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DESIGNING A LOW-COST WIRELESS SENSING SYSTEM FOR REAL TIME DAMAGE ASSESSMENT OF R/C BRIDGES

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Abstract

This paper presents an overview of an ongoing project that aims to develop a low-cost system and software platform for real-time identification and evaluation of the damage state of reinforced concrete bridges, with a focus on extreme events such as earthquakes. The project includes the design and manufacturing of a portable, battery-powered, wireless acceleration streaming device, a software tool to optimize a parameterized finite element model, and an integrated methodology for damage identification and evaluation. The effectiveness of the proposed system will be tested on a typical existing R/C bridge in a region of high seismicity, with validation in both real field conditions and simulated experiments. The paper discusses the project methodology, current progress, and expected outcomes, including the potential to reduce the cost and time for bridge inspection and provide real-time safety information after an extreme event. This project presents a significant contribution to the field of structural health monitoring and has the potential to further enhance the application of SHM techniques in both academic and practical structural engineering communities.

Keywords: Reinforced concrete bridges, real-time identification, acceleration, damage evaluation, structural health monitoring.

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1 INTRODUCTION

Bridges play a pivotal role in transportation systems, acting as vital connections that enhance the economy, improve quality of life, and promote community integration. However, the current infrastructure is struggling to meet the growing demands, requiring both immediate measures to maintain existing structures in a satisfactory condition and long-range transformations using advanced technologies to boost their durability and resilience. Following a severe earthquake event, civil protection agencies and highway stakeholders are faced with critical decisions regarding the closure or continued operation of highway networks, with particular attention paid to bridges, which are often their most vulnerable components.

Bridge damage poses risks to road safety, causes traffic disruptions, and triggers significant direct and indirect economic losses. Past incidents, such as the collapse of the Mississippi River bridge, USA (2007), the Pinios (2016) and Kompsatos (2017) bridges in Greece, and the Morandi bridge in Genoa, Italy (2018), have highlighted the devastating consequences of bridge failures. Moreover, bridges are susceptible to multiple natural hazards, including earthquakes, and also environmental threats. Prompt inspection of critical road infrastructure becomes imperative in the aftermath of a strong earthquake. Motorway administrators face the challenge of making decisions, such as the precautionary closure of bridges pending post-seismic inspection, which can affect serviceability, rescue operations, and evacuation efforts. Conversely, leaving bridges operational without inspection poses significant risks, as subsequent earthquake events could compromise their stability, potentially leading to additional casualties. Therefore, administrators must decide whether the motorway network can continue to operate without restrictions. Insufficient coordination during such critical periods may also increase anxiety among motorway users.

Structural Health Monitoring (SHM) techniques have emerged as essential tools to address these challenges by facilitating the identification of structural characteristics and behaviors. SHM can involve continuous or periodic measurements, as well as assessments following severe loading events, to capture the static or dynamic mechanical response of bridges. Although SHM in its simplest form focuses on comparing measured responses to design model predictions, advanced strategies involve calibrating and updating theoretical bridge models to align with measured data. Although Finite Element (FE) model updating algorithms have been widely employed, a comprehensive and integrated approach that fully leverages SHM measurements for model verification, damage identification, and evaluation is still lacking. Recent research efforts [1,2] have begun to address this gap, but holistic methodologies considering the entire bridge system and employing highly accurate finite element models remain limited.

In response to these challenges, there is an urgent need for the development and implementation of systems capable of assessing the structural condition of bridges in real-time [3,4]. The present project, titled RISE (Real-time Identification and Evaluation of Damage in Reinforced Concrete Bridges), aims to provide a novel real-time assessment system specifically designed for reinforced concrete (R/C) bridges. The primary objective of this project is to develop an innovative low-cost sensing system and an integrated software platform to identify the damage state of R/C bridges in real-time conditions.

The suggested system encompasses the development of an integrated, low-cost solution to rapidly assess structural damage in existing bridges. This solution relies on vibration-based system identification procedures and features an innovative device along with appropriate control software to facilitate short-term multipoint acceleration recording on bridge structures. The monitoring device will be designed and manufactured based on a high precision MEMS acceleration sensor and will reduce the cost and time required for routine bridge inspections, thereby offering an efficient solution for field researchers. The in-house production of these devices will enable their patenting and mass production, enabling broader applications within both academic/research and practical structural engineering communities.

Additionally, RISE is committed to developing a software platform capable of optimizing a parameterized finite element model as part of the SHM process. This platform, based on measurements of vehicle-induced bridge vibrations, will utilize signal processing and optimization algorithms to update the finite element model. In addition, the RISE project aims to surpass the current research forefront by integrating the process of finite element model updating into a software tool that utilizes a Functional Mockup Unit (FMU). This FMU-based tool will operate as a model exchange and co-simulation standard, allowing for future expansion and co-simulation purposes across a variety of solvers. An improved version of GID-OpenSees, a graphical user interface developed for OpenSees [5], will also be developed within the RISE project and will enable the export of parameterized finite element models.

Another key objective is the development of an integrated methodology for real-time damage identification and evaluation of the damage state of R/C bridges. This methodology will employ a damage identification process that uses measured data at different time intervals ($t_0 \ldots t_i$) to compare the initial and current response of the bridge. Information from this process will then be used to define suitable damage state criteria based on capacity curves of the structure. Finally, the project aims to apply the proposed system to a typical existing R/C bridge in a region of high seismicity, to identify structural damage states using monitoring data. This practical application of the system will provide valuable insights into the effectiveness and potential areas of improvement for the developed technologies and methodologies.

By addressing these critical aspects of the current state-of-the-art, the RISE project aims to enhance the utilization of structural health monitoring techniques in assessing bridge performance and providing real-time safety information following extreme events. This advancement will enable the identification and evaluation of bridge damage in a comprehensive manner, thus significantly contributing to the field of structural health monitoring. Fig. 1 shows a comprehensive chart of the project roadmap.

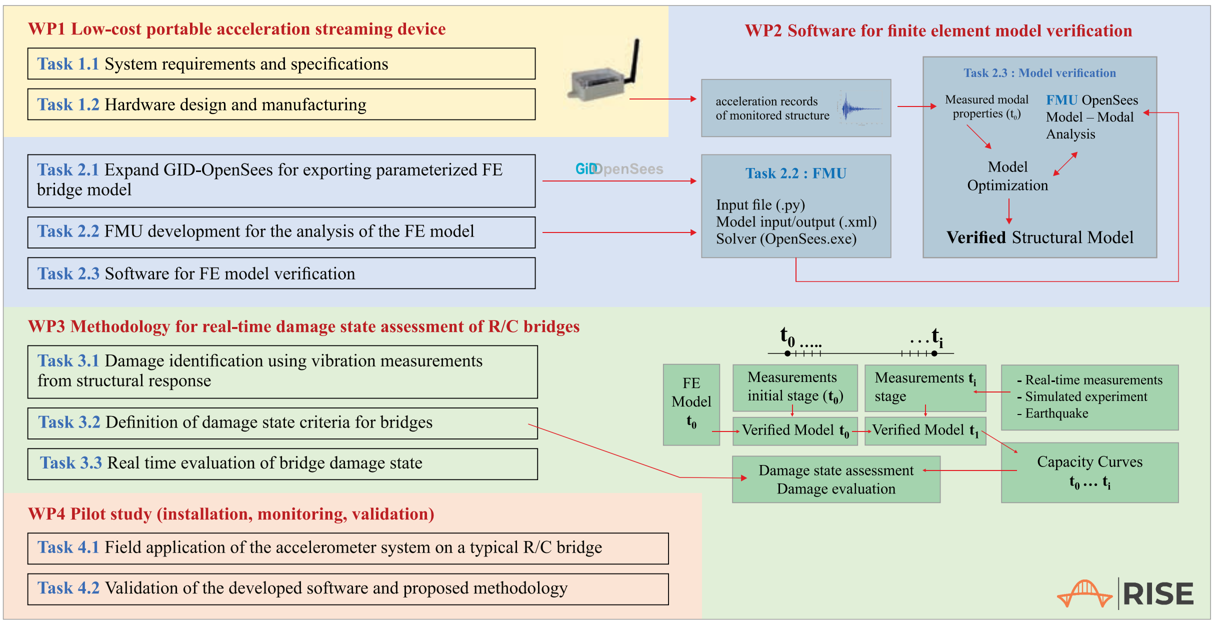


Fig. 1 : Overview of the RISE project roadmap.

During the current phase of the RISE project, primary attention is placed on establishing system requirements and initiating the design process for the required multi-point acceleration recording device, which is currently under development. This paper will concentrate on the decision-making process during its design phase, specifically the reasoning behind component selection, how these choices align with the overarching objectives of the project, and early decisions influencing the expected functionality of the device.

2 DESIGN REQUIREMENTS AND DECISIONS

In alignment with the project roadmap described in the previous section, the initial aim of the RISE project is to design an effective sensing system capable of short-term recording of vehicle-induced vibrational data from multiple points on the bridge deck. The collected time vs. acceleration data series (aka. accelerograms, acceleration records) will serve as the fundamental input for the subsequent signal processing and optimization algorithms. When combined with the FMU-based analysis, these data will facilitate the production of verified structural models for real-time damage assessment of bridge structures. The primary requirements for designing the acceleration sensors proposed herein, listed in descending order of importance, are as follows:

1. *Absolute Time Synchronization*: This feature is essential for accurate and efficient post-processing of acceleration data in the context of system identification procedures. It ensures that data from multiple sensors can be correctly aligned and compared, thereby enabling a comprehensive and accurate understanding of the bridge's dynamic behavior.
2. *Multi-Directional, High Resolution, and Low Output Noise Measurements:* A high-performance triaxial sensor capable of detecting vibrations in all three spatial dimensions at high resolution is preferable. This allows the sensor to capture small changes in acceleration accurately. Additionally, the sensor should produce low output noise to preserve the quality and integrity of the recorded data. Circuit design should also consider the potential for data interference and aim to minimize it to ensure the fidelity of the captured signals. However, these performance demands should be balanced with cost, which needs to remain within a reasonable range to keep the overall project budget manageable.
3. *Quick and Temporary Field Installation/Deinstallation and Data Collection*: The device should be compact, battery-powered, and capable of wireless data transmission to enable rapid deployment and retrieval in the field. Although establishing a sufficiently long wireless range without transmission latency or data loss issues can be challenging, wired connections, such as Ethernet, would significantly undermine the rapid assessment objective of the project by increasing setup and teardown times.
4. *Low Component and Manufacturing Costs*: Keeping the production cost low will facilitate the manufacture of a greater quantity of devices. This allows for measurements at a greater number of locations on a bridge concurrently and promotes a policy of direct unit replacement, rather than repair, in the unlikely event of hardware malfunction. However, it is critical to balance cost with the need for reliability and precision in data collection.
5. *Robustness and Durability*: Given the environment where these devices will be deployed (outdoors, on bridges, exposed to various weather and temperature conditions), they must be robust enough to withstand these conditions without failure or loss of accuracy.

6. *Data Management*: The device should be connected to a reliable remote storage system where data can be saved and accessed for analysis.
7. *Ease of Use*: The device should be user-friendly with easy installation, operation, and data collection processes. This can significantly save time and reduce the chances of errors during setup or use.

As outlined in the design requirements, *absolute time synchronization* is of utmost importance for the proposed acceleration sensor devices. This requirement becomes particularly crucial in a distributed sensing system, where accurate time alignment from multiple sensors is necessary. There are several methods to achieve this, including the Global Positioning System (GPS), Network Time Protocol (NTP), and synchronization pulse techniques. Each method comes with unique characteristics, rendering them suitable for certain applications while less optimal for others. In this context, GPS synchronization offers numerous advantages that make it a favorable choice for synchronizing acceleration sensors in a distributed system:

(a) GPS synchronization provides time accuracy within a few nanoseconds globally, significantly surpassing the millisecond accuracy offered by NTP.
(b) GPS synchronization does not depend on internet connectivity. This independence from the internet, which is a requirement for NTP, increases system robustness. It is particularly useful in remote locations where reliable internet service may not be available or in situations where the device needs to operate in an offline environment.
(c) GPS synchronization is independent of wired connections, compared to traditional sync pulse methods that require a physical connection. This independence allows greater flexibility in device placement and simplifies the installation process, a critical factor in scenarios involving temporary installations. Although the sync pulse method usually relies on a wired connection for the transmission of the common trigger signal, it can also be configured as a point-to-point wireless transmission within a local wireless network. However, this alternative requires careful setup to avoid potential latency and may only be used as an alternative when the GPS signal is weak due to weather conditions.
(d) GPS synchronization can support a virtually unlimited number of sensors, an important advantage when monitoring multiple points on a bridge. In contrast, the performance of systems using NTP might degrade as the number of devices in the network increases.

Taking all the above factors into account, GPS synchronization emerges as a robust, scalable, and flexible solution for time-synchronizing acceleration sensors for the proposed application.

Moving further into design considerations, another critical requirement for the proposed sensing system involves the quick and temporary field installation and data collection, which highlights the importance of *wireless connections* for data transmission. Wireless connectivity options vary, including cellular networks (4G/5G), Bluetooth, LoRaWAN, Zigbee, and WiFi, among others. Each of these technologies has its strengths and potential drawbacks, but for the proposed application of temporary, short-term acceleration data recording from multiple points, WiFi is the most suitable choice:

(a) WiFi maintains a balance between range and data rate that few other wireless technologies can match. While a typical WiFi network has a range of up to 100 meters, special high-gain antennas or WiFi range extenders can be utilized to extend this range beyond the usual limit, if required. This expanded range can cover a broad area on most bridge structures. Coupled with the high data rate that WiFi offers, the technology is well-suited for transmitting the large amounts of data generated by high-resolution triaxial accelerometers.

(b) While a pre-existing WiFi infrastructure may not always be available at a bridge site, establishing a local WiFi network using a gateway (e.g. WiFi access point or router) is a straightforward and cost-effective process. This characteristic of WiFi further facilitates quick and temporary installations and reduces setup time and costs.
(c) Compared to other wireless technologies, WiFi exhibits lower latency, which ensures real-time or near real-time transmission of acceleration. However, even if minor latency issues occur, the use of GPS synchronization ensures precise timestamping of the data, thus mitigating potential impacts on data alignment.
(d) WiFi supports a large number of devices connected concurrently, aligning well with the need to collect data from multiple sensors placed at various points on a bridge. Furthermore, with the WiFi gateway connected to a computer, easy and reliable data storage becomes feasible, enhancing the overall efficiency of data management.
(e) Devices equipped with WiFi capabilities, such as ESP8266 or ESP32 microcontrollers, are readily available and affordable. They offer a high level of integration, enabling compact device designs for quick deployment and retrieval in the field.

Considering various aspects such as range, data rate, availability, latency, and the capacity to support multiple devices, it becomes clear that WiFi stands out as the most suitable wireless connection option. Its capabilities align effectively with the requirements of rapid and temporary field installation and data collection for this specific application.

For the remaining design considerations, the following additional decisions align with the outlined requirements for the proposed acceleration sensor device:

(a) A rechargeable Lithium Polymer (LiPo) battery has been selected as the power source for the device, ensuring autonomous operation. This choice is particularly advantageous given the general scarcity of continuous power availability on bridge structures. LiPo batteries offer the advantage of high energy density in a compact and lightweight form, making them particularly suitable for this application. Their flexible form factors also facilitate seamless integration within the compact design of the device.
(b) Employing 3D printing technology, a compact and robust enclosure will be designed for a precise fit, ensuring the protection of electronic components from external elements. This enhances the durability and lifespan of the device. The enclosure is designed to house all components, including the necessary GPS and WiFi antennas. An additional design feature is the inclusion of a small OLED screen in the device. This screen provides real-time data and status information, offering immediate feedback and diagnostics. The advantage of this feature is that it eliminates the need to connect the device to a computer for status updates or troubleshooting.
(c) To expedite rapid field installations, a magnetic mounting system needs to be embedded in the enclosure to secure the sensors to the bridge, using a reusable metallic base plate. This system will provide a secure, non-invasive attachment method, eliminating the need for additional tools or hardware for installation. It simplifies the setup process while also reducing the time for both installation and removal.

In conclusion, each design consideration, from power source to physical construction to ease of use, has been carefully made to ensure the proposed sensing system fulfills the essential requirements while maximizing performance and user-friendliness. Fig. 2 illustrates a representative bridge installation, depicting sensor devices placed at key points on the bridge. Each of these devices is equipped with wireless connectivity and GPS, ensuring efficient data transmission and synchronized data timestamping, respectively. They are wirelessly connected to a central WiFi gateway, forming a comprehensive monitoring system for recording vehicle-induced vibrations.

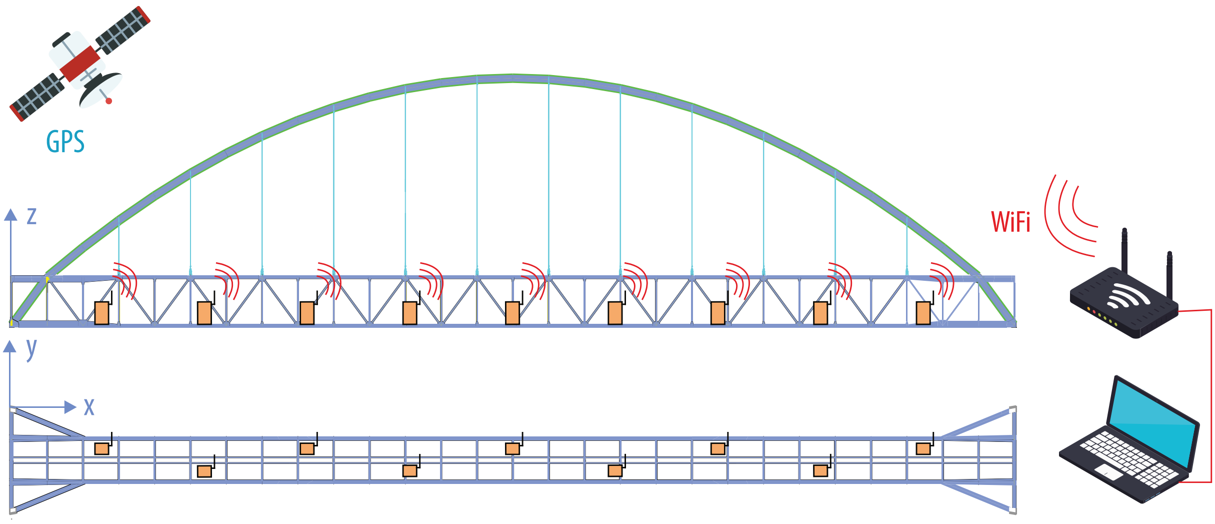


Figure 2: Distributed sensor network on a bridge structure.

3 COMPONENT IDENTIFICATION

Moving from general design considerations and system layout, this section turns attention to detailed component identification. Specifically, it focuses on the choice of the acceleration sensor, GPS module, and WiFi platform, discussing the particulars of each and their role in the overall system operation.

3.1 Acceleration sensor

In the process of selecting an appropriate acceleration sensor for this project, Micro-Electro-Mechanical Systems (MEMS) accelerometers emerge as a more favorable option in comparison to other types, such as Piezoelectric (PZT) sensors. Primarily, MEMS accelerometers gain recognition for their compact size, robustness, and lower power consumption, attributes that align well with the requirements of a portable and energy-efficient device for field applications. Their large-scale production in the consumer electronics industry further leads to competitive pricing, making them a cost-effective choice compared to other types of accelerometers.

MEMS accelerometers come with either analog or digital interfaces. For this project, a digital interface was chosen due to the simplification it brings to the system design. Specifically, it facilitates direct connection to microcontrollers, eliminating the need for additional costly analog-to-digital converters. Moreover, it is better shielded against electromagnetic interference, making it a superior choice for operation in noisy environments.

Key characteristics to consider when selecting a MEMS accelerometer include resolution and noise density. The resolution, expressed in bits, indicates the sensitivity of the sensor, with higher resolution enabling the detection of smaller accelerations. Noise density, expressed in $\mu g/\sqrt{Hz}$ or root mean square (RMS) noise (mg), is the most critical parameter that defines the smallest acceleration changes that can be distinctly detected by the sensor. A lower noise density, as well as a constant noise response across the frequency range of interest (e.g. DC to 30 Hz) is preferable as it ensures more accurate and reliable acceleration measurements.

Following a comparison of various low-cost MEMS accelerometers available in the market, the Analog Devices ADXL355 accelerometer was selected for the device. This decision was driven by its superior performance in terms of resolution and noise density, making it an optimal choice for capturing high-quality and precise acceleration data from bridge vibrations (Table 1). To further validate its performance, a pilot test was performed in which the accelerometer demonstrated an impressively low noise level (< 0.1 mg RMS), confirming its suitability for the task. Fig. 3 presents the measured noise floor in terms of power spectral density among the selected sensor, a lower-spec MEMS sensor [6], and a commercial grade force-balance accelerometer.

Manufacturer	Model	Range (g)	Resolution (bits)	Noise density (μg/√Hz)	RMS noise[1] (mg)	Price[2] (€)
TDK InvenSense	MPU-6000	± 2,4,8,16	16	400	2.83	12.8
STMicroelectronics	LIS331DLH	± 2,4,8	16	218	1.54	4.1
Analog Devices	ADXL313	± 0.5,1,2,4	10-13	150	1.06	11.2
Bosch Sensortec	BMA456	± 2,4,8,16	16	120	0.85	2.6
NXP	MMA8451Q	± 2,4,8	14	99	0.70	3.7
STMicroelectronics	LIS3DHH	± 2.5	16	45	0.32	14.3
Analog Devices	ADXL355	± 2,4,8	20	22.5	0.16	61.1

[1] calculated approximately as : noise density × √(bandwidth), for a typical 50 Hz bandwidth.
[2] price for one piece, extracted on 30/05/2023 from a major distributor.

Table 1: Characteristics of various digital MEMS accelerometers.

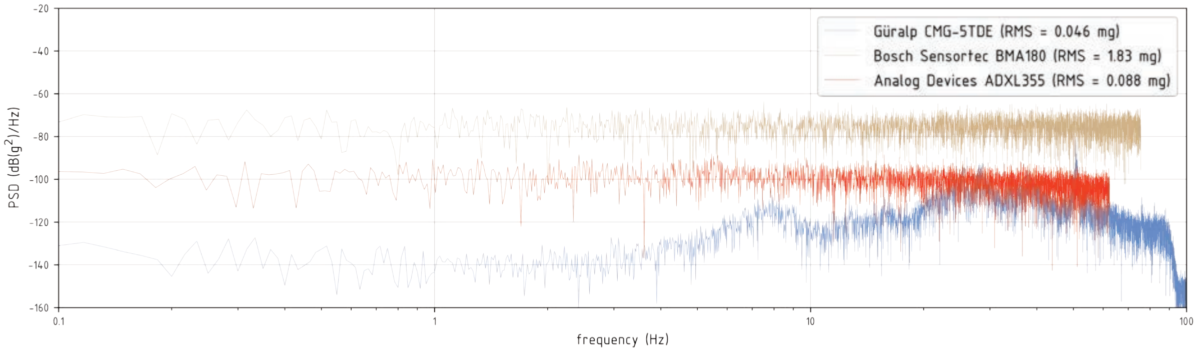


Figure 3: Noise performance (power spectral density) between the ADXL355 accelerometer compared to an obsolete 14-bit sensor and a commercial-grade accelerometer.

3.2 GPS module

The GPS module embedded in the device serves a crucial function by providing an absolute time reference. This is achieved through a Pulse-Per-Second (PPS) digital signal, enabling nanosecond-precise synchronization across all deployed devices. As explained in the previous section, this feature is essential for consistent data collection and subsequent analysis. Several GPS modules were examined during the selection process, the details of which can be found in Table 2.

Although spatial accuracy was considered, it was not the decisive factor in this selection. All modules under consideration offer spatial accuracy down to 2-3 meters, depending on the number of satellites locked and subject to varying weather conditions. However, the overall accuracy could potentially be improved through continuous monitoring and subsequent post-processing of the stationary device locations on the bridge during measurements. Other selection criteria included power consumption, form factor, and cost. All GPS modules also require a small active ceramic antenna for satellite signal acquisition. The choice of antenna depends on factors such as its gain (dB) and size. Ultimately, the u-blox NEO-6M module was chosen for its comprehensive blend of features and performance.

Module	PPS signal	Accuracy (m)	Tracking channels	Consumption (mA)	Form
u-blox NEO-6M Red	Yes	2.5	22	45	
ATGM336H	Yes	2.5	32	25	
Quectel L80	Yes	2.5	22	25	
Grove - GPS (Air530)	Yes	2.5	22	60	

Table 2: Characteristics of various GPS modules.

3.3 WiFi platform

In the process of choosing the most appropriate WiFi platform, various factors were evaluated. First, there was the need for a fast and reliable connection to a wireless gateway, which ensures efficient transmission of acceleration data. Additionally, interface compatibility of the platform with the selected MEMS accelerometer and GPS module was critical to ensure the seamless integration of these different components. Furthermore, cost effectiveness, energy efficiency, programming language, and the active engagement of its user community were all essential considerations in the decision-making process.

Various WiFi platforms were evaluated during the selection process, each offering a different combination of features and performance. Preference was given to platforms with an integrated development environment (IDE) that simplifies programming and debugging. Other key considerations included cost, power consumption, and availability of support resources, such as online tutorials and community forums. Furthermore, the option of an external antenna connection was deemed essential to ensure better signal reception. Several WiFi modules were examined during the selection process, the details of which can be found in Table 3.

From the pool of potential options, two WiFi platforms from Espressif Systems, ESP8266 and ESP32, stood out as promising candidates due to their affordability, performance and strong support community. After careful consideration, the ESP8266 platform was ultimately selected. This decision was primarily driven by its affordable cost, adequate number of input/output (I/O) pins, and the availability of standard communication protocols such as serial, SPI, and I2C for interfacing with other components. It is worth noting that while the ESP32 offers even more I/O pins and includes a Bluetooth feature, these added functionalities were not deemed necessary for this project. It should be mentioned that there are several variants of the ESP8266 and ESP32 platforms available on the market as different module implementations. In the context of this project, the selected variant of the ESP8266 included an onboard LiPo battery charging circuit. This added feature, beyond the fundamental capabilities of ESP8266, contributes to the operational efficiency of the device by providing an integrated power management solution.

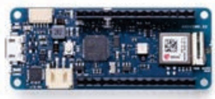
Platform	Processor	Programming	Price (€)	Form
ESP8266	Tensilica L106 32-bit RISC	Arduino C++ MicroPython	3.5 to 27	
ESP32	Xtensa LX6 32-bit Dual-Core	Arduino C++ MicroPython	8 to 32	
Arduino MKR WiFi 1010	SAMD21 Cortex-M0+	Arduino	42	
Raspberry Pi Zero W	Broadcom BCM2835	Python C++ Java	20	
NRF24L01	nRF24L01+	C/C++	2.5 to 5	

Table 3: Characteristics of various WiFi platforms.

4 CONCLUSIONS

This paper provided an in-depth discussion on the design and development of a cost-effective, easily deployable, compact, and energy-efficient structural health monitoring (SHM) system intended for application in bridge structures, in the form of a distributed acceleration sensor network. The system relied on a high-performance MEMS accelerometer, GPS, and WiFi technology, which were described in detail throughout the paper.

A detailed presentation of the proposed system architecture was provided, including aspects such as synchronization, data transmission, and power management. Attention was turned to the selection process for each critical component of the system. MEMS accelerometers emerged as an optimal choice due to their compact size, robustness, and lower power consumption. Among several candidates, the Analog Devices ADXL355 accelerometer was selected for its superior resolution and low noise density. The GPS module, which serves as an absolute time reference for synchronization, was considered necessary, and the NEO-6M module was chosen for its combination of features and performance. Finally, the WiFi platform was selected based on the need for a fast and reliable connection to a wireless gateway, with the ESP8266 platform emerging as the optimal choice due to its affordability, performance, and strong support community. The robust integration and programming of the above components, mounted on a custom 3D printed enclosure, is expected to provide an efficient distributed acceleration recording solution.

This SHM system is a key component of the RISE project, which is dedicated to improving the utilization of structural health monitoring techniques for bridge performance assessment and real-time safety information provision, particularly after extreme events. Despite its compact and cost-effective design, the system is expected to deliver accurate acceleration data, indicating potential applicability in real-world situations. The project roadmap establishes the framework for ongoing system improvement, a rigorous assessment of its reliability and performance, and an exploration of potential enhancements to its existing capabilities. These efforts are expected to make a significant contribution to the progression of structural health monitoring.

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REFERENCES

[1] Iranmanesh, A. and Ansari, F. Energy-Based Damage Assessment Methodology for Structural Health Monitoring of Modern Reinforced Concrete Bridge Columns. Journal of Bridge Engineering, 19(8), 2014.

[2] Prendergast, L. J., Limongelli, M. P., Ademovic, N., Anžlin, A., Gavin, K., & Zanini, M. Structural Health Monitoring for Performance Assessment of Bridges under Flooding and Seismic Actions. Structural Engineering International, 28(3), 2018.

[3] Anastasopoulos, I. et al. Development of RApid REsponse (RARE) System for Motorway Bridges: Overview and Pilot Application to Attiki Odos Motorway. Int. J. Geoengin. Case Hist., 2018.

[4] Androutselis, T. et al. Real-Time Seismic Damage Assessment of Various Bridge Types Using a Nonlinear Three-Stage Least Squares Approach. J. Infrastruct. Syst. 26(3):04020019, 2020.

[5] Papanikolaou, V.K., Kartalis-Kaounis, T., Protopapadakis, E. and Papadopoulos, T. A New Graphical User Interface for OpenSees”, OpenSees Days Europe, Porto, Portugal, June 2017.

[6] Papanikolaou, V.K and Karakostas, C.Z. A low cost MEMS-based accelerograph, Experimental Vibration Analysis for Civil Engineering Structures EVACES’13, Ouro Preto, Brazil, October 2013