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Low-Cost Civil Structure Health Monitoring Using Wireless Sensor Network

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Abstract- **This research presents a low-cost, real-time, reliable, and scalable solution for Structural Health Monitoring (SHM) using an IoT-based multi-node system. The study's objective is to timely detect and identify damages and weaknesses in civil structures such as bridges, buildings, and dams, which environmental factors, overuse, or natural phenomena may cause. Each sensor node, fabricated using NodeMCU, is equipped with sensors for measuring vibration, shock, tilt, strain, humidity, and temperature. The data collected by multiple sensor nodes is transmitted to Amazon Web Services (AWS) cloud platform via Wi-Fi and analyzed for damage detection and predictive maintenance. The field testing on a pedestrian steel bridge showed over 99% success in data transmission with a frequency of 1 second per reading, resulting in 18,000 readings over 5 hours. With a fabrication cost of $40 per sensor node and scalable AWS resources, the proposed solution is highly scalable and can operate for 15 days without human intervention.**

Index Terms-- **Structural Health Monitoring, Internet of Things, NodeMCU, Sensors, Amazon Web services.**

I. INTRODUCTION

The need and dependency on civil structures such as bridges, buildings and dams are growing with increasing urban sprawl. New building codes are being implemented to build safe, reliable, and natural disasters withstanding civil structures such as earthquakes, flooding, and other catastrophes to counter any untoward incident. However, structural health monitoring of civil structures weakened by weather, deterioration, and aging is imperative. Even in new structures, there is a need for real-time monitoring of applied load and strain, temperature, humidity, and vibration for intimation of any structural damage. Reliable internet of things (IoT) based structural health monitoring solutions are needed to prolong operational life and avoid any untoward incident because of associated human and capital costs [1].

This process for early detection of damages and tracking their evolution through constant monitoring of structures is referred to as Structural Health Monitoring (SHM). SHM is achieved through data analytics, using different applied forces on a structure, such as vibrations, stress, strain, and shocks, as input. The insights gained are used for corrective actions to prevent future structural failures.

While designing SHM systems, the deciding factors range from compute boards, sensors, cost, sensing frequency, power consumption, communication, and network design. For example, different accelerometer types (such as Micro Electromechanical and piezoelectric) can be employed for abnormal vibration detection in civil structures due to external forces [2, 3, 4]. Sensors (such as fibre optic grating, piezo-resistive, and foil strain gauges) can measure stress and strain. Stress and strain are developed in concentrated areas of a civil structure because of pin-loaded holes, joints, and geometrical shapes [5]. Furthermore, a multi-sensor node solution is imperative for in-depth analysis to measure forces developed at different points of civil structure.

The objectives for undertaking this work were,

- To propose a low-cost, real-time and reliable SHM solution,
- The proposed solution should be able to scale easily, operating for a long time with minimum human intervention.

Regarding keeping the overall solution's cost low, off-the-shelf sensors (such as stress, strain, tilt, vibration, temperature, and humidity) have been integrated with NodeMCU. Each multi-sensor SHM solution sensor node is powered with a 20,000mAh power bank. For a real-time solution, sensed parameters are transmitted to Amazon Web Services (AWS) cloud platform every second. The sensed parameters are also logged in an SD card module integrated with each sensor node for reliability. This is done to prevent data loss in case of a faulty internet connection. Each sensor node transmits its sensed parameters independently to AWS cloud platform for scalability. Thus, there is no single source of failure, with each sensor node operating independently.

AWS's processed and archived data is then employed for fault diagnostics and preventative measures.

The rest of the paper is organized such that related work has been detailed in section 2. The system Design of the proposed solution has been detailed in section 3. Results and Conclusion have been presented in sections 4 and 5.

II. RELATED WORKS

In this section, related work has been presented to highlight the limitations of proposed SHM solutions in the existing literature. This discussion also helps provide our proposed solution's full scope and justification.

Patel et al. [1] proposed an IoT-based SHM solution for monitoring bridges. In the proposed solution, an accelerometer was integrated with Arduino Uno. Sensed parameters are transmitted to a local server using Bluetooth. Using MATLAB, a Fast Fourier transform-based algorithm was employed to calculate different severity levels and their effect on the bridge's integrity. Harms et al. [6] proposed an IoT-based SHM solution for continuously monitoring bridges and flyovers. The proposed solution was developed using Raspberry Pi 3 with integrated vibration, load, ultrasonic and water level sensors. The sensed parameters are transmitted to a local server using Wi-Fi. Whenever any sensed parameter exceeds a predefined threshold, an alarm is sounded, with an alert is sent to concerned personnel.

Haroon et al. [5] proposed an IoT-based SHM solution with the capability to measure vibration, shock, pressure, temperature, and humidity on the installed civil infrastructure. These sensed parameters are then transmitted to a cloud platform 'ThingSpeak' for storage, analysis, and visualization. An SD card module has been integrated for data storage for data reliability. With a 10,400 mAh power bank, the proposed solution can operate for 2.5 days without human intervention. Abruzzese et al. [2] proposed an SHM solution that compares a traditional/expensive and a low-cost SHM system. A rectangular steel bar with two strain gauges attached on each side and pressure inserted on the bar. One side is connected to the expensive instrument, and the other is to a Low-Cost/Arduino instrument. The result from both instruments came out the same. The low-cost instrument is finalized when a vibration sensor is added. Both sensors are integrated with a microcontroller. The data is stored in a database and uploaded using Wi-Fi onto the cloud having a GUI.

Chowdhry et al. [7] proposed an IoT-based SHM solution using NodeMCU and an accelerometer (ADXL320). It can observe the nonlinear vibration in the structure. The real-time data recorded by the system is stored in the cloud platform (ThingSpeak) using a secure API. The user can access the account remotely and observe the structure's frequency response. Gupta et al. [8] proposed an IoT-based SHM solution to monitor concrete temperature, humidity, and vibration. The proposed solution can monitor concrete damage in real time and upload data to a cloud server using an edge router. The sensed parameters are transmitted using Wi-Fi to 'ThingSpeak.' In [9], a low-cost SHM solution was proposed to monitor buildings' integrity. The proposed solution integrated flex sensors with Arduino Uno to detect abnormal bends in the building's pillars. An emergency alert is generated through an LED light and alarm whenever an abnormal bend above a predefined threshold is observed. Sensed flex sensor data is transmitted to ThingSpeak through GSM SIM900 for analysis and storage.

Thiruvasagar et al. [3] proposed a low-cost SHM system for temperature monitoring of early-stage concrete. The proposed solution employed NodeMCU with a DS18B20 temperature sensor. The sensed temperature readings were uploaded to ThingSpeak using Wi-Fi. The proposed solution was field tested for 24 hours on two different concrete mixtures with data uploading frequency of 10 minutes. Abdelgawad et al. [4] proposed an SHM solution for civil structure damage detection using piezoelectric transducers integrated with Raspberry Pi 2. A combination of pulse-echo and pitch-catch techniques is employed. One PZT transmits a signal toward the second PZT and picks up any waves reflected by structural defects. On the other hand, the second PZT receives wave feedback in a pitch-catch manner. These signals are converted using ADC and DAC and, with the help of a buffer, sent to Raspberry Pi, which is uploaded to a cloud platform using Wi-Fi.

Muttillo et al. proposed an IOT-based SHM for structural behaviour over time [10]. The proposed system comprises a customized datalogger and multiple nodes. The datalogger receives the data from different nodes communicating using RS485 communication. Additionally, each node has an internal memory to process the data collected from the sensors, i.e., a digital triaxial accelerometer. A microcontroller and external storage are also used in the node, which communicates with the accelerometer and stores the data in the storage. The proposed system has been evaluated and tested on the testing structure. Junaid et al. proposed an IOT-based SHM consisting of two modules: a transmitter and a receiver [11]. The transmitter side contains Piezo-Vibration and Accelerometer (ADXL335) sensors integrated with Arduino Nano and a Wi-Fi module. The receiver has an LCD integrated with Arduino Nano and a Wi-Fi module. The transmitter is installed on a prototype bridge, transmitting sensed parameters to the receiver node that uploads the data to the Blynk server. The data can be remotely monitored using the Blynk app on any mobile device.

In [12], the authors reviewed multiple frameworks for IoT-based SHM solutions. Data routing strategies and technologies involved were explored. The overview of SHM implementation based on Wireless Sensor Networks (WSN) and big data tools was presented. In [13], the author gave an overview of SHM implementation based on Wireless Sensor Networks (WSN), big data tools, and IoT. SHM has been integrated during the manufacturing of civil structures to monitor the condition, perform evaluation, and check the structural integrity.

The proposed solution in this work has been developed to overcome the design limitation of proposed solutions in the existing literature. The design improvements were undertaken to enhance cost optimization, reliability, and scalability.

- By choosing the optimum compute board and sensors as opposed to [4, 6], each sensor node's fabrication cost is under $40. In addition to being low-cost, the proposed solution can be scaled WSN depending upon under civil observation structure.
- Compared to existing SHM solutions, the proposed SHM solution can measure detailed parameters such as vibration, tilt, stress, strain, shock, temperature, and humidity.
- For cost optimization, off-the-shelf sensors have been employed. However, vibration and tilt parameters are an average of three accelerometer readings for data accuracy. Furthermore,
- As opposed to solutions in existing literature, the proposed SHM solution's sensing and transmission frequency is every second. This is instrumental in monitoring heavily used infrastructures such as bridges. Each sensor is power-optimized and can operate for 3.33 days without human intervention.
- In most proposed solutions, free and open-source cloud platforms such as ThingSpeak, and Blynk have been employed [3, 5, 7, 8, 9, 11]. However, for scalability, a public cloud AWS has been integrated. They are enhancing data uploading frequency, data storage/processing and the ability to increase the number of sensor nodes under a civil observation structure.

III. SYSTEM DESIGN

This work aims to provide a low-cost, real-time, reliable, and scalable civil SHM solution. During the design phase, the primary objective was overall system cost. Through an optimum selection of compute board and sensors, each sensor node can be fabricated for approximately $40. For reliability, instead of employing an edge router, each sensor node transmits sensed parameters independently to the AWS cloud platform. Thus, there is no single source of failure, with each sensor node operating independently.

This also achieves our objective of scalability, as the number of sensor nodes can be increased with minimum architectural change. The proposed SHM solution can be subcategorized into three modules: (A) Sensor node, (B) Current consumption, and (C) Cloud platform.

A. Sensor Node

In the existing literature, different compute boards such as Arduino Uno\Nano\ Mega [1, 6, 9, 14], and Raspberry Pi [4, 6] have been employed for sensor node development. However, for low-cost sensor node development, deciding factors for choosing a compute board range from cost (monetary and power consumption), computation requirement and design complexity. Considering the parameters above, NodeMCU ESP32 has been employed as compute board. NodeMCU, with a dual 32-bit processor operating at 240 MHz and 512 kb of RAM, has requisite computation capabilities (see Fig. 1).

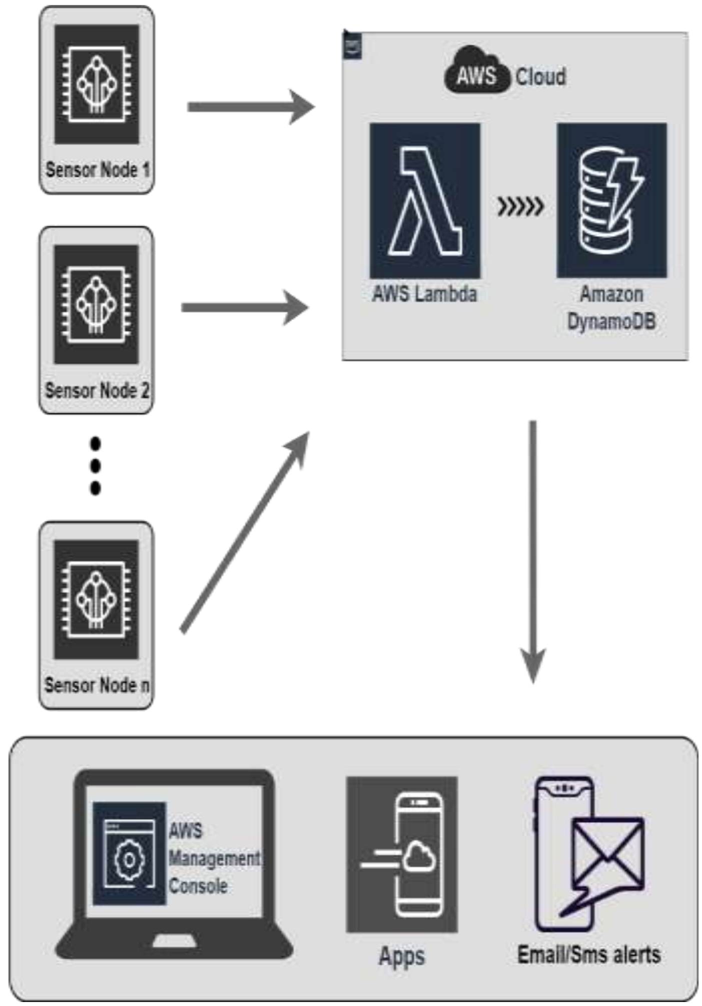

FIGURE 1. Architectural block diagram of proposed SHM.

It has built-in Wi-Fi and Bluetooth modules, thus reducing the design complexity of a sensor node. With a price tag of $3 and power consumption of 250mA/hr, it is both cost and power efficient. For real-time monitoring of civil structures, five off-the-shelf sensors have been integrated with NodeMCU. The sensed parameters by each sensor node are vibration, tilt, shock, strain, humidity, and temperature. The architectural block diagram of the proposed SHM can be seen in Figure 2. MPU-6050 accelerometer has been integrated with each sensor node to measure vibration and tilt. MPU-6050 has a built-in accelerometer and gyroscope. Using the built-in accelerometer and gyroscope of MPU-6050, vibrations (Roll, Pitch and Yaw) in the civil structure are measured. Considering the vibration impact on the civil structure's integrity, the vibration reading averages three integrated MPU-6050 accelerometers, as seen in Fig. 2.

Furthermore, MPU-6050 can provide tilt in civil structures through an in-built gyroscope. This reading is instrumental in measuring tilt in natural phenomena such as earthquakes and its effect on civil structure.

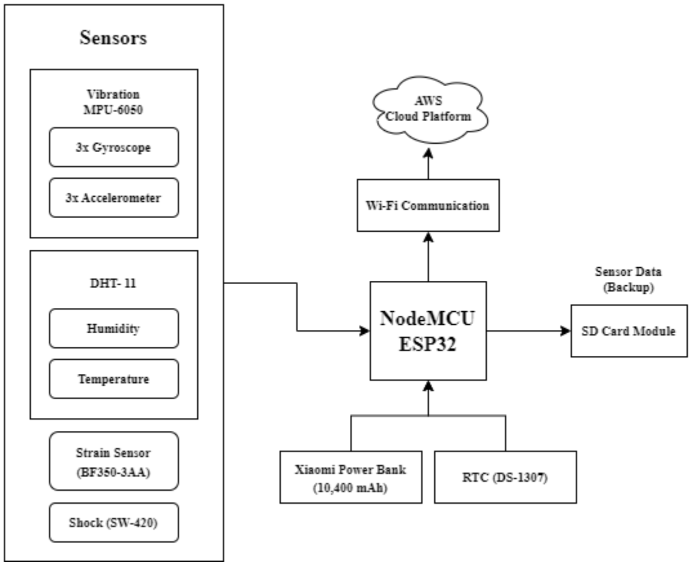

FIGURE 2. Architectural block diagram of the sensor node.

The integrated strain sensor (BF350-3AA) [2, 5] is instrumental in detecting at what time and points the overloading affect the civil structure. Strain sensor operates by proportionally measuring electrical resistance variance to strain developed in civil structures. Measured readings can be calibrated using the strain sensor's built-in amplifier and potentiometer. Operating on 5V, the strain gauge has nominal resistance and strain limit of 350 ohms and 2%, respectively.

Shock, temperature, and humidity are other parameters that are being measured. A shock sensor (SW-420) has been used to detect if any abnormally great shock is being applied under observed civil structures. Overloaded heavy traffic or pedestrian traffic beyond capacity generates shock in civil structures. A correlation between applied shock and vibrations generated under an observed civil structure can be developed. The impact of humidity and temperature on civil structures has already been established in existing literature [15]. For example, gaps are left in railway tracks to mitigate expanding and shrinking of metallic tracks during hot summers. DHT11 sensor has been integrated with each sensor node for measuring humidity and temperature.

As the proposed solution comprises multiple sensor nodes, time synchronization is imperative. This time synchronization helps synchronize readings from different sensor nodes for data analysis. For this purpose, a real-time clock DS1307 is integrated with each sensor node for sensed parameter's time stamping. The software flow chart of the proposed sensor node can be observed in Fig. 3. Sensed parameters of each sensor node are transmitted to the AWS cloud platform by employing the in-built Wi-Fi module of NodeMCU. An SD card module has been integrated in each sensor node for reliability purposes. In case of communication link disruption, sensed parameter readings are stored in the SD card. Retransmission is undertaken whenever a communication link is re-established.

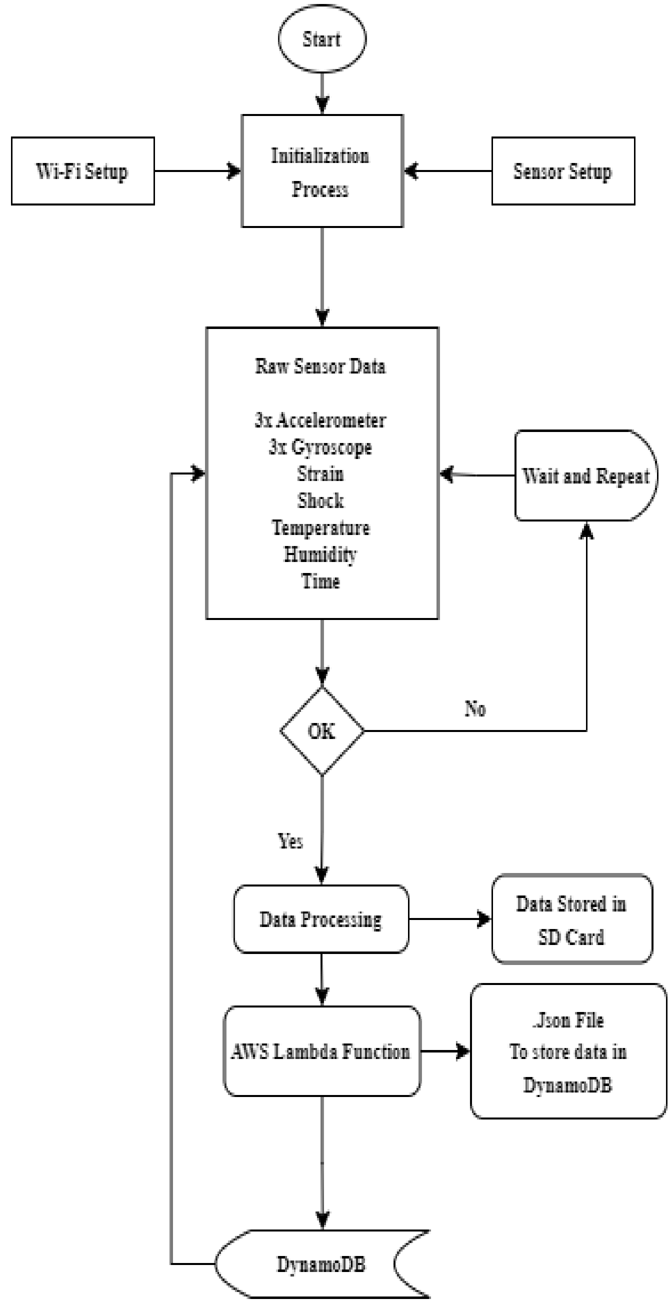

FIGURE 3. Each sensor node's flow chart for sensing, processing, and transmission to AWS.

B. Current Consumption

As with any IoT-based solution, current consumption was a serious consideration during the design phase of the proposed SHM solution. The proposed system was designed to be power efficient to keep human intervention to a minimum. It is powered by a 5V-20,000 mAh Xiaomi power bank (Model: PLM06ZM). The sensor node's individual components' current consumption is detailed in Table I.

TABLE I
CURRENT CONSUMPTION AND COST OF INDIVIDUAL COMPONENTS OF A SENSOR NODE.

Components	Current Consumption (mA)	Cost ($)
NodeMCU ESP 32	40	3
NodeMCU ESP 32 Active	~200	-
MPU- 6050	4.1	4.5 (1.5*3)
DHT11	0.3	0.7
Shock Sensor [SW-420]	~5	0.5
Strain Sensor [BF350-3AA]	0.5	2.5
SD Card Module	0.21	0.5
Real Time Clock [DS1307]	~0.00065	0.5
Power bank [PLM06ZM]	-	20

Using (1), the current consumption of a sensor node when fully operational was estimated at 250mA per hour. Thus, each sensor node current consumption stands at 6000mAh per day. These current consumption measurements were verified using a USB Digital multimeter. Each sensor node can operate for approximately 3.33 days on a 20,000 mAh power bank without any human intervention.

$$\mathbf{I}_{[Total]} = \mathbf{I}_{[Node\ MCU]} + \mathbf{I}_{([DHT11] + (3 * \mathbf{I}\ [MPU\text{-}6050]))} + \mathbf{I}_{[RTC]} + \mathbf{I}_{[Shock]} + \mathbf{I}_{[Strain]} + \mathbf{I}_{[SD\ Card]} \quad (1)$$

C. Cloud Platform

In the existing literature, the most common cloud platform choice for IoT-based solutions in general and SHM, in particular, is 'ThingSpeak' [3, 4, 5, 7, 10]. ThingSpeak is a free and open-source cloud computing platform. However, ThingSpeak is limited in scope and data uploading capabilities. In this context, the AWS cloud platform has been employed for this work. AWS has a data upload capability of per second instead of 15 seconds for ThingSpeak [14, 16]. Among the plethora of services offered by AWS, for this work, AWS lambda and DynamoDB have been used.

AWS Lambda [15, 17] is a computing service for the provisioning and managing of servers without coding requirements. AWS lambda is highly optimized, automated, and scalable for requests ranging from a few daily requests to thousands per second. AWS Lambda executes our code in response to HTTP requests using Amazon API Gateway, thus triggering services for data storage in Amazon DynamoDB. Amazon DynamoDB is a fully managed NoSQL database. Salient features are its automated setup and configuration, hardware provisioning and replication for reliability. Data encryption is another service for sensitive data protection. AWS cloud platform offers a pay-as-you-go approach to pricing for services being used. The cost breakdown for AWS cloud computing services has been calculated using the "AWS Pricing Calculator" and verified through field testing.

Each sensor node transmits 3,600 measurements/hour, with a sensing frequency of per second. Thus, each sensor node senses and transmits 86,400 measurements per day. For data storage of these 86,400 measurements/day, 4.4 MB of storage is required in AWS DynamoDB. The monthly data space requirement in AWS DynamoDB for 2.6 million (86,400 measurements/day * 30 days) measurements are 132MB. But since AWS only offers data storage in GBs, 1GB will cost $0.25/month. Thus, the total cost of AWS DynamoDB per month per sensor node will be $9.59 (AWS DynamoDB data storage cost = $0.25 and AWS DynamoDB write cost = $9.34).

AWS Lambda service charges users based on 'number of requests' and 'duration of each request for code to execute'. The pricing is $0.000066667 per request and duration (in GB-compute seconds). With each sensor node's 86,400 transmissions per day, a sensor node makes 259,200 AWS Lambda requests per month. Thus, AWS Lambda charges for requests are $0.52 per sensor node per month (259,200 * $0.000066667). The duration of each request is 100ms and the amount of memory allocated for each node is 128MB (0.125GB). Total duration charges are $0.54 per sensor node per month (0.125 * 259,400 = 32,400 GB-compute seconds * $0.000066667). The total AWS Lambda cost per sensor node per month comes to $1.06. Thus, AWS services charges (AWS Lambda + DynamoDB) have been estimated at $10.65/sensor node/month.

IV. RESULTS

For field evaluation, a pedestrian bridge of Bus Rapid Transit (BRT) Hashtnagri station in Peshawar, Pakistan was selected as can be seen in Fig. 4. The under-observation pedestrian bridge is used for both accessing BRT station as well as overhead pedestrian crossing. The aforementioned bridge is constructed using steel as can be seen in satellite image in Fig. 5.

FIGURE 4. Side view of Bus Rapid Transit (BRT) Hashtnagri Station.

Two sensor nodes were installed on the metallic pedestrian bridge. Sensor node 1 was installed on the west side of the pedestrian bridge, while sensor node 2 was installed on the south side. Real time testing was conducted for 5 hours on Monday, 2nd November 2020, from 7 AM to 12 PM. Installed sensor node 1 can be observed in Fig. 6.

FIGURE 5. Satellite view of Bus Rapid Transit (BRT) Hashtnagri Station**.**

FIGURE 6. Installed sensor node 1 on the west side of the pedestrian bridge.

Frequency and amplitude of vibration are the most important parameters for integrity of any civil structure [1]. Overloading beyond a bridge's capacity results in severe vibrations thus deforming it permanently. To keep the proposed solution's overall cost low, MPU6050 has been chosen to measure vibrations. For reliability and accuracy, each sensor node's vibration readings are an average of three MPU6050 integrated in each sensor node. Both sensor nodes vibration readings can be observed in Fig. 7. The Formulas used for measuring vibration i.e. (Roll, Pitch and Yaw) are given in (2), (3) and (4) respectively:

$$\text{Pitch} = \arctan\left(Ax / \text{sqrt}\left(Ay^2 + Az^2\right)\right) \tag{2}$$

$$\text{Roll} = \arctan\left(Ay / \text{sqrt}\left(Ax^2 + Az^2\right)\right) \tag{3}$$

$$\text{Yaw} = \arctan\left(\text{sqrt}\left(Ax^2 + Ay^2\right) / Az\right) \tag{4}$$

As can be seen in Fig. 7(a), peak vibration by sensor node 1 was measured between 8:00 to 9:00 AM and 11:00 to 12:00 AM. This peak vibration values correspond to high pedestrian rush hour. Bridge vibration readings are lower between 9:30 and 11:00 AM because of lower pedestrians' use of the bridge. Vibration readings of sensor node 2 are shown in Fig. 7(b). Stress and shock sensors were integrated to detect stress and strain developed in bridge structure due to vibrations caused by pedestrians. Stress and strain sensed by both sensor node 1 and sensor node 2 can be observed in Fig. 8.

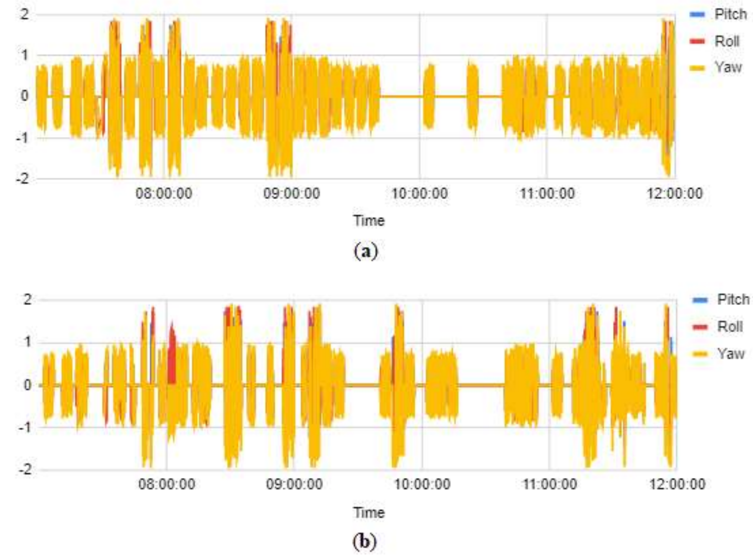

FIGURE 7: Vibration reading measured by sensor node.

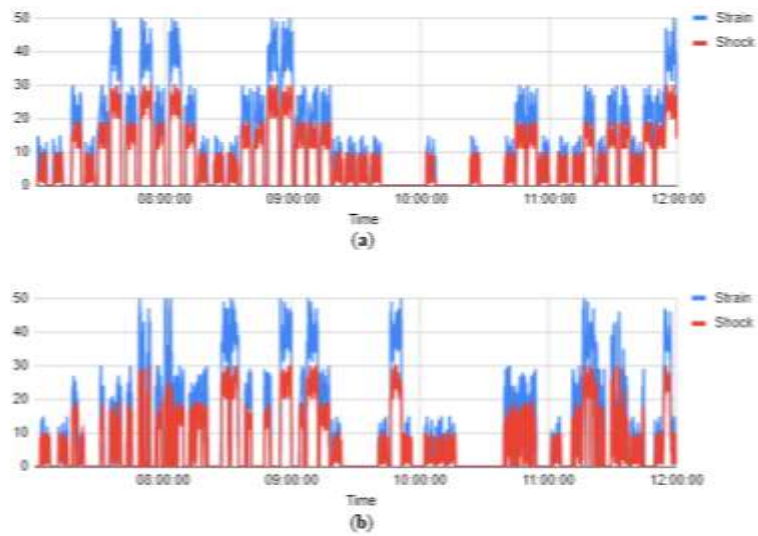

FIGURE 8: Recorded strain and stress readings of sensor node.

As shown in Fig. 8 (a), the highest values for stress and strain were recorded at 50 and 30, respectively. From Figs 7 (a) and 8 (a), it can be observed that spikes in stress and strain in bridge structure are linearly proportional to vibrations caused by passing pedestrian numbers.

Recorded stress and strain readings from sensor node 2 can be observed in Fig. 8 (b). As shown in Fig. 8 (b), the highest values for stress and strain were recorded at 50 and 30, respectively. Figures 7 (b) and 8 (b) show that spikes in stress and strain in bridge structure are linearly proportional to vibrations caused by passing pedestrian numbers.

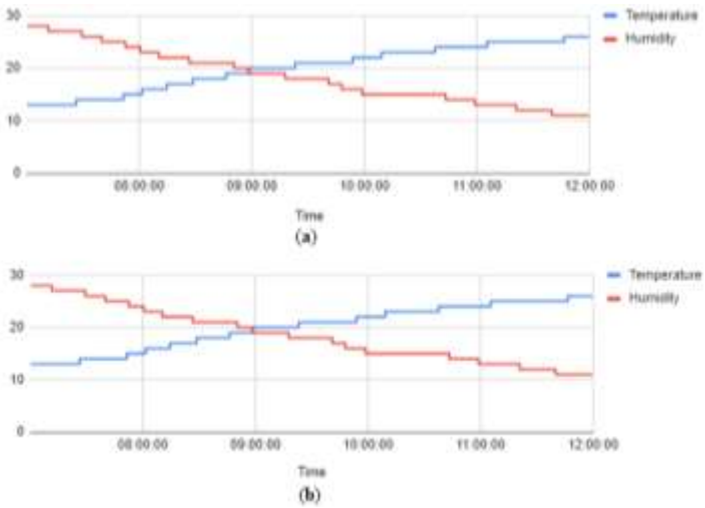

FIGURE 9: Sensed temperature and humidity readings of Sensor node 1 and Sensor node 2

Atmospheric temperature and humidity impact civil structures' thermal properties, strength, flexibility, and integrity [5, 8]. As the under-civil observation structure is a metallic bridge, the expansion of metallic parts due to atmospheric heat results in stress and strain in joints, pin loaded holes. Through data analytics, relationships between atmospheric temperature, humidity, stress and strain can be developed. Sensed temperature and humidity parameters of both sensor node 1 and sensor node 2 can be seen in Figure 9 (a) and (b), respectively.

V. CONCLUSION

In this work, we have proposed an IoT-based structural health monitoring solution. The proposed solution can be used for civil structure monitoring, fault diagnostics and preventive measures to avoid disasters culminating in human life losses. The solution is a step toward the realization of future smart cities. From a technical perspective, the proposed SHM solution is composed of multiple sensor nodes.

- The proposed solution is low-cost, where each sensor node can be fabricated for approximately $40.
- Each sensor node can sense vibration, tilt, shock, strain, humidity, and temperature.
- With each sensor node's low cost and independent sensing data transmission capabilities to the AWS cloud platform, the proposed solution can be scaled to hundreds of sensor nodes without any modification in basic system architecture.
- For reliability, each sensor node has the data logging capability on an integrated SD card module.
- With a 20,000mAh power bank, each sensor node can operate for 15 days without human intervention.

The proposed solution was evaluated in a real-world setting on a metallic pedestrian bridge for five consecutive hours, with a data transmission frequency of 1 sec. Each sensor node transmitted 18,000 readings to AWS over 5 hours with 99% accuracy. The sensed parameters are transmitted through Wi-Fi to the public cloud platform AWS. AWS Lambda services were used for data streaming from different installed sensor nodes. The sensed parameters are stored in DynamoDB for further processing and analysis. AWS resources were estimated at $10.65/sensor node/month.

In the future, we aim to extend the sensor node's battery operating life without human intervention. Solar panels and energy harvesting techniques will be explored to extend sensor nodes' operational time.

FUNDING STATEMENT

The authors declare they have no conflicts of interest to report regarding the present study.

CONFLICTS OF INTEREST

The authors state they have no conflicting interests related to this study.

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