A DIGITAL TWIN-BASED PLATFORM FOR STRUCTURAL HEALTH MONITORING: PRELIMINARY RESULTS

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This paper describes the preliminary results of the REVOLUTION project, focused on designing and implementing an open-source, digital twin-based platform for the structural health monitoring of architectural buildings and infrastructures. The platform leverages several technologies, such as 2D/3D digitalization techniques, sensor networks, numerical modelling, and damage detection algorithms. Integrating such technologies will allow us to build accurate digital twins of historical buildings, monitor their dynamic properties, model their mechanical behaviour, detect damages and anomalies and plan intervention strategies.

Keywords: *historical buildings, structural health monitoring, numerical simulations, digital twin, open-source*

1. Introduction

The idea of digital twin dates back to the first years of 2000 [1], and its application to architectural heritage is relatively recent and has yet to be thoroughly exploited. A review of the literature on using the digital twin approach to monitor, maintain and protect architectural constructions is given in [2].

This paper presents the preliminary results of the REVOLUTION project aimed at designing and developing an open-source digital twin platform for buildings of historical importance and infrastructures. After briefly outlining the platform under development, the paper describes an application of the digital twin paradigm to the Guinigi tower in Lucca. The results of the long-term dynamic monitoring campaign conducted on the tower via a sensor network are briefly recalled and the importance of experimental data for calibrating a finite element model of the tower and assessing its structural safety is emphasised.

2. The REVOLUTION project and its open-source platform

Digital twins are virtual representations of physical systems that use sensor networks, hardware and data to provide probabilistic and deterministic previsions on such systems' actual and future states. Implementing a digital twin platform for structural health monitoring is based on the (i) development of flexible and efficient protocols for 3D digitalization and CAD modelling of complex scenario and (ii) integration of data provided by advanced numerical simulations and data measured by the monitoring system and development of tools to make predictive assessments and support the decision process. Algorithms for detecting damages induced by the environmental impact, human activities and seismic actions and highlighting anomalies in the dynamic behaviour of the structure under examination will complement the platform's capabilities.

The platform's core is NOSA-ITACA, a code developed by ISTI-CNR to disseminate the use of mathematical models and numerical tools in the field of Cultural Heritage. NOSA-ITACA [3] combines the finite element solver NOSA and SALOME [SAL], an open-source platform for pre- and post-processing operations and enables static and dynamic analysis of structures made of linear elastic and masonry materials, thermomechanical analysis in the presence of thermal loads and can be applied to modelling restoration and reinforcement operations on constructions of architectural interest. The code adopts the constitutive equation of masonry-like materials and models

masonry as a homogeneous isotropic nonlinear elastic material with zero or weak tensile strength and infinite or bounded compressive strength. Recently, numerical methods for constrained generalized eigenvalue problems have been implemented in NOSA-ITACA to address the modal analysis of linear elastic structures. The latest developments of the code focused on the integration of numerical simulations with experimental tests. Thus, algorithms for the finite element model updating, aimed at calibrating the FE model of a structure using its experimental frequencies and mode shapes, have been implemented in NOSA-ITACA, along with a new numerical procedure, which relies on linear perturbation and allows to model the influence of cracks on the dynamical properties of a masonry structure. A description of the main features of the NOSA-ITACA code is provided in [3], where several case studies are presented.

Within the framework of the REVOLUTION project, NOSA-ITACA will be modified in such a way as to work as a platform able to interface with other tools necessary to build and manage the digital twin of historical structures and infrastructures. The main functionalities of the platform developed within the REVOLUTION project are sketched in Figure 1.
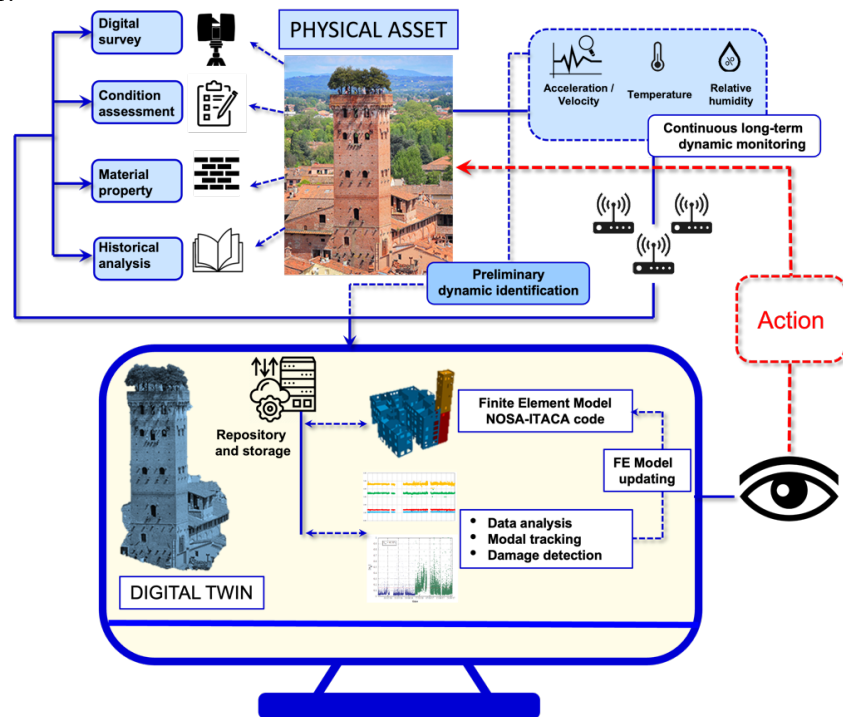

Figure 1: Sketch of the platform implemented within the REVOLUTION project.

In particular, the platform will feature the following activities.

1. To carry out the 3D digital acquisition of the under-study structure's geometry via laser scanner techniques. A semiautomatic algorithm will be developed to process and transform the point cloud into a finite element mesh for structural analyses. The acquisition phase of the construction will be conducted by the European Research Infrastructure for Heritage Science (https://www.e-rihs.it) coordinated by the CNR.

2. To apply OMA techniques to the data recorded by the sensor network installed on the structure and calculate the modal parameters of the structure (frequencies, modal shapes, damping ratios). The monitoring system will measure the vibrations induced on the structures by natural and anthropic actions (wind, earthquakes, traffic, crowd movements, etc.) and some environmental parameters (temperature, humidity, wind velocity and directions, etc.). The recorded data will be sent via the Internet to the platform hosted on a remote workstation at ISTI-CNR, where the processing and analysis operations will be carried out. Modal tracking and damage detection tools will be implemented.

3. To calibrate the finite element model of the structure described in 1. FE model updating algorithms will make it possible to determine some unknown parameters of the model (mechanical properties, boundary conditions, etc.) using the experimental data obtained in 2. The updated model will be used to simulate its behavior in the presence of dynamic loads and temperature variations and assess its structural safety.

The Guinigi tower in Lucca (Figure 2), dating back to the XIV century, was chosen as test bed of the platform. The tower, one of the most iconic monuments in Lucca, was continuously monitored from June 2021 to October 2022 by high-sensitive seismic stations that recorded the structure's response to the dynamic actions of the surrounding environment. A Virtual Private Network allowed sending the data recorded from the instruments to a server hosted at ISTI-CNR for storage and processing. A detailed analysis of the velocities recorded on the tower and the experimental frequencies calculated via the SSI/Cov algorithm is reported in [4], where the dependence of frequencies on temperature and humidity, as well as the effect of the visitors on the tower's dynamic behaviour, were investigated. A finite element model of the structure was calibrated via the optimization algorithm implemented in NOSA-ITACA aimed at minimizing the distance between the structure's natural frequencies evaluated experimentally and their numerical counterparts evaluated by modal analysis, in a feasible set.
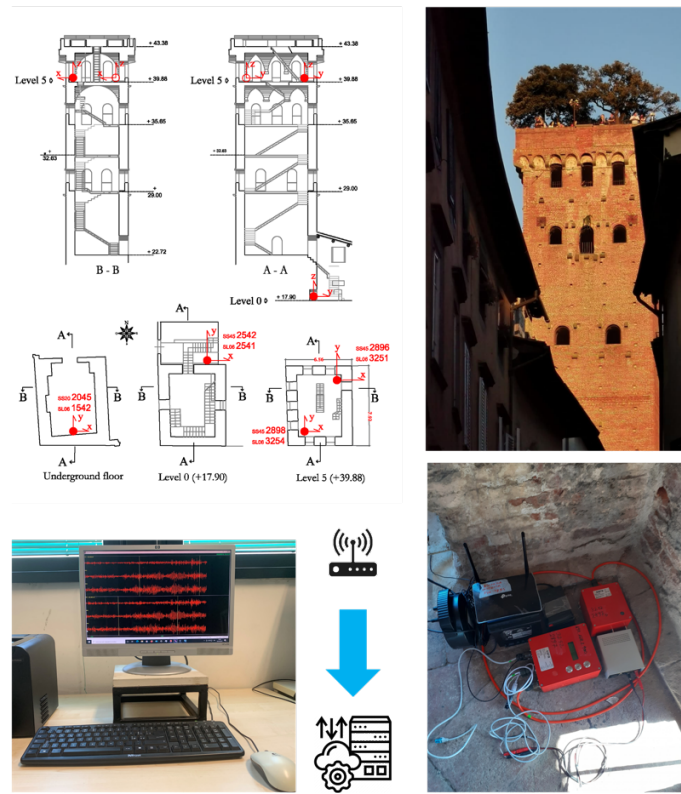

Figure 2: The Guinigi tower.

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