# Smart Structural Health Monitoring for High-Speed Railway Bridges

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## ABSTRACT

The management of ageing civil infrastructure represents one of the most pressing challenges of modern societies. The last Infrastructure Report Card of the American Society of Civil Engineers (2017) estimated that 39% of the more than 600.000 bridges in USA are over 50 years old and estimated the rehabilitation costs at $123 billion. A similar picture emerges across Europe. Spain counts more than 2.606 km of high-speed railway, and a total of 207 critical bridges. An important number of them presents of one form of degradation or damage. The replacement rate is very low and that means an increase of ageing bridges in the next years. Despite large financial efforts have been dedicated to research in this field, the methodology has not been successfully completed/integrated, and life-extension of bridges is still sparsely implemented in practice. The last report of the European Joint Research Centre warned about the weak link between research and the wide-scale adoption of Structural Health Monitoring (SHM) technologies. The economic efficiency of the bridge is the total life cycle cost divided by its service life. New alternatives such as reliability-centered maintenance and reconditioning programs play an ever increasingly important role. However, these improvements are just the first glimpse of an ambitious and promising opportunity: bridge life-extension. To address these deficiencies the present methodology involves important advances on the real application of: SHM methodologies for high-speed railway ageing infrastructures, smart sensors, energy autonomy of the long-term monitoring system, and structural prognosis based on data-driven decision making.


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## WHY EXTENDING THE OPERATIONAL LIFE OF HIGH-SPEED RAILWAY AGEING BRIDGES?

The huge socio-economic impacts stemming from the retrofitting and replacement of structurally deficient bridge infrastructures require the increasingly frequent implementation of reliability-oriented maintenance. The management of ageing civil infrastructure represents one of the most pressing challenges of modern societies. In the past, life-cycle cost of a bridge was usually defined as the sum of initial costs, operation costs, maintenance costs, rehabilitation costs and disposal costs. Today, we may add environmental costs and societal costs to achieve at a more realistic "total life cycle cost". The economic efficiency of the bridge is the total life cycle cost divided by its service life. The main factor affecting the service life is the durability. New alternatives such as Reliability-Centered Maintenance (RCM) and reconditioning programs play an ever increasingly important role. However, these improvements are just the first glimpse of an ambitious and promising opportunity: Bridge Life Extension. The extension of service life is an ongoing upgrade idea that could be applied to most bridges and other civil infrastructure. Is it possible to extend the operational life of ageing bridges? Why is life extension now possible? Even though large financial efforts have been dedicated to research and development actions in this field, the methodology has not been fully or successfully completed/integrated and Life-Extension of bridges is still scarcely implemented in practice. The last report of the European Joint Research Centre (JRC) warned about the weak link between research and the wide-scale adoption of structural health technologies. To address these deficiencies the proposed methodology involves important advances on:

- Development of advanced SHM methodologies for high-speed railway ageing bridges.
- Evolution of monitoring technologies to the concept of Smart Sensors for long-term SHM.
- Energy autonomy of the long-term monitoring system.
- Prognosis of structural response based on data-driven decision.

## SMART SENSING BASED ON IoT

The traditional SHM sensing system was based on wires. Thus, the deployment of cables in the structure is very time-consuming, expensive, and requires a lot of workforces, either for installation or maintenance. Continuous advances in the communication and sensing device technologies have made the use of Wireless Sensor Networks (WSN) to gain large interest in this field. The first application aims at reducing the cost of the installation. Soon, the use of WSN allows for the easy deployment of a very large amount of sensing devices for better structure inspection. In this sense, the installation of new devices, such as cameras, laser, thermal 3D sensors, etc. opened new capabilities for SHM including crack detection and classification. These new services created large requirements of time computing, memory, and specifically network bandwidth. Moreover, the irruption of the Internet of Things (IoT) paradigm has burst the capabilities of this approach in SHM, as every node can be accessed and even can take decisions independently from the rest of the nodes. The use of advanced networks protocols allows for an efficient use of the communications by controlling when a message is necessary based on the novelty of the new data acquired by the sensors of each local node. Thus, IoT plays a main role in the future of efficient SHM. However, several challenges must be faced to make these systems work highly capable and properly. These are the most relevant challenges.

**Node lifetime**

Wireless SHM systems should last for large periods without electric power. For this purpose, Wireless SHM nodes include batteries, which have limited capacity. The lifetime of the battery depends largely on many factors. One of which is the battery capacity: the larger the battery, the longer the lifetime. The sensors used to sample the environment consume the battery power load. Thus, a proper use of the sampling is required to optimize the use of the current. Another element which causes a fall in the battery capacity is the computing time taken by the CPU and other processing elements. This is a complex issue as many facts get involved in the amount of consumed current. A strategy which includes both two factors is to include a low-power sensor which triggers the execution of highly efficient mesh of sensing when a certain event is detected [1]. However, the most significant power consuming element is the communication component. Therefore, special attention should be given to the transmission of data to provide a balance between power consumption and freshness of the data received by the server. In this sense, the use of efficient sending techniques to obtain the best sampling rate, resolution, and sending periods should be considered [2].

**Node synchronization**

The timing accuracy is essential for a proper monitoring of the structure, especially when the nodes are distributed. In this case, the clock of every node is different, and thus, the timing of each node may differ. This would make a shift in the temporal comparison of the samples obtained by the sensors in each different node. Therefore, all nodes must be synchronized. The timing error should be lower than twice the maximum sampling rate, following the Nyquist-Shannon sampling theorem. There are several factors that affect the oscillators that rule the timing of the internal clocks of the nodes: cut of the crystal oscillator, temperature, shock, ageing… There are several protocols for compensating the drift of the clocks taking into consideration temperature, crystal cut… providing synchronization errors below 5 ppm. [3].

**Network infrastructure**

Transmissions have a very large impact in the performance of the deployed SHM systems. Long-range communications usually require large amounts of energy. However, LoRaWAN and other wide-area network protocols can send small messages of few bytes for long distances expending very limited amount of energy. These protocols are not suitable for sending large amounts of data, but for event notification, synchronization, control management… Thus, a multiprotocol system is usually deployed: a cluster of sensor nodes sending data to a central coordinator node, which is responsible of sending the collected data to the Cloud level. Furthermore, this type of system requires nodes shipped with multiple antennas of different protocols: a long-range low-bitrate antenna for event notification and other critical issues, and a short-

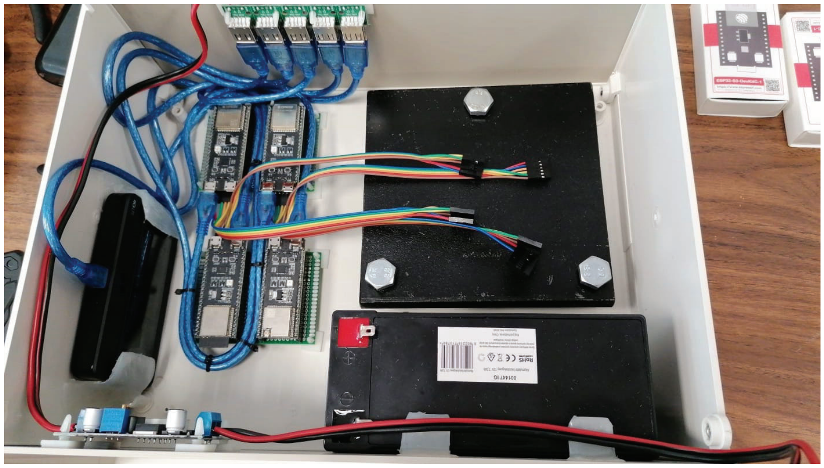

Figure 1. Smart Sensing.

range with higher-bitrate for sending data to the coordinator of the cluster, and finally, a long-range with high-bitrate for sending the collected data to the Cloud.

### Critical data issues

Because of the critical nature of the data involved in SHM, both the information, the communications and the deployed infrastructure must be secured. This issue requires including secure communications, fault-tolerance, and for the synchronization, real-time is also mandatory.

## VIBRATION-BASED ENERGY HARVESTING

SHM systems such as sensors, actuators, Wi-Fi emitters, etc. require power. Commonly, it is supplied by electro-chemical batteries which pollute the environment at the end of their useful life. On the contrary, there exist devices called energy harvesters that produce energy from residual sources such as mechanical vibrations, heat, sun light, etc. Therefore, the use of harvesters may be considered as compulsory and renewable or green energy for long-term SHM monitoring. The main trend advances in Energy Harvesting can be classified in the following fields:

### Smart Materials

The common point of all type of harvesters is that they are made of active (smart or multi-coupled) materials since these materials hold the ability to couple several fields of physics. Consequently, a thorough understanding of these materials is essential to any future design. Recent works claim about the need to use hybrid harvester that combine active materials to collect the maximum possible waste energy, not only from mechanical sources but also from waste heat due to the heat dissipation in ferroelectric materials [4].

Figure 2. Energy harvesting station.

**Natural Frequency Tuning and Adaptive Energy Harvesting**

Regarding civil structures and since they are subject to continuous mechanical vibrations induced by vehicle traffic, the passage of people, wind flow, micro-earthquakes, etc., the use of cantilever-based harvesters is commonly preferred. In literature, most of the works are focused on the design and optimization of these harvesters by incorporating auto-tuning systems through two methods: active and passive. While the former requires external energy input, the latter, based on electromechanical designs such as flexible seesaws, beam sliders or the use of magnets [5].

**Real Applications of Energy Harvesting**

A huge research effort has been made to theoretical development of vibration-based energy harvesting. However, applications to real structures under operational service is a research field with just a few publications [6].

## HIGH-SPEED RAILWAY GUADIATO BRIDGE (CORDOBA, SPAIN)

To develop the real application of these ideas, the authors have contacted Spanish railway national company with the aim of listening to their concerns. After verifying their interest in the deployment of SHM techniques on the bridges of the Spanish railway network, and because of these conversations, they have proposed several field demonstrators in which to validate the system proposed herein. Two different high-speed railway bridge typologies have been selected according to usually observed damage, degradation scenarios and maintenance costs. It concerns short-to-medium span double-track beam bridges for high-speed railway lines in Spain (train speed over 250 km/h) with the following properties:

Figure 3. A panoramic view of the Guadiato bridge.

TABLE I. SELECTED CASE-STUDY BRIDGES

| Railway line | Bridge Denomination | Location | Typology | Total length (m) | Nº spans | Max. span length (m) | Max. train speed (km/h) |
|---|---|---|---|---|---|---|---|
| Madrid-Sevilla | Guadiato Viaduct | CORDOBA | Type 1 | 110.54 | 4 | 31.41 | 250 |
| Madrid-Sevilla | PTE S/A-431 | CORDOBA | Type 1 | 28.3 | 1 | 26.3 | 250 |
| Madrid-Sevilla | Bembézar Viaduct | CORDOBA | Type 1 | 53 | 2 | 26.5 | 250 |
| Madrid-Sevilla | Retortillo Bridge | CORDOBA | Type 1 | 22 | 1 | 22 | 250 |
| Córdoba-Málaga | A-4 Viaduct | SEVILLA | Type 2 | 85 | 4 | 23.5 | 300 |
| Córdoba-Málaga | A-92 Viaduct | MALAGA | Type 2 | 73 | 3 | 33 | 300 |
| Córdoba-Málaga | Bridge over railway Sevilla-Granada | MALAGA | Type 2 | 74 | 3 | 34 | 300 |
| Córdoba-Málaga | Arroyo del Tajo Viaduct | MALAGA | Type 2 | 51 | 2 | 25 | 300 |

### Type 1

I-beams (5 to 8 beams) with in-situ concrete continuity slab. Span length in the range 30 meters, with 2-3-4 span configurations. Skewness effects. Maximum line speed 250 km/h. Bridges located in the Madrid-Sevilla high-speed railway line, close to Cordoba. This is a very particular typology that is not so systematically used in any of the other subsequent high-speed lines of the Spanish network.

### Type 2

U-beams with in-situ concrete slab. Span length in the range 32-35 m. Skewness effects. Maximum line speed 300 km/h. Bridges located in the Cordoba-Malaga high-speed railway line, close to Malaga. This is a typology with a wider deployment in the network, which would facilitate the extrapolation of results to other cases.

## EXPERIMENTAL VIBRATION RESULTS

Several measurements were taken on two different working days. On both dates, data were taken under two different situations: with railway traffic (operational vibration) and without traffic (ambient vibration). Some vibration measurements and vibration-based voltage are plotted in Figure 4 and Figure 5. More specific results will be presented in IWSHM-2023.

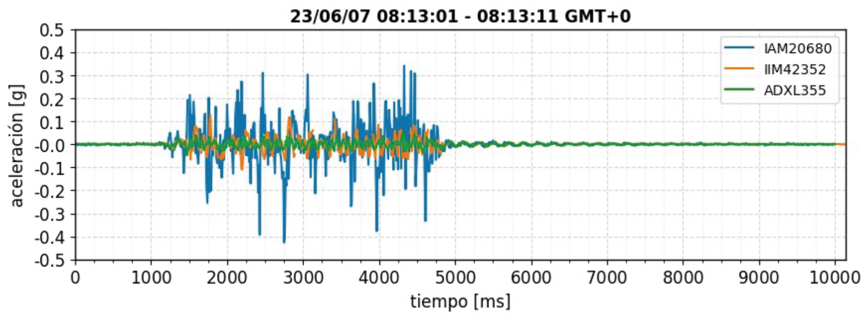


Figure 4. Operational vibration record of the Guadiato bridge (June 2023).

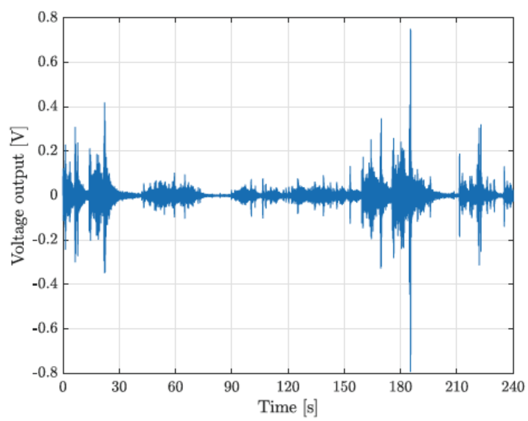


Figure 5. Output voltage from operational vibration.

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