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Original article

Open-source digital technologies for low-cost monitoring of historical constructions

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ABSTRACT

This paper shows new possibilities of using novel, open-source, low-cost platforms for the structural health monitoring of heritage structures. The objective of the study is to present an assessment of increasingly available open-source digital modeling and fabrication technologies in order to identify the suitable counterparts of the typical components of a continuous static monitoring system for a historical construction. The results of the research include a simple case study, which is presented with low-cost, open-source, calibrated components, as well as an assessment of different alternatives for deploying basic structural health monitoring arrangements. The results of the research show the great potential of these existing technologies that may help to promote a widespread and cost-efficient monitoring of the built cultural heritage. Such scenario may contribute to the onset of commonplace digital records of historical constructions in an open-source, versatile and reliable fashion.

1. Introduction

The set of strategies aimed at identifying damage as well as the overall health conditions in structural systems is known as structural health monitoring (SHM). SHM is an active field of research ranging from high precision aeronautical and automotive industries, the energy sector to, in a broader sense, civil engineering structures [1–5]. Roughly speaking, SHM systems include:

- sensors capable of acquiring a desired physical magnitude;
- data acquisition systems capable of storing and/or sending the obtained data;
- a complex post-processing that involves the analysis of the obtained results.

Structural systems of all kinds can be monitored and decisions are taken based upon real observations. Monitoring activities are usually costly since tailor-made installations, heavily-wired deployments and sophisticated post-processing analysis are necessary for obtaining and understanding the health records of those structures.

SHM is a non-invasive survey process of paramount importance in the analysis of structures of the built cultural heritage. As a matter of fact, it represents an essential part of the modern integrated knowledge-based methodologies that establish a framework of multidisciplinary activities for the conservation and protection of heritage structures [6–8]. The design and implementation of a monitoring system in an historical construction is framed within a rigorous scientific process, including historical and geometrical survey of the structure, inspection on materials by in situ and laboratory testing, mapping of existing damage and deformation and a subsequent structural analysis [9,10]. Combining and cross-correlating data from all these complementary activities, it is possible to detect relevant parameters to be controlled for defining the optimal deployment of the SHM system. SHM installations in historical constructions generally can gather environmental and behavioral data during either short- or long-term periods of time. Available systems for SHM of historical constructions are considerably expensive nowadays and are usually limited to highly valuable built heritage or eminently endangered zones [11,12].

On the other hand, open-source digital modeling and fabrication (DMF) platforms are relatively novel tools that are bringing traditional industrial concepts related to computer-aided design (CAD) and computer-aided manufacturing (CAM) to the grasp of individuals. Do-it-yourself (DIY) practitioners, enthusiasts and entrepreneurs are developing a fertile ecosystem of low-cost applications. The convergence of affordable additive and subtractive technologies (3D printing and laser-cutting), as well as the advent of open-source prototyping electronic platforms of hardware [13–15] and software [16–18], are unearthing endless possibilities for individuals in which creativity, entrepreneurship

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and innovation are fostered. The entire community is benefiting from these technologies in the age of open access information, in which ideas, methodologies and know-how is shared and cross-pollinated relentlessly [19,20].

This research presents a study on the possibility of building and testing a novel reproducible DIY system for SHM of historical structures. The paper is organized as follows. Section 2 presents a review of recent applications of DMF, as well as a brief overview of SHM for historical constructions. Section 3 analyses the simpler parts of a typical standard SHM deployment. The available open-source DMF technologies are then explored to select the most suitable counterparts of the typical components of a continuous static monitoring system. Section 4 presents a case study on a pilot case with active cracking problems on brickwork structural members, already known by the authors. This benchmark problem allowed the definition and calibration of a digital deployment intended to be applied to structures of the built cultural heritage. Finally, Section 5 includes a critical discussion of the incomes of the research mainly based on advantages, limitations and challenges of the proposed methodology.

The results of the study are promising, since they show the real possibilities that open-source technologies may provide for acquiring useful digital data about the built cultural heritage, in a widespread but yet cost-efficient fashion.

2. Review of background knowledge

2.1. Digital modeling and fabrication

DMF is a rather broad term. It encompasses processes in which physical models can be recreated digitally by means of modeling tools and/or vice versa, by means of manufacturing tools. The back-and-forth nature of this physical-to-digital gap bridging includes hardware, software and manufacturing technologies that put together offer a vast array of possibilities to individuals. One may arguably state that DMF does not represent any novelty to the public, since it inherently includes the main cornerstones of any industrial process. However, two key aspects make DMF incredibly appealing for a vast array of collectives nowadays:

- the open-source philosophy in both hardware and software prototyping platforms;
- the increasingly large community that share and cross-pollinate information through the Internet.

Entire codes, circuitries, models, files and ideas are enthusiastically shared and implemented by entrepreneurs, DIYers, hobbyists, makers, students and in a broader sense, the whole community. This particular radical openness has fostered an exponential growth in fields, such as environmental sensing [21,22], robotics [23,24], architecture [25,26], medicine and prosthetics [27,28], education [29,30] and a countless number of applications in manufacturing. Even though academic publishing relentlessly includes such enthusiasm, the vast majority of information is found in blogs, open-source video channels and content is spread out via social networks. Furthermore, there is a growing consensus that additive and subtractive technologies, such as 3D printing, may represent a major game-changer in the technological revolution. In fact, for some products, the manufacturing process may be totally tailor-made by the end-user and thus the need of industrial standard processes might vanish [31]. From the cultural heritage point of view, few academic researches involving DMF technologies have been recently published only for historical artefacts [32–34].

2.2. Structural health monitoring of historical constructions

SHM systems are usually composed by a set of sensors connected to an external data acquisition unit. Most modern solutions adopt wireless transmitters and receivers to overcome the limitations given by use of cables. Current systems usually adopt automatic sensors capable to monitor the structure continuously, i.e. providing real-time measurements of the controlled variables. Continuous monitoring requires the adoption of huge storage capacity acquisition systems. In order to limit the amount of measures stored into the database, the systems can save the data at given time intervals. Another possibility is to set certain warning thresholds above which the system is activated (triggered monitoring). The stored raw data are eventually processed to extract relevant information (feature extraction) that is carefully analyzed by experts in order to draw valuable conclusions about current structural performance or serviceability. The results of SHM are essential to create and update reliable structural models, which can be utilized to evaluate possible interventions or to understand better the origin of the detected anomalies.

In the last decades, the growing interest in efficient SHM systems for historical constructions has found the increasing support by the scientific community through advanced research [35–37]. Different types of monitoring strategies can be planned: one-time or periodical monitoring can be used to control the structural behaviour at a certain moment, before or after an intervention. Static monitoring is oriented to either long- or mid-term measurements of the gradual variation of environmental (e.g. temperature, humidity, wind, etc.) and structural variables (e.g. crack opening, displacement, deformation, etc.) by fixed sensors on the structure. Dynamic monitoring encompasses solutions for the repeated, episodic or continuous measurement of the dynamic response of the structure under forced or ambient vibrations [38]. Early warning monitoring is specifically oriented to the early detection of anomalous responses for decision-taking and timely actions [39].

SHM deployments aimed at monitoring the amplitude of the existing cracks are also available for heritage structures [40]. Digital crack meters are normally distributed over the most damaged parts of the investigated building, providing measurements either discretely or continuously. Digital crack meters should be always accompanied by temperature and humidity sensors to decouple the daily or seasonally cyclic effects of these environmental variables from the general behaviour trend. The analysis of the long term response of the crack, adequately depurated from periodical variations of temperature and humidity, can reveal if the damage is stable or if it is increasing and thus causing concern. Measurement of crack's width is recognized as a simple but efficient monitoring solution, which is normally able to provide a quick and valuable insight into the current response of the building.

3. Parts of a SHM deployment in historical constructions

3.1. Sensors

The sources of information for a SHM system are the sensors. These analog components usually transform magnitudes associated with physical or chemical phenomena to voltages. Sensors associated with temperature, humidity, displacement, strain, air quality, noise, light, acceleration and pressure, are commercially available with a wide variety of prices and accuracy. Usually, for the depicted applications, the accuracy-price balance is affordable and provides satisfactory results. Sensors need to be powered and signals can be gathered and sent to the acquisition systems. Energy supply may include batteries, direct current, solar powered cells or others. Nowadays, these power supply components can also be found in the market with a vast range of prices.