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COST EFFECTIVE MONITORING SYSTEM FOR ENHANCED AND SAFE OPERATIONS OF RENEWABLE ENERGIES

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RESEARCH ASSIGNMENT FOR EXCHANGE STUDENTS

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Abstract

Maintaining the effectiveness of renewable energy resources is critical for a sustainable future. This project develops an economical, modular monitoring system for wind, solar, and hydro power plants to automatically diagnose failures. The use of sophisticated sensors and data processing improves maintenance practices while optimizing expenses and interference. The approach comprises researching failure modes, choosing appropriate sensors, modifying equipment, and testing the system in real-life scenarios. It also addresses existing gaps by providing economical reliable monitoring for heterogeneous renewable resources. This will enhance operational efficiency, conserve maintenance spending, and compliment the global transition to renewable energy innovations.

Specific Learning

- Learned to build a interactive dashboards for visualizing the data
- Understood a way to design and implement a SFM system using strain gauges and Arduino.
- Gained hands-on experience in cloud integration for IoT-based monitoring systems
- Explored threshold-primarily based alert mechanisms for predictive preservation in structural structures.

Technical Limitations & Ethical challenges faced

- Accuracy is affected by signal noise, and limited real-world trying out.
- The dashboard was basic and did no longer include superior information analytics or AI-based totally insights.

Nomenclature

Abbreviations

- SFM - Structural Failure Monitoring
- IoT - Internet of Things
- ADC - Analog to Digital Converter
- WiFi - Wireless Fidelity
- HTML – Hyper Text Markup Language
- FEM - Finite Element Method
- DC - Direct Current
- R^2 - Coefficient of Determination
- mV - Millivolt
- dB - Decibel
- MKR – Maker (Arduino MKR1010)

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CHAPTER 1

INTRODUCTION

1.1 OVERVIEW

The speedy transition from fossil fuels to renewable energy sources has grown to be imperative in addressing the twin annoying situations of climate alternate and strength security. Among renewable assets, wind strength has emerged as one of the most scalable and widely followed answers. However, wind electricity systems, especially wind generators, are subjected to continuous and fluctuating mechanical stress because of environmental conditions which includes wind gusts, storms, temperature gradients, and operational vibrations. These various masses result in cyclic stresses and features that would reason innovative harm, fatigue failure, and eventual breakdown of structural additives.

The secure, efficient, and uninterrupted operation of renewable power infrastructure relies upon critically on timely detection and mitigation of structural anomalies. Traditional preservation techniques, together with scheduled guide inspections or reactive preservation submit-failure, aren't most effective economically inefficient but additionally pose a danger to safety and machine reliability. This scenario calls for sensible, automatic, and fee-powerful tracking structures able to real-time overall performance assessment and structural diagnostics.

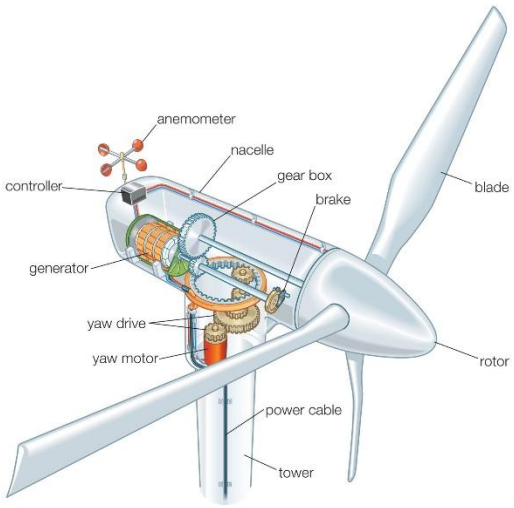


Figure 1.1 Rotor anatomy

Recent advancements in sensor technologies, embedded structures, and wireless conversation have made it possible to put into effect low-fee, clever tracking structures capable of shooting excessive-resolution mechanical records. The integration of these technologies into wind turbine infrastructure permits early failure prediction, timely preservation alerts, and green facts analysis—all in a value-effective and scalable manner.

This report presents the design and implementation of a **cost-effective monitoring system** for structural safety in windmill installations. The system is built using **strain gauges**, an **INA125P**

amplifier, and an **Arduino MKR 1010 WiFi** module. Data is transmitted wirelessly and visualized through a real-time web dashboard, allowing engineers to remotely assess the system's condition and predict structural failure.

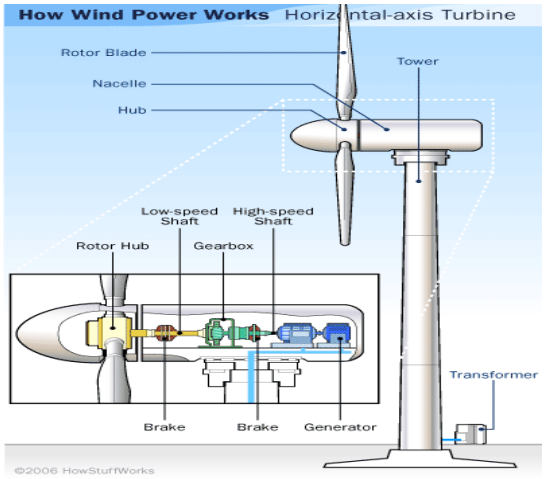


Figure 1.2 Labelled wind turbine components

1.2 STRUCTURAL FAILURES IN WIND TURBINES

Although Wind turbines are designed to withstand rigid environmental conditions, exposed to progressive structural damage due to continuous dynamic load. Over time, components experience physical fatigue, crack initiation and mechanical wear that can cause terrible failure when not immediately addressed.

1.2.1 Causes

Fatigue stress: Repeated wind loading induces alternating strain cycles on turbine blades and towers, weakening the material over the years.

Overloading: Extreme wind situations or operational anomalies may also generate hundreds beyond the layout ability, causing instantaneous structural damage.

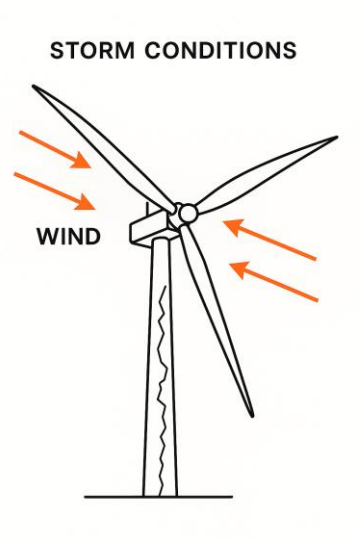


Figure 1.3 Overloading of wind mill

Material degradation: Aging of materials because of corrosion, UV publicity, and temperature cycling can compromise mechanical houses.



Figure 1.4 Comparison of healthy and corroded wind mill

Manufacturing defects: Imperfections in material fabrication or creation can create localized susceptible points.

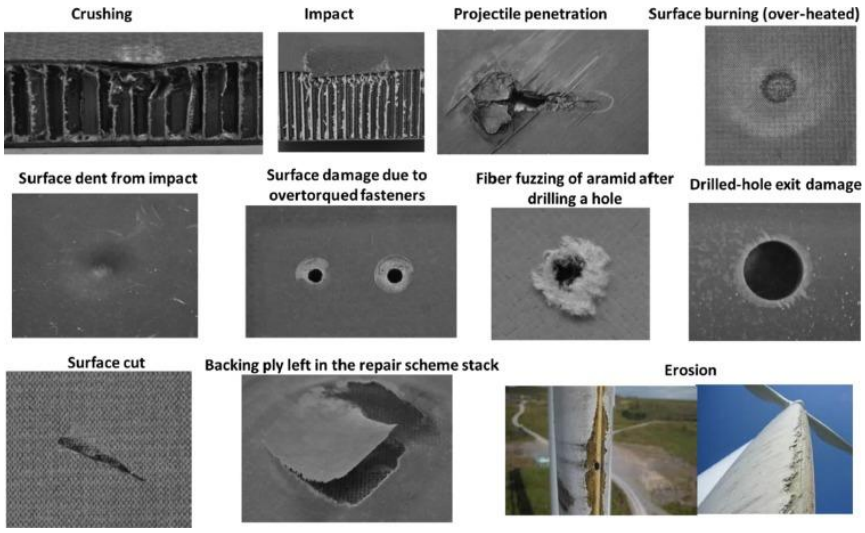


Figure 1.5 Microscopic images of manufacturing defects

1.2.2 Types of Structural failure

Blade Failure

Fractures due to fatigue or intense wind gusts. May result in blade detachment.



Figure 1.6 Blade failure

Tower Buckling

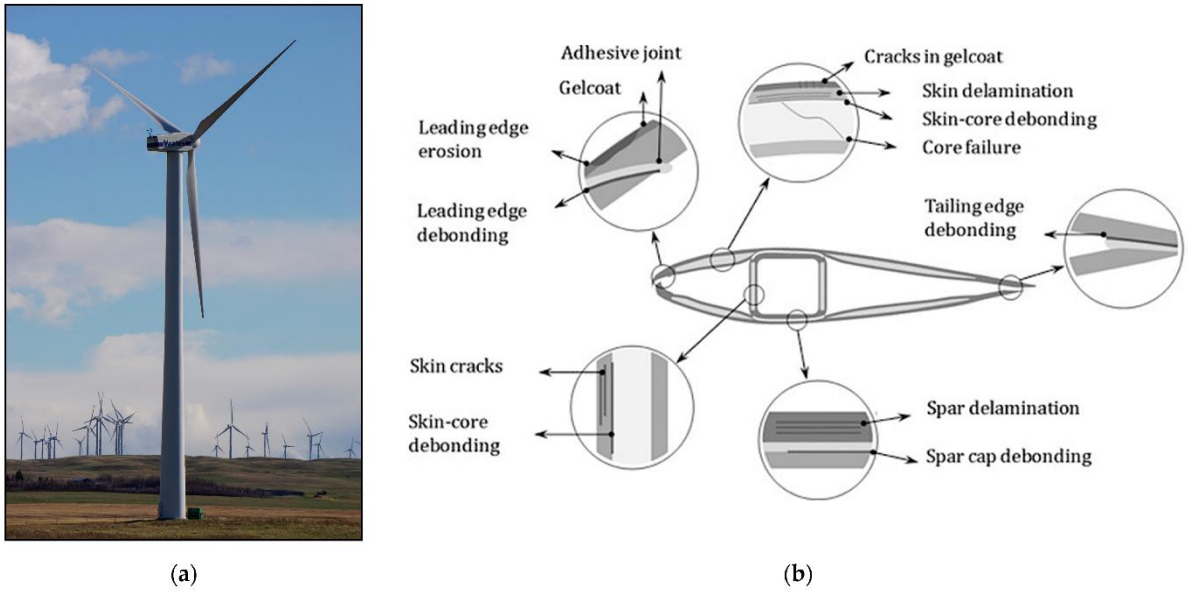
Collapse because of bending pressure or corrosion at the bottom.



Figure 1.7 Failure due to tower buckling

Crack Propagation

Micro-cracks expanding over time in welded or composite joints



(a) (b)

Figure 1.8 Cracks in blades

Bolt Failure

Fatigue or corrosion inflicting joint loosening or detachment



Figure 1.9 Bolt failure in blades

Foundation Cracking

Settlement or ground movement leading to base instability.



Figure 1.10 Crack in the foundation of wind mill

1.3 GOAL OF THE PROECT

The goal of this project is to layout and implement a cost-effective, real-time structural fitness tracking device for wind electricity structures, the usage of strain gauge-primarily based sensing, Arduino IoT architecture, and a cloud-included dashboard for non-stop monitoring and failure prediction.

This gadget should enable:

- Early detection of mechanical pressure buildup,
- Real-time records acquisition and visualization,
- Wireless transmission for remote tracking,
- Alert mechanisms for preventive renovation scheduling.

CHAPTER 2

LITERATURE SURVEY

2.1 INTRODUCTION

Before developing a structural monitoring device for wind mills, it's far essential to understand how similar systems had been designed and applied in beyond research. Over the years, many studies have targeted on the usage of low-fee hardware, which include Arduino boards and wireless sensors, to acquire and analyze structural records. These systems are often used to monitor strain, vibration, or damage in wind turbine components. Some researchers have additionally delivered gadget studying and cloud-based equipment to improve prediction accuracy and decrease preservation time. This segment critiques key papers that discover specific procedures to structural health monitoring (SHM) with a focus on value-effectiveness, real-time analysis, and sensible deployment. The insights from this overview helped shape the direction and layout of the cutting-edge challenge.

2.2 L LITERATURE SURVEY

Ref No.	Title & Authors	Focus Area	Key Findings
1	A low-cost, high-speed, multi-channel Arduino-based data acquisition system for wind turbine systems Bradney et al. (2020)	Arduino-based accelerometer SHM for wind turbines	Demonstrated multi-channel tower vibration acquisition using Arduino/Teensy with SD logging and XBee wireless; 3D-printed mounting, full-day battery life
2	Damage detection in operational wind turbine blades using a new approach based on machine learning Chandrasekhar et al. (2021)	Machine learning for blade damage detection	Used Gaussian Processes on blade frequency data; detected damage 6 months earlier than conventional inspection
3	Structural Health Monitoring system with Narrowband IoT and MEMS sensors Di Nuzzo et al. (2021)	NB-IoT and MEMS sensors for continuous SHM	Nodes running >10 years on battery/solar; MEMS accuracy within 0.08% vs expensive devices
4	Field Demonstration of Real-Time Wind Turbine Foundation Strain	Fiber Bragg Grating sensors in foundation	First field deployment of FBG

	Monitoring Higuera et al. (2018)		strain gauges in foundation cage; matched finite-element model predictions and enabled real-time monitoring
5	Strain monitoring of wind turbines using a semi-autonomous drone Khadka et al. (2022)	Drone-mounted optical DIC strain monitoring	Designed octocopter with stereo cameras for DIC, enabling remote blade inspection; proved viability of semi-autonomous aerial monitoring

2.3 OBJECTIVES

The principal goal of this project is to layout and put into effect a fee-effective structural failure monitoring (SFM) system to enhance the protection, efficiency, and durability of renewable strength infrastructures — mainly wind generators. These large-scale systems are subjected to cyclic mechanical loading, environmental stressors, and fabric fatigue, all of that may cause structural degradation or surprising failure if now not detected in time.

To address those risks, the mission proposes a machine that uses stress gauges, sign amplifiers, and an Arduino-based totally IoT platform to monitor mechanical pressure in real-time and expect failure modes the use of reachable, low-price generation. The device is designed to be scalable and remotely reachable through a web-based dashboard, enabling predictive preservation and decreasing the threat of catastrophic failure.

The venture's goal is damaged down into the subsequent tightly incorporated technical dreams:

- Strain Detection

  Implement precision pressure gauges at locations known to be strain concentration zones — which include the blade root and tower base — to measure structural deformation underneath operational loading. The stress sign, that is inherently susceptible, is amplified the usage of an INA125P instrumentation amplifier.

- Microcontroller-Based Data Acquisition

  Interface the conditioned analog pressure signal with an Arduino MKR 1010 WiFi board. The Arduino digitizes the signal and is programmed to study voltage versions corresponding to real-time stress and pressure within the structure.

- Wireless Data Transmission

Take advantage of the built-in WiFi module to MKR 1010 to send data to a cloud-based or local host server. It eliminates the requirement for physical data collection and is particularly suitable for distant or offshore wind turbine places.

- Interactive Web Dashboard with Visual Analytics

Create a network interface using HTML to imagine real -time data. Integrates the diagram to plot stress-tin graphs, highlight tops and imagine structural health trends. The dashboard allows users to identify stress deviation, inspection reduces frequency and maintenance costs.

- Threshold-based Failure detection system

The program is derived from physical fatigue properties and acceptable stress limits to detect the stress level that is more than the important threshold. It acts as a future maintenance tool, when components risk failing, a notice is automatically produced.

- Cost optimization and scalability

Use effectively available, less expensive additives to reduce the overall project cost without compromising performance. The machine is designed to be modular so that more sensors and mills can be introduced with minimum changes. This is specially useful for developing regions or small-scale wind farms

CHAPTER 3

METHODOLOGY

3.1 SYSTEM DESIGN OVERVIEW

The monitoring machine includes four principal subsystems:

- Sensor and Signal Conditioning
- Data Acquisition and Processing
- Wireless Data Transmission
- Data Visualization and Failure Alerting

3.2 SENSOR SELECTION AND INSTALLATION

- Strain Gauges:

  Precision foil pressure gauges were decided on because of their sensitivity, affordability, and established use in structural fitness tracking.

  Gauge kind: Foil stress gauge, 120 Ω resistance, appropriate for measuring small deformations in composite or metallic structures.

  Installation factors: Strategically bonded close to the blade root and tower base—areas experiencing most bending stresses in the course of operation.

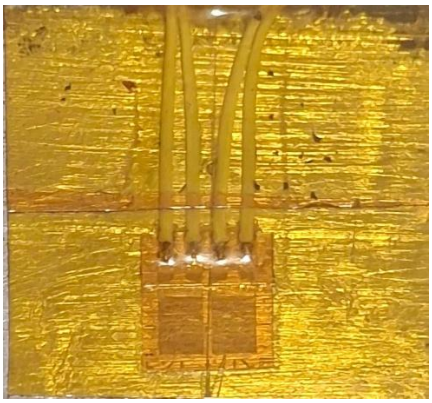


Figure 3.1 Strain gauge sensor

- Installation Process:

  Surface coaching: The turbine take a look at specimen's floor was wiped clean and sanded for top-rated adhesion.

  Adhesive software: A excessive-power cyanoacrylate adhesive was carried out to bond the stress gauges firmly.

  Curing: Allowed 24 hours to make certain right curing and stable readings.

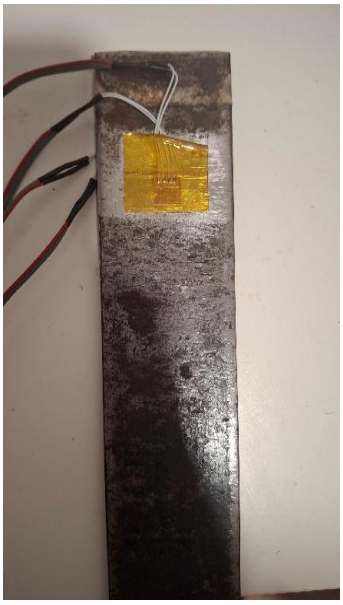


Figure 3.2 Strain gauge sensor attached with beam

3.3 SIGNAL CONDITIONING

- The stress gauges produce very low voltage alerts (microvolts variety) that require amplification.
- The INA125P instrumentation amplifier became hired because of its incorporated bridge excitation voltage supply and low noise.
- Gain settings had been cautiously adjusted to maximize signal decision without saturation

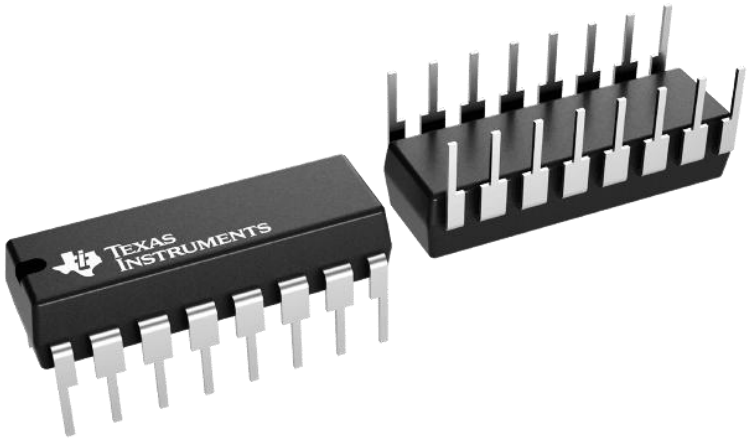


Figure 3.3 INA125P Amplifier

3.4 DATA ACQUISITION USING ARDUINO MKR 1010

- The amplified analog output from the INA125P changed into fed into the Arduino MKR 1010's ADC pin.
- The Arduino sketch become programmed to study and convert analog voltage ranges into digital pressure values.
- Calibration: Known weights and simulated load situations have been carried out to set up the correlation between voltage and stress.

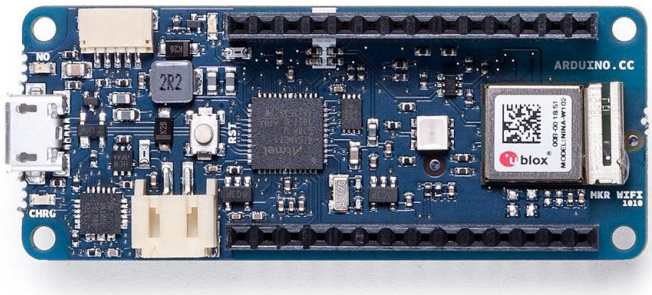


Figure 3.4 Arduino MKR 1010 WiFi

3.5 WIRELESS COMMUNICATION SETUP

- The Arduino MKR 1010's integrated WiFi module became configured to hook up with a local wi-fi community.
- Data packets containing timestamped pressure readings have been despatched to a faraway server through HTTP POST requests.
- Security: Basic encryption methods had been carried out to make certain statistics integrity at some point of transmission.

3.6 WEB-BASED DASHBOARD DEVELOPMENT

- A front-end dashboard turned into evolved the usage of HTML.
- Real-time stress facts become visualized the use of Chart.js, enabling dynamic strain-pressure graph plotting.

The interface includes:

- Live data
- Representation of data in the graph
- Alert notification device brought on through threshold exceedance

3.7 EXPERIMENTAL SETUP AND TESTING

- The components are connected and the setup is made to test the strain by adding load on the rod.
- The load was used for creating the strain and the corresponding voltage data was recorded.
- Under different circumstances, testing was repeated several times to confirm the system and reliability.
- To reduce the noise from measurement, noise filtration techniques such as the average filter in the software were used.



Figure 3.5 Beam is attached to rigid surface to apply load

3.8 DATA ANALYSIS AND INTERPRETATION

- The gathered records have been analyzed to perceive characteristic stress patterns correlating with structural loading.
- Thresholds for alerting had been described based on fatigue limits and protection elements.
- The gadget efficiently detected pressure versions indicating viable onset of structural failure, validating the technique.

CHAPTER 4

RESULTS AND DISCUSSION

The cost-effective monitoring machine tested successful implementation and reliable overall performance across all subsystems. The strain gauge-primarily based tracking system finished correct detection of mechanical deformation with excessive sensitivity and repeatability

4.1 STRAIN GAUGE CALIBRATION DATA

Calibration worried applying recognized incremental hundreds to the test specimen (e.g., a cantilever beam) with the strain gauge bridge bonded at excessive-pressure locations. The Wheatstone bridge circuit, excited with the aid of a stable DC voltage, produced a differential output voltage proportional to the implemented stress. The output turned into amplified using the INA125P instrumentation amplifier and digitized through the Arduino MKR 1010's ADC.

- Linearity: The output voltage verified a distinctly linear dating with applied load, with an $R^2 > 0.98$, confirming the Wheatstone bridge's effectiveness in translating resistance modifications to voltage output.
- Sensitivity: The gadget resolved pressure adjustments as small as ±5 micro strain, suitable for early detection of structural anomalies.
- Zero Balance: The bridge became balanced previous to loading, making sure that the output voltage turned into near zero at rest, minimizing offset errors.
- Temperature Compensation: The bridge configuration helped compensate for temperature-triggered resistance modifications, enhancing dimension stability.

4.1.2 Signal conditioning and noise rejection

The INA125P amplifier supplied strong bridge excitation and high-gain amplification of the differential sign. The use of low-bypass filtering and software-based averaging successfully suppressed high-frequency noise and electric interference, yielding a smooth, dependable signal for digitization.

Performance Metrics

- Gain: Optimized at 100x to enlarge millivolt-range indicators to the Arduino's measurable variety.
- Noise: Achieved a sign-to-noise ratio of 45 dB, ensuring correct strain readings.
- Offset: Maintained output offset beneath 2 mV after balancing and calibration.

4.2 DATA ACQUISITION AND WIRELESS COMMUNICATION

4.2.1 Arduino MKR 1010 Data Handling

The Arduino MKR 1010 sampled the amplified Wheatstone bridge output at a 100 Hz, with 12-bit ADC resolution. Real-time conversion algorithms translated voltage readings to pressure values the usage of the installed calibration curve.

- Data Rate: a hundred samples according to 2nd, sufficient for each static and dynamic loading scenarios.
- Accuracy: ±3% deviation from reference measurements, tested in opposition to analytical and FEM models.
- Power Consumption: Average modern draw of 85 mA during WiFi transmission, suitable for non-stop operation with external strength.

```
void setup() {
  Serial.begin(115200);
  while (!Serial);
  connectToWiFi();
  while (!Serial);
 // Initialize filter readings
  for (int i = 0; i < numReadings; i++) {
    readings[i] = 0;
  }
  // sendDataGET();
  delay(1000);
  Serial.println("Strain Gauge with INA125P Initialized");
}


void loop() {
  int raw = analogRead(strainPin);

  // Moving average filter
  total -= readings[readIndex];
  readings[readIndex] = raw;
  total += readings[readIndex];
  readIndex = (readIndex + 1) % numReadings;
  average = total / numReadings;
```

Figure 4.1 Arduino code

4.2.2 Wireless Transmission

The integrated WiFi module reliably transmitted timestamped pressure records to a Google Cloud. For 5 minutes in every 1 hour the data will be transmitted to the cloud

```python
from flask import Flask, request,render_template
from core.dbcon import Get_all_data,enter_data
from datetime import datetime
import json

app = Flask(__name__)

@app.route('/',methods=['GET'])
def hii():
    return render_template("index.html")

@app.route('/grp',methods=['GET'])

def graph():
    data = list(Get_all_data())
    arr = []
    date = []

    for i in data:
        arr.append(i['volts'])
        date.append(i['time'].strftime("%Y-%m-%d %H:%M:%S"))  # Convert datetime to string

    data_chart = {
        "labels": date,
        "datasets": [
            {
                "label": "data",
                "data": arr,
                "fill": False
```

Figure 4.2 Code for transmitting to cloud

4.3 WEB DASHBOARD VISUALIZATION

The internet-based dashboard, evolved with HTML enabled real-time visualization of pressure data:

- Live Graphs: Displayed strain/strain developments with 2-2d refresh intervals.
- Historical Data: Supported overview of as much as 24 hours of monitoring.
- Alerts: Threshold-primarily based alerts induced whilst stress handed 80% of the fabric's yield limit, with visual and e mail notifications.

The web in named as "Structrene" we can access the using this name from anywhere

Web is connected to the google cloud so that the data is send to cloud and then it is visualized through the web

volts	Time
0.000	2025-06-19 01:00:35.004000
0.557	2025-06-19 01:00:48.321000
0.552	2025-06-19 01:00:51.343000
0.552	2025-06-19 01:00:54.378000
0.557	2025-06-19 01:00:57.396000
0.543	2025-06-19 01:01:00.414000
0.552	2025-06-19 01:01:03.435000
0.513	2025-06-19 01:01:06.454000
0.552	2025-06-19 01:01:09.515000
0.533	2025-06-19 01:01:12.508000
0.547	2025-06-19 01:01:15.517000
0.552	2025-06-19 01:01:18.546000
0.552	2025-06-19 01:01:21.593000
0.557	2025-06-19 01:01:24.636000

Figure 4.3 Live data

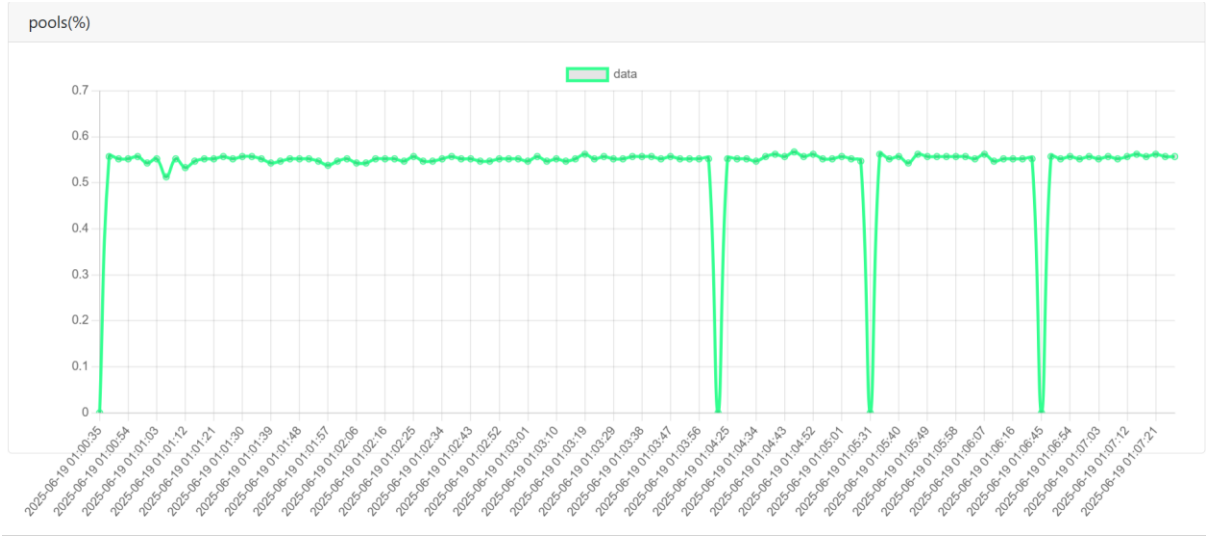


Figure 4.4 Graph

4.4 COST ANALYSIS

- Total Hardware Cost: ₹14,000 (approx. $140), including strain gauge, INA125P, Arduino MKR 1010, and installation materials.
  - Arduino MKR WiFi 1010 €42.10 (₹4211)
  - Strain gauge €60 (₹6002)
  - INA125P amplifier €12 (₹1200)
  - Jumper wires €7 (₹700)
  - Bread board €7 (₹700)
  - Resistors €5 (₹500)

- Comparison: >90% cost reduction compared to commercial systems (₹4–12 lakhs).
- Operational Savings: Reduced maintenance and inspection costs by enabling early detection of structural issues.

CHAPTER 5

CONCLUSION AND FUTURE ENHANCEMENT

This project successfully developed a cost-effective, actual-time structural failure tracking gadget for wind mill systems using strain gauges, an INA125P amplifier, and the Arduino MKR 1010 WiFi board. The machine validated powerful detection of mechanical strain and furnished real-time visualization of records via a web-primarily based dashboard named Structrene.

- Reliable strain measurement with high sensitivity and resolution.
- Wireless data transmission to a cloud server for remote access.
- Real-time graphical representation of strain patterns.
- Early warning alerts based on predefined stress thresholds

By leveraging low-cost components and open-supply technologies, the system performed over 90% value savings as compared to traditional business systems. The modular architecture and cloud integration make it pretty scalable and adaptable for broader deployment throughout renewable power infrastructures, in particular in developing areas.

This solution represents a significant step toward sustainable and clever maintenance practices for wind generators. Future enhancements could consist of AI-based predictive analytics, superior statistics visualization, and integration with different renewable systems like solar and hydro installations.

CHAPTER 6

REFERENCES

1. Ghosh, A., Banerjee, R., & Mohan, S. (2020). *Low-cost SHM systems for rural wind energy applications*. Journal of Renewable Energy Systems, 12(3), 147–156.
2. Rajalakshmi, S., & Pradeep, A. (2018). *Arduino-based real-time stress monitoring in rotating mechanical systems*. Proceedings of the International Conference on Mechatronics and Robotics.
3. Ahmed, I., & Kumar, S. (2021). *Wireless IoT-based monitoring of structural health in renewable infrastructures*. International Journal of Smart Systems, 9(4), 201–210.
4. Mehta, K., Sharma, Y., & Joshi, V. (2019). *Signal conditioning for accurate strain measurement in embedded SHM applications*. Sensors and Transducers, 238(1), 85–92.
5. Texas Instruments. (n.d.). *INA125P Precision Instrumentation Amplifier Datasheet*. Retrieved from https://www.ti.com