Digital Twin Bridge Monitoring System

Kowshik Dey, Rongjian Chen, Hanchi Ge
ECE 445 Project Proposal — Spring 2024
Advisor: Dr. Cristoforo Demartino

1. Introduction

1.1 Problem

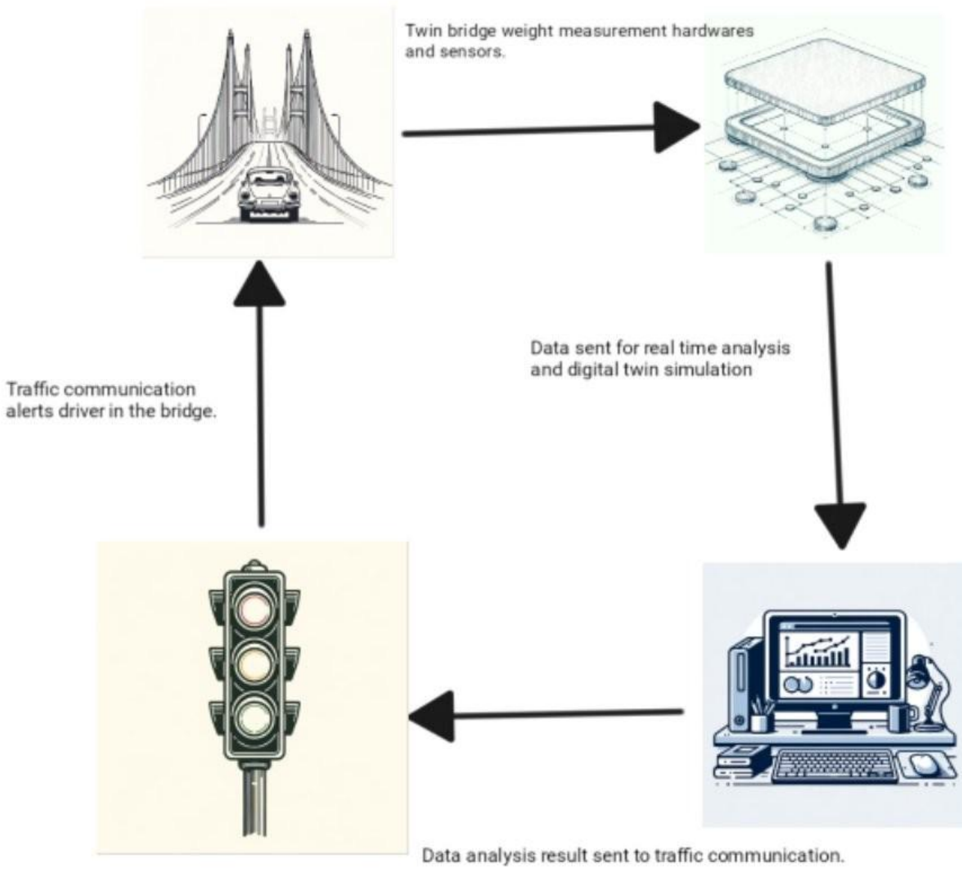
Bridges are one of the most vital infrastructures that serve as connectors both inside and outside of a country. They facilitate the movement of people, goods, and vehicles. Despite being marvels of engineering and architecture, accidents in bridges have become more frequent as time passes. The significant causes can be attributed to as being vehicle overloading and structural concerns of the bridge. These type of accidents are more prominent in third world countries, like Bangladesh, where most of the bridges have no monitoring system due to the cost involving these traditional monitoring systems. As a result, the drivers are left to their own assessments and judgements which may lead to accidents and structural damage to the bridges. The development of digital monitoring system can effectively save the money wasted on repetitive maintenance and repair of bridges due to overloading and structural damage.

1.2 Solution

The Digital Twin Bridge Monitoring System is designed to address the critical issue of bridge safety and maintenance. This innovative system involves the creation of a digital counterpart for a physical bridge, which is outfitted with advanced pressure sensors. These sensors are crucial for accurately gauging the weight of vehicles as they traverse the bridge, ensuring that the bridge's load capacity is not exceeded. Additionally, the system is equipped with a traffic light mechanism. This feature plays a vital role in warning drivers about potential overloading or existing structural issues, thereby enhancing safety measures.

To demonstrate the practicality and functionality of this system, we plan to construct a scaled-down prototype model. This model will serve as a platform for installing our hardware components, which include various modules such as sensors and a micro-controller. The key to our system's effectiveness lies in the ability to transmit the sensor's processed data to the digital twin platform. This enables the real-time monitoring and detection of the bridge's condition, allowing for immediate responses to any detected problems. Through this advanced monitoring system, we aim to revolutionize how bridge safety is managed, ensuring the longevity and reliability of these critical infrastructures.

1.3 Visual Aid

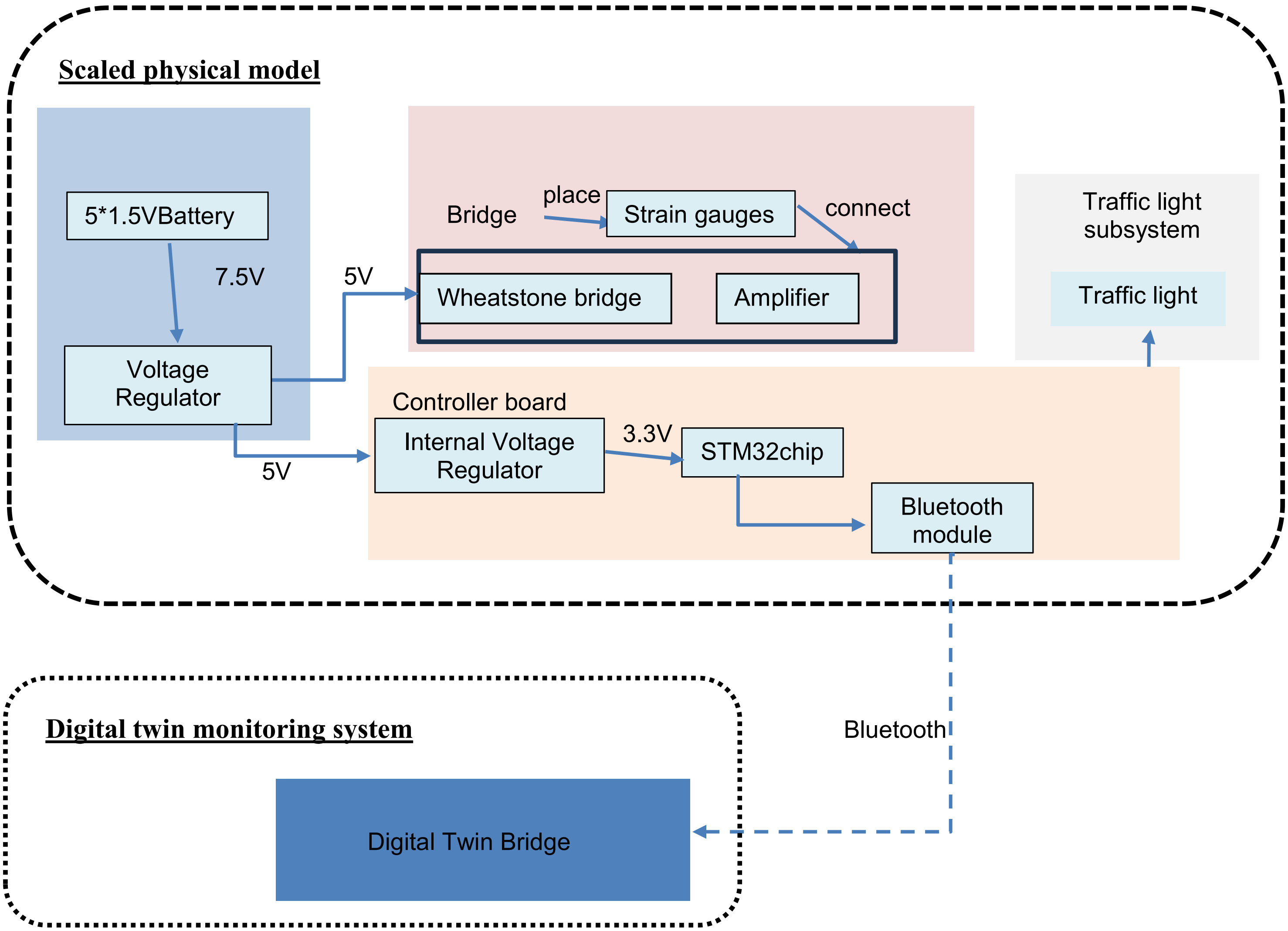


1.4 High-level requirement list

- The hardware weight measurement sensors installed on the bridge must be capable of accurately measuring the weight of crossing vehicles to a high degree of precision.
- The system must have the capability to process and analyze sensor data in real-time which involves the use of robust computational resources and efficient algorithms that can quickly interpret data from multiple sensors, perform calculations, and make determinations about the structural integrity and safety of the bridge.
- The traffic light or communication mechanism used to alert drivers about overloading or structural concerns must be highly reliable and responsive which requires a system that can instantaneously receive and act upon data from the analytics platform, with minimal delay between the detection of a potential issue and the activation of warning signals.

2. Design

2.1 Block Diagram



2.2 Subsystem Overview

- Power Subsystem

The power subsystem consists of five 1.5v batteries and a 5V output regulator module, which can supply 5V voltage to other modules. There is also a voltage regulator in the control circuit, but the role of this regulator is to convert the 5V voltage into a 3.3V voltage (the voltage required by stm32).

- Strain gauge Subsystem

Strain gauges are attached to the bridge to measure its physical deformation, which can indicate potential structural problems. The bending of the strain gauge will cause a voltage change in the output segment of the subsystem, and this information is passed to the data acquisition board to detect safety problems.

- Traffic light Subsystem

The traffic light subsystem is an important security component of the digital two-bridge monitoring system. Directly connected to the board controller, its function is to provide immediate visual alerts to the driver. When the processing subsystem detects a potential overload or structural problem, the system activates a warning light. This is a pre-emptive measure to warn drivers to stop or drive carefully, thus improving the safety of the bridge. The decision to trigger the traffic lights is based on an analysis of the data collected from the strain graph system, ensuring that the alerts are accurate and timely.

- Processing Subsystem

This subsystem is composed of stm32 chip, SWD module, crystal oscillator module, Bluetooth module and voltage regulator module. Responsible for processing the signal from the strain gauge, transmitting the signal to the PC, and controlling the signal light.

- Digital Twin Subsystem

A digital twin is a virtual representation of a physical bridge. It receives data from the control circuit via Bluetooth and then imports the data into the digital twin. This digital model allows for real-time monitoring and simulation, providing a platform for predictive analysis and maintaining forecasts.

2.3 Subsystem Requirement

- Power Subsystem Requirements

Description: The power subsystem includes a battery, as well as a voltage regulator to ensure a stable power supply. It is required to drive sensors, microcontrollers, transceiver modules and traffic light subsystems.

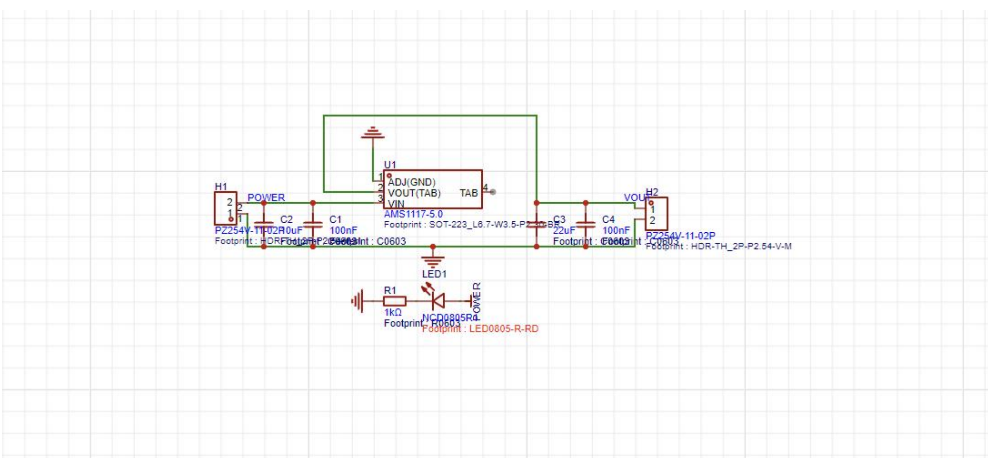
Contribution to Overall Design: It powers all electronic components

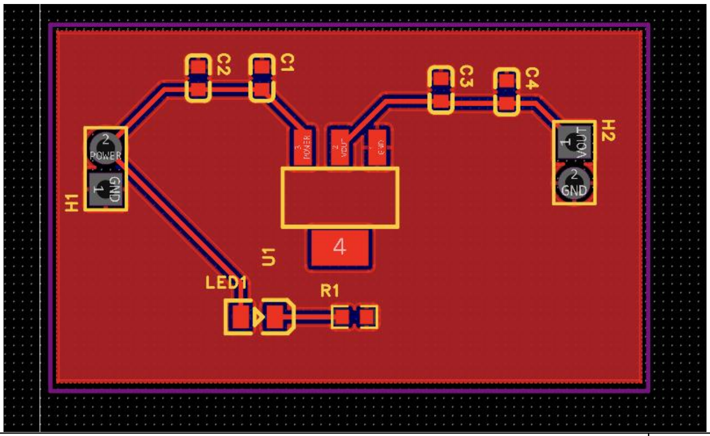
Interfaces with Other Blocks:

Voltage output to the processing subsystem and sensors, traffic light: 5V ± 0.1V.

RV table:

For voltage regulator:





Requirements	Verifications
1. Adjustable output voltage is 1.25-37v. 2. When the voltage drops to 1.2V, the current is 1A.	1. Use the constant - current circuit , connecting the output of the voltage regulator to VCC and draw 1A. 2. Measure the output voltage using an oscilloscope, ensuring that the output voltage. stays within 5% of 5V.

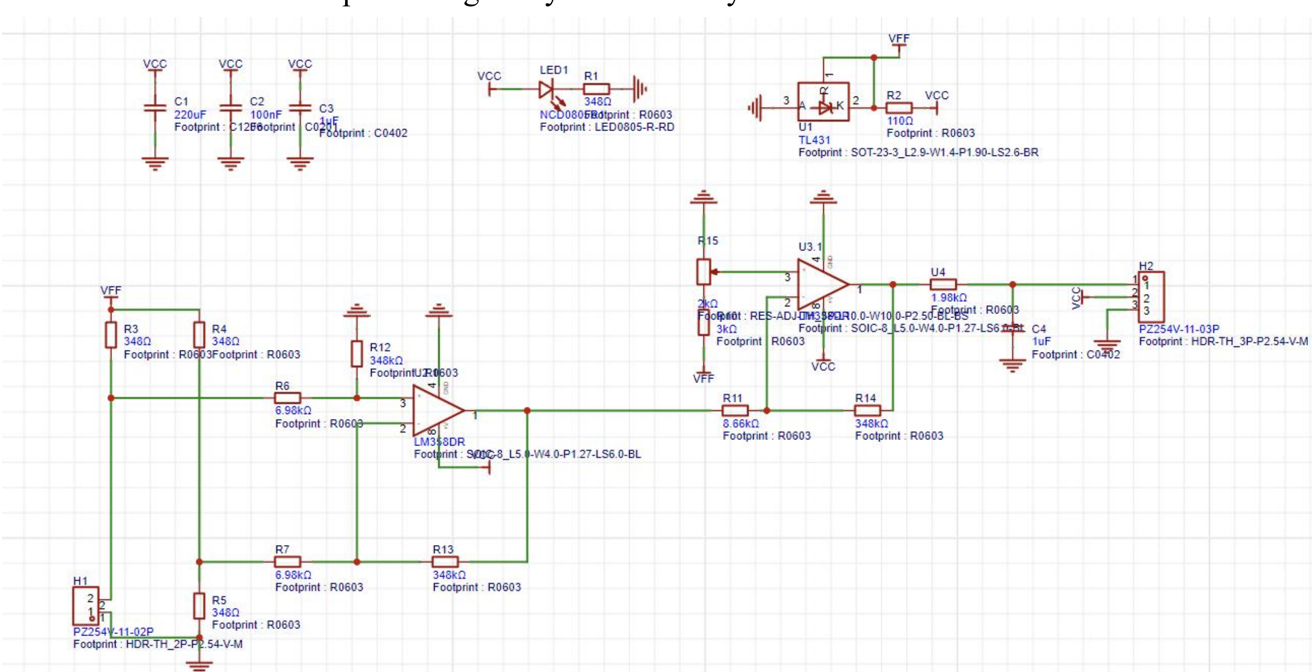
■ Strain gages Subsystem Requirements

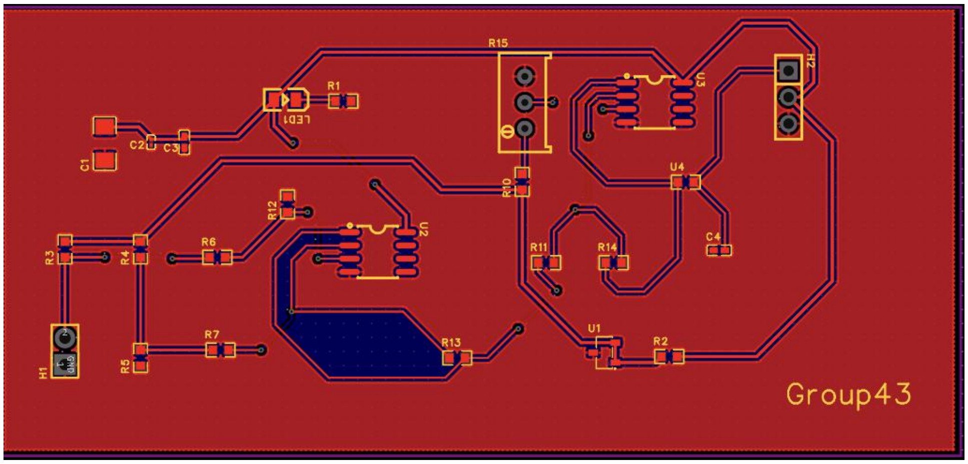
Description: Strain gauges are included to measure the deformation of the bridge, indicating structural safety issues.

Contribution to Overall Design: The deformation data is fed to the processing subsystem to realize the structural health monitoring in the digital twin model.

Interfaces with Other Blocks:

Data communication with processing subsystem: Directly connected to the controller board.





RV table:

Requirements	Verifications
1. The supply voltage is 5V. 2. The sensitivity is 2.0±1%. 3. The output voltage range is 0-5V.	1. Use the power subsystem to provide 5V input and confirm that it is working properly. 2. When the strain gauge force is 0, the AO output voltage should be 2V. When the force is 10000g, the output is 3V to confirm the accuracy of the sensitivity. 3. Increase the bend in the range of 30 degrees and ensure that the output voltage is always below 5V.

■ Traffic Light Subsystem Requirements

Description: This subsystem uses a traffic light to communicate with drivers, indicating when it is unsafe to cross the bridge.

Contribution to Overall Design: Directly impacts driver behavior, enhancing safety by providing immediate visual feedback based on sensor data.

Interfaces with Other Blocks:

Control signals from the board micro-controller: must be capable of receiving digital signals with voltage levels of 5V.

List of Requirements:

Requirements	Verifications
1. The supply voltage is 2V. 2. Must switch from green to red within 100ms of receiving a control signal. 3. Must be able to withstand outdoor conditions, including a temperature range of -20° C to 60° C and adverse weather.	1. LED bulbs normally light up when the input voltage is 2V. 2. Switch color normal.

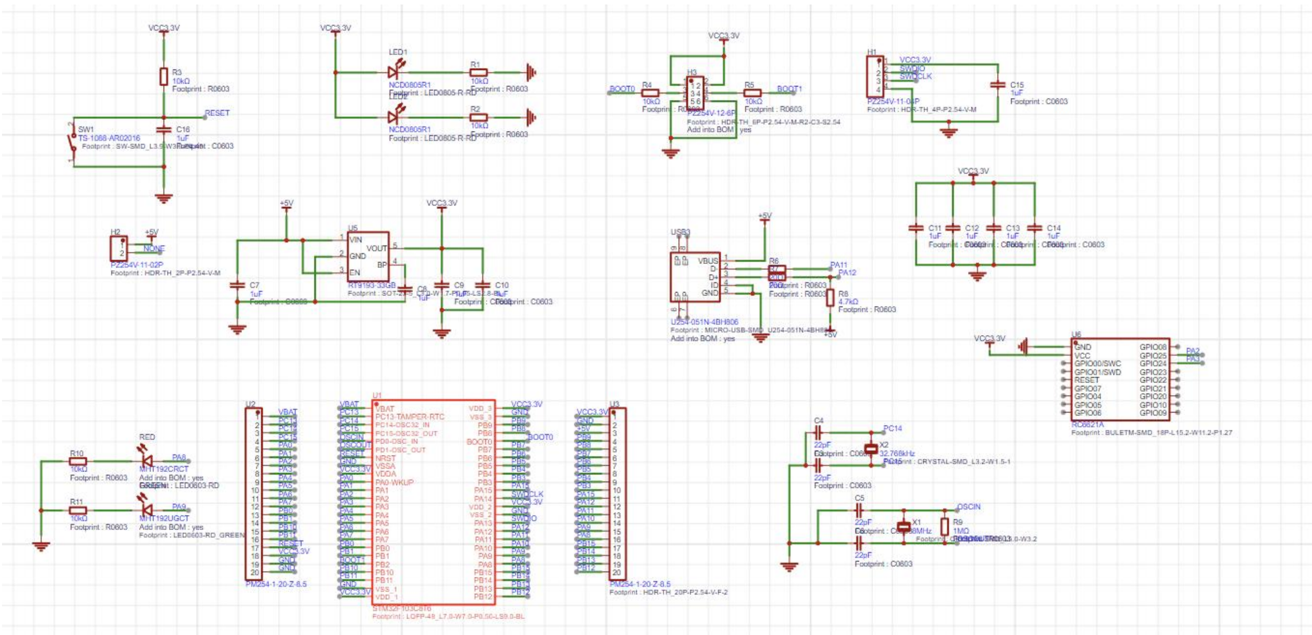
■ Processing Subsystem Requirements

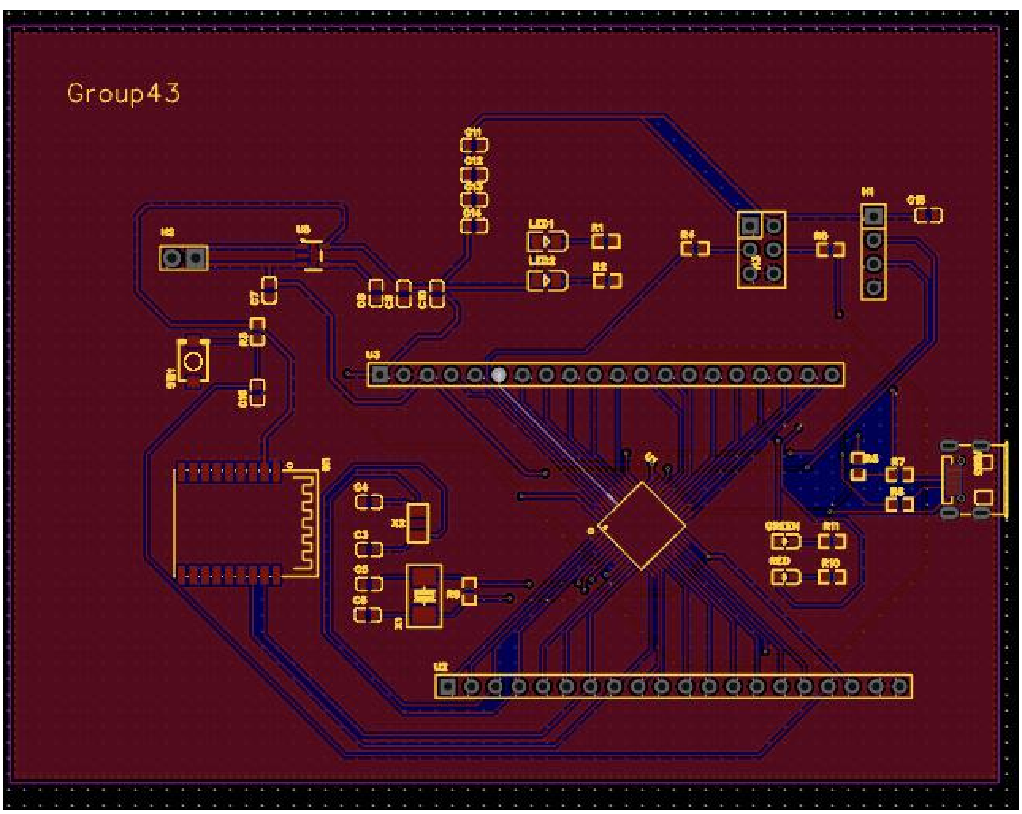
Description: The subsystem consists of a control board and a data acquisition board for processing data from sensors and managing communications.

Contribution to Overall Design: It processes sensor inputs, sends commands to the traffic light subsystem, and sends data to the digital twin.

Interfaces with Other Blocks:

The sensor data is transferred to the PC through the Bluetooth.





RV table:

For controller board:

Requirement	Verifications
1. Must process sensor data in real-time with a	1. Verify that the error time is within the

latency of no more than 10ms. 2. The traffic light system works according to the design logic.	allowable range. 2. Check traffic light status.

■ Digital Twin Subsystem Requirements

Description: This subsystem is the virtual counterpart of the physical bridge, receiving and utilizing data from the processing subsystem.

Contribution to Overall Design: It allows for the real-time assessment and prediction of bridge health, supporting decision-making for maintenance and safety.

Interfaces with Other Blocks:

Receives data from processing subsystem via USB.

RV table:

Requirements	Verifications
1. Must update the digital model in real-time with a maximum delay of 5 seconds from data receipt. 2. Must simulate bridge behavior with an accuracy of 98% compared to the physical model. 3. Must be capable of running predictive algorithms to forecast potential structural issues.	1. Give the pressure sensor an input to confirm whether it can receive a signal within 5 seconds. 2. Confirm errors in pressure signal and strain gauge signal. 3. Check the running status of the algorithm.

2.4 **Tolerance Analysis**

There are mainly three aspects critical to the success of the project. One aspect is related to the digital model of the bridge, while the other two are concerned with the physical model.

One aspect of the design that poses a risk to the successful completion of the project is the integration of real-time data analytics for safety and maintenance as described in our proposal. This component involves processing large volumes of data collected from sensors installed on the bridge to identify potential structural concerns or overloading issues promptly. However, implementing real-time data analytics can be challenging due to factors such as data transmission delays, processing time, and the complexity of the analytics algorithms.

To test the feasibility through mathematical analysis, we first assume the distance between pressure sensor and signal light is X_1, distance for a man with normal vision to recognize the number on the display screen is X_2, time a driver takes to react to the signal light is T_1, time the controller takes to complete integration of real-time data analytics is T_2, speed limit is V. Above variables should satisfy $V \cdot (T_1 + T_2 + 3) < X_2, X_1 \in [V \cdot (T_1 + T_2 + 3), X_2]$.

Another aspect is the comparison between weight of the remote-control car and thickness of the aluminum beam. If the weight of the remote-control car is quite large or the thickness of the aluminum beam is too small, then the strength of the bridge is relatively too high and the deformation of the aluminum beam will be tiny, and the signal collected by strain gauges will be very weak. Therefore, the precision demands on the sensors would be heightened, leading to an escalation in project expenses.

To test the stability of the physical model of the bridge, methods are typically divided into two dimensions. One way is determining bending stress applied on the bridge using data collected by the pressure sensors. Suppose the moment exerted by the remote-control car on the bridge is M, moment of inertia of the bridge is I, and thickness of the beam is h, then the bending stress is $\sigma = \frac{Mh}{2I}$. Another way is calculating deflection of the beam based on data collected by the strain gauges. Assuming the car is a concentrated load, with a distance a from one stool and a distance b from the other stool, the self-weight of the car is W, the length of the aluminum plate is L, the modulus of elasticity is E, and the moment of inertia is I, then the deflection of the beam is $\delta = \frac{Wa\left(\frac{1}{3}b(L+a)\right)^{\frac{3}{2}}}{3LEI}$.

The last one is the effect of the not negligible width of the two stools along the direction of the bridge. Given the fact that the two stools are idealized to two triangle supports when computing the deflection and transverse load, the relationship between the deflection and transverse load with the concentrated load applied on the bridge will be disturbed to some extent. However, as the shear strength of the Aluminum 7075 is large enough to hold the transverse load produced by the remote-control car, error of transverse load does not matter.

3. Cost & Schedule

3.1 Cost

Labor	Rongjian Chen	87769 dollars / year	130 hours	3908 dollars
	Hanchi Ge	87769 dollars / year	130 hours	3908 dollars
	Kowshik Dey	87769 dollars / year	130 hours	3908 dollars

Part	Cost (Prototype)	Cost (Bulk)
Aluminum Beam (Taobao)	118.8 yuan	118.8 yuan
Pressure Sensor (Taobao, DF9-40)	77 yuan	77 yuan
Voltage regulators (Taobao, LM2586)	7.6 yuan	7.6 yuan
LED (Taobao)	5 yuan	5 yuan
Strain Gauge (Taobao, BFH120-5AA)	60 yuan	30 yuan
Data acquisition board	339 yuan	339 yuan
Total	607.4 yuan	577.4 yuan

3.2 Schedule

1) 3.18 - 3.24

- Read some articles and videos to review learnt skills and learn new skills that required by building bridge models
- Building physical model of the bridge. Completed bridge modeling based on Unreal Engine 5.
- Start PCB Design

2) 3.25 - 3.31

- Build physical model and design PCB board.

3) 3.18 - 4.18

- The simulation of the digital twin bridge is successfully completed, and the signal transmission and processing from the physical model to the digital twin model are completed.
- Complete the actual test, drive the remote control car onto the physical model bridge, and adjust the experimental data.

4) End of Project

- Debug the digital twin bridge monitoring system to ensure reliable operation of the system.
- Improve the visualization of digital twin bridge monitoring data. Finish the project.

3.3 Distribution of work

1) Hanchi Ge

- Acquiring the required physical materials needed for the project.
- Building the physical model of the bridge

2) Rongjian Chen

- Responsible for the deployment of the digital twin simulation
- Bridge alert system and sensors.

3) Kowshik Arko Dey

- In charge of designing the whole PCB schematic.
- Map out the whole sensor distribution for accurate data analysis and assist in data analysis.

4. Ethics and safety

Issues during development of our project and corresponding solutions

Issue: Gathering real-time data about vehicles crossing the bridge may raise privacy concerns, especially if the collected data contains identifiable information about individuals or vehicles. This could breach the principle of respecting privacy as outlined in the IEEE Code of Ethics, which emphasizes the protection of individuals' privacy and confidentiality.

Solution: Ensure that the data collected is anonymized and aggregated to prevent the identification of individuals or specific vehicles. Implement strict access controls and encryption protocols to safeguard the collected data.

Issue: The development process should ensure transparency about the capabilities and limitations of the system. There should be clear accountability for any decisions made based on the data collected.

This aligns with the IEEE Code of Ethics, which emphasizes honesty and integrity in professional activities.

Solution: Document the development process thoroughly, including the algorithms used for data analysis and the criteria for generating alerts. Provide clear explanations to stakeholders about how the system operates and its potential implications.

Issue: When calculating the force situation of the physical model of the bridge, the model is idealized, neglecting the influence of the self-weight of the steel plates in the middle and on the outside of the stools acting as piers on the force situation and deflection of the bridge, as well as the influence of the width of the stools along the direction of the bridge on the deflection results, resulting in some discrepancies between the simulated data of the bridge and the data from actual experiments.

Solution: Use experimental statistics to correct the relationship between the ideal model and the actual model based on the average error between the results obtained from the ideal model and the actual model. Since the maximum transverse shear force of aluminum 7075 is much greater than the maximum shear force calculated based on the ideal model, the error in transverse shear force will not affect the experimental results.

Issues during accidental or intentional misuse of our project and corresponding solutions

Issue: If the system generates false alerts or fails to detect actual safety concerns, it could lead to unnecessary disruptions in traffic flow or, worse, accidents due to drivers reacting to false alarms. This could violate the principle of avoiding harm as stated in the ACM Code of Ethics, which emphasizes the importance of minimizing negative consequences.

Solution: Conduct extensive testing and validation of the system to ensure its reliability and accuracy. Implement fail-safe mechanisms to prevent false alarms, such as setting conservative thresholds and incorporating redundancy in sensor measurements.

Issue: Security Vulnerabilities: Malicious actors could potentially exploit vulnerabilities in the system to tamper with the data or disrupt the operation of the bridge. This could compromise the safety of both drivers and the structural integrity of the bridge, violating the principle of professional responsibility outlined in the ACM Code of Ethics.

Solution: Employ robust cybersecurity measures, including encryption, authentication, and intrusion detection systems, to protect the integrity and confidentiality of the data. Regularly update and patch the system to address any newly discovered vulnerabilities.

Issue: Interference has affected the decision-making process of the system, resulting in incorrect judgments regarding whether the current vehicle weight can safely cross the bridge. If the maximum load used for the judgment exceeds the set value, it could lead to bridge collapse; conversely, if it is below the set value, it could result in traffic congestion.

Solution: Strengthen the system's resistance to interference by inputting the set value as a constant parameter into the control system. Add a step to compare the set maximum load and the maximum load used for the current judgment. If the difference is too significant, automatically trigger an error alert for warning purposes.

Relevant Safety and Regulatory Standards

The bridge's design and construction must adhere to relevant safety standards set by regulatory bodies such as the American Society of Civil Engineers (ASCE) and the Federal Highway Administration (FHWA). These standards ensure that the bridge can safely withstand the loads imposed by crossing vehicles.

Compliance with data privacy regulations, such as the General Data Protection Regulation (GDPR) in Europe or the California Consumer Privacy Act (CCPA) in the United States, is essential to protect the privacy rights of individuals whose data is collected by the system.

Potential Safety Concerns

Ensuring the accuracy and dependability of the sensors utilized for weighing passing vehicles is crucial to the system's effectiveness. Dysfunctional sensors or inaccurate readings may lead to erroneous evaluations of the bridge's structural soundness.

Any breakdowns in communication channels or flaws in data processing algorithms could cause delays or oversights in identifying potential safety hazards. This jeopardizes the system's ability to achieve its primary goal of bolstering safety and upkeep.

To prevent damage from overload, refrain from connecting devices to power sources that exceed their designated voltage or current. It's imperative to use power adapters that meet the devices' specifications and standards. Additionally, ensure proper ventilation for the devices by positioning them in well-ventilated areas. Avoid excessive clutter or covering around the devices, and regularly clean the surrounding space to maintain adequate airflow.

References

Code of Ethics (acm.org)

IEEE - IEEE Code of Ethics

Policy statement 208 - Bridge safety | ASCE

National Bridge Inspection Standards - Bridge Inspection - Safety Inspection - Bridges & Structures - Federal Highway Administration (dot.gov)

General Data Protection Regulation (GDPR) – Official Legal Text (gdpr-info.eu)

Privacy and Data Security | State of California - Department of Justice - Office of the Attorney General