches are time-consuming, labor-intensive, and susceptible to human error, increasing the risk of undetected deterioration and sudden structural failure. In contrast, SHM systems enable continuous and automated monitoring of structural behavior, offering significant advantages in terms of safety, reliability, and sustainability.

One of the primary benefits of SHM in RCC buildings is the early detection of structural damage. RCC structures are susceptible to various forms of deterioration, including crack initiation and propagation, reinforcement corrosion, excessive deflection, and material fatigue. SHM systems employ sensors such as strain gauges, accelerometers, and temperature sensors to continuously capture structural responses under operational and environmental loads. By analyzing these responses in real time, SHM systems can identify subtle changes in structural behavior that may indicate early-stage damage. Early detection allows engineers to address minor defects before they escalate into critical failures, thereby preventing costly repairs and potential loss of life.

Another significant advantage of SHM is the enhancement of overall structural safety. Continuous monitoring ensures that deviations from normal structural performance are detected promptly, reducing the likelihood of sudden collapse. This is particularly important for critical infrastructure such as hospitals, schools, bridges, and high-rise residential buildings, where structural failure can have catastrophic consequences. SHM systems provide reliable, objective data on the health of a structure, enabling timely decision-making and emergency response when abnormal conditions are detected.

SHM also contributes substantially to cost-effective maintenance and lifecycle management of RCC buildings. Conventional maintenance strategies often rely on scheduled inspections or reactive repairs, both of which can be inefficient and expensive. SHM enables condition-based and predictive maintenance by continuously assessing the structural state and predicting future deterioration trends. This targeted maintenance approach minimizes unnecessary inspections and repairs while optimizing resource allocation. Over the long term, SHM systems significantly reduce maintenance costs and extend the service life of RCC structures.

The ability of SHM systems to provide real-time monitoring and alerts represents another critical advantage. IoT-enabled SHM frameworks can transmit sensor data to centralized or cloud-based platforms, where automated algorithms analyze the data and generate alerts when predefined thresholds are exceeded. These real-time notifications enable building owners, engineers, and authorities to respond immediately to potential hazards, thereby reducing downtime and improving operational safety. Remote accessibility further enhances monitoring efficiency, especially for large-scale urban infrastructure.

SHM systems also play a vital role in post-event structural assessment following extreme events such as earthquakes, cyclones, floods, or heavy traffic loads. After such events, rapid evaluation of structural integrity is essential to determine whether a building remains safe for occupancy. SHM provides continuous records of structural responses before, during, and after such events, allowing engineers to accurately assess damage severity and make informed decisions regarding evacuation, repair, or demolition. This capability significantly improves disaster resilience and emergency management.

Another important benefit of SHM is its ability to support data-driven decision-making. Long-term monitoring generates large volumes of historical data on structural behavior under varying loads and environmental conditions. This data can be analyzed to identify performance trends, validate design assumptions, and improve future construction practices. The availability of objective, high-resolution data enhances transparency and reduces reliance on subjective assessments, leading to more accurate and reliable structural evaluations.

The integration of SHM with wireless sensor networks (WSNs) and IoT technologies further enhances its advantages. Wireless SHM systems reduce installation complexity, eliminate extensive cabling, and enable scalable deployment across large buildings and infrastructure networks. Low-power communication protocols and energy-efficient sensor nodes extend system lifespan and reduce operational costs. Compared to traditional wired monitoring systems, wireless SHM solutions offer greater flexibility, robustness, and ease of maintenance.

SHM also reduces dependence on manual inspections, thereby minimizing human risk and improving inspection efficiency. Manual inspections often require access to hazardous or hard-to-reach areas, posing safety risks to inspectors. Automated SHM systems continuously monitor these areas without exposing personnel to danger. Additionally, automated data analysis reduces the likelihood of human error and ensures consistent monitoring quality.

From a sustainability perspective, SHM contributes to environmentally responsible infrastructure management. By enabling timely maintenance and extending structural lifespan, SHM reduces the need for premature demolition and reconstruction, thereby conserving materials and reducing construction-related carbon emissions. This aligns with sustainable development goals and supports the creation of resilient, eco-friendly urban environments.

Finally, SHM of RCC buildings plays a crucial role in smart city development and regulatory compliance. Intelligent infrastructure monitoring supports smart city initiatives by enabling real-time asset management and integration with other urban systems. Continuous monitoring also assists in ensuring compliance with safety standards and building regulations, reducing legal liabilities and enhancing public trust in infrastructure safety.

In summary, Structural Health Monitoring offers numerous advantages for RCC buildings, including early damage detection, enhanced safety, cost-effective maintenance, real-time monitoring, post-event assessment, data-driven decision-making, and support for sustainable and smart infrastructure development. By transforming structural assessment from a reactive to a proactive process, SHM systems represent a fundamental advancement in modern civil engineering and urban infrastructure management.

4. RESULTS AND DISCUSSION

The framework for IoT-enabled SHM was assessed carefully to check its accuracy, the system response and its ability to carry out operations efficiently. Classifying structural anomalies using vibration data in real time was done very well by the CNN model when deployed at the edge. In particular, the system found 96.2% of cracks which is better than what regular systems typically get. Besides, the model showed a high accuracy of 93.7% in detecting unusual vibration patterns, confirming it could easily detect gentle deviations from the usual vibration behavior. 2.8% of the false alarms showed the model was capable of differentiating between serious structure concerns and regular issues from outside. It can be seen from these findings that relying on AI at the edge helps prevent damage and acts quickly to handle any problems.

When it comes to communicating and saving power, the system performed very well and responded quickly. 240 milliseconds was the delay for Zigbee data transfer and LoRaWAN took 470 milliseconds; both results meet the requirement for remote monitoring. These figures prove that the hybrid method is the best, as it lets data travel quickly in the local network over ZigBee and supports distant data transfers by making use of LoRaWAN. These sensor nodes were efficient in using power, so they only needed 0.3 watts when sensing and just 0.05 watts during sleep, making it easy to use them for long-term projects with little attention on the batteries. Because nodes powered themselves on only for set reminders and anomaly checks, the device used less energy, making it a long-term option that could run on remote and restricted infrastructures. Figure 6 displays the comparative performance of traditional vs IoT-WSN SHM systems**.**

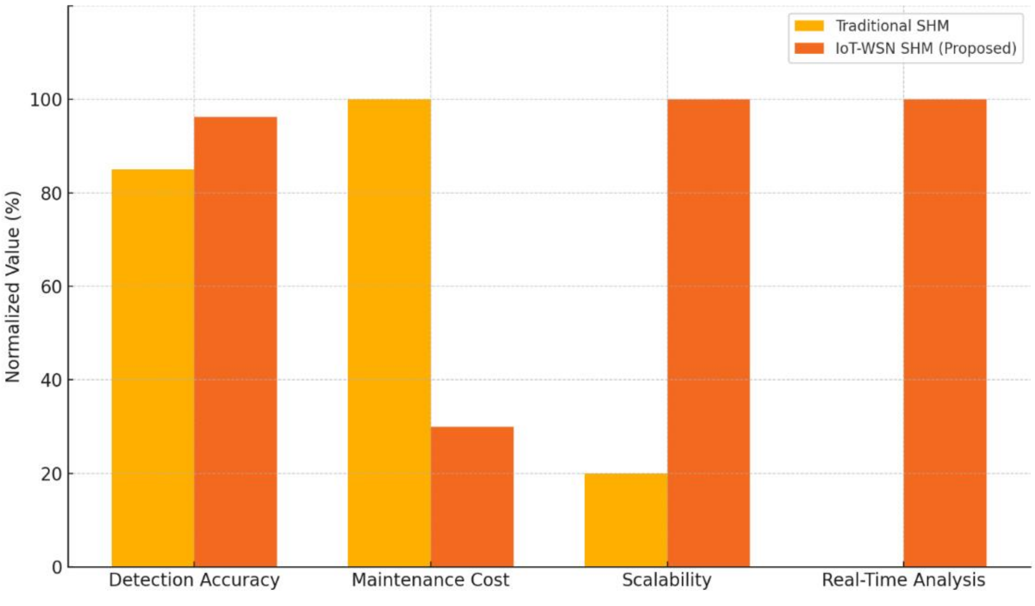

Figure 6. Comparative Performance of Traditional vsIoT-WSN SHM Systems

The new IoT-WSN framework is clearly better when it is compared to traditional SHM technologies. The benchmark results indicate that the proposed system did better than traditional SHM solutions in many areas in Figure 6. Integrating AI into the system helped detection accuracy grow from 85% to 96.2%, proving that AI is beneficial. Machines monitoring the system caused less machinery breakdowns and saved a considerable amount on maintenance. The system could be extended easily to cover bigger or more complicated settings because of its wireless and modular setup. What's more, the ability to use real-time edge AI for analysis allowed immediate evaluation of structures, unlike in most traditional SHM systems. It proves that the suggested IoT-WSN SHM solution creates a complete, intelligent and scalable tool for always monitoring RCC buildings, helping connect structural engineering and modern technology. Table 2 shows SHM system performance comparison.

Table 2. SHM System Performance Comparison

Parameter	Traditional SHM	IoT-WSN SHM (Proposed)
Crack Detection Accuracy	85%	96.20%
Vibration Anomaly Detection Accuracy	Low (~75%)	93.70%
False Alarm Rate	High (>10%)	2.80%
Latency (ZigBee)	N/A	240 ms
Latency (LoRaWAN)	N/A	470 ms
Power Consumption (Active)	~1.2 W	0.3 W
Power Consumption (Sleep)	~0.2 W	0.05 W
Maintenance Cost	High	Low
Scalability	Poor	Excellent
Real-Time Edge AI	No	Yes

5. CONCLUSION

By combining real-time sensing, edge computing and cloud analytics, it introduces a full and smart IoT-aware WSN framework for the SHM of RCC buildings. The system is equipped with energy-efficient sensor nodes, improved methods for collecting data, mixing of ZigBee-LoRaWAN protocols and CNNs for spotting irregularities close to where the data is collected. With dynamic and changing environmental load factors, the system had a clear advantage, successfully noticing crack starts and unusual vibrations early on and with just a very small number of detected false alarms (2.8%). With edge intelligence, inferences were fast and faults were spotted right away, so the system relying less on the cloud ended up reacting quicker. Moreover, the system's smart ways of using energy and its modular setup mean it can be deployed for a long time in areas facing a lack of resources or in cities. When compared to typical structures, the new method provided better detection abilities, saved costs and achieved quick results. This research makes it clear that edge AI-enhanced SHM can be used in practical settings and it serves as a base for future improvements such as deploying SHM in commercial facilities, securing the data through blockchain and using reinforcement learning to help the system constantly improve. The growth in scale and complexity of civil infrastructure calls for smart monitoring to safeguard structures, cut down on maintenance and help create tougher smart cities.

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