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COLLEGE OF SCIENCE AND TECHNOLOGY

AFRICAN CENTER OF EXCELLENCE IN INTERNET OF THINGS

Research Thesis Title: Design and implementation of IoT-Based Structural Health Monitoring System for Suspension Bridges.

A dissertation submitted in partial fulfilment of the requirements for the award of Master of Science degree in internet of things: wireless intelligent sensor network.

Submitted by:

SHYAKA Olivier (REF.No: 221031220)

December 2023

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December 2023

Declaration

I SHYAKA Olivier, Master 'student from African Center of Excellence in internet of things, at University of Rwanda. I declare that this research thesis is my own original work and it has never been presented before anywhere in the world.

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Date: 01/12/2023

Bonafide certificate

This is to certify that this submitted Research Thesis work report is a record of the original work done by **SHYAKA Olivier (Ref. Nu: 221031220)**, MSc. IoT-WISNET Student at the University of Rwanda / College of Science and Technology / African Center of Excellence in Internet of Things, the Academic year 2022/2023.

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Acknowledgement

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Abstract

Suspension bridges are distinctive bridge designs that make use of suspended cables and towers and are frequently seen in difficult terrain. This research project developed an IoT system to monitor the structural health of cable-supported suspension bridges in remote areas in real-time.

The designed system takes into account the structural characteristics of suspension bridges and their exposure to dynamic loads and environmental factors, and data collection is done on bridge structural and environmental parameters like loading, vibration, strain, water level, humidity, soil moisture and corrosion impact by using sensors installed on key parts of the monitored bridge and collected data transmitted to a remote server.

The system addresses the need for continuous and remote monitoring, detection of structural abnormalities and potential failures. The system allows to determine when maintenance and repair are needed and send out notifications to personnel in charge of maintaining the bridge and this shall help to reduce the possibility of catastrophic suspension bridge breakdowns.

The IoT-Based Structural Health Monitoring System for Suspension Bridges tackles the particular difficulties associated with suspension bridges located in distant areas and rugged terrains to assure their optimal operation and the project output is intended to increase the monitoring capabilities of suspension bridges and enable early interventions, which will increase their safety, reliability, and longevity.

List of Acronyms and Symbols

ACEIoT: African Center of Excellence in Internet of Things.

AI: Artificial Intelligence.

B2P: Bridge to prosperity.

BD: Big Data

SBCs: single-board computers

CDPWJE: Curvature Difference Probability waveform.

GPRS: General Packet Radio Services.

GPS: Global Positioning System.

GSM: Global System for Mobile Communications.

IP: Internet Protocol.

KNN: K-Nearest Neighbors.

LCD: Liquid crystal display.

MCDWJE: Mean Normalized Curvature Difference of Waveform Jerk Energy.

NN: neural network.

MySQL:My Structured Query Language

PHP: Hypertext Preprocessor

UR:University of Rwanda

RAM: Random Access Memory

RF: Random Forest.

RISC: Reduced instruction set computer.

RMS: Remote Monitoring Solution

SBC: single-board computer.

SHM: Structural health monitoring.

SMS: Short Message Service

SVM: support vector machines.

TCP: Transmission Control Protocol.

WBHM: Wireless Bridge Health Monitoring.

Wi-Fi: Wireless fidelity.

WiSenet: Wireless Intelligent Sensor Networking.

List of Tables

Table 1: Technical specification of Arduino Mega 2560.	22
Table 2: Actuation Rules and conditions.	36

List of Figure

Figure 1:Suspension bridge Parts[3].....	1
Figure 2:Nyirakibehe suspension bridge (Source: Taken by myself).....	3
Figure 3:Marengé Suspended bridge(Source: Taken by myself).....	11
Figure 4:Nyirakibehe suspension bridge_Photo2 (Source: Taken by myself).....	12
Figure 5:Perception of bridge users on bridge structural health.....	13
Figure 6:Recommended parameters to be monitored.....	14
Figure 7:Top-down list of parameters recommended by B2B for being monitored.....	14
Figure 8:System units.....	17
Figure 9: Accelerometer sensor (ADXL335).....	17
Figure 10: Flex sensor SEN52.....	18
Figure 11:Soil moisture sensor (SN54/R14).....	18
Figure 12:Water proof Ultrasonic Sensor.....	19
Figure 13:Load cell sensor.....	19
Figure 14:Buzzer.....	20
Figure 15:Blue, Yellow, Red and Green LEDs.....	20
Figure 16:Servo Motor.....	21
Figure 17:Arduino Mega 2560.....	21
Figure 18:GSM/GPRS SIM900.....	23
Figure 19:System Flow Chart.....	24
Figure 20:Embedded system diagram.....	26
Figure 21:Circuit Diagram.....	27
Figure 22:Physical Prototype.....	28

Figure 23:User interface.	30
Figure 24:Backend.	31
Figure 25:Prototype setup.	34
Figure 26:Arduino sensor data reading.	35
Figure 27:Flooding senario (Red LED ON and bridge closed)	37
Figure 28:Overweight scenario.....	37
Figure 29:SMS notification.....	37
Figure 30:Dashboard.....	38
Figure 31:Water level time series graph.	39
Figure 32:Cable bending time series graph	39
Figure 33:Soil moisture time series graph.	40
Figure 34:Time series graph for accelerometer data.....	41
Figure 35:Live load and accumulated time series weight graph.....	41

Table of Contents

Declaration.....	ii
Bonafide certificate.....	iii
Acknowledgement.....	iv
Abstract.....	v
List of Acronyms and Symbols.....	vi
List of Tables.....	viii
List of Figure.....	ix
Chapter 1: Introduction.....	1
1.1. Background and Motivation.....	1
1.2. Problem Statement.....	2
1.3. Research questions.....	4
1.4. Study Objectives.....	4
1.4.1. General Objective.....	4
1.4.2. Specific objectives.....	4
1.5. Hypothesis.....	5
1.6. The scope of the study.....	5
1.7. Significance of the Study.....	5
1.8. Organization of the Study.....	5
1.9. Conclusion.....	6
Chapter 2: Rationale and Literature Review.....	7
2.1. Related work.....	7
2.2. Gaps.....	10
2.3. Contribution.....	10

Chapter 3: Research Methodology.....	11
3.1. Research approach.....	11
3.2. Data Collection.....	11
3.2.1. Interview.....	11
3.2.2. Observation.....	12
3.4. Design and development of prototype system	15
Chapter 4: System Analysis and Design.....	17
4.1. Hardware Components.....	17
4.1.1. Sensing unit	17
4.1.2. Actuating unit	19
4.1.3. Processing unit.....	21
4.1.4. Communication Unit	23
4.2. System Flow Chart.....	24
4.3. Embedded System block diagram	25
4.4. System circuit diagram.....	27
4.5. Physical prototype system.....	27
4.6. Data transmission	28
4.6.1. POST Method for Hypertext Transfer Protocol (HTTP).....	28
4.6.2. Data Transmission Process	28
4.6.3. Advantages of Cellular Communication and HTTP.....	29
4.7.1. Embedded System Layer	30
4.7.2. Communication Module	30
4.7.3. Remote Server Layer	30
4.8.1. Remote Cloud Platform: AwardSpace	31

Reasons for Choosing AwardSpace	31
4.8.2. Backend Components	31
4.8.3. Frontend Components.....	32
4.8.4. Integration of Languages	32
Chapter 5: Results and Analysis	34
5.1. Data Collection Results.....	34
5.2. System Prototype.....	34
5.2.1. Prototype Setup.....	34
5.3. Sensor data readings.....	35
5.4. Prototype system actuation.....	36
5.4.1. Servo motor & LED Actuation simulation.....	37
5.4.2. SMS notification.....	37
5.5. Remote data acquisition and Visualization	38
5.5.1. Water level results and visualization	39
5.5.2. Suspension cable bending results and visualization.	39
5.5.3. Soil moisture results and visualization.....	40
5.5.4. Accelerometer results and visualization.....	40
5.5.5. Weight data results and visualization	41
Chapter 6: Conclusion and Recommendation.....	42
6.1. Conclusion.....	42
6.2. Recommendation.....	42
References.....	43
Appendix1: Interview questionnaire for bridge users.....	50
Appendix 2: Interview questionnaire for B2P Experts	52

Chapter 1: Introduction

Bridges are a very old art of man and are a built structures designed to traverse a physical obstacle such as a roadway, railroad track, valley, river, or body of water[1]. The purpose of a bridge is to provide a smooth route that would otherwise be difficult or uneven for people or cargo to travel over an obstruction. According to the structural configuration[2], There are five primary types of bridges that may be distinguished: cantilever, beam, arch, truss, and cable-supported bridges. Suspension and cable-stayed bridges are examples of cable-supported bridges. A suspension bridge is a kind of bridge where the bridge deck or roadway is supported by hanging cables. It is characterized by its main load-bearing elements, which are the vertical suspension cables anchored at each end of the bridge and attached to large towers or pylons. The deck is suspended from these cables, creating a visually distinctive appearance with a gently curved or catenary shape[3]. Particularly, in Rwanda all suspension bridges are designed for pedestrian and sometimes bicycles, and moto cycles use them, but vehicle can never use these bridges. These bridges are called trail bridges[4].

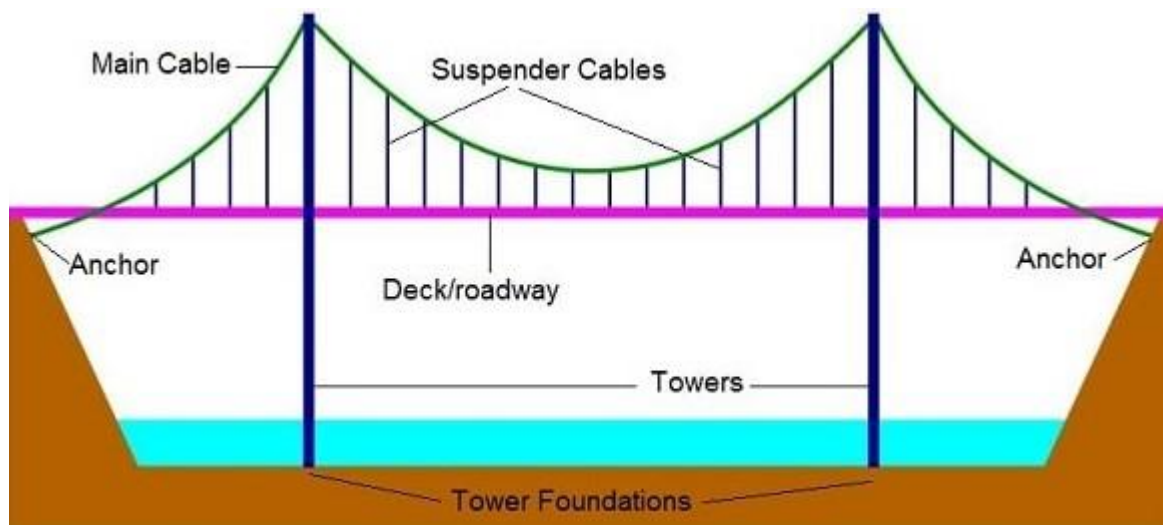


Figure 1: Suspension bridge Parts[3]

1.1. Background and Motivation

In general bridges are one of the most susceptible infrastructures since they are present almost everywhere and in a variety of environments, making them subject to frequent external influences[5]. The condition of the bridge is significantly influenced by factors including floods, friction, the weight on the bridge, temperature, fractures, vibrations, the age of the bridge, and

failure to perform timely maintenance[6]. These factors can cause bridges to collapse, putting lives and property at risk. In order to prevent damage and degradation, bridges must be frequently monitored, and this has to be done in a consistent and effective way[7].

Traditional methods of bridge safety monitoring and management consist of visual assessments, use of large-size electronic equipment and periodic maintenance which are inaccurate and very expensive. The use of the Internet of Things is a solution to this problem[8]. Therefore, An IoT-based system for real-time monitoring and predictive maintenance can provide a more accurate and cost-effective approach to bridge inspection and maintenance to avoid catastrophic failures.

The system proposed in this project is for monitoring suspension bridges located in villages that are very essential for the economic growth of developing countries including Rwanda where pedestrian bridges are largely used for daily activities in rural area communities[9]. The proposed system will use different sensors placed at different parts of the bridge to collect data on various parameters such as vibrations, strain, water level, soil moisture. The data will then be transmitted using a GSM module to a cloud server, where predictive algorithms will be used to analyze the data and predict when maintenance is required. Real-time alerts will be provided when the data indicates that the bridge is at risk of failure.

At present there isn't any other automatic system to monitor the structural health of bridges in Rwanda, but the literature review shows that in developed countries they are various IoT systems proposed to monitor bridges[6]. What makes the proposed system different from the rest is that it will be designed in a such way that it can monitor bridges located in remote and rural areas and consume low energy and will use GSM modules for data transfer.

1.2. Problem Statement

Globally, bridges play an important role in transportation infrastructure and most importantly in Rwanda and other developing countries trail bridges play a crucial role in the daily lives of rural communities. These bridges link communities and foster economic development by providing crucial access to marketplaces, hospitals, schools, and other essential services[10]. However, as these bridges get aging the need for frequent monitoring and maintenance increases to ensure their safety and reliability.

The collapse of bridges may have disastrous consequences including loss of life and particularly rural communities may also lack alternative routes to access essential services[11]. Moreover, Rwanda's mountainous terrain and heavy rainfall make it susceptible to natural disasters such as landslides and flooding, which can damage bridges and render them unsafe for use[12]. In recent past, these events have damaged bridges in the main part of the country including the Bugesera-Ngoma bridge washed away by floods in 2020[13].



Figure 2:Nyirakibehe suspension bridge (Source: Taken by myself).

In Rwanda they are a lot of suspension trail bridges that are being constructed in different district of the country in partnership with ministry of infrastructure and bridge to property organization where 355 bridges will be built by 2024[14]. For this reason, there is a pressing need to develop innovative and effective solutions to ensure the safety and longevity of these bridges.

Based on available solutions in the related work to monitor the structural health of bridges and reference to the gaps identified regarding IoT-enabled bridge structure monitoring, and the nature

of suspension trail bridges used in rural areas in Rwanda[15], this research will provide a tailored IoT solution that will take into account the unique characteristics and challenges of these bridges, such as limited access to electricity and Wi-Fi connectivity.

Acknowledging the challenge of limited historical data on structural health, especially for suspension trail bridges[16], this research will implement data-driven approaches to identify damages and anomalies in bridge structure for predictive maintenance by collecting and analyzing real-time data from sensors deployed on the bridges.

1.3. Research questions

- 1.Are there existing IoT solutions for monitoring suspension bridges and what are the gap vis a vis the suspension trail bridges located in Rwanda?
- 2.How to determine key parameters and factors that should be monitored to assess the structural health of suspension bridges and how to build an appropriate data acquisition system?
- 3.What are the suitable algorithms and techniques for analyzing the collected data, providing timely alerts, and predicting maintenance needs for suspension bridges?
4. What challenges and limitations exist in implementing an IoT-based monitoring system for suspension bridges in remote areas.

1.4. Study Objectives

1.4.1.General Objective

The main objective of this research is to design a real time IoT based SHM for suspension trail bridges with the ability to predict and schedule required maintenance and send warning alerts in case the bridge faces an abrupt damages or situation that shall lead to the collapse before the maintenance is done.

1.4.2.Specific objectives

- 1.To design and assemble a hardware setup for monitoring the structural health of suspension bridge.
- 2.To collect data on various parameters such as loading, vibration, strain, water level, humidity, soil moisture by using the sensors installed on the bridge.

- 3.To transfer collected data in real time on remote server.
- 4.To analyze the collected data and predict when maintenance is required.
- 5.To provide real-time alerts when the data indicates that the bridge is at risk of failure.

1.5. Hypothesis

Integrating IoT for structural health monitoring in suspension bridges enhances safety and longevity by providing real-time data for early issue detection and informed decision-making.

1.6. The scope of the study

This study is limited to the designing and implementation of a prototype IoT system capable of monitoring the structural health of suspension trail bridges. The designed system will be capable of determining the needed maintenance in advance, providing alerts and preventing incidents when bridge structural health reaches critical conditions.

1.7. Significance of the Study

The significance of this research lies in its potential to address critical aspects of suspension bridge safety, maintenance, and research advancement by detecting structural issues before they lead to failure and providing early warning alerts, the system can help prevent catastrophic accidents and ensure the continued safe operation of bridges.

The proposed system can lead to substantial cost savings in bridge maintenance by reducing the need for frequent visual inspections and enabling more targeted maintenance practices.

1.8. Organization of the Study

This research thesis document is structured as follows:

Chapter one serves as an introductory section, encompassing the study's background, motivation, study objectives, hypothesis, limitations, areas of interest, and a concluding statement.

Chapter two delves into previous research efforts, identifying gaps in the existing literature and elucidating how this study aims to enhance and address those gaps.

Chapter 3 provides an overview of the techniques utilized in this study as well as a description of the instruments and processes that were applied.

The analysis and design of the system are covered in detail in Chapter 4.

The findings of the study are presented, analysis is done, and discussions are held in Chapter 5.

The thesis is concluded in Chapter 6, which also offers conclusions, suggestions, and ideas for more research.

1.9. Conclusion

This chapter, the background and motivation for this study are outlined to establish its significance. A specific problem statement concerning the need for enhanced structural health monitoring in suspension bridges is thoroughly discussed. The chapter also delineates the research's scope and limitations to provide a clear boundary for the study. Furthermore, the organizational structure of the research is presented, offering readers a roadmap for subsequent chapters. Finally, a strong interest in advancing this field of study is expressed, underscoring its potential to improve the safety and sustainability of suspension bridges.

Chapter 2: Rationale and Literature Review

To be able to propose an IoT solution for monitoring the structural health of bridges, it is important to review related works done by other researchers and investigate the problems they have addressed, study the methodology approach they used, and results found. This eventually leads to identify the gaps in the previous related research and motivate the justification to undertake this proposed research for an IoT-based system for real-time monitoring and predictive maintenance.

2.1. Related work

Gorakh Pawar P et al. built a prototype of IOT-embedded system using series of small single-board computers (SBCs) processor, Tensilica L106 32-bit RISC processor and load cell sensors, to control the live load on the structural elements of the bridge[17]. Collected data are sent on Blynk cloud platform using Wi-Fi module (ESP8266) for visualization and analysis. The deployment of load cell sensors was supposed to be done during the construction work which makes this prototype inappropriate for monitoring bridges that have already been built.

In [7] Bhondave, A et al. proposed Bridge Health Monitoring System using IOT that consists of sensors like flex sensors, ultrasonic sensor to collect data and send them on thingspeak cloud database through Wi-Fi module by TCP/IP stack as sensing devices. The implementation of this prototype in rural areas on the bridge where there is no wifi would be impossible.

The system proposed in[18] by McKerahan, T. helps to monitor and maintain the condition of the bridges in the water bodies and to prevent the public on the bridge at the emergency situations. Apart the monitoring and alert, this system includes a barrier system so that whenever the parameters of the bridge cross the value the barrier will close, and the bridge traffic will be stopped. Its disadvantage is that it only uses Wifi and the system has is very high power consumption.

An approximative formula for estimating the cumulative displacement at the expansion joint for long-span suspension bridges that is suitable for manual calculations was developed based on findings from Li G et al's research on Wear Evaluation on Slide Bearings in Expansion Joints Based on Cumulative Displacement for Long-Span Suspension Bridge under Monitored Traffic Flow[19].

The study carried by La H et al concentrated on gathering and evaluating data from bridge decks, resolving issues with software and analysis along the route, and making recommendations. Subsequent endeavors center on developing an algorithm that integrates sensor and camera information to provide a more thorough comprehension of bridge deck circumstances[20].

VH P, Shubhangi D designed and implemented a prototype for Real time monitoring of bridge using Wireless technology by using sensors connected on Raspberry pi and sending data on server through wifi and at the same time displaying the status on the screen to avoid accident. The system is capable of closing the gate of the bridges by using a servo motor if sensor data gets above the peak value. The implementation of this system is very costly, and it can't be deployed at the bridge located in areas without Wi-Fi[21].

A technique to assess fatigue damage and forecast the life of bridge-deck sections in already-constructed bridges is presented in the study by Li Z et al [22]. It takes into account structural components and connections, using continuum damage mechanics to create a fatigue damage model, and examines strain history data from structural health monitoring systems. It also presents an updated method for comparing and validating the fatigue damage model's predictions.

An IoT-based bridge safety monitoring system was developed by Jin-Lian Lee et al[23]. It consists of a monitoring device placed in the bridge environment, communication devices linking the monitoring devices, a dynamic database storing data about the condition of the bridge, and a cloud server that computes and analyzes data transmitted from the monitoring devices. This study uses ZigBee for communication to transmit data on cloud.

Amira Zrelli et al [24] adopted the use of WBHM using IoT and implemented two methods MCDWJE and CDPWJE to detect and measure damage in bridges. This project uses raspberry pi and Wi-Fi and Health of the bridge only monitored considered is vibrations.

The technique used to track the scouring depth of the bridge piling foundation is presented in the article in[25]. Using a suggested scour detection technique, the robust sensor system can identify the bridge scour in real time. This technique is only useful for bridges that are situated over bodies of water since it can only measure the scouring depth.

This paper [26] presents an investigation on the premature damage to expansion joints and bearings of long-span suspension bridges, in which failure patterns, locations and mechanism are presented and discussed.

The study in the paper of Chakrabarti et al. used an accelerometer and flex sensor to measure inclined angles and analyze bends where it is mounted. The data was sent to a smartphone app via Bluetooth Low Energy (BLE) for real-time viewing, but the system is not efficient enough. To improve safety, we can also monitor some more advanced structural parameters using IoT-enabled devices or sensors[27].

Mohapatra A. et al.[28] proposed a system for the estimation of load distribution on suspension bridge using FBG sensors and IoT where two machine learning models which are KNN and RF are implemented in the prototype of suspension bridge structure. The results showed that RF model has a very good prediction accuracy. The implementation and deployment of this prototype is very expensive as it couldn't be done by using normal microcontroller boards like Arduino or raspberry pi and data transfer on cloud server from a bridge located in a remote area requires high-cost infrastructure.

The concept of Bridge SHM aided by BD and AI was revised in [29] from condition assessment to damage detection. This research examined the use of many BD and AI techniques and suggested the pipeline of BD analysis, while recommended AI techniques are represented by deep learning. The conclusion is that even though there are a lot of techniques, their applications in real bridges still need to be investigated.

Zinno R et al. in [17] explored the use of Artificial Intelligence (AI) for monitoring the health of bridges. Various machine learning methods, including fuzzy-c-means, k-means clustering, KNN, NN, SVM, decision tree, deep learning, and random forests algorithm, are analyzed. The study finds that AI, particularly artificial neural networks, has been successfully applied to detect bridge damage. However, there are still challenges to overcome. The sensitivity of neural networks to input changes and the decrease in accuracy with limited data pose concerns[30]. Nevertheless, deep learning techniques, with their multiple layers and parameters, offer advantages for handling large datasets. Despite the benefits, deep learning methods have limitations, such as difficulties in replicating human perception in vibration- or vision-based algorithms[31]. Additionally, generalized numerical models struggle to accurately simulate environmental challenges[32].

2.2. Gaps

The reviewed related work tackled different problems in bridges monitoring by using different IoT approaches and the focus of all of them is on big bridges used by vehicles and none of related work considered to monitor trail bridges located in rural areas. For this reason, the considered way of communication to transfer data on server is using Wi-Fi module, zig bee or Lora which are not practical on the case of suspension trail bridges located in remote area. The literature shows only the research done in countries with advanced technology but for developing country including Rwanda there is a big gap, no research yet done in this field. The predictive maintenance of bridges is still a challenge because they are few historical data on structural health of bridges in general but on in particular, suspension trail bridges like the ones we have in Rwanda there is almost no historical data.

2.3. Contribution

The proposed research focuses on leveraging IoT technology to monitor suspension bridges and implement predictive maintenance. A notable contribution of the research is that the designed system will be capable of being deployed on cable suspension bridges located in a rural area where there is no Wi-Fi and electricity. This allows for the extension of IoT technology to remote locations, where infrastructure may be limited.

the conversation[33]. The sample size for this interview is 20 people, ten from Marenge and ten from Nyirakibehe.

Data from bridge experts are collected in the organization called bridge to prosperity (B2P) that is constructing suspension trail bridges around the country in Rwanda. So far, they have constructed more than 150 bridges in different districts[34]. We used semi-structured interview method where we have set a meeting with bridge designers and technicians. Before the meeting we administered open ended questionnaire to guide the interview conversation.



Figure 4:Nyirakibehe suspension bridge_Photo2 (Source: Taken by myself).

3.2.2. Observation

Observation is crucial in understanding the real problem to be solved[35]. On the case of suspension bridges, it was very important to go on on-site and observe the structural health issues and all dynamics these bridges face in Rwanda. The observation helped to go beyond what is in papers or what people say. By directly observing the bridges and connecting it with theoretical

knowledge and insights from interviews, it is possible to develop a suitable IoT solution, applicable to the real issues faced by suspension bridges in Rwanda.

3.3. Analysis of collected data.

The ball charts in Figure 5 and Figure 6 summarize the results of interviews with people who use suspension bridges.

A. Perception of bridge users (Marengye & Nyirakibehe) on structural health of suspension bridges.

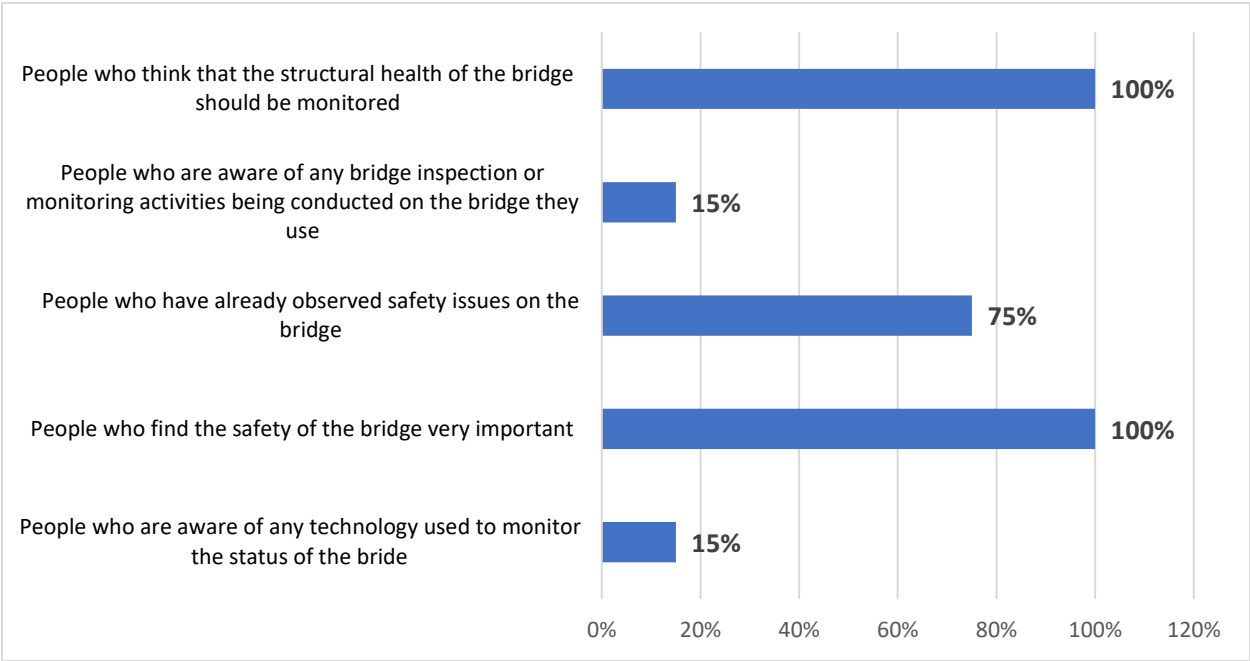


Figure 5: Perception of bridge users on bridge structural health.

B. Parameters recommended by bridge users for being monitored.

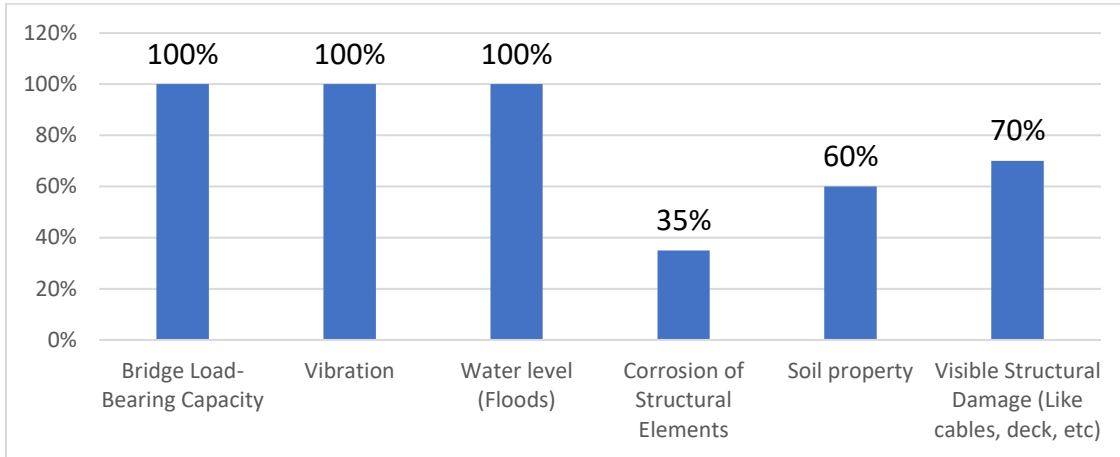


Figure 6: Recommended parameters to be monitored.

The interview with B2P gave also very important information on structural health monitoring of suspension bridge and the key results are summarized in Figure 7.

Top-down list of parameters recommended by B2P for monitoring.

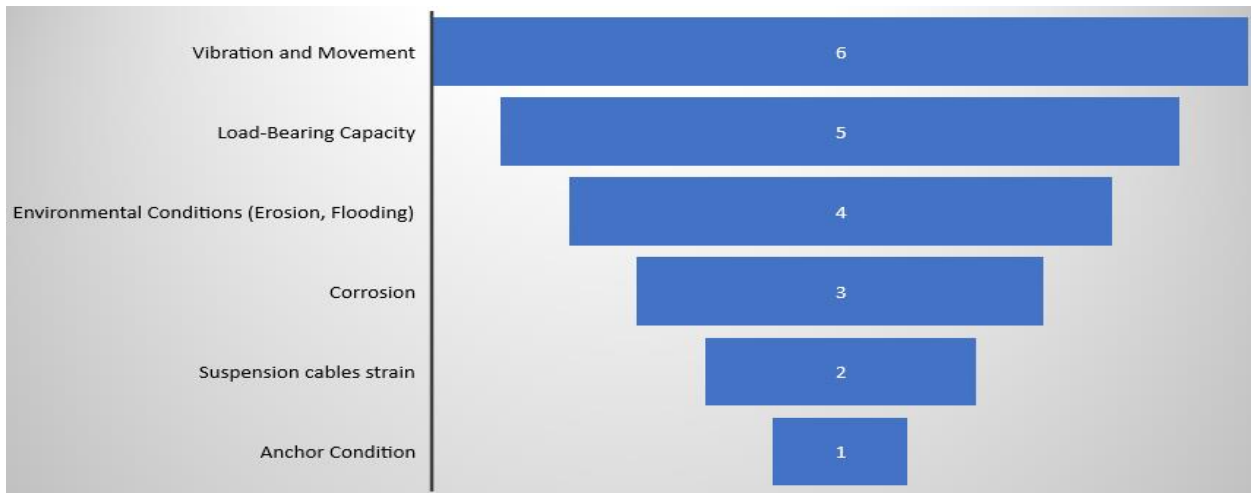


Figure 7: Top-down list of parameters recommended by B2B for being monitored.

After carefully analyzing the information gathered from both interviews and on-site observations, we now know what kind of IoT system we need. The input from the population, bridges experts and observations helped us figure out the specific requirements for a needed Structural Health Monitoring system addresses the unique challenges posed by suspension bridges.

3.4. Design and development of prototype system

Based on the information obtained on structure health issues of a suspended bridge and the monitoring requirements, the needed IoT monitoring system should have the following distinctive functionalities to ensure comprehensive monitoring and timely response for a suspended bridge.

Load Monitoring: The needed system must have a sensor to continuously monitor the load on the bridge. This data is crucial for assessing stress levels and ensuring that the bridge operates within safe limits[36].

Suspension Cable Bending monitoring: It is also important to incorporate a sensor dedicated to measuring the bending of suspension cables, providing real-time information on cable integrity. Any deviations from expected values trigger alerts for prompt intervention[37].

Vibration and Movement Tracking: To identify irregularities that might indicate structural issues or external influences, the system should be equipped with an accelerometer or vibration sensor[38].

River Water Level Monitoring: An ultrasonic sensor should be positioned strategically under the bridge to monitor the water level in the river[39]. This information is vital to assess potential flood risks and make informed decisions regarding bridge closure to prevent incidents.

Soil Moisture Assessment: Sensors around bridge pillars and foundations measure soil moisture levels. This data aids in understanding the soil's stability, helping prevent foundation issues that could compromise the bridge's integrity[40].

User Warning System: In case of identified risks, the system is required to issue warnings to bridge users through alert mechanisms, such as lights or sound signals, prompting them to avoid using the bridge until the situation is resolved.

Automatic Bridge Closure: Upon detecting a critical risk, the system should have the ability to automatically trigger the closure of the bridge. This immediate response prevents potential incidents and ensures the safety of users.

Real-Time Data Access for bridge controllers: Bridge control personnel must get real-time data, enabling them to monitor the bridge's health continuously. This data-driven approach will

empower them to schedule preventive maintenance and repairs based on the ongoing analysis. The system should also employ predictive analytics to issue alerts to control personnel before potential incidents occur. This proactive feature allows for timely intervention, reducing the risk of catastrophic events.

Off-Grid and cellular network connectivity Capability: Considering the infrastructure challenges in remote areas where most of these bridges are built, the system should be able to utilize solar power and connects via cellular networks which is the only way of communication in those areas. This way, it keeps working in remote spots, ensuring real-time data and alerts for bridge control.

By combining these functionalities in system prototype design, will give robust framework for the efficient monitoring, management, and maintenance of suspended bridges, prioritizing safety and proactive decision-making.

Chapter 4: System Analysis and Design

This chapter presents the design and analysis of IoT based SHM for suspension bridges.

4.1. Hardware Components

The hardware aspect of the system comprises five units: Sensing, actuating, processing, and communication and power units, each aligned with specific system functionalities.

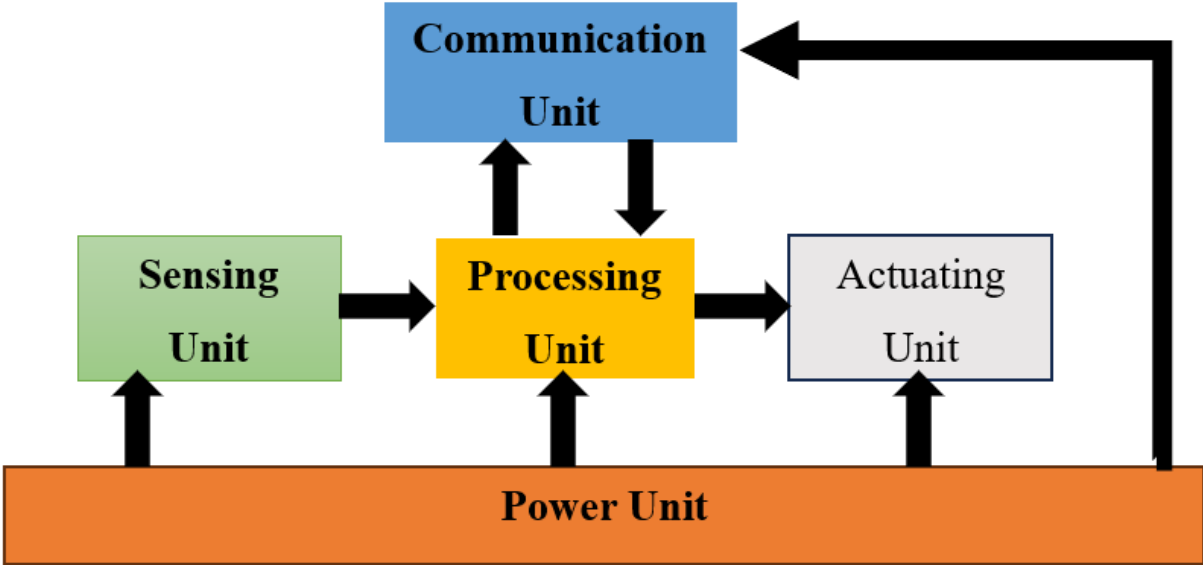


Figure 8: System units

4.1.1. Sensing unit

Based on the preliminary review and data analysis, the following sensors are used on the prototype system.

A. Accelerometer (ADXL335)

ADXL335 is a three-axis accelerometer sensor that measures acceleration in three dimensions (X, Y, Z). It is used to monitor the vibrations and accelerations experienced by the bridge structure[41]. Anomalies in the acceleration data can indicate potential structural issues or excessive movement.

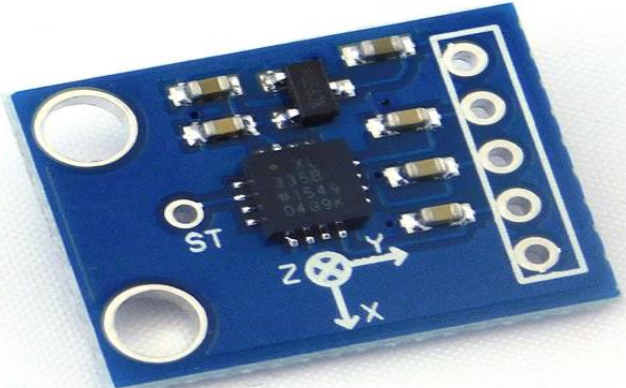


Figure 9: Accelerometer sensor (ADXL335)

B.Flex Sensor (SEN52)

The SN52 sensor measures changes in resistance based on how much it is bent. Positioned on the suspension cable, this flex sensor actively monitors the cable's curvature. Given that cable bending is subject to specific limits, any deviation could potentially indicate structural deformation or stress on the cable.



Figure 10: Flex sensor SEN52

C.Soil Moisture Sensor (SEN54/R14)

The soil moisture sensor measures the volumetric water content in the soil. Installed near the base of the pylons and anchorage, it monitors soil moisture levels to detect any potential water-induced issues, like soil erosion or weakening of the foundation.

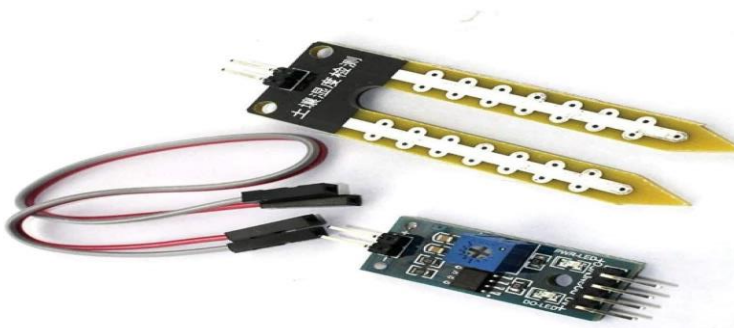


Figure 11:Soil moisture sensor (SN54/R14)

D.Ultrasonic Sensor (HC-SR04)

This sensor uses sound waves to measure distances and is placed under the bridge to check water levels. If the distance changes a lot, it means the water level might be going up, especially during heavy rain that causes flooding. This is important to know, as the flood could make the bridge unstable and even cause it to collapse.



Figure 12:Water proof Ultrasonic Sensor

E.Load Cell Weighing Sensor (+HX711)

The load cell measures the force applied to it and converts it into an electrical signal.Placed on the bridge structure, it measures the load passing over the bridge. Anomalies in load data can indicate overloading or changes in traffic patterns[42].

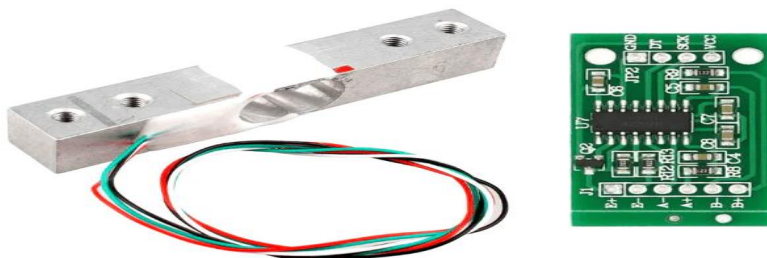


Figure 13:Load cell sensor

4.1.2.Actuating unit

In Structural Health Monitoring for suspension bridges, the actuating unit is key for making things happen. It translates system decisions into real actions, like issuing warnings or closing the bridge when potential issues are detected. This ensures the system functions effectively in keeping the bridge safe. We have three actuators for this system.

A. Buzzer (90 DB Alarm buzzer)

The buzzer generates audible sound when it receives an electrical signal. The buzzer is used to provide an audible alert when any of the sensors detect anomalies. It warns users about potential dangers. In this project the buzzer is used to simulated audio alerts for the prototype system and can be replaced by any high intensity speaker.



Figure 14: Buzzer

B. LEDs (Green, Yellow, Blue, and Red)

The LEDs are used as visual indicators of the bridge's condition. Green indicates that the bridge is in good condition, yellow is used as warning, Red and blue are used that the bridge is not passable due to critical issues. In this project the LEDs are used to simulated visual alerts for the prototype system and can be replaced by any high intensity flashing lights.

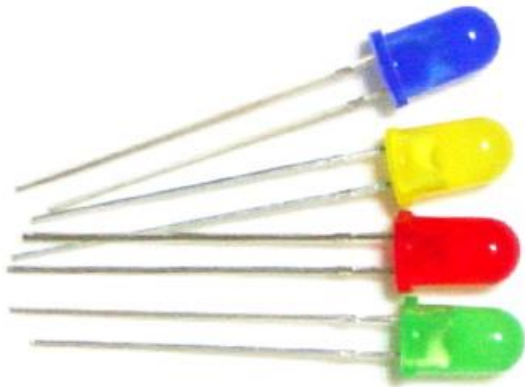


Figure 15: Blue, Yellow, Red and Green LEDs.

C. Servo motor (SG 90)

The SG90 servo motor functions as a pivotal actuator in our system, specifically tasked with managing bridge accessibility. When prompted by the monitoring system, the SG90 swiftly closes the bridge in response to potential hazards, ensuring safety. Conversely, during normal conditions, it efficiently opens the bridge, allowing for regular use. In this project, the servo motor is used to simulate the closing of the bridge for the prototype system and can be replaced by any DC Gear motor capable of supporting the bridge gate system.



Figure 16: Servo Motor

4.1.3. Processing unit

The processing unit of the system is made up of Arduino mega 2560 microcontroller because of it is capable to process many inputs and outputs signals in real time and for instance our system has 5 input sensors and 3 output actuators. This microcontroller serves as the central brain, responsible for interpreting and executing the code that governs the functionalities of the SHM system. With its robust processing capabilities, the Arduino Mega 2560 efficiently manages data from various sensors, implements control algorithms, and facilitates real-time decision-making for ensuring the structural integrity and safety of the monitored bridge.

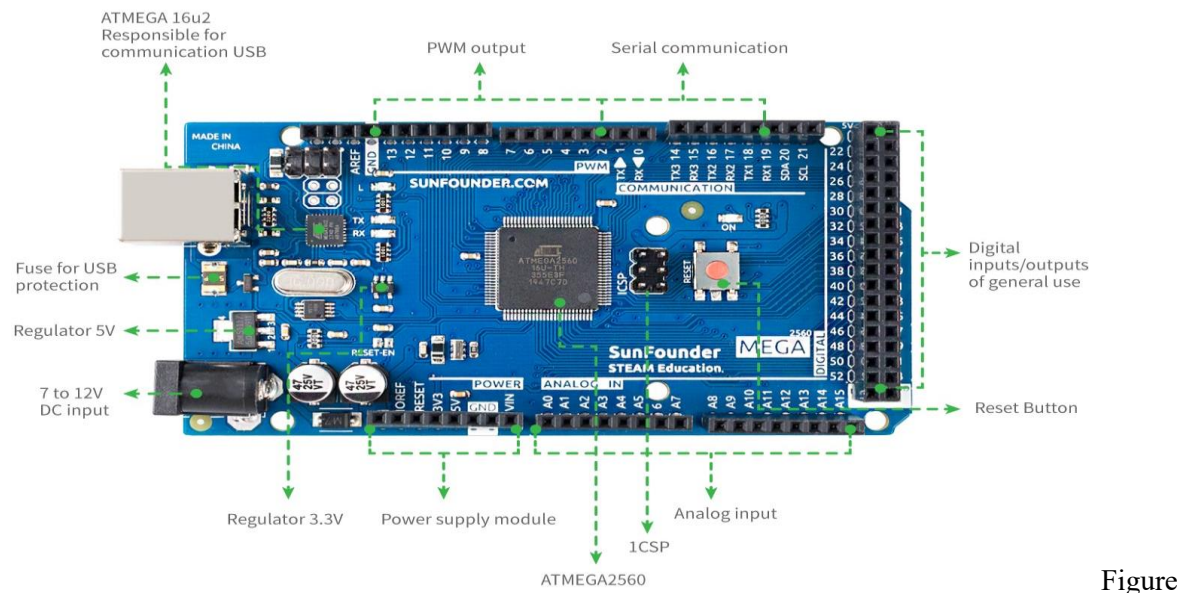


Figure 17: Arduino Mega 2560.

The ATmega2560 microcontroller is chosen for Structural Health Monitoring (SHM) applications over other Arduino models for several reasons[43]:

Enhanced Capabilities: The ATmega2560 offers more digital and analog pins compared to other Arduino models, providing greater flexibility for connecting and interfacing with a variety of sensors and components essential for SHM.

Ample Memory: With 256 KB of flash memory and 8 KB of RAM, the ATmega2560 provides substantial space for storing and processing the complex code required for SHM algorithms, ensuring efficient handling of large datasets.

High Processing Speed: Operating at 16 MHz, the ATmega2560 delivers a faster clock speed than some other Arduino microcontrollers, enabling quicker data processing and real-time decision-making, crucial for monitoring dynamic structural changes in bridges.

Compatibility with Libraries: The ATmega2560 is compatible with a wide range of libraries and code examples, simplifying the implementation of sophisticated algorithms for SHM. This compatibility streamlines development and allows for the integration of advanced features.

Multiple Communication Ports: The presence of multiple serial communication ports (UART, SPI, I2C) on the ATmega2560 facilitates seamless connectivity with various sensors, communication modules, and peripherals, enhancing the overall versatility of the SHM system.

Technical specifications:

Board Size	101.52×53.3mm
Microcontroller/	ATmega2560/
Clock Speed	16MHz
SRAM (Main Memory)	8kB
Flash Memory	256kB
EEPROM	4kB
Operating Voltage	+5V
Input Voltage	+7~+12V
Output Voltage	+5V, +3.3V
Digital I/O Pins	54
PWM Digital I/O Pins	15
Analog Input Pins	16
Rated Current per Pin	20mA/Pin
Program Writing Pins	USB Type-B
Interfaces	ICSP, UART, I2C, SPI

Table 1: Technical specification of Arduino Mega 2560.

4.1.4. Communication Unit

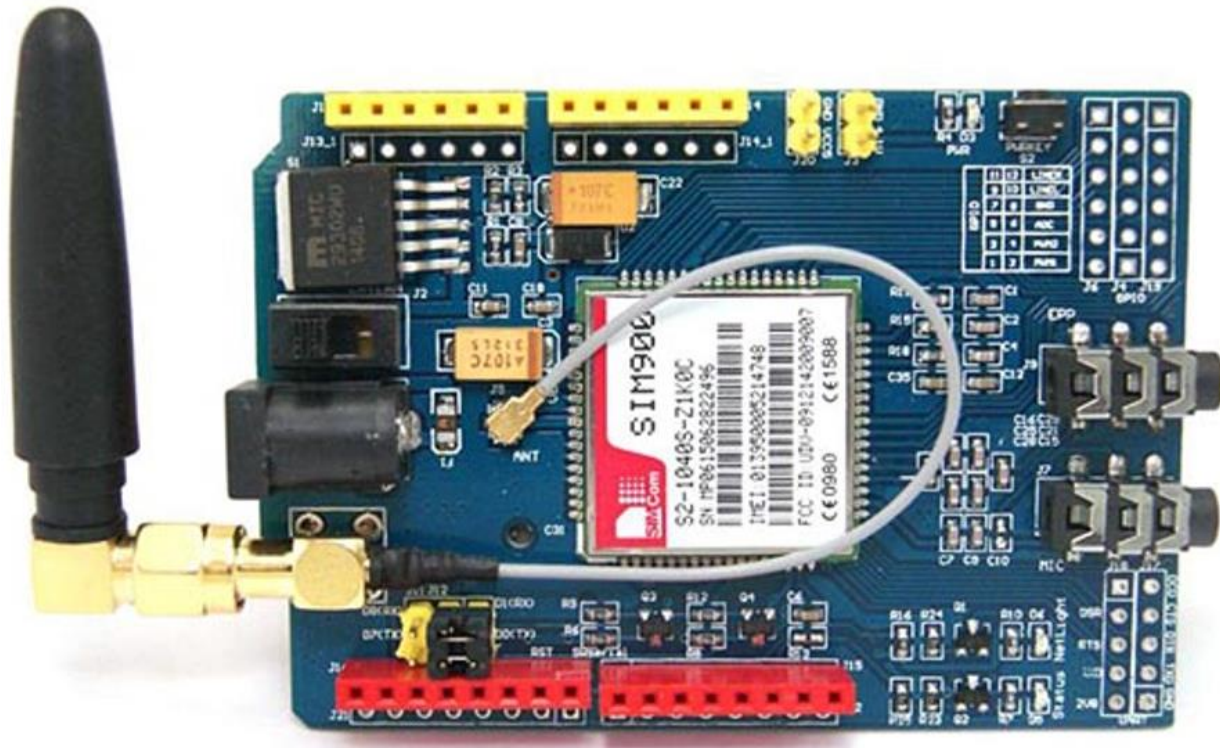


Figure 18:GSM/GPRS SIM900

The Communication Unit of the system relies on the GSM/GPRS SIM900 module, specifically designed for cellular communication[44]. This choice is pivotal, especially for bridges located in remote areas without Wi-Fi or alternative communication infrastructure. The SIM900 utilizes both 2G and 3G technologies, which are notably reliable in rural and remote settings. Its capability to operate on these networks ensures consistent and robust connectivity, enabling the SHM system to efficiently transmit real-time data to the server. In essence, the GSM/GPRS SIM900 module plays a crucial role in establishing a dependable and resilient communication link for monitoring the structural health of suspension bridges, even in challenging and remote environments.

4.2. System Flow Chart

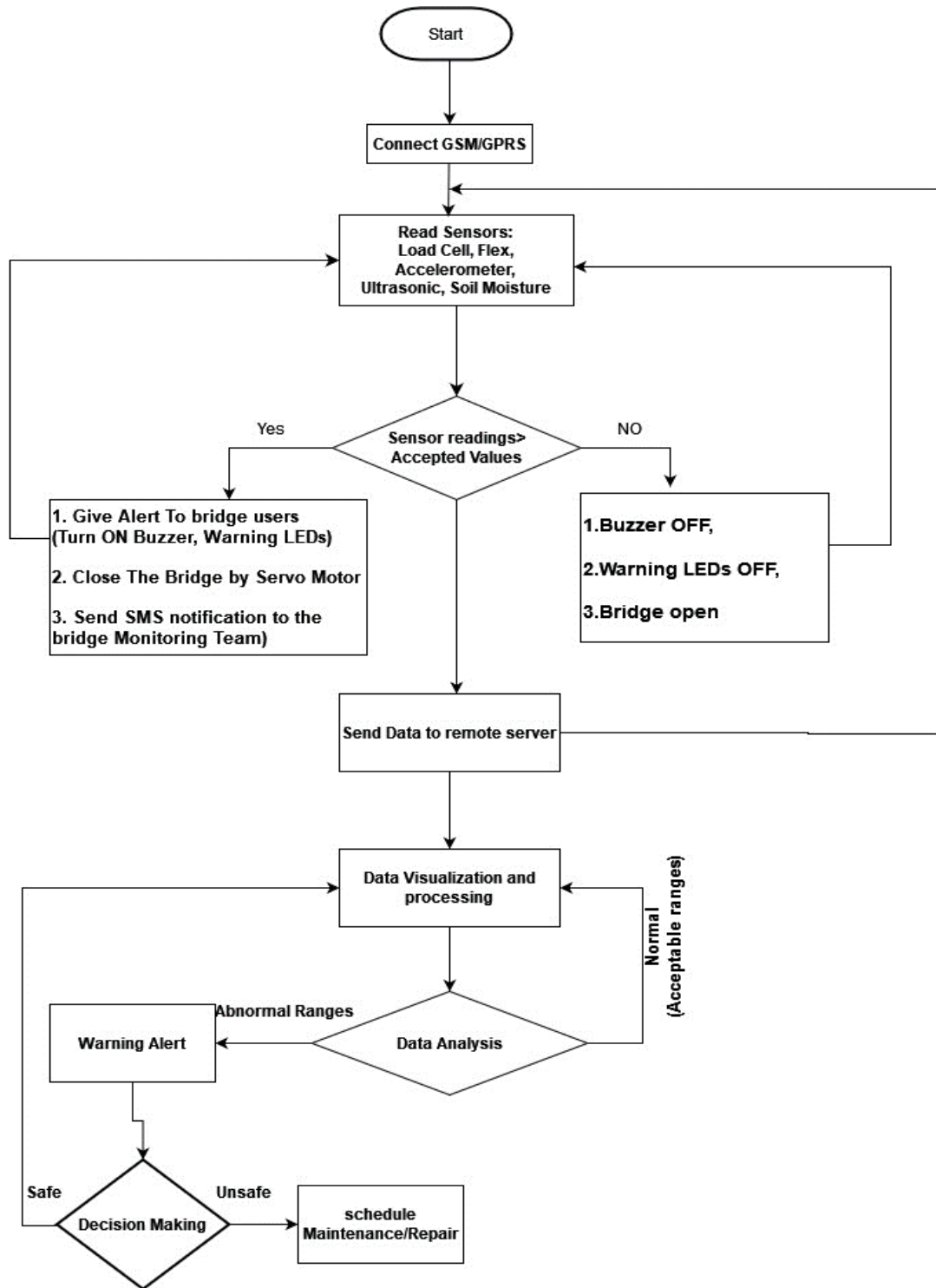


Figure 19: System Flow Chart.

The flowchart provides a high-level overview of a bridge monitoring system, and it illustrates the sequential steps of the system functionalities as describes below:

At the beginning the system turns on it connects to the internet, and it starts reading the data signals from sensors. As data are being received, they are subjected to edge processing and analysis using based on rules algorithm in order to evaluate the bridge's structural integrity.

When anomalies in the monitored parameters are found, a number of warning measures are triggered if the risk level is above predefined threshold. In the case of greatest risk, a servo motor closes the bridge, while high-intensity LEDs turn on the visual warning to inform bridge users of possible danger. A short message alert is simultaneously sent to the bridge control center. In case there is no detected incident in the data, the system continues to collect data and no warning is activated.

Collected data are continuously sent to a cloud server for remote access, visualization and advanced analysis. On remote server, received data are stored in a secured database. Bridge engineers and maintenance staff are given real-time insights on the structural health of the bridge on dashboard gauges and graphs. In case an abnormal situation is detected, warnings will be displayed, and structural engineers will do analysis and schedule the predictive maintenance and repairs.

4.3. Embedded System block diagram

The embedded system comprises of sensors and actuators to monitor and maintain the structural integrity of a bridge. The system's power supply ensures continuous operation of all components, including the load cell sensor for measuring weight on the bridge, the three-axis accelerometer for detecting vibrations, the soil moisture sensor for monitoring soil hydration levels, the ultrasonic sensor for tracking river water levels, and the flex sensor for assessing the bending angle of suspension cables.

The data acquired from these sensors is fed into a microcontroller for processing and analysis. Subsequently, the processed data is transmitted to a remote server via a GSM communication module. The remote server provides a user-friendly interface dashboard for visualizing the sensor data and performing advanced data analysis. Furthermore, the embedded system incorporates actuating elements such as a buzzer, LEDs, and a servo motor to respond to critical situations. The

buzzer emits audible alerts, LEDs provide visual indications, and the servo motor can be activated to close the bridge based on real-time data analysis.

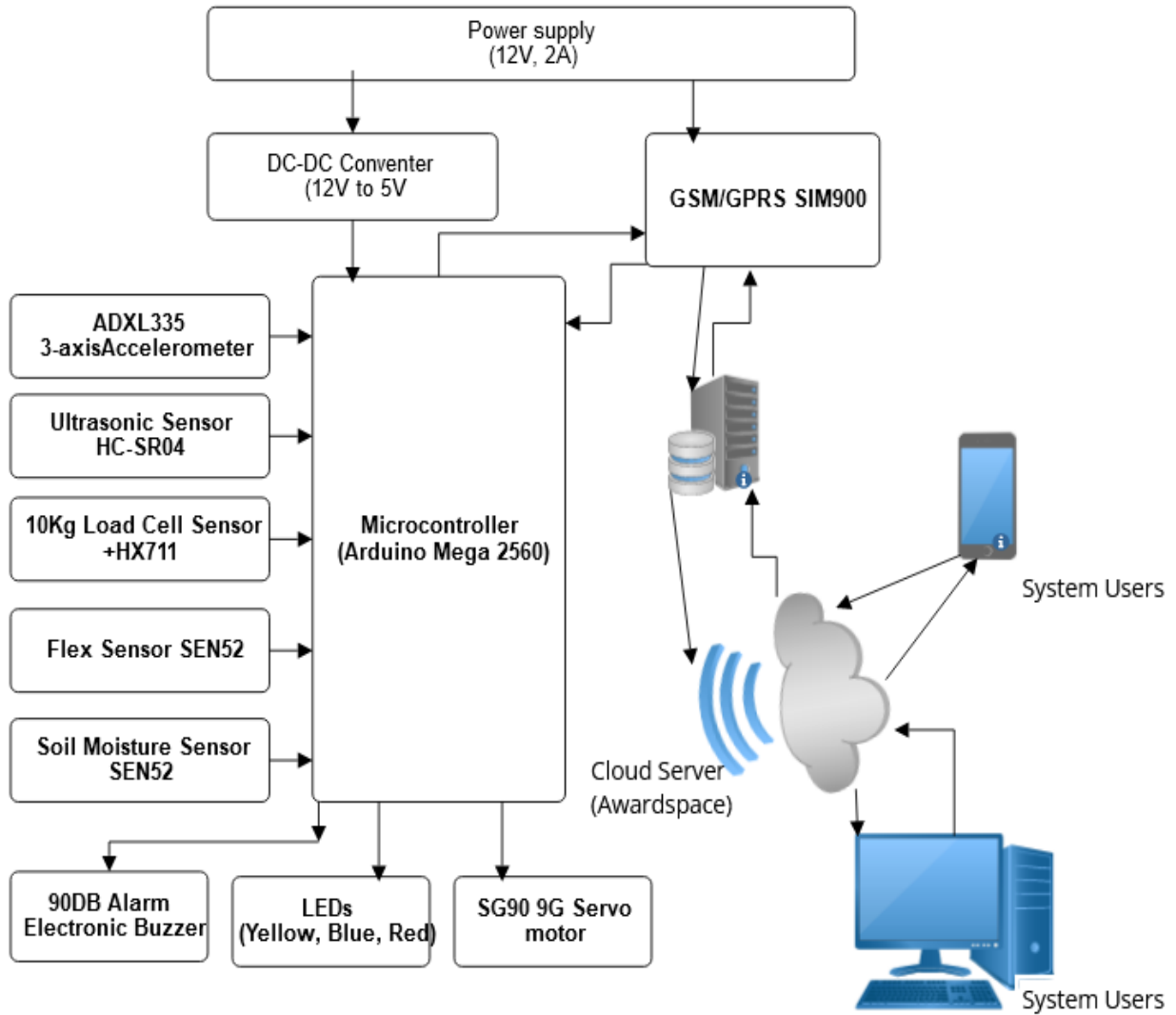


Figure 20: Embedded system diagram.

4.4. System circuit diagram

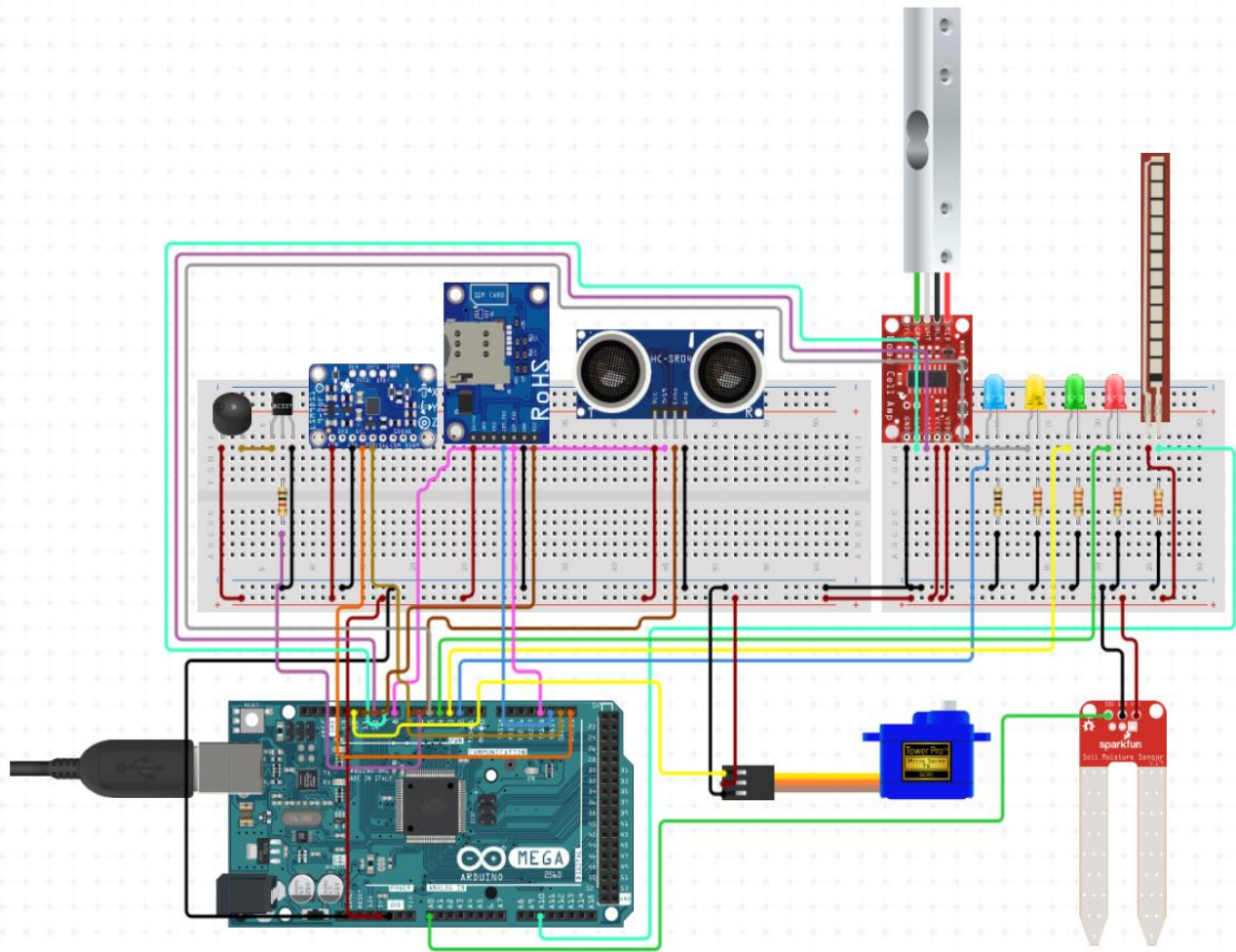


Figure 21:Circuit Diagram.

The system circuit diagram of the prototype system shows how all components are connected. As arduino Mega 2560 is the central controlling unit, it is interfaced with all sensors, actuators and communication unit. The connection of all components is done on printed circuit board (PCB).

4.5. Physical prototype system

The prototype system consists of an embedded system made by four interconnected units, as detailed in section 4.1, and includes a prototype bridge specifically designed for simulating the functionalities of the system. This prototype bridge serves as a crucial element for the proof of concept, allowing practical validation and testing of the envisioned capabilities.

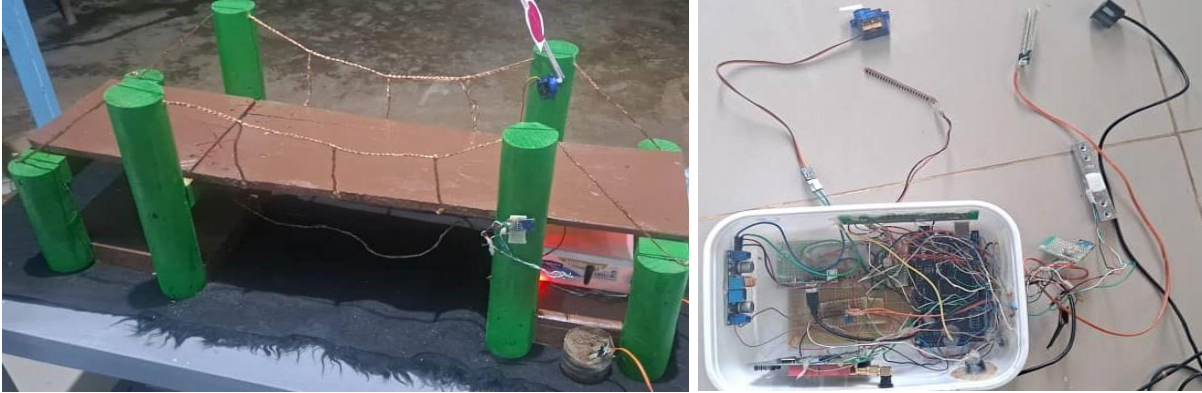


Figure 22:Physical Prototype.

4.6. Data transmission

In the context of the structural health monitoring system for a suspension bridge, the data transmission mechanism plays a pivotal role in enabling remote access and real-time monitoring. The chosen communication method for this system is cellular communication, leveraging a GSM/GPRS module. This decision aligns with the broader IoT paradigm, granting end-users the flexibility to access field-collected data from any location. The GSM/GPRS module serves as a bridge to transfer data across cellular network [45].

4.6.1.POST Method for Hypertext Transfer Protocol (HTTP)

For data transfer, the embedded system makes use of the Hypertext Transfer Protocol (HTTP). The HTTP protocol is extensively utilized for data exchange between web servers and clients.[46] Regarding bridge monitoring, the embedded system facts as the client, transmitting information to the cloud server, which takes on the role of the web server.

The HTTP POST method is specifically employed for data transmission in this system. The POST method allows the client to send data to the server along with the request, making it suitable for transferring sensor readings and additional information.

4.6.2.Data Transmission Process

1. The embedded system uses a microcontroller to process data that it gathers from the sensors.
2. After processing the data, they are formatted into a structured format message to be transmitted.
3. A connection to the cellular network is made using the GSM/GPRS module.

4. The HTTP POST request is sent embedded system to the remote server and the formatted data include in the request.
5. The sensor data is extracted from the request body by the remote server when it receives the HTTP POST request.
6. The sensor data is kept on remote server in a database for remote access, visualization and advanced analysis.
7. Then the GSM/GPRS ends the the connection to the cellular network.

4.6.3. Advantages of Cellular Communication and HTTP

There are several benefits in combining cellular communication and HTTP in the context of structural health monitoring for suspension bridges[47]:

Wide Coverage: Suspension bridges are located in remote areas, due to the fact that Cellular network has a wide coverage area and it is the best communication channel.

Scalability: As the need for monitoring increase, the system can manage a larger volume of data and more sensors.

Reliability: Sensor data is reliably transmitted to the distant server using cellular networks, which provide dependable data transfer.

Standard Protocol: To ensure interoperability between the embedded system and the remote server, HTTP is a standardized communication protocol.

Data Integrity: HTTP makes use of a number of techniques to safeguard data integrity while it is being transmitted, guaranteeing that the data that is received is correct and unmodified.

4.7. Software architecture

The software architecture of an IoT-based structural health monitoring system for suspension bridges consists of three main layers. In order to provide efficient structural health monitoring and preventive maintenance of suspension bridges, this layered design allows for real-time data collecting, rapid data transfer, thorough data analysis, and user-friendly data interface.[48].

4.7.1. Embedded System Layer

Uses C++ programming language in an Arduino board to read sensor data[49].

4.7.2. Communication Module

Uses a GSM/GPRS module to create a cellular connection and send sensor data to a remote server using HTTP POST requests.

4.7.3. Remote Server Layer

The data processing, visualization, and storage are handled by the remote server layer. The main location for sensor data storage is the MySQL database. PHP scripts are utilized to establish a connection to the database, obtain data, and carry out essential calculations.

A crucial part of the software design is the remote server, where data visualization and analysis are also carried out. An interactive dashboard user interface is made using HTML, CSS, PHP, and JavaScript. Real-time sensor data, historical trends, and analytical insights are all shown on the dashboard. Effective data visualization is achieved by creating charts and graphs using JavaScript frameworks such as Chart.js and D3.js[50].

4.8. Remote server and user interface

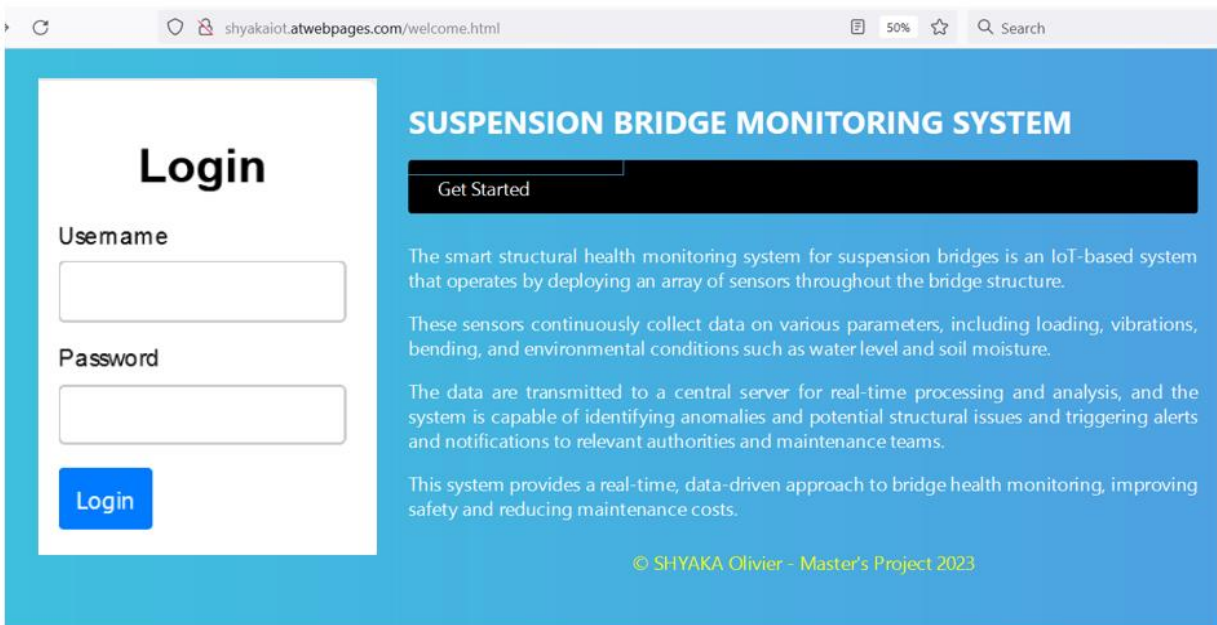


Figure 23: User interface.

4.8.1.Remote Cloud Platform: AwardSpace

AwardSpace was used in this project as our remote hosting platform where it host the database, back-end and front end components of the system. AwardSpace is the best alternative for guaranteeing the system's dependability, security, and scalability because of its strong infrastructure and extensive hosting choices[51].

Reasons for Choosing AwardSpace

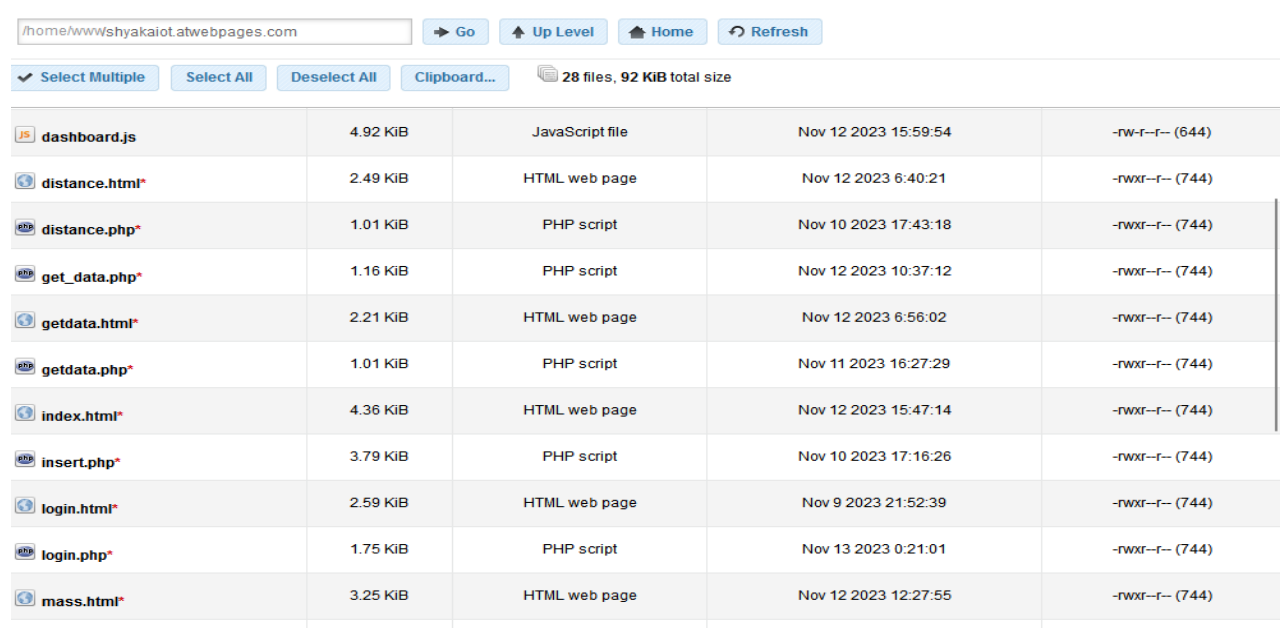
A. Reliability: AwardSpace is well known for offering dependable hosting services, which guarantee that the remote server is always up and running.

B. Security: To safeguard the hosted data and applications and guarantee the integrity and confidentiality of the system, AwardSpace employs strong security protocols.

C. Scalability: As the bridge infrastructure grows, AwardSpace's scalable hosting plans can handle the increasing amount of data and processing needs of the structural health monitoring system.

D. Cost-Effectiveness: AwardSpace is a cost-effective option for hosting the remote server components because of its competitively priced hosting options.

4.8.2.Backend Components



File Name	Size	Type	Date	Permissions
dashboard.js	4.92 KIB	JavaScript file	Nov 12 2023 15:59:54	-rw-r--r-- (644)
distance.html*	2.49 KIB	HTML web page	Nov 12 2023 6:40:21	-rwxr--r-- (744)
distance.php*	1.01 KIB	PHP script	Nov 10 2023 17:43:18	-rwxr--r-- (744)
get_data.php*	1.16 KIB	PHP script	Nov 12 2023 10:37:12	-rwxr--r-- (744)
getdata.html*	2.21 KIB	HTML web page	Nov 12 2023 6:56:02	-rwxr--r-- (744)
getdata.php*	1.01 KIB	PHP script	Nov 11 2023 16:27:29	-rwxr--r-- (744)
index.html*	4.36 KIB	HTML web page	Nov 12 2023 15:47:14	-rwxr--r-- (744)
insert.php*	3.79 KIB	PHP script	Nov 10 2023 17:16:26	-rwxr--r-- (744)
login.html*	2.59 KIB	HTML web page	Nov 9 2023 21:52:39	-rwxr--r-- (744)
login.php*	1.75 KIB	PHP script	Nov 13 2023 0:21:01	-rwxr--r-- (744)
mass.html*	3.25 KIB	HTML web page	Nov 12 2023 12:27:55	-rwxr--r-- (744)

Figure 24:Backend.

A. MySQL Database: The main repository for sensor data gathered from the suspension bridge is MySQL, a popular open-source relational database management system (RDBMS). It effectively handles the substantial amount of data, guaranteeing data integrity and simple retrieval[52].

B. Data Insertion API: To make it easier to input data from the embedded system on the bridge into the MySQL database, an application programming interface (API) has been designed. To ensure smooth data transfer, this API specifies a set of guidelines and procedures for data exchange between the two systems[53].

C. Data Fetching APIs: These APIs are also made to fetch data from the MySQL database so that it may be shown on the dashboard of the user interface. The dashboard functionalities rely on these APIs, which grant access to the stored sensor data.

4.8.3. Frontend Components

A. Welcome Page: The user interface's entrance point is the welcome page. It offers broad details on the goals and advantages of the structural health monitoring system. It could also provide a synopsis of the system's features and a quick how-to manual for using the dashboard.

B. Dashboard Monitoring Platform: The centerpiece of the user interface, the dashboard monitoring platform offers up-to-date information on the suspension bridge's structural stability. Only system administrators and bridge controllers may access it, guaranteeing that only individuals with permission can examine vital bridge data.

4.8.4. Integration of Languages

A. JavaScript: It is mostly utilized for front-end development. The creation of dynamic visualizations and interactive features for the dashboard monitoring platform and welcome page is a critical component of this project[54].

B. PHP: It is a server-side scripting language that is mostly employed in back-end programming. In this project, The APIs that link the database to back-end, back-end to front-end are done using PHP scripts[55].

C. CSS: Cascading Style Sheets, or CSS, is a language for style sheets that controls how web pages look and feel. It helped us specify the design elements of the dashboard monitoring platform and the welcome page, such as colors, fonts, and layout[56].

D.Java: Java is a general-purpose programming language often used for back-end development. In this project we used it to develop specific functionalities on the backend like sending emails notification and alert displaying [54].

Chapter 5: Results and Analysis

This chapter describes the results achieved during the design and the implementation of the project in line with the study objectives and scope of work. The analysis of results is also done to get insights into the importance of this project.

5.1. Data Collection Results

The qualitative data gathered from the observations and interviews described in Chapter 3.3 provide thorough insights on the characteristics of suspension bridges in Rwanda. This data helped define important system operations and identify critical structural health parameters for monitoring.

The findings demonstrated that we must design a system capable of monitoring the loading of the bridge (Live load and accumulated load), suspension cable bending, bridge vibration, soil moisture near the foundation and encourage structure and to determine the water level under the bridge. The system should also be able to alert users of the bridge to any problems in advance and take preventative action, like closing the bridge, when deemed necessary.

5.2. System Prototype

5.2.1. Prototype Setup



Figure 25: Prototype setup.

The prototype setup is the most important part of the project because everything relies on it. It involved the connection of different embedded system devices tailored to collect data on the bridge for edge processing and decision making and also to be transmitted on the remote server. The testing and validation of system functionalities was conducted on a prototype bridge for simulating the operation conditions of the system in order to verify performance in real-time scenarios.

5.3. Sensor data readings

The prototype system employs an Arduino mega ATM2560, to which a script code is written in order to take sensor signals at various pins and translate them into usable data, as displayed on the serial monitor in Figure26.

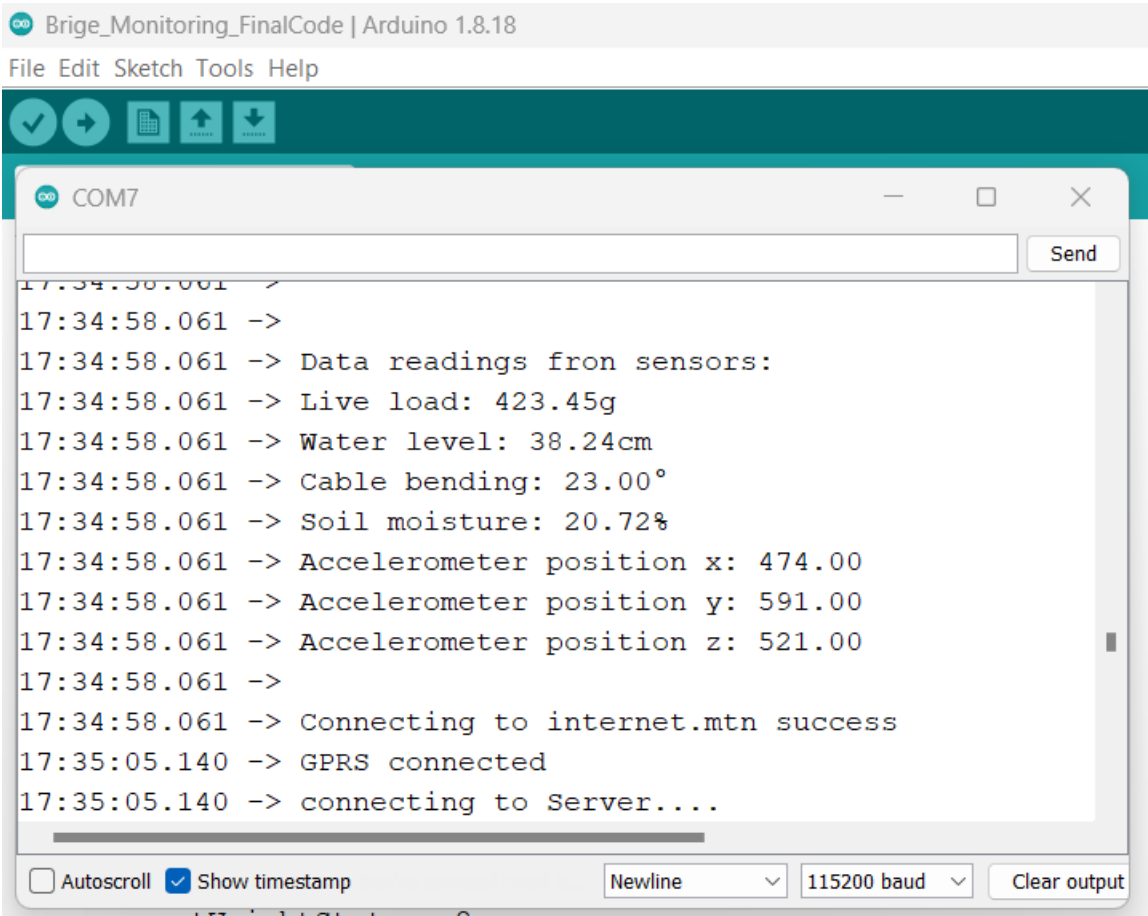


Figure 26:Arduino sensor data reading.

5.4. Prototype system actuation

We have mounted sensors on prototype bridge and simulated different scenarios of incidents that can happen on the bridge to test the system actuating response. We tested the system on 2 key parameters of the bridge which are loading, and water level and we set the conditions for the system to respond.

S/N	Monitored parameter	Set conditions	Actuation
1	Weigh	If the live load on the bridge reaches the maximum set values	-Turn on Blue LED (As visual indication that the bridge is overweight. -Sending Audio warning by turning on the buzzer. -Wait for some time and close the bridge with servo motor on one side and let people leave the bridge on the other side. -Send SMS to bridge controllers informing the that the is overweighted at the moment
		If the live load comes back in normal range	-Open the bridge -Remove visual and audio warnings
2	Water level	If the water under the bridge increase and reach a critical set level	-Send sms to bridge controllers to take action before the flood happened. -Turn on a warning LED (Yellow LED) on the device to warn the bridge users to take care.
		If the water level reaches the bridge (i.e the flood happens)	-Close turn on audio alarm (buzzer) -Turn ON alarming light (Red LED) -Close the bridge with servo motor -Send sms to bridge controllers
		If the water level becomes normal	-Remove all alarms -Open the bridge

Table 2:Actuation Rules and conditions.

5.4.1.Servo motor & LED Actuation simulation



Figure 28:Overweight scenario
(Blue LED ON and Bridge closed)



Figure 27:Flooding senario (Red LED ON and bridge closed)

5.4.2.SMS notification

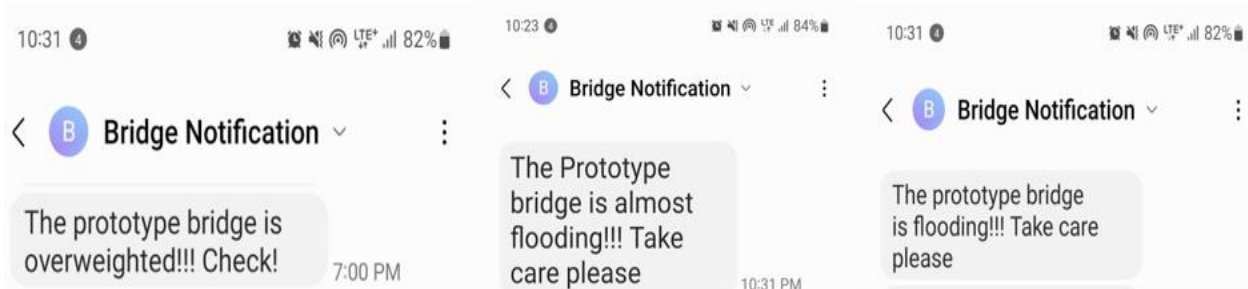


Figure 29:SMS notification.

5.5.Remote data acquisition and Visualization

The data are sent on remote server hosted on award space cloud platform where a database is configured for real time data acquisition.

A web-based application having a dashboard for data visualization is also developed hosted on ward space platform. This platform may help bridge monitoring personnel to get real-time information of the structural health of the bride and avail them that for advanced structural health analysis to schedule repairs and maintenance.

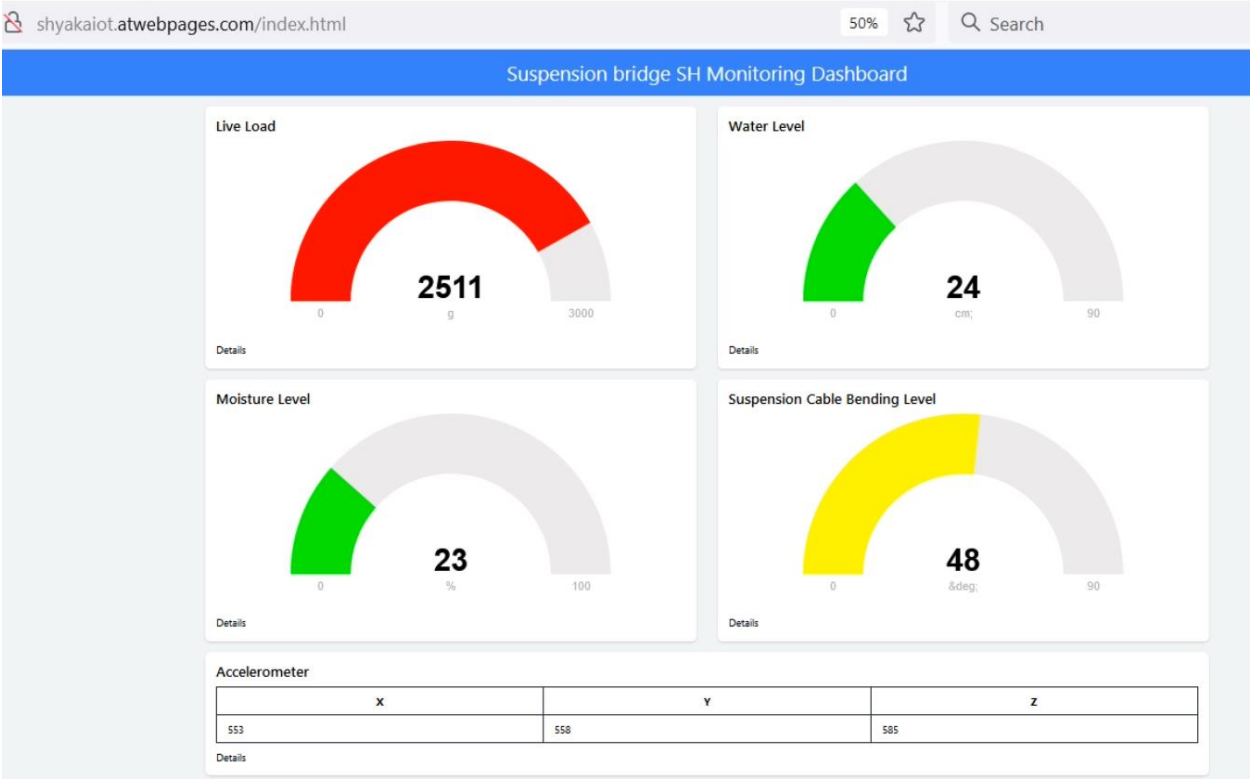


Figure 30:Dashboard

The dashboard provides a real-time view of key structural indicators. The image above depicts the project dashboard, which acts as a comprehensive interface showing critical information important for monitoring bridge health. Live load, water level, soil moisture, cable bending, and accelerometer data (x, y, z) are all shown. The dashboard's gauges automatically update every 10 seconds, offering instant insight into the current values for each parameter. Color coding is used in these gauges to indicate the state of data ranges (Green for average values, Yellow shows data

nearing critical levels, while red indicates data above safety criteria, perhaps indicating an impending bridge incident.)

When values exceed the safety limits, alert messages display on the dashboard immediately, and matching emails are sent to bridge controllers, ensuring quick action in reaction to dangerous situations.

5.5.1. Water level results and visualization

The graph in the illustration is a time series graph that shows how the water level under the bridge is being monitored. The graph visualization is done in real time on the monitoring dashboard. As a result, the system can display water level patterns and this information may be used to predict flooding[57].

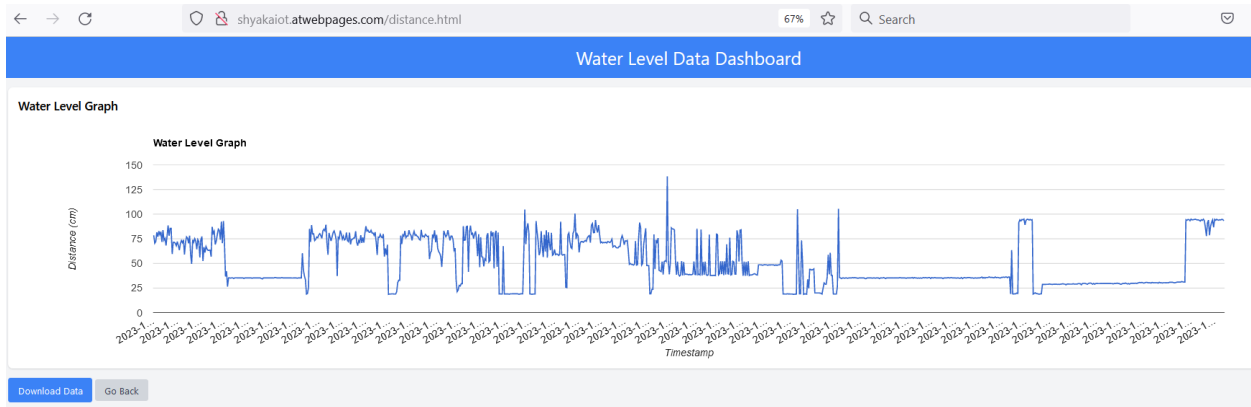


Figure 31: Water level time series graph.

5.5.2. Suspension cable bending results and visualization.

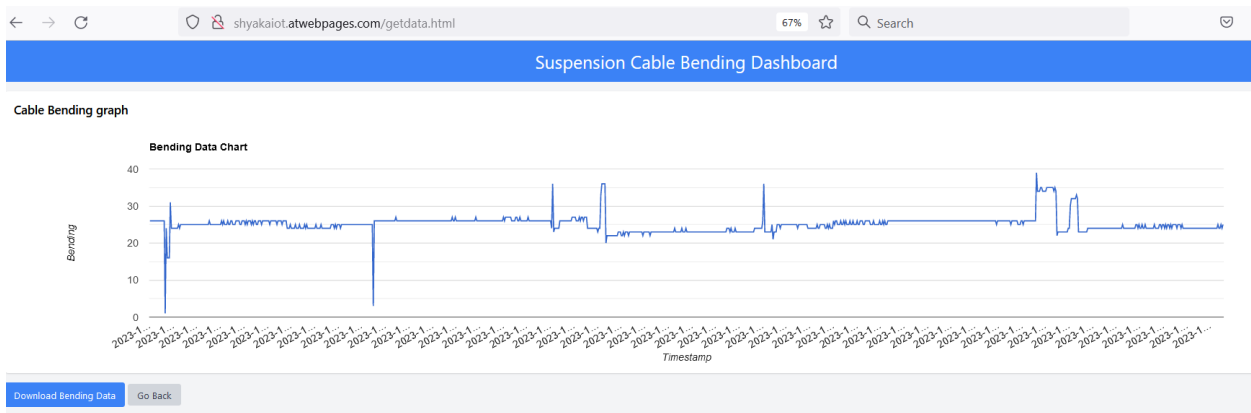


Figure 32: Cable bending time series graph

The results of the suspension cable visualization on the dashboard chart illustrate the system's efficiency. Even if the cables swing and the bending degree fluctuates sometimes, the time series graph above indicates that the bending degree of the suspension cables is constantly at 20 degrees. This shows that the cable's first bend is 20 degrees. If the cable does not return to its original bending, the cable bending degree has changed, implying that the cable strain is changing. This might be a major structural health issue for the bridge[58].

5.5.3. Soil moisture results and visualization

The soil moisture was measured in an experimental setting where we could add water to the soil. However, because this was not the true moisture in the soil, it evaporated fast, and the moisture level dropped to 0%. This demonstrates the system's efficiency. The graphs clearly illustrate the trend, and people who monitor the system may rely on them. It gives the true trend on the visualization chart, according to our testing.

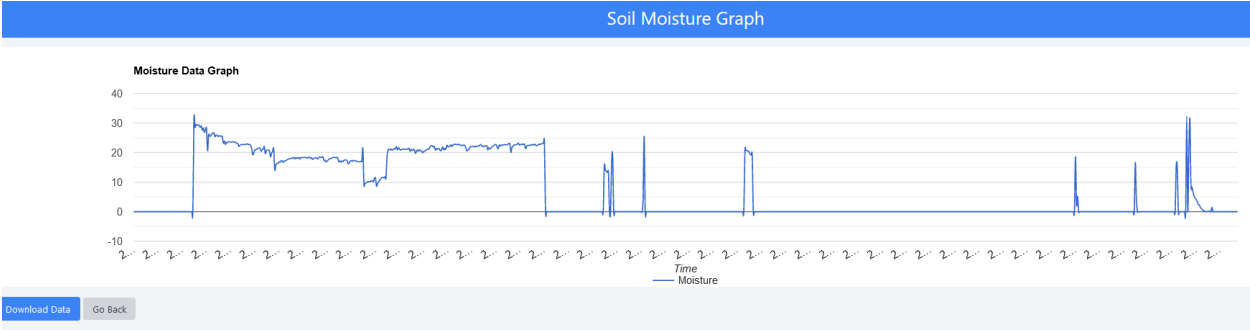


Figure 33: Soil moisture time series graph.

5.5.4. Accelerometer results and visualization

The time series analysis of accelerometer data from the suspension bridge monitoring revealed a similar pattern: coordinated variations in the X, Y, and Z axis measurements, suggesting uniform movement or structural integrity. This synchronous change indicates a coordinated reaction to external stimuli or internal forces impacting the bridge structure, emphasizing the coordinated behavior inside the bridge structure[59].

These data were acquired on an experimental prototype bridge and show the efficiency of the technology. Because there were no external vibrations, the observed pattern was predicted. When intentional vibrations were applied, all values (x, y, z) moved in the same direction at the same time, showing the system's accuracy in detecting vibrations.

These findings suggest that the technology may be used to monitor the bridge's structural condition and provide reliable results.

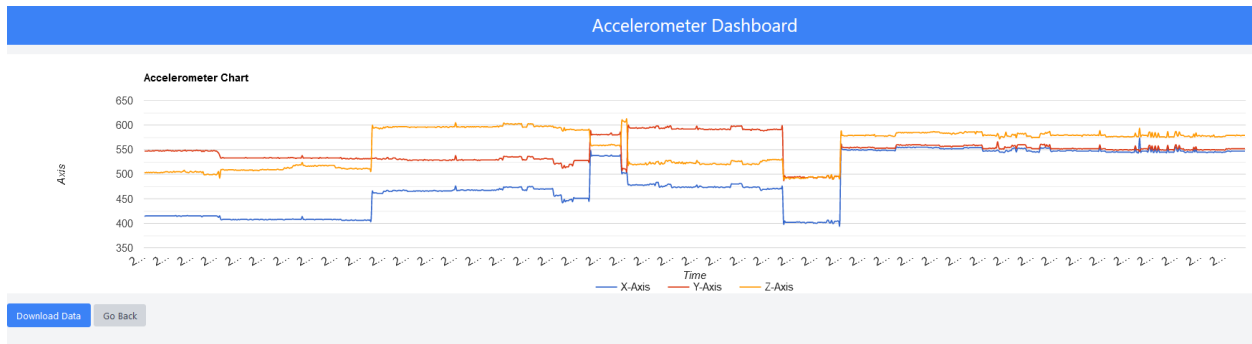


Figure 34: Time series graph for accelerometer data.

5.5.5. Weight data results and visualization

The system records and displays live load and cumulative weight data, as seen in the image below. As a result, exact monitoring of the bridge's weight-bearing capability is possible, which is critical for predictive maintenance and preventive repairs[60]. Our prototype estimates total weight passage effectively, giving engineers significant insights for data-driven decision-making and preventive structural maintenance. This feature allows a thorough grasp of the bridge's durability under varying stresses, improving maintenance techniques, and preserving long-term structural integrity.

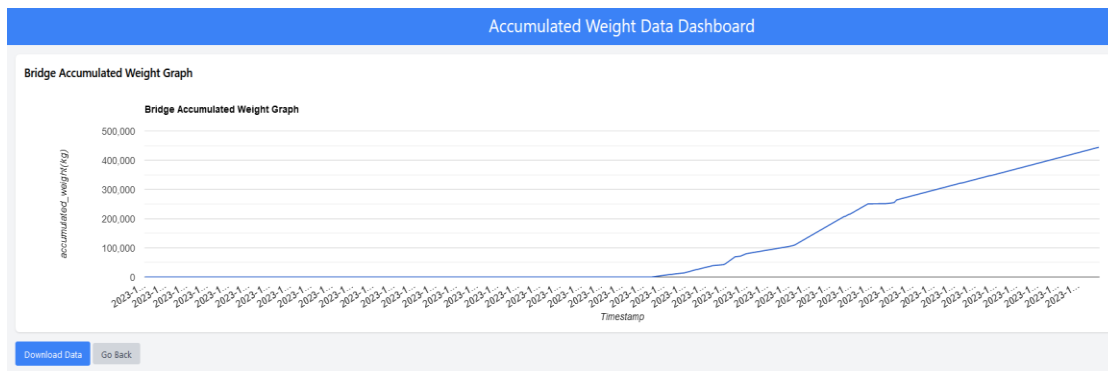
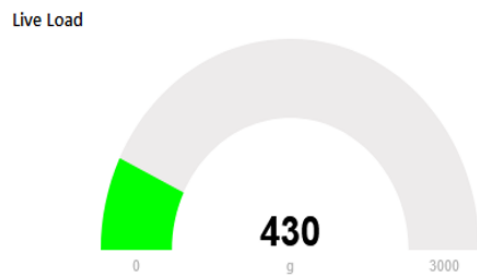


Figure 35: Live load and accumulated time series weight graph.

Chapter 6: Conclusion and Recommendation

6.1. Conclusion

This research project marks an important step forward in the field of structural health monitoring, notably in the application of IoT technology within the domain of bridges, with an emphasis on the widespread usage of suspension bridges in Rwanda. This study intended to bridge the gap in structural health monitoring studies by exploiting IoT capabilities, presenting a pioneering technique to monitor and analyze the structural integrity of bridges. The project's achievement in establishing a prototype system that successfully records, analyzes, and visualizes crucial data relating to live load, cable bending, moisture levels, and other factors highlights the project's significance in improving the safety and maintenance of suspension bridges. This endeavor not only proves the viability of IoT-based monitoring, but it also lays the path for future infrastructure developments.

6.2. Recommendation

Given the results of this research, its feasibility is possible, and I recommend its implementation on real bridges. After the implementation, collected data on real bridges shall be used for further research in the field of predictive maintenance by using machine learning algorithms.

Future work on this technology might concentrate on improving algorithms, incorporating cutting-edge sensors, scaling its implementation over different bridge types.

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Appendix 1: Interview questionnaire for bridge users

Thank you for your willingness to participate in this survey. We are interested in your perspective as a user of a suspension cable-stayed bridge. Your input is invaluable in helping us understand your views and concerns regarding bridge safety.

Section 1: General Information

1. Name (Optional): _____

2. Age: _____

3. Gender:

-Male

-Female

4. How often do you use the suspension cable-stayed bridge?

-Everyday

-2-4 Days a Week

-Once a week

-Occasionally

5. Are aware of any technology used to monitor the status of the bridge?

-Yes

-No

-If yes, please describe that technology.

Section 2: Bridge Usage, Safety and monitoring

1. How important is the safety of the bridge to you and your community?

-Very Important

-Important

Not Important

2. Have you ever observed any safety issues on the bridge?

-Yes

-No

- Not Sure

-If yes, please briefly describe the issue:

3. Are you aware of any bridge inspection or monitoring activities being conducted on the suspension cable-stayed bridge you use?

-Yes

-No

- Not Sure

-If yes, please briefly describe what was used in the inspection

4. According to what you have seen on the bridge, what indicators or parameters do you believe should be monitored regularly for the safety of the bridge? (Select all that apply)

-Bridge Load-Bearing Capacity

-Visible Structural Damage (e.g., cable integrity, support pillars)

-Vibration

-Water level, Floods

-Corrosion of Structural Elements

-Soil property

-Others (please specify) _____

5. How often do you think structural health monitoring should be performed on the suspension cable-stayed bridge?

Never

Annually

Quarterly

Monthly

Weekly

-Daily

As Needed

Not Sure

Section 4: Suggestions

Do you have any suggestions or concerns related to bridge safety and structural health monitoring that you would like to share?

Thank you for participating in this survey. Your input is crucial in ensuring the safety and maintenance of suspension cable-stayed bridges.

Appendix 2: Interview questionnaire for B2P Experts

- 1. In your experience, what are the most critical parameters that should be continuously monitored to ensure the structural health and safety of suspension cable-stayed bridges?**
- 2. What advanced technologies or methods do you consider highly effective for the structural health monitoring of suspension bridges, and why?**
- 3. Can you describe any specific challenges or unique considerations associated with monitoring suspension bridges, and how do you address them in your professional practice?**
- 4. How frequently should structural health assessments and inspections be conducted on suspension cable-stayed bridges to ensure their long-term safety and durability, and what factors influence this frequency?**
- 5. In your professional opinion, what are the common signs of structural distress or potential safety issues in suspension bridges, and how should these issues be addressed and mitigated?**
- 6. Do you have any recommendations for optimizing maintenance and repair strategies for suspension bridges, particularly in challenging environmental conditions or high-traffic areas?**
- 7. What role does data analysis and predictive modeling play in the structural health monitoring of suspension bridges, and how do you utilize these tools in your work?**
- 8. Are there any emerging technologies or research areas that you believe will significantly impact the future of suspension bridge monitoring and safety, and could you elaborate on their potential benefits?**