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STRUCTURAL HEALTH MONITORING OF ANCIENT CONSTRUCTIONS WITHIN THE FRAMEWORK OF THE MOSCARDO PROJECT

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Summary. This paper presents some results about the MOSCARDO system, a structural health monitoring platform specifically developed for long-term measurement of heritage structures. The main features of the system are shown with reference to a case study: the Voltone in Livorno (Italy).

1 INTRODUCTION

Last decades have seen an increasing interest in the structural monitoring of historic constructions, which plays nowadays a crucial role in the assessment of the structural health of the built heritage and its maintenance[1,2,3,4,5,6] also providing an effective tool for supporting retrofitting and strengthening operations.

MOSCARDO (ICT technologies for structural monitoring of Ancient Constructions based on wireless sensor networks and drones, www.moscardo.it) is a research project funded by the Region of Tuscany (Italy) and developed by a consortium which includes the National Italian Research Council (Institute of Information Science and Technologies "A. Faedo", ISTI-CNR), the University of Florence (Department of Civil and Environmental Engineering), and two private companies (Infomobility srl - www.infomobility-italia.com - and Engineering Italy Solutions srl - www.eisolutions.it).

This paper describes some issues dealt within the project, which was aimed at designing, developing and testing new ICT tools for structural health monitoring, including networks of wireless sensors able to operate in both ordinary and emergency conditions, for long-term monitoring purposes.

The results of the MOSCARDO project, completed in October 2018, make it possible to: i) check the structural health of the monitored structures at any time and from any location; ii) provide historical data sets that can be used to permanently monitor the tested structures and develop predictions (and promptly act for repairing when needed); iii) gain an in-depth knowledge of the structural behaviour of the historical construction, iv) reduce management costs and security risks due both to environmental factors and anthropic activities (such as vibrations due to vehicular and pedestrian traffic), i.e. the system can be used as a system to support building maintenance and safeguard.

Three representative case studies in Italy have been selected to test and validate the system developed in the project: two historic masonry towers (the Torre Grossa in San Gimignano and the Mastio di Matilde in Livorno) and the Voltone in Livorno. The paper focuses on the Voltone, a large vaulted masonry tunnel subjected to traffic vibrations coming from the above square (Piazza della Repubblica).

2 AN OVERVIEW OF THE MOSCARDO SYSTEM

The main result of the MOSCARDO project was the development of some management tools aimed at improving the knowledge of the static and dynamic behaviour of historical buildings, assessing their structural health and providing information on any damage in operational conditions and in the presence of exceptional events. The system developed is therefore targeted at Local Agencies of the Ministry of Cultural Heritage and Activities, Local and Regional Administrations, Civil Protection and all the authorities and organization responsible for the architectural heritage safeguard.

MOSCARDO is a scalable and flexible system, which can be easily deployed on buildings and infrastructures. It encompasses a Monitoring Control Centre (MCC) collecting and analysing data coming from the sensor networks deployed on the building of interest. Unmanned Aerial Vehicles (UAVs) can also be used for visual inspection, providing a dedicated video feed to both close and remote operators.

In particular, the MOSCARDO system is composed of:

- integrated Wireless Sensor Networks (WSNs) for the acquisition of structural and environmental data, providing a low cost, high resolution, low energy consumption, and limited visual impact monitoring system;
- flexible and reliable IoT communication infrastructure built upon a publish / subscribe communication paradigm;
- Monitoring Control Centre (MCC) designed according to a cloud architecture that provides services for storage, processing, and interpretation of data coming from the WSNs and from the aerial vehicle;
- algorithms and models for the analysis of the collected data and the numerical simulation of the dynamic behaviour of monitored structures;
- multi-channel and multi-platform interfaces for accessing and analysing data, images and videos, so to promptly notify any trespassing of the alert thresholds or any other events of interest captured by the monitoring system;

- front-end Augmented Reality (AR) for the interactive display of video streams and data collected by the deployed sensors day by day, during UAV inspections, and for offline playing, displaying the 3D model of the structure in an immersive setup, with the possibility to also showing historical data stored at the MCC.

3 THE CASE STUDY OF THE VOLTONE IN LIVORNO

The MOSCARDO system is currently working on two masonry towers (the Matilde tower in the Old Fortress of Livorno and the Torre Grossa in San Gimignano) and on a masonry tunnel located beneath Piazza della Repubblica in Livorno.

Figure 1: Piazza della Repubblica and the underlying structure of the Voltone from the northern side.

This paper is focussed on the Voltone, a 220-meter long vaulted masonry structure shown in Figure 1. Built in the first half of the nineteenth century by the architect Luigi Bettarini, under the government of Leopoldo II d'Asburgo-Lorena[7], it is constituted by a segmental vault spanning about 12.5 m and standing on two lateral walls, through which the "Fosso Reale" canal flows. The walls are strengthened by buttresses placed at intervals of about 5.8 meters one from the other. In the past years a survey of the structure including laser scanner digital acquisition, geo-radar tests and masonry coring allowed acquiring the outer geometry of the structure, as well as thickness and stratigraphy of the vault and the walls (Figure 2, finite element mesh built via the NOSA-ITACA code[8]). The ends of the vault, whose thickness is about 0.7 m, support some trafficked roadways ("Viale degli Avvalorati" in the northern side and "Via del Voltone" in the southern), while the central part of the structure - 0.4 m thick - supports the square, which is reserved to pedestrians.

A preliminary test aimed at measuring the vibrations of the vault under the roadways was performed in October 2017. Fifteen mono-axial piezoelectric accelerometers (type PCB393C) where installed at the intrados of the vault in the southern part of the structure, and the accelerations were acquired for two days at a sampling frequency of 400 Hz in the radial and tangential directions.

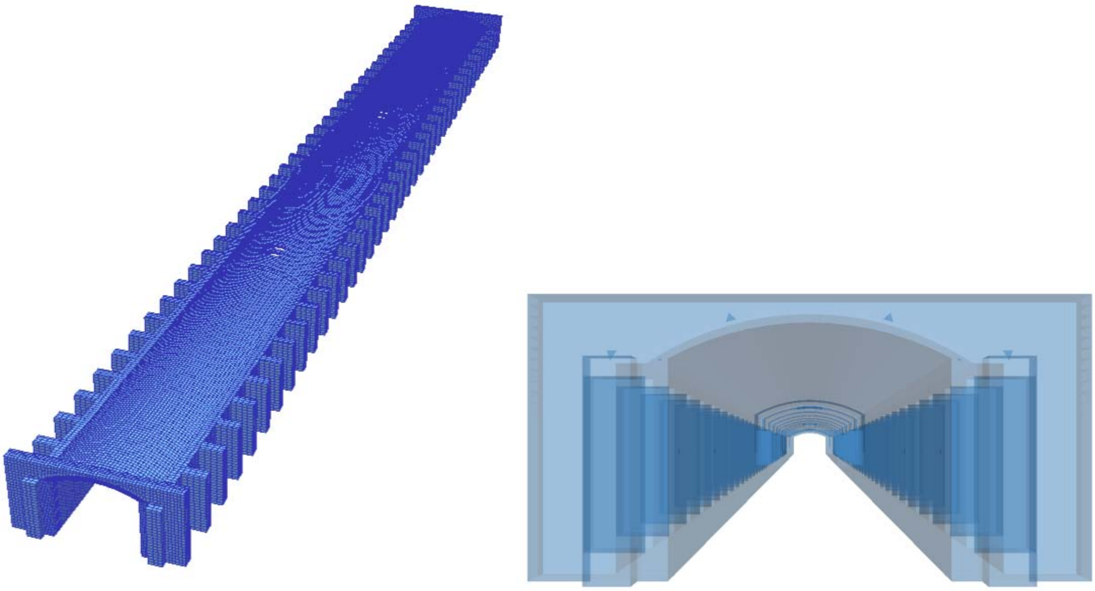

Figure 2: Geometry and finite element mesh of the Voltone.

Figure 3: Installation (on the left) and final layout of the sensors (on the right).

The current MOSCARDO monitoring network, consisting of twenty-two transducers (fifteen MEMS accelerometers "Colybris VS1002", two linear transducers for crack monitoring, a thermometer installed inside the tunnel and a weather control unit on the square) grouped in sixteen sensor nodes, was installed in October 2018 and is currently working. Figure 3 shows the installation operations and the final layout of the sensors in the southern end of the vault. The general sensor layout is reported in Figure 4; all the accelerometers measure in the radial direction with respect to the intrados of the vault, except two bi-axial sensors (encircled in blue in the figure), which measure in the radial and tangential directions. The accelerometer sensors record fifteen minutes per hour, at a sampling frequency of 50 Hz, while the environmental sensors acquire one sample per hour. All data are sent to the on-line MMC (https://ccm.moscardo.it/), where data are stored and processed in order to allow a real time visualization of the measured quantities. The MCC can be accessed by the researchers of the MOSCARDO project and the technicians in charge with the maintenance of the vaulted structure.

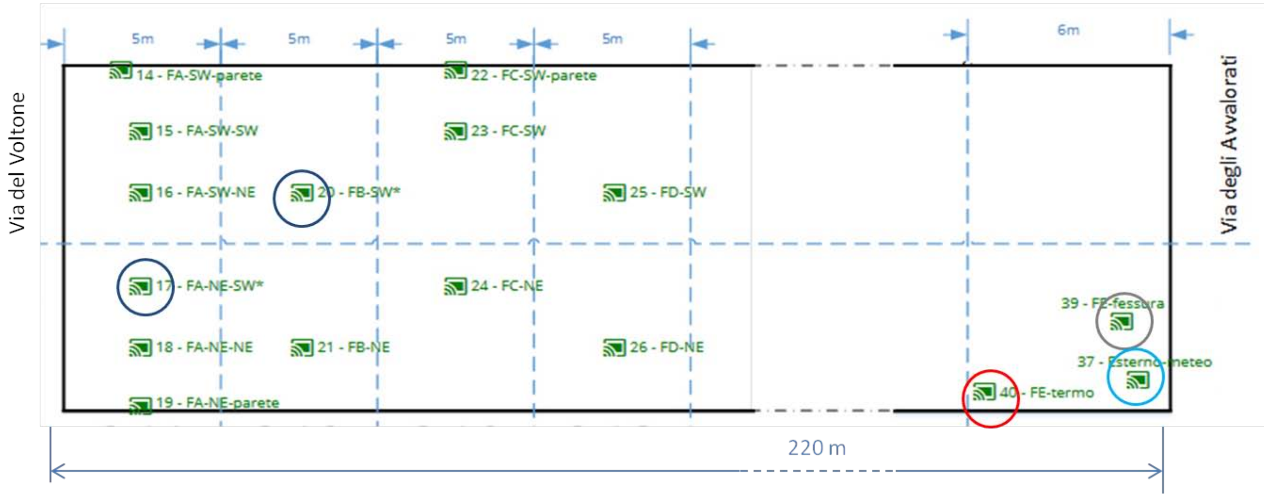

Figure 4: Map of the MOSCARDO sensors on the Voltone: mono-axial accelerometers, bi-axial accelerometers (blue circles), linear transducers (gray), thermometer (red), weather control unit on the square (cyan).

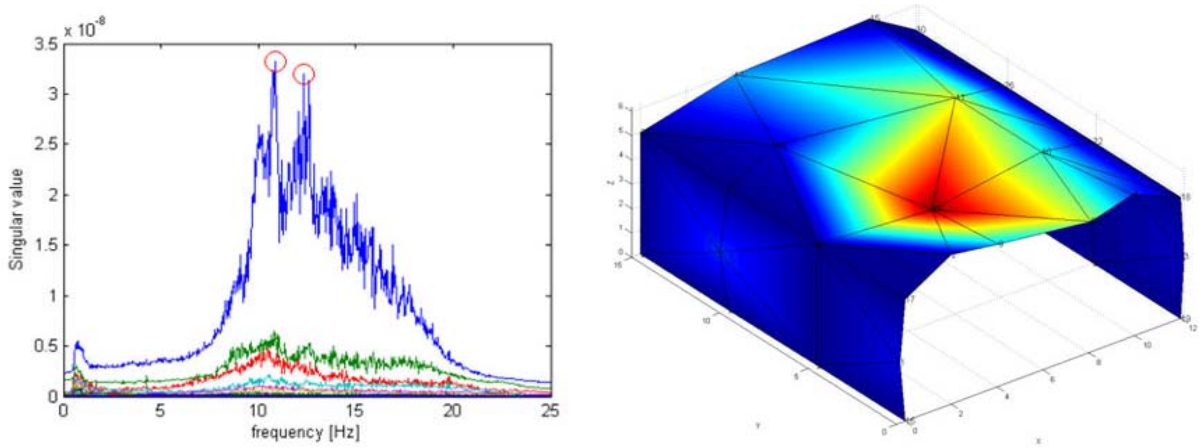

Figure 5:Singular value decomposition of the spectral density matrix obtained from the signals recorded on 5 October 2017 (PCB accelerometers).

Some preliminary results of the data analysis are presented in the following. With regard to the frequency content, the signals measured in October 2017 revealed dominant frequencies in the range 10-15 Hz. Figure 5 shows the singular values decomposition of the spectral density matrix obtained from the signals measured on 5 October 2017 by the piezoelectric accelerometers; two peaks are evident in the first singular value at about 11 and 13 Hz, corresponding to vertical oscillations of the vault (signals were processed using the Enhanced Frequency Domain Decomposition method[9]). This finding is essentially confirmed by Figure 6, where the frequency content of the signal measured by sensor n. 16 in radial direction (see Figure 4 for the sensor layout) is plotted, with reference to a congested time (19:00, cyan line) and to midnight (blue line).

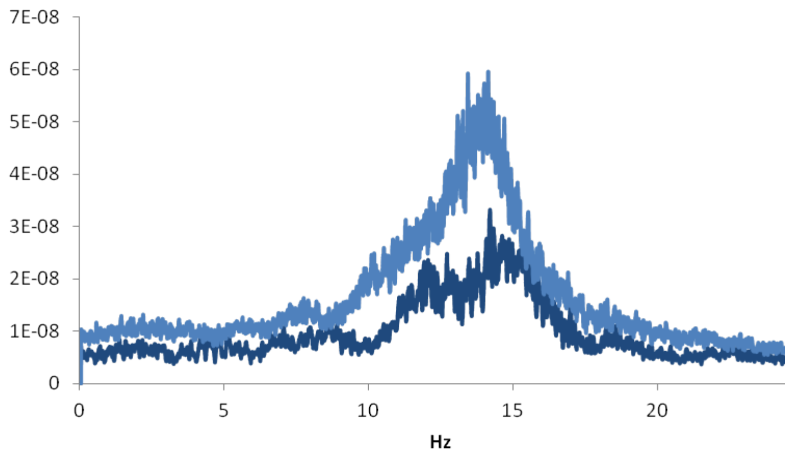

Figure 6:Frequency content of the signals recorded by MOSCARDO sensor n. 16 in the radial direction on 4 – 5 November 2018 at 19:00 (cyan) and at midnight (blue), Central European time.

In Figure 7 the Root Mean Square (RMS) of the signals recorded by sensors n. 16, 20 and 24 in the radial direction on 5 November 2018 is shown. The effects of the traffic in the central hours of the day are clearly highlighted, in terms of both energy and variability of the signal. Sensors n. 16 and n. 20, which are placed under the roadways, measure as expected greater values of acceleration than sensor n. 24, which is placed under the square. In particular, sensor n. 20, placed under the inner lane of Via del Voltone, exhibits the greatest values. Figure 8 shows peak velocities in the radial direction deduced from the signal of sensor n. 20, again with reference to 5 November. These values were deduced from the accelerations measured by the sensor via numerical integration and after the application of a sixth order high pass Butterworth filter with cut-off frequency of 1 Hz, as suggested by [10]. The maximum velocity recorded during the day approaches 8 mm/s at 16:00 and at 22:00 (Central European time). The peak acceleration measured by the sensor is 0.18 m/s^2; this value is close to that found on other monuments subjected to traffic, such as the Colosseum in Rome[11]. Both the peak velocities and accelerations fall inside the expected values of traffic-induced vibrations identified by[12]: in particular, the rules report the ranges of (0.2 to 50 mm/s) for the peak velocity and (0.02 to 1 m/s^2) for the peak acceleration. However, high values of the velocities and accelerations are reached in many hours during the day, as an effect of the passage of heavy vehicles - such as bus, trucks, etc - on the vaulted structure. In fact, it is worth noting that, although specific rules for the assessment of historical buildings subjected to traffic vibrations are not present in literature, a vertical velocity in the order of 10 mm/s is reported in several codes[10, 13] as a limit value not to induce damage in slabs. These preliminary results, which need to be confirmed and extended in future works, clearly highlight the role of permanent monitoring systems in assessing the structural health of ancient constructions in the urban context.

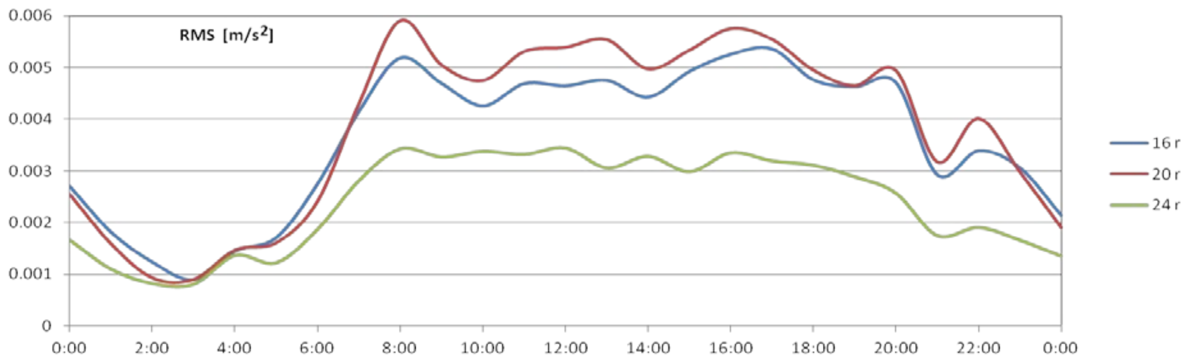

Figure 7: RMS of the signals recorded on the Voltone on 5 November 2018.

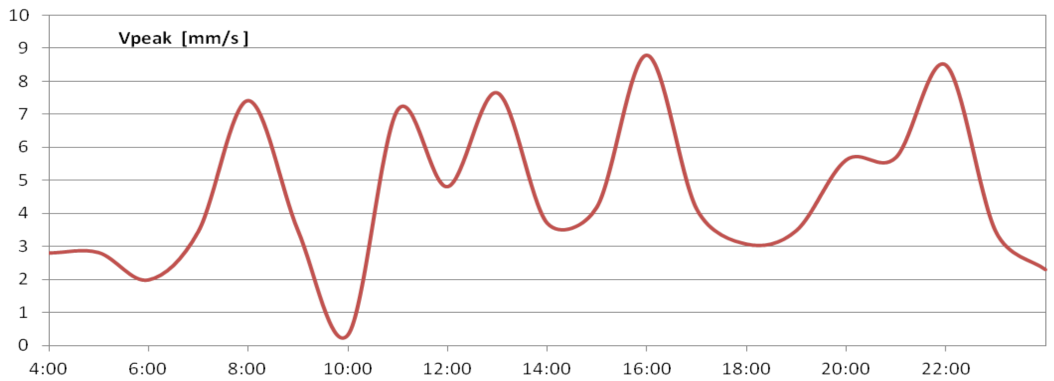

Figure 8: Hourly peak velocities in radial direction deduced from the signal recorded by sensor n. 20 (5 November 2018).

4 CONCLUSIONS

The paper reported on some results obtained in the framework of the MOSCARDO project, and focused on the dynamic monitoring of the Voltone, a masonry tunnel located under Piazza della Repubblica in Livorno. A wireless sensor network was installed on the structure in October 2018 and connected to a remote server, where data are collected and processed; the monitoring system is currently working. The potentialities of the MOSCARDO system, which can be easily extended to different structural types and modern structures, are highlighted and briefly discussed with reference to the case study. The obtained results, although preliminary, clearly highlight the crucial role of permanent monitoring systems in assessing the structural health of ancient constructions, with particular regard to vibrations coming from the urban context.

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