Abstract of Research Project
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RESEARCH PROJECT (max 3 pages):

TRANSFER LEARNING APPROACHES FOR STRUCTURAL HEALTH MONITORING OF ROADWAY BRIDGES

Introduction and state of the art

Structural Health Monitoring (SHM) has been receiving a growing interest in the field of Civil Engineering in the last years. The main reason lies in the significant number of ageing structures and infrastructures that are inevitably subjected to materials' degradation. Furthermore, catastrophic events such as the collapse of the Genoa bridge in 2018 have recently brought to the light the urgency to invest in the infrastructure management. For this reason, a strategy of maintenance and conservation to ensure structural integrity and durability of roadway bridges is hardly required.

SHM is a broad interdisciplinary research field that involves experimental testing, system identification, data acquisition and management, as well as long-term measurement of environmental and operational conditions.

In order to overcome several issues associated to the local approaches for damage detection based on visual inspections and non-destructive tests, considerable efforts have been put into vibration-based methods, which are well suitable for continuous SHM systems [1]. Such methods exploit the recorded data under normal operating conditions to obtain reliable modal parameter estimates through Operational Modal Analysis (OMA). The idea is to detect damage by tracking deviations of properly selected damage-sensitive features from their normal conditions, at an early stage.

Although being highly attractive, purely vibration-based methods may fail at detecting local damages such as those associated to pitting fatigue in cable tendons of prestressed concrete bridges or those associated to corrosion in rebars/tendons. For this reason, data fusion techniques [2] able to effectively build a decision based on a synergistic analysis of heterogeneous sensing data (e.g. static and dynamic, environmental and structural) are highly needed for bridge SHM but still in their infancy.

Vibration-based methods, belonging to data-driven techniques, are often employed in Artificial Intelligence and Machine Learning fields, where algorithms have to learn the structural behavior from the experience or past data (following the same principle of human brain) and to perform statistical pattern recognition [3] for damage detection and conditions assessment [4]. Compared to physics-based methods for SHM, a data-driven approach avoids building and validating a numerical model and, moreover, it allows to quantify uncertainties through statistical models. Despite these advantages, the availability of sufficient training data with correct labels represents a big challenge in the context of civil engineering, where data of the damaged structure are often lacking due to costs and practicality constraints. Moreover, the main drawback of dealing with data-driven approaches is the difficulty in achieving damage localization and quantification. For these purposes, the use of numerical models linking damage mechanisms and the intrinsic properties of structures to their modal signatures is usually required, as they represent the best way for a full understanding of bridge's behavior. In this regard, digital twins could reveal particularly useful, contributing to diagnosis and prognosis of bridges as well as to local conditions assessment [5]. They serve as a virtual representation of the physical structure, which can be updated in near real time as new data is collected, provide feedback and perform "what-if" scenarios for assessing risks and predicting the system performance.

Research objectives

In order to provide a more accurate view about the current state of a bridge structure, as well as to facilitate the decision-making process aiming at a correct maintenance, this research project aimed at synergistically integrating data-driven and physics-based approaches in SHM of bridges, so that their merits get preserved and their shortcomings become less critical. By exploiting the combined use of both techniques, the goal would be to accomplish damage detection, localization and quantification and, besides this, to make future prediction about structure's health.
Furthermore, due to the unavoidable presence of uncertainties associated to monitoring results, the evaluation of the errors is addressed by means of statistical tools, in order to get reliable and more accurate outcomes in view of a proper structure management.

Methodology

The research involves the following steps:

• <u>Literature review (months 0-4)</u>

A detailed literature review on bridge SHM will be carried out in the first 4 months of the project and will be structured in a report and possibly in the publication of a review paper. A preliminary review has been already carried out highlighting that previous works have recently dealt with the aforementioned topic: Chao Sun et al. [6] implemented a method by incorporating the results of FE model updating into a neural network model, A. Santos et al. [7] showed that a FE model can be used to predict undamaged and damaged scenarios not observed by permanent monitoring systems and thus, to generate new data in order to improve the training process of the machine learning algorithms and their damage identification performance. Furthermore, E. Garcìa-Macìas et al. [8] studied a surrogate model-based procedure, which bypasses a fully detailed 3D FEM of the structure and allows to identify certain modal parameters in real time by minimizing the mismatch between theoretical estimates and experimentally identified modal features by automated OMA.

• Development of AI algorithms for transfer learning (months 0-24)

In order to combine data-driven with model-based methods, the idea is to monitor the structure with continuous SHM systems and, in parallel, simulate different damage scenarios in a FE model or a surrogate one.
Transfer Learning is a convenient way to deal with problems in which one wants to investigate a little-known system, while jointly using a lot of available information from another system, which is somehow connected to the first one. The use of TL is particularly useful in SHM due to the lack of labelled data relating to damaged conditions, which are typically not present in the training set [9]. For many structures, especially in the civil engineering field, the request of data relating to structural damage could involve a lot of time, high costs, as well as a significant amount of advanced and specific professional knowledge in structural engineering. In this context, a FEM is a valuable tool because it allows simulation of a large number of structural conditions, gaining data without affecting the real structure.
The development of the procedure for bridges' damage assessment will be supported by some real case studies, mainly referring to the category of prestressed concrete and reinforced concrete bridges. This will be possible thanks to the precious collaboration with the National Company of Roads (ANAS) and to the participation of UNIPG within the FABRE Consortium, dealing with infrastructures' management.

• Development of methodologies for uncertainties' analysis (months 12-36)

It should be highlighted that SHM results, although reflecting a significant efficiency in analysing sensor data, inevitably present some uncertainties, related to the measurement system, to data cleansing techniques and to model's imperfections (e.g. the way material properties and damage mechanisms are modelled). For this reason, getting reliable outcomes becomes a challenging issue. In fact, if monitoring results are not enough accurate, the decision-making phase for the bridges' future health management will be tricky accordingly. In order to address this aspect, a specific task of the research project will be devoted to developing techniques for handling uncertainties in bridge SHM and considering them in the decision process. To this aim, uncertainties associated with damage classifications within virtual damage scenarios will be studied and specific target metrics for designing the SHM system will be defined using the whole confusion matrix, including ROC curves and precision-versus-recall curves.

• Validation of the procedure (months 12-36)

The final stage of the project will be the validation of the developed tools in two real case studies. The idea is to test and validate the methods, based on the synergistic integration between data-driven and model-based approaches as well as on uncertainties evaluation, by means of several case studies. If possible, the two case studies will be selected in such a way to include one prestressed concrete bridge and one reinforced concrete bridge. The validation will consist of a continuous processing of data recorded on the two real bridges, using a proprietary code developed at UNIPG called MOSS [10], after conveniently extending such a code in such a way to include the new methods developed with this project and, particularly, the interaction with numerical models according to the TL approach.

Expected results

By jointly exploiting monitoring data stemming from real measurements and from a Finite Element Model able to simulate different damage scenarios, the goal of this research is to improve the interpretation of experimental data as well as the classification of different structural conditions.
Manifold purposes can be pursued, among which visualization, monitoring, assessment, simulation, prediction, optimization and management of real structures.
Thus, the procedure, overcoming the pure damage detection, should provide a direct physical interpretation of damage, which is pretty useful for civil engineers facing with decision-making theory.
Furthermore, the analysis of the uncertainties correlated to monitoring results should allow to exploit the Machine Learning full potential, resulting in more intelligible outcomes and in an easier decision-making.
After software implementation and validation of the developed methods, an enhanced version of MOSS will be released at the end of the research project as a major expected result, where main advances will be related to (i) uncertainty management in the decision process and (ii) interaction with numerical models/digital twins.

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