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DESIGN AND ARCHITECTURE OF AN IoT-ENABLED ADVANCED STRUCTURAL HEALTH MONITORING DEVICE FOR CIVIL INFRASTRUCTURE

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ABSTRACT :

Structural health monitoring (SHM) supports the assessment of civil infrastructure by tracking changes in structural response and environmental conditions over time. Conventional inspection remains essential, but periodic visual surveys may not capture every transient event or gradual change between inspections. This paper presents the design architecture of an advanced, wireless SHM device intended for bridges, buildings, dams, industrial structures and other critical infrastructure. The proposed system combines multi-parameter sensors, an edge-processing node, wireless communication, cloud-based storage and analytics, and a web/mobile dashboard. The sensor suite may include strain gauges, accelerometers, displacement transducers, tilt sensors, temperature sensors, crack sensors, corrosion sensors and humidity sensors. A solar-assisted power supply and backup battery are proposed to improve deployment flexibility. The system workflow comprises sensing, signal conditioning, local processing, wireless transmission, cloud analysis, and alert generation. The paper also discusses sensor selection, data quality, communication options, deployment considerations, indicative costs and limitations. The cost range reproduced from the project concept is approximately ₹78,000–₹1,45,000 per node, depending on sensor configuration, installation and platform costs; it is an estimate rather than a supplier quotation. As no prototype measurements or field validation data were supplied, the paper does not claim demonstrated detection accuracy or verified performance. Instead, it establishes a reproducible design framework and identifies laboratory and field tests required before practical deployment.

Keywords: Structural health monitoring; Internet of Things; wireless sensor network; edge computing; cloud analytics; multi-parameter sensing; early warning; civil infrastructure.

1. Introduction

Civil infrastructure is exposed to repeated loading, environmental variation, material ageing, corrosion, fatigue, settlement and occasional extreme events. These actions can alter stiffness, vibration characteristics, deformation patterns and local material condition. Structural health monitoring (SHM) uses measurements and data interpretation to support condition assessment and maintenance planning. Research on wireless sensor networks has highlighted their potential to reduce extensive cabling and support monitoring across distributed locations, while also identifying challenges associated with power, communication reliability, sensor placement and data processing [1–4].

The proposed concept, titled “Advanced Structural Health Monitoring Device,” is a compact sensor node intended to collect structural and environmental data and transfer it to a remote platform. Its main design objective is to combine several sensing modalities with local processing and remote visualisation in a modular system. Instead of treating the dashboard, sensors and communication unit as separate products, the architecture connects them into one monitoring workflow.

The contribution of this paper is a system-level design description rather than an experimental performance claim. It organises the device concept into functional layers, maps candidate sensors to measurable parameters, outlines a data-processing sequence, discusses implementation risks and proposes a validation plan. The actual hardware selection, calibration and field performance remain to be established through prototype testing.

2. Aim and Objectives

The aim is to develop a conceptual architecture for a smart, wireless and remotely accessible SHM node suitable for integration with civil infrastructure.

- Identify a multi-parameter sensor suite for measuring structural response and environmental conditions.
- Define an edge node for signal conditioning, time-stamping, local storage and basic data-quality checks.
- Describe wireless transfer to a cloud platform and a user-facing dashboard for trends, alerts and decision support.

- Consider solar-assisted power, backup energy, enclosure protection and remote maintenance.
- Establish the limitations and validation activities required before the concept can be treated as a field-ready monitoring system.

3. Literature Review

3.1 Wireless sensor networks for SHM

Wireless sensor networks have been investigated for infrastructure monitoring because they can simplify deployment at distributed measurement points and reduce the need for long sensor cables. Sonbul and Rashid reviewed wireless sensor network platforms and energy-harvesting approaches for bridge SHM, emphasising the influence of sensor type, response type, monitoring scale and power constraints on system design [1]. Abdulkarem et al. also discussed wireless SHM architectures, communication technologies and practical challenges such as network design and long-term operation [2].

3.2 Integrated sensing and data interpretation

SHM performance depends on more than sensor connectivity. Sensor placement, calibration, sampling rate, synchronisation, environmental compensation and damage-identification methods all affect whether recorded data can support a defensible engineering interpretation. Sofi et al. reviewed wireless smart-sensor networks and data-acquisition and diagnosis workflows, noting the gap that can remain between research advances and broad field implementation [3]. Zhang et al. provide a recent review of bridge SHM methods, including sensing technologies, wireless transmission, data processing, damage identification and warning systems [4].

3.3 Position of the proposed concept

The proposed device follows the established layered pattern of sensors, local processing, communication, remote analytics and user interface. Its intended value is the integration of multiple parameter types within a modular node. This integration is a design proposition, not a claim of novelty over all existing SHM systems. A formal novelty assessment would require a broader, database-based literature search and a comparison with commercial and research prototypes.

4. Proposed System Architecture

The architecture consists of five main layers: (1) sensing, (2) edge node and data acquisition, (3) wireless communication, (4) cloud storage and analytics, and (5) user interface and alerts. The layers are described below.

4.1 Sensing layer

Sensors are installed at selected locations based on the structural form, expected load paths, critical details and monitoring objectives. The proposed sensor options are listed in Table 1. The final selection should be limited to sensors that answer a defined engineering question; installing every sensor type is not automatically necessary.

Sensor	Primary measurement	Potential use
Strain gauge	Local strain/deformation	Track strain changes in selected members
Accelerometer	Acceleration and vibration	Dynamic response and modal-feature tracking
Displacement sensor / LVDT	Relative linear displacement	Deflection, movement or joint response
Tilt sensor	Inclination/rotation	Settlement, rotation or alignment changes
Temperature sensor	Temperature	Environmental compensation and thermal trends
Crack sensor	Crack opening or change	Local crack-width trend monitoring
Corrosion sensor	Corrosion-related indicator	Monitor selected corrosion-prone zones
Humidity sensor	Ambient or enclosure humidity	Environmental context and enclosure checks

4.2 Edge node and data acquisition

The SHM node receives sensor signals through suitable analogue front ends, bridge circuits, amplifiers or digital interfaces. It converts signals into digital records, applies time stamps, checks for missing or out-of-range values, and temporarily stores data if the network is unavailable. Sampling frequency, resolution, anti-alias filtering and synchronisation must be chosen according to the target response. Slow environmental or displacement trends may need lower sampling rates than vibration measurements. A single sampling configuration should not be assumed suitable for every sensor.
The edge processor can calculate basic statistics, detect sensor faults and flag threshold exceedances before transmitting data. More advanced damage diagnosis should only be introduced after an appropriate baseline dataset, engineering thresholds and validation method are established.

4.3 Wireless communication

The concept allows communication technologies such as Wi-Fi, cellular 4G/5G or low-power wide-area networking (for example, LoRaWAN) to be selected according to coverage, data volume, latency, power use and installation constraints. The infographic identifies LPWAN, 4G and 5G as options. The communication technology should be selected per deployment rather than treated as interchangeable: high-rate vibration data can require a different strategy from periodic low-rate sensor readings. Secure device identity, encrypted transmission, retry handling and offline buffering should be included in the implementation.

4.4 Cloud platform and analytics

The cloud layer stores time-stamped measurements, sensor metadata, calibration records and event logs. Analytics may include trend plots, comparison against a baseline, statistical anomaly flags and rule-based notifications. A dashboard can display current values, historical trends, node status, battery condition and the location of installed sensors. Any health index shown to users should be explicitly defined, calibrated and validated; a dashboard score alone must not be interpreted as a certified measure of structural safety.

4.5 User interface and alerts

A web or mobile interface can support remote access by engineers and asset managers. Alerts should be configurable and should distinguish between a sensor/data-quality warning and a structural-response warning. Each alert should record the measured parameter, time, sensor location, threshold or rule triggered, and the recommended verification action. Automated alerts are intended to support engineering review and must not replace statutory inspections or professional judgement.

5. Working Principle and Data Flow

1. Install and document sensors at selected critical locations; record sensor IDs, orientation, calibration and mounting details.
2. Acquire physical responses such as strain, vibration, displacement, tilt, temperature, crack change, corrosion-related indicators and humidity.
3. Condition and digitise signals; apply time stamps and basic quality checks at the edge node.
4. Store data locally during communication interruptions and transmit valid records through the selected wireless link.
5. Store and visualise records on the cloud platform; compare measurements with baselines and engineering-defined thresholds.
6. Generate notifications for threshold exceedance, abnormal trends, missing data, low battery or communication failure.
7. Review flagged events by a qualified engineer and, where needed, arrange confirmatory inspection or testing.

6. Power Supply, Enclosure and Deployment

The concept includes a solar panel, backup battery and rugged enclosure. Solar assistance may reduce the frequency of battery replacement, but actual energy autonomy depends on local solar exposure, panel orientation, shading, battery capacity, sensor duty cycle, radio transmission frequency and temperature. A power budget should therefore be calculated before final component selection. The enclosure should be selected for the expected water ingress, dust, ultraviolet exposure, vibration, temperature and corrosion conditions. Cable glands, connectors and sensor attachments require attention because they can become failure points in long-term deployments.

Sensor locations should be chosen with reference to structural drawings, load paths, likely damage mechanisms and accessibility for maintenance. For a bridge, this may include selected girders, bearings, joints or other critical details; for a building, it may include selected columns, beams, floors or lateral-load-resisting components. These examples are not a universal placement plan. A structural engineer should define the monitoring layout for each asset.

7. Indicative Cost Assessment

The project infographic provides the following approximate per-node cost ranges. These figures are reproduced as preliminary estimates and should be verified through supplier quotations before procurement. They are not a formal bill of quantities and may vary with sensor accuracy, channel count, enclosure rating, communication plan, installation complexity and software subscription.

Component	Indicative cost (INR)
SHM node hardware	₹35,000–₹60,000
Sensors (per set)	₹25,000–₹50,000
Installation and setup	₹10,000–₹20,000
Cloud and platform (1 year)	₹8,000–₹15,000
Total per node (approximate)	₹78,000–₹1,45,000

The estimate is sensitive to the selected sensor package. A basic node with a small number of low-rate sensors may cost less than a configuration requiring precision strain measurement, high-rate dynamic acquisition or specialised corrosion monitoring. A lifecycle cost assessment should include calibration, battery replacement, connectivity, cloud storage, inspection access, maintenance visits and eventual sensor replacement.

8. Expected Benefits and Technical Limitations

8.1 Expected benefits

- Continuous or scheduled monitoring can provide information between conventional inspections.
- Wireless transmission can reduce the amount of signal cabling and support distributed installations.
- Multiple sensor types can provide complementary information about structural response and environmental conditions.
- Remote dashboards can help organise data, trends, device status and maintenance records.
- Early alerts may help engineers prioritise verification and inspection when defined thresholds are exceeded.

8.2 Limitations and risks

- Sensor readings are affected by calibration drift, mounting quality, noise, temperature and sensor failure.
- Wireless coverage, network congestion and power constraints can cause delayed or missing data.
- Large datasets require suitable storage, time synchronisation, quality control and data governance.
- Thresholds and anomaly-detection algorithms require validation to avoid false alarms and missed events.
- Corrosion and crack sensors measure local indicators and may not represent the condition of the entire structure.
- A composite health index can be misleading unless its inputs, weighting, uncertainty and validation are documented.
- The current concept has not been supported by prototype results, field trials or measured accuracy data.

9. Proposed Validation Plan

Before the system is presented as a validated product, a staged evaluation should be conducted. The following plan is recommended; it is a proposed future programme and no results are claimed here.

1. Bench verification: compare each sensor channel against a calibrated reference instrument over its intended measurement range.
2. Data-acquisition checks: verify sampling rate, resolution, time stamps, channel synchronisation and data-loss behaviour.
3. Communication tests: measure packet delivery, latency, reconnect behaviour and local buffering under representative signal conditions.
4. Power tests: measure average and peak current draw, battery autonomy and solar charging performance under realistic duty cycles.
5. Environmental checks: inspect enclosure and connectors under the relevant temperature, moisture, dust and vibration conditions.
6. Controlled structural test: install the system on a laboratory beam or frame and compare recorded strain, acceleration or displacement with reference instrumentation.
7. Alert evaluation: define test cases for normal response, threshold exceedance, sensor disconnection and communication failure; report false-positive and false-negative rates where appropriate.
8. Field pilot: deploy on a selected structure with owner approval, an agreed safety plan, documented baseline measurements and periodic expert inspection.

Results should report the sensor model and calibration, specimen or structure details, sampling settings, test conditions, reference measurement method, error metrics, data completeness, latency, power consumption and limitations. Only after these results are available should the paper make quantitative claims about accuracy, reliability or early-damage detection.

10. Discussion

The proposed architecture is technically plausible as a modular SHM framework because it connects sensing, local processing, wireless communication and remote visualisation. However, system usefulness depends on matching each measurement to a defined structural question. For example, acceleration data may help track dynamic-response changes, while strain and displacement data can quantify local response under known loading. Environmental variables are important context because temperature and humidity can influence both the structure and the sensors. Consequently, raw threshold exceedance should be interpreted with sensor quality checks and environmental context.

A key design decision is the balance between local and cloud processing. Edge processing can reduce communication demand and provide basic alarms when connectivity is intermittent, while cloud resources can support long-term storage and cross-node comparison. The balance should reflect the required sampling rates, network availability, privacy/security requirements and operational budget. Energy harvesting may improve deployment duration, but it does not eliminate the need for battery-health monitoring or a verified power budget [1,2,4].

The concept should be positioned as a decision-support tool rather than an autonomous structural-safety certification system. Any warning related to a potentially unsafe condition must be reviewed through the asset owner's established procedures and by appropriately qualified personnel.

11. Future Scope

- Develop and test a prototype node with a documented bill of materials and circuit architecture.
- Integrate secure device provisioning, encrypted communications, access control and audit logs.
- Investigate event-triggered sampling to reduce power use while preserving important transient events.
- Evaluate machine-learning methods only after collecting representative, labelled and quality-controlled datasets.

- Add uncertainty estimates and sensor-fault diagnosis to distinguish structural changes from measurement problems.
- Conduct a field pilot and compare system performance and lifecycle cost with conventional inspection practice.

12. Conclusion

This paper has presented a design framework for an advanced structural health monitoring device that integrates multi-parameter sensors, an edge-processing node, wireless communication, cloud-based analytics and a remote dashboard. The architecture is intended to support monitoring of strain, vibration, displacement, tilt, temperature, crack change, corrosion-related indicators and humidity, subject to the sensor package selected for each application. Solar-assisted power, local data buffering and remote alerts are included as design features. The indicative cost supplied in the concept is ₹78,000–₹1,45,000 per node, but this range requires verification through quotations and a deployment-specific cost analysis. The principal limitation is that no experimental or field results were provided; therefore, detection accuracy, reliability, energy autonomy and economic benefit remain unverified. Future work should implement a prototype, calibrate its sensors, conduct controlled structural tests and complete a field pilot before making performance claims or deploying the system for safety-critical decisions.

Declarations

Funding: No funding information was provided in the source material. Complete this declaration according to the actual project circumstances.
Conflicts of interest: The authors should declare any actual competing interests according to the target journal's policy.
Data availability: No experimental dataset is reported in this design paper. If prototype data are collected later, provide the dataset or a statement describing access restrictions.
Author contributions: Please confirm the actual contribution of each author and amend this statement before submission.
Ethics and safety: Any field deployment should be conducted with asset-owner permission and an appropriate site-safety plan.

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