The ‘AMBROSE’ System: Outcomes of an Alta Scuola Politecnica Project on Structural Health Monitoring

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THE 'AMBROSE' SYSTEM: OUTCOMES OF AN ALTA SCUOLA POLITECNICA PROJECT ON STRUCTURAL HEALTH MONITORING

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Abstract

From May 2023 to September 2024, in the framework of the Alta Scuola Politecnica, seven M.Sc. students and six academic tutors dedicated themselves to the project AMBROSE - A Multisensor BRidge MOnitoring SystEm. The team, composed of Structural, Geotechnical, Mechanical, Electronic, and Data Engineers from Politecnico di Torino and Politecnico di Milano, aimed at envisioning a holistic, multidisciplinary, and hierarchical novel concept for Bridge Structural Health Monitoring. To this aim, three workgroups were formed, dedicated to (I) hardware solutions for direct monitoring, (II) hardware solutions for indirect monitoring, and (III) software solutions for data modelling. This short contribution briefly summarises the final results of each workgroup, the current state of the proposed solutions, and the future works ahead.

Keywords: Bridge Monitoring, vibration-based inspection, indirect monitoring, sensors, Machine Learning.

1 INTRODUCTION – THE LIMITATIONS OF CONVENTIONAL SHM APPROACHES.

In recent years, several major infrastructure failures on the national road network have shaken Italian public opinion [1]. The lack of proper monitoring of the existing infrastructure has emerged as one of the roots of these events. In particular, most Italian bridges are now over 50 years old, which, combined with the general lack of modern and effective monitoring techniques, paints an appalling picture [2].

Most of the road infrastructure is still inspected manually by human technicians and according to a time-fixed, not condition-based, schedule. Consequently, acting in advance on possible structural issues is difficult until they become evident by visual inspection, often resulting in rushed and expensive maintenance work and road closures that impact road users. That is to say, standard reactive maintenance, rather than the more efficient predictive maintenance, is still the norm. On the other hand, current structural health monitoring (SHM) solutions have their own limitations: for instance, the conventional deployment of physically attached sensors on each bridge lacks cost-effectiveness as it would require designing ad hoc solutions for every bridge.

1.1 Research aim of the AMBROSE project

Within the AMBROSE (A Multisensor BRidge MOnitoring SystEm) team project (Figure 1), the ultimate goal was to significantly improve the network of Italian road infrastructures by introducing a modern SHM framework and providing a reliable way for early discovery of structural criticalities. This framework includes hardware (sensors) and software (data analysis techniques) integrated solutions, with several intertwined components.

Specifically, the research team focused on an automated monitoring systems strategy to overcome the main limitations of existing methods, such as the need for human supervision in the data acquisition and processing phases. Automating the monitoring process allows structural information to be obtained (potentially even in real-time) while avoiding human error. Furthermore, using different sensors for dynamic, static, and environmental monitoring provides more gathered data to be jointly analysed, resulting in a more complete overview of the bridges' conditions.

Figure 1: members of the student team of the AMBROSE project and logo.

2 THE PROPOSED HOLISTIC SOLUTION.

The proposed novel SHM framework and strategy is made up of different, integrated components to address all the limitations of current procedures.

The strategy is multi-scale and sequential, involving a first pre-emptive, large-scale monitoring strategy, followed by the selection and continuous monitoring of selected target infrastructures deemed most at-risk, and finally, by use of calibrated and predictive bridge Digital Twins for asset management. This concept is graphically summarised in Figure 2. In this framework, four different aspects have been defined and addressed. These are enlisted one by one in the following sections.

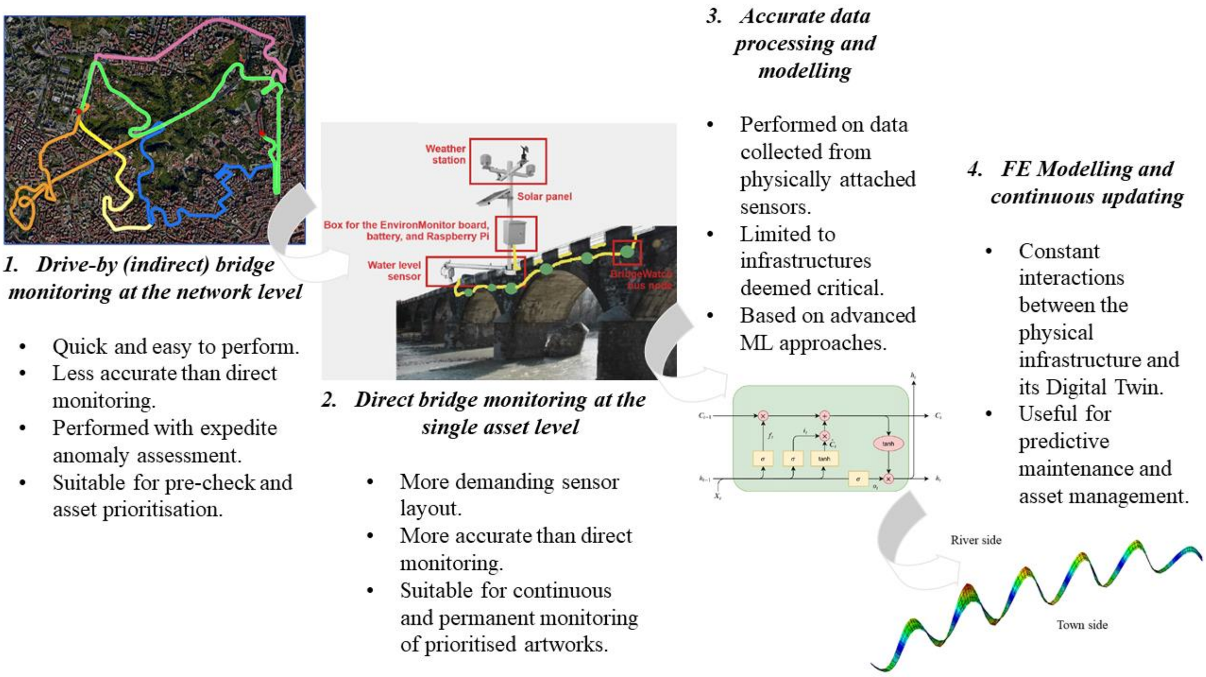

Figure 2: conceptual steps of the proposed approach, from network to single asset level and from preliminary monitoring to predictive asset management.

3 COMPONENT 1: INDIRECT PRE-EMPTIVE MONITORING.

First of all, the AMBROSE project proposes to combine the use of direct and indirect bridge health monitoring (iBSHM) approaches. In this regard, physically-attached sensors have long been recognised as a tool for monitoring infrastructure conditions; yet, their adoption has been constrained by the need to develop customised solutions for each individual bridge. Instead, in the iBSHM concept, the monitoring approach becomes much more flexible and adaptable.

In fact, since direct monitoring with installed sensors is economically demanding and time-consuming, the proposal is to equip a vehicle for preliminary drive-by monitoring. This proposal, well detailed separately in [3], is intended to allow for cost-efficient and fast assessment of entire road sections at once, with the potential to identify and prioritise the single infrastructures deemed more at risk. This selection can be done with a sensor apparatus dedicated to the acquisition of its vibration properties, as these are a known proxy index for structural integrity and damage occurrence. The measurement can be performed drive-by over any bridge, optimising the monitoring with minimal traffic disruption. In fact, through proper preliminary data processing, it is possible to extract the resonating frequencies of the bridges, depurating the vehicle's own vibrations from the accelerometers’ readings. At this preliminary step, anomaly detection can be performed by simply comparing the identified modal parameters with the expected target values, as demonstrated in parallel works [4].

From an economic perspective, this solution allows the asset manager to perform data acquisition on many bridges on the same day, making it the best way to analyse different portions of the infrastructure to assess short-term changes. More specifically, with the help of an external industrial partner, a prototype system composed of a vehicle and several sensors installed on board was developed and preliminarily field tested (Figure 3). This is an electric vehicle - needed to avoid the noise produced by combustion engines – specifically selected so that its autonomy grants relatively long travelling distances. The sensors included strategically placed accelerometers, plus GPS localisation and ambient condition sensors. A more detailed discussion of the results will follow in future works.

Figure 3: Pictures taken from the field tests of the drive-by iBSHM prototype vehicle.

However, indirect bridge SHM is intrinsically and unavoidably less reliable than tailored, case-specific, and customised direct monitoring systems. Hence, the AMBROSE framework proposes it as a component of a multi-step, sequential strategy; after this first preliminary check by means of the instrumented vehicle, only the bridges and viaducts deemed critical (if any) will be further inspected and, if needed, instrumented with a permanent direct bridge monitoring apparatus.

4 COMPONENT 2: INNOVATIVE HARDWARE SOLUTIONS FOR DIRECT CONTINUOUS MONITORING.

The current vibration-based direct approaches, while far more common and standardised than iBSHM methods, still present several unsolved limitations as well. Mainly, the shifts in natural frequency values – the most widely used damage-sensitive feature [5], [6] - are usually affected by damage-unrelated variables, such as environmental and meteorological factors.

As one aims to obtain the most accurate damage assessment with no false alarms, the intent here is to depurate the recorded measurements from these confounding influences. At this stage, the AMBROSE team proposes an integrated solution, resorting to both novel hardware and software applications.

Focusing in this Section on the hardware side, the main aim is data fusion between different physical variables: static, dynamic, and environmental monitoring. More specifically, the idea is to use a wired sensor network to collect data on the structural and environmental condition of the bridge and send it to an on-site computer that acts as a data collector.

The sensor network consists of two different boards: “BridgeWatch”, responsible for structural monitoring and equipped with an accelerometer, a gyroscope, and the input connector for the RTD sensor, and “EnvironMonitor”, dedicated to environmental monitoring and equipped with the input connectors for the external weather station sensors such as a rain gauge, anemometer, bridge water level sensor, and thermo-hygrometer. The overall concept and architecture are outlined in Figure 4.A. The complete system consists of several BridgeWatch boards placed in strategic locations to capture the accelerations required for our purposes and a single EnvironMonitor board. A Raspberry Pi acts as the overall coordinator: it communicates with the boards’ microcontrollers to receive data, processes them, and creates an output file for subsequent data analysis. The system is powered by a 12V battery recharged by solar panels, eliminating the need for external power. Some simple preliminary tests carried out in-house demonstrated the system's effective functioning (Figures 4.B and 4.C), which will be detailed in future works.

These sensing devices provide a complete set of data from multiple physical properties that, when combined together, can help in discerning structural damage and/or scour effects [7] from unrelated confounding influences. The gathered data then undergoes processing through AI-based software tools, which extract information about anomalies in the structural health of the bridges. This results in a comprehensive system that can provide a complete overview of the bridge, with a much-reduced effort in terms of operating needs and costs.

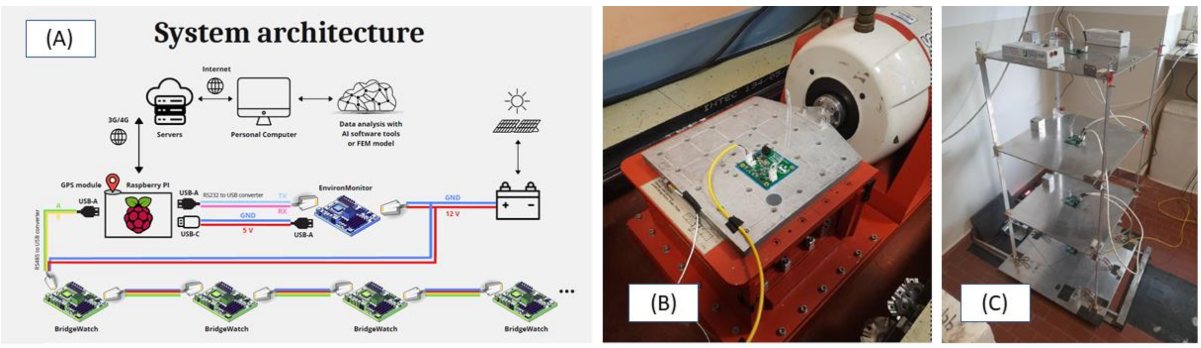

Figure 4: (A) architecture of the BridgeWatch and EnvironMonitor multi-sensor systems; (B) shaker tests of BridgeWatch; (C) laboratory tests on a scaled-down multi-story structure of BridgeWatch

5 COMPONENT 3: DATA ANALYSIS AND FEATURE EXTRACTION.

Concerning the software part of the direct monitoring stage, new damage assessment algorithms have been proposed and tested in the framework of this project. In particular, the anomaly detection software developed in this study aimed to monitor and identify anomalies on bridges, either in real-time, quasi-real-time, or retrospectively. Temperature was observed to be a critical feature for this purpose due to its significant impact on structural responses, such as changes in vibrational frequencies and strain levels. The software can effectively detect potential damage by leveraging temperature variations, as well as other environmental variables.

The Z24 bridge – a well-known benchmark dataset about an R.C. road bridge in Switzerland that underwent a campaign of controlled damage before demolition [8] - was chosen as an ideal case study for testing the software because its well-documented damage history provides an exhaustive data set for model training and validation. This data-driven approach allowed the software to learn from past conditions and apply that knowledge to ongoing monitoring efforts.

The study employed advanced techniques, including Gaussian processes [9] and Long-Short-Term Memory (LSTM) neural networks [10], which are especially suited for modelling the complex, time-dependent relationships between temperature variations and structural responses. By integrating these techniques, the software can identify deviations from expected behaviour, signalling potential damages. An illustration of the results for the 2nd natural frequency is shown, by means of example, in Figure 5. A more detailed discussion of the results will follow in future publications.

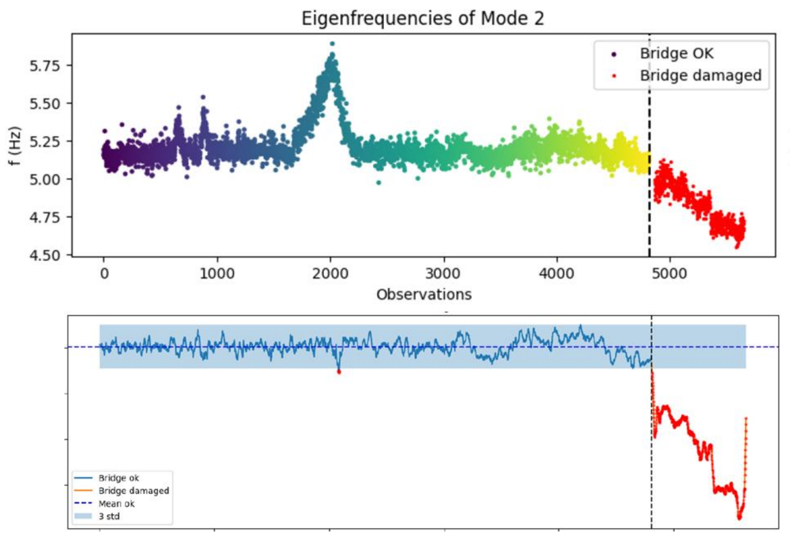

Figure 5: Some results from the proposed algorithm, as validated on the Z24 case study for anomaly detection.

6 COMPONENT 4: FINITE ELEMENT MODEL AND DIGITAL TWIN FOR ASSET MANAGEMENT.

Another key limitation of existing SHM and maintenance strategies, as currently implemented by key public and private asset managers, concerns their data management and the so-called 'last mile'. Indeed, in many cases, the processed data are unfruitfully archived in digital repositories. In this regard, this project's framework proposes, as a last component, the development of a digital replica of the permanently monitored infrastructure, numerically calibrated to predict its expected behaviour based on its current vibration response. Any deviation from this predicted behaviour can be further used for model-driven damage assessment. Furthermore, it will also serve as a graphical, intuitive, and easy-to-access platform for data access.

All these components make up the envisioned framework. Its viability will be field tested in the near future on real case studies such as the Inverso Pinasca viaduct [11], for which a structural Finite Element (FE) model has been realised using the software ABAQUS, or the Tangenziale di Napoli [12]. In the case of the Inverso Pinasca bridge, dynamic analyses were performed on the numerical model to extract the structure's natural frequencies and modal shapes. The results obtained through the numerical computation were compared with those obtained during a previous measurement campaign. A satisfactory correspondence between numerical and experimental data was noted, with a residual error after model calibration equal to $\Delta f_1 = 0.06$ Hz for the first global mode (first flexural oscillation) and $\Delta f_2 = 0.10$ Hz for the second global mode (first torsional oscillation), as depicted in Figure 6. More details will be provided in future dedicated publications.

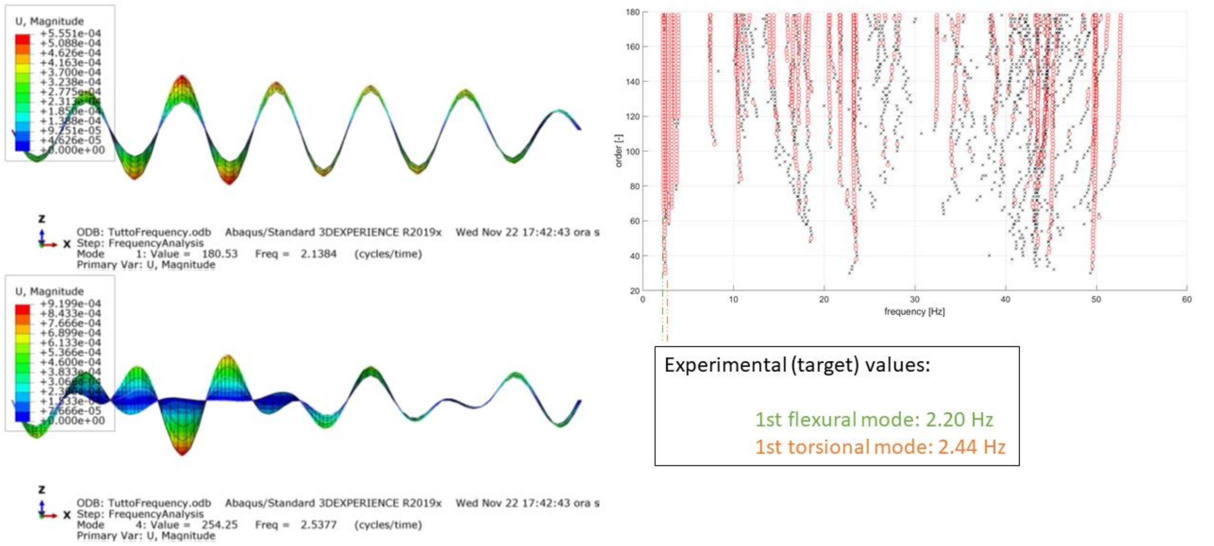

Figure 6: Comparison of experimental and numerical results from the calibrated FE model of the Inverso Pinasca bridge.

7 CONCLUSIONS

The Alta Scuola Politecnica AMBROSE project was not limited to a single object or product. Rather, a whole new SHM concept and environment was envisioned and pursued. This is made of several components, encompassing physical prototypes (new sensors and vehicles), software codes and algorithms, and a multi-level, multi-step framework and strategy for structural assessment of bridges and viaducts on road networks. Indeed, the envisioned strategy englobes a hierarchical direct-indirect framework for bridge pre-emptive and continuous monitoring, leveraging the advantages of both solutions and compensating for each one limitation. Recalling the key aspects of the proposed approach:

- A novel instrumented vehicle can be used for (preliminary) drive-by bridge monitoring, aimed at early warning and asset prioritisation for a potential following in-depth analysis by direct monitoring.
- A novel multi-physical sensor for direct monitoring can be used to gather useful raw data from static, dynamic, and environmental monitoring to be passed to the software component.
- A novel AI-based, data-driven algorithm can be used on the damage-sensitive features extracted from multi-physical direct monitoring to provide reliable damage assessment, insensible to uninteresting (damage-unrelated) events.
- A Finite Element model and Digital Twin of the target infrastructure can be calibrated, constantly updated, and populated with data from the monitoring system to provide predictive maintenance and asset management capabilities in the long term.

The work started and developed so far by the group of seven talented students of Politecnico di Torino and Politecnico di Milano will be carried on in future works, aiming at refining the proposed framework and reaching a final product.

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