2020 IMEKO TC-4 International Conference on
Metrology for Archaeology and Cultural Heritage
Trento, Italy, October 22-24, 2020

Motion Magnification Analysis for monitoring Cultural heritage buildings and archeological sites

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***Abstract* –The present paper focuses on the application of an innovative image-based monitoring methodology derived from the Motion Magnification (MM). The method proved to be very useful for monitoring structural vibration of buildings, included cultural heritage. In particular, some case studies of outdoor experiments on Cultural Heritage sites were carried out: the so-called Temple of Minerva Medica in Rome, the Ponte delle Torri of Spoleto and the Archeological complex of the Crypta Balbi, in Rome. The studied structures were monitored by a smart but low-cost device (camera, smartphone, tablet etc.). Small movements in the taken videos were recorded and analyzed to understand the dynamic behavior and detected the weak parts with possible evolution of the state of damage. Possible analyses include modal analysis and identification of natural frequencies. Results were also compared with conventional vibration measurement methods showing encouraging perspectives.**

Keywords: *Motion Magnification, vibration monitoring, historic buildings, non-contact method*

I. INTRODUCTION

Cultural heritage buildings represent both valuable assets and critical elements within a modern city. On the one hand, they are symbols and constitute a reference for citizens, as they are unique for their historical and aesthetic instances. On the other hand, there are a lot of factors that endanger their structural health and aesthetic preservation, such as: lack of maintenance, exposure to pollution and meteoric phenomena, intense vibrations due to seismic events and anthropic activities, natural disasters, explosions etc. Monitoring such valuable objects is fundamental to prevent decay and avoid further damage after disaster events. Nowadays a great variety of devices for monitoring structures' vibrations are available: capacitive sensors, contact accelerometers, optical sensors etc. These established technologies are not always low-cost, need encumbrance, require energy supply and specialized operators capable of installing the proper devices. On the way to find low-cost, friendly and easy applicable methods machine-video technologies, such as the ones derived from the Motion Magnification (MM) process, were explored. Through the proper processing of video footages taken with a common camera it is possible to monitor structural part of buildings from a distance, without installing devices in dangerous or impracticable locations. MM is an image based method that permits to detect imperceptible motions and to amplify them so as to make them visible in a common digital videos and to analyze the dynamic behavior of the studied object. This is viable also for ambient vibrations if a camera with proper resolution and speed is used.

The video processing was derived from the algorithms recently implemented by MIT of Boston [1-2]. magnified videos are then processed for performing modal analysis and extracting the fundamental frequencies of the studied buildings. The present paper is focused on three outdoor experiments carried out at the so-called Temple of Minerva Medica in Rome, the Ponte delle Torri of Spoleto and the Archeological complex of the Crypta Balbi, in Rome. In Fig. 1 readers can find a QR code for connecting to some examples of processed videos.

Fig. 1. "Videos produced by ENEA Channel"

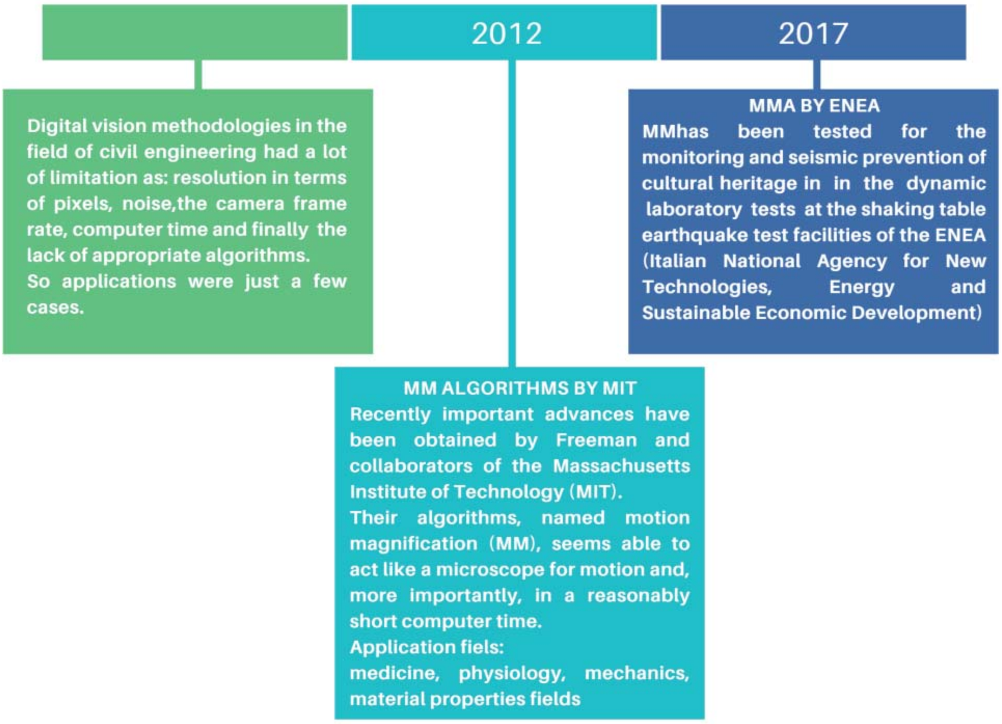

Fig. 2. Motion Magnification Analysis development.

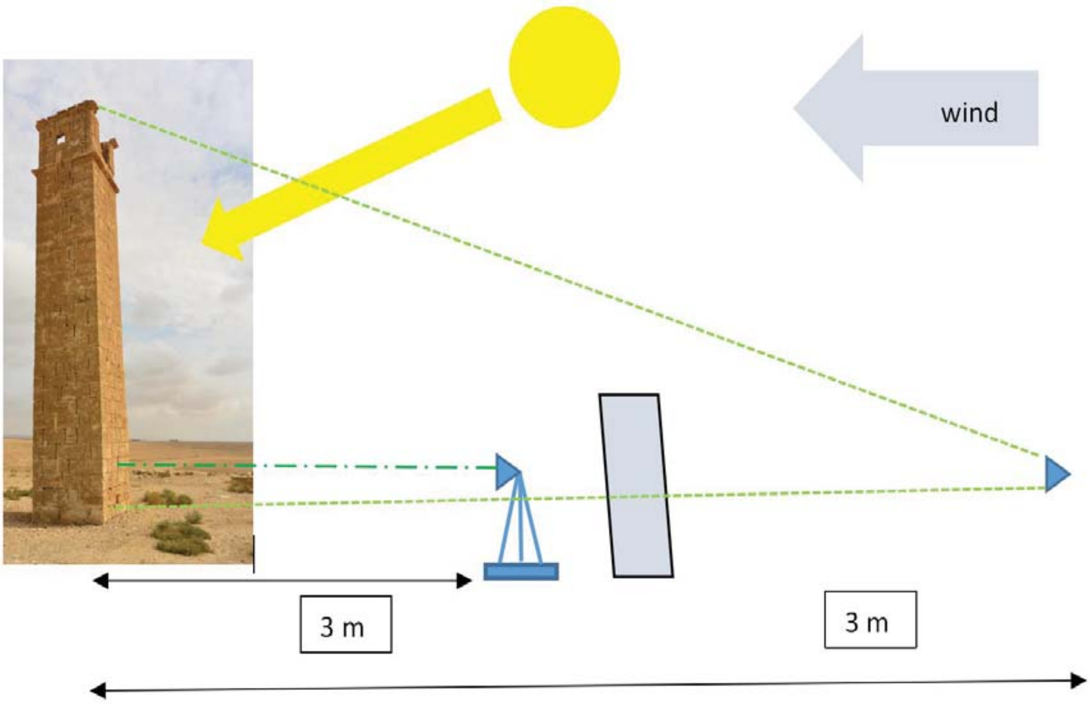

Fig. 3. Typical acquisition geometry and set-up.

II. PROCESSING METHODOLOGY

The implemented video processing methodology is derived from the MM principles. Theoretically, any kind of digital video format can be processed, even if taken by a common digital vision device. The view point and the acquisition set-up must be planned in accordance with the studied motion direction (Fig. 3). The pixels of a recorded footage are considered as a matrix or an array of contactless "virtual sensors", which are able to measure the light variation at a given measurement point along the duration of the video, frame by frame. Motion Magnification Analysis development can be summarized as in Fig. 2. The variation of each pixel value is computed and conventional techniques can be applied to analyze the obtained signal in the frequency domain. The effectiveness of the analyses results is dependent on the video quality in many senses. However, recent researches have explored the viability of the utilized video processing method also with footage taken by low-quality cameras, typically mounted on ordinary cell phones. It was proved that if the recorded object vibrates at a frequency of less then 10 Hz, which is typical of most buildings, the MM methodology can provide interesting indications. For an optimized application of MM to structural vibration in outdoor environment, some critical issues must be particularly taken into consideration. As one the main problems for a satisfactory MM application is the signal noise, it is crucial avoiding large motions. For example, people and objects passing by in front of the camera, disturbances due to non-fixed mechanical supports, dust, vibrations of camera or people talking near the camera, in general anything that can interfere with shooting, and of course it is also necessary to pay attention to wind, temperature, humidity, illumination, shadows, poor pixel resolution, low frame rate, the distance from the object.

Camera positioning is an important issue. It is better to use a tripod in order to reduce vibrations as much as possible. A recording angle of 90° with respect to the studied motion direction would be preferable. Typical frequencies of interest are below 50 Hz, so a frame-rate of 120 fps is might be considered an optimal compromise between camera speed and data size. Studied objects should have recognizable edges or texture, which would help the MMA algorithm detect motion. Anyway, a certain amount of noise, which add to other disturbances, is unavoidable. Obviously, MM is not able to provide a direct measurement of the objects displacements without a metric calibration of the used camera. Nonetheless, using a constant contours method can help estimate also displacements [2]. On the other hand, they may be used to calculate the power spectral density (PSD) or the fast Fourier transform (FFT). This opens the way to performing a complete modal analysis of the recorded object. At present stage in many cases a rough estimate of the fundamental frequency by frequency response function (FRF) is achievable.

III. CASE STUDIES

The case studies examined in the present paper refer to three relevant Cultural Heritage sites in Italy:

- the so-called temple of Minerva Medica [3-4]. It is an ancient ruined building of late Roman Empire period (4th century AD). Located in the city-center of Rome, it used to be interpreted erroneously as a temple dedicated to the goddess Minerva the Doctor ("Minerva Medica" in Italian). But more recent studies led archaeologists prefer a different attribution, most probably as the remains of an ancient nymphaeum of a private villa (*horti* in Latin);
- the Ponte delle Torri [5-6]. This is a 230-m-long construction with a pedestrian deck connecting two hills, namely Colle Sant'Elia and Mount Monteluco, in Spoleto, Central Italy. It was probably mainly built in the 13th century, possibly on Etruscan or Roman ruins of towers (*torri* in Italian). In the past centuries it was used both as a bridge and an aqueduct, as witnessed by Goethe in his *Italienische Reise*;
- the archeological complex of the Crypta Balbi [7]. The complex corresponds to the area where the smallest of the three theatres of ancient Rome was located. It was built in 13 BC. Alongside the theatre was a vast, rather narrow colonnaded courtyard, referred to as the crypt. In the following centuries up to the 19th century, several buildings and structures were erected within this site.

Different vibration sources may excite constructions and induce vibrations. In the case of the temple of Minerva Medica (Fig. 4) the main vibration source is given by trams passing by very close to the studied building.

Fig. 4. View from North of the so-called temple of Minerva Medica, Rome.

Fig. 5. Ponte delle Torri, Spoleto.

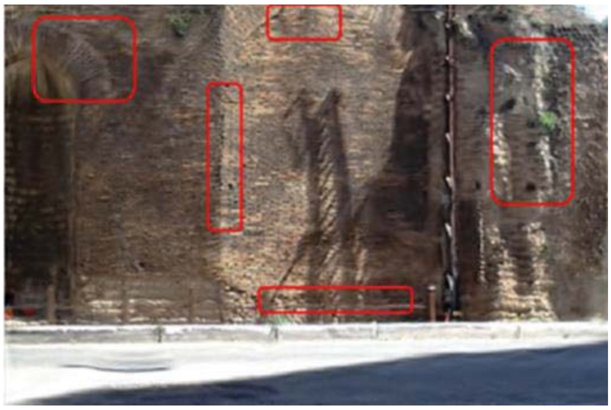

Fig. 6. Red boxes indicate areas showing larger vibration motion after tram passages.

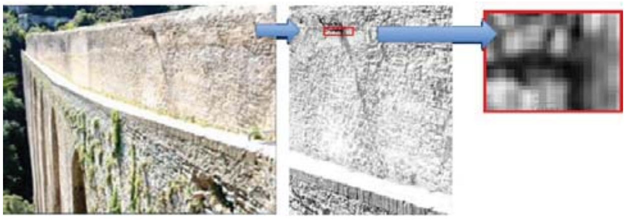

Fig. 7. Camera viewpoint (left) and detail zoom of analyzed Region Of Interest (ROI)(right).

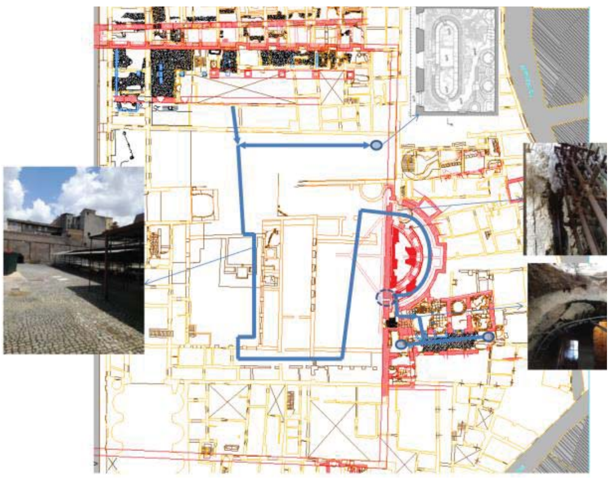

Fig. 8. Plan view of the Crypta Balby complex: proposed visitors tour (blue line).

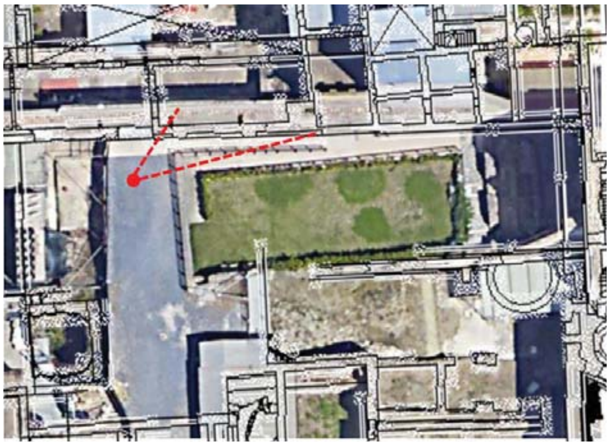

Fig. 9. Plan view of the Crypta Balby complex: camera position and field of view (in red).

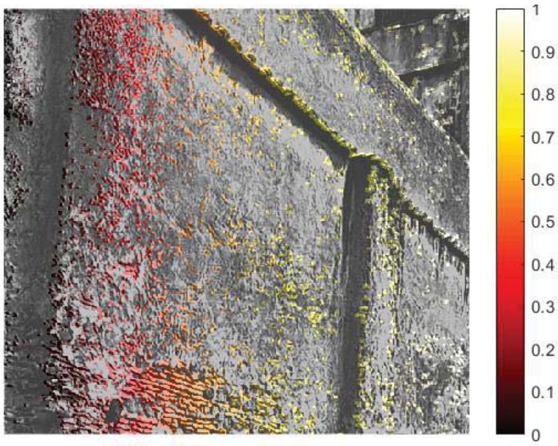

Fig. 10. Digital video analysis of the relative normalized displacement patterns of the main wall along the proposed visitors tour (see Figure 9).

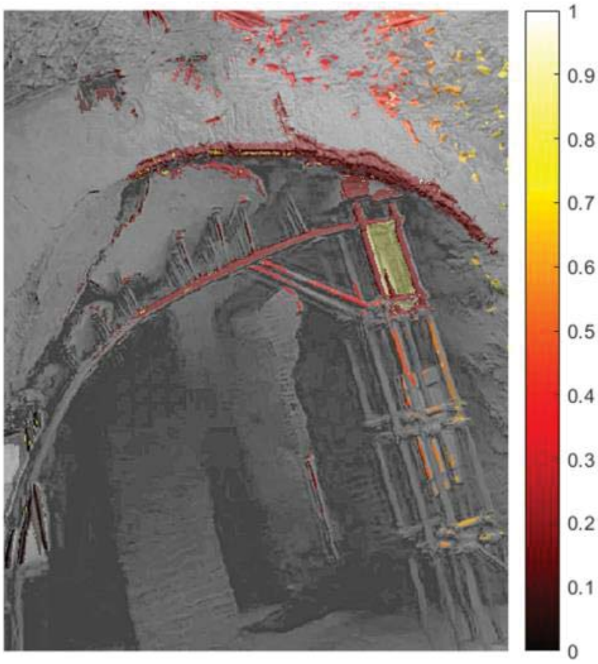

Fig. 11. Digital video analysis of the relative normalized displacement patterns of a reinforced arch.

In the case of the Ponte delle Torri (Fig. 5) the main vibration source is the wind. Results show that after the MM processing, modal shapes are distinguishable to the naked eye also for the outdoor recordings and moreover the vulnerable parts of the monument are unveiled (Fig.6). The modal parameters extracted after MM of the recorded videos were compared with the results obtained by conventional seismograph data processed through different Operational Modal Analysis (OMA) techniques [5]. The used seismographs mounted triaxial linearized velocimeters with a high value of amplification (400 V/m/s). The above comparison revealed that MM-based video processing was able to identify the first modal frequency with an accuracy of less than 1%.

On-the-field data at Ponte delle Torri the were recorded on 29 May 2017. The acquired velocity data were processed and analyzed to extract the modal parameters related to first four modes [5]. The identified frequencies for the first modes were between 0.6 Hz and 2.0 Hz. Subsequently, the video processing algorithm was designed to mainly focus on the bridge motion within this frequency range. The same four modal frequencies were identified by quantitative analysis in the frequency domain using the MM methodology. The second modal frequency by video processing had a quite significant error (6.79 %), while the other three modes were obtained with a satisfactory accuracy (around 1-2 %). In this case study it must be considered that the positioning of the camera was at a remarkable distance from the target and the monument did not present any suitable image edges on its surface. On the other hand, the major source of vibrations was a light wind. If we consider the wind as the input to the structure of the bridge, and the displacements as the output, it is clear that the signal-to-noise ratio (SNR) is lower than the Minerva Medica SNR. As a consequence, noise will cause a larger calculation error in the Ponte delle Torri analysis.

An evolution of the basic algorithm was developed to analyze a limited Region Of Interest (ROI) in order to reduce computational time and required resources. The ROI can be selected manually or with semi-automatic criteria, such as the criterion of the maximum image entropy. In fact, image entropy is maximized in the higher contrast areas of the image [6].

The application to the archeological site of the Crypta Balbi complex was mainly dedicated to assess the structural vulnerability of some walls and structures along a possible visitors tour (Fig. 8). In this case, video processing derived from MM proved to be very useful to provide the in-charge authority with indications for visitors safety. The main wall that lies along the proposed visitors tour was subject to stability verification, in particular with regards to its projecting parts (Fig. 9). The false color visualization used in Fig 10 maps the normalized displacements revealed by magnified vibration. It goes from a minimum (dark red) to the maximum values (clear yellow). Normalization values are in a scale from 0 to 1. This particular processing displays the points of the wall with larger displacements, which might be used to extract the modal shapes, once the MM algorithm is set up to enhance vibrations in a given frequency range around the modal frequency. It can also be used to identify the most instable portions of the wall (Fig. 11). In the archeological site of the Crypta Balbi situations of instability were identified, e.g. some roofs and some walls.

IV. CONCLUSIONS

The presented experimental applications showed that the utilized video processing derived from the MMA provided satisfactory indications on the dynamic behavior of structures and their most vulnerable parts. Obviously, the used method can not compete in terms of accuracy with more consolidated techniques for ambient vibration testing, such as the ones based on the sue of high-sensibility accelerometers and velocimeters. But many advantages arise in term of easy set-up and acquisition of data from a distance and with relatively low-cost instrumentation.

The obtained modal frequencies resulted surprisingly good approximation of the ones estimate by consolidated OMA methods based on the measurements carried out with conventional velocimeters. The differences in terms of estimated fundamental frequencies were limited to only a few percentage points of error. Furthermore, the MMA methodology have huge margins of improvements and will possible make rapid developments. Implementation of the MM method permits intuitive and low-cost visual analysis. It also revealed a potential in terms of sustainability of the process. The use of vision-based technology allows monitoring potentially millions of points by a cheap smart portable device without installing a contact sensor at each measurement position with cables and through specialized operators.

With the illustrated method satisfactory results were obtained both in laboratory and in outdoor environment, even using low frame-rate cameras. Of course, outdoor applications are very much challenging and much more difficult than laboratory controlled experiments. Currently, the major issues are related to the high impact of noise into the signal, but it can be fixed with further developments of the utilized hardware technologies. The recent advances in the digital image and video processing are very promising and give reasonable hopes of opening the door to applications to the analysis of ambient vibrations in the toughest outdoor environments. By the analysis of magnified motion of videos, it will be possible a permanent monitoring of structures behavior, similarly to the most advanced structural health monitoring systems. In particular, cultural heritage assets can be monitored so as to recognize the evolution of the state of damage and quantify the risk of collapse. Innovative cameras are already available today, which can record and elaborate the MM in real time. In conclusion, MM and related video processing revealed to have a good potential for the monitoring of the structural health of cultural heritage constructions. This might be the basis of implemented valuable tools to support decision-makers on restoration and safety interventions for effective conservation strategies.

REFERENCES

[1] H.Yu-Wu, et al., “Eulerian Video Magnification for Revealing Subtle Changes in the World”, 2016. https://people.csail.mit.edu/mrub/papers/vidmag.pdf, last accessed 2017/3/2

[2] N.Wadhwa, H.Wu, A.Davis, M.Rubinstein, E.Shih, G.Mysore, J.Chen, O.Buyukozturk, J.V.Guttag, W.T.Freeman, F.Durand, “Eulerian Video Magnification and Analysis,” Communications of the ACM 60(1), 2017, pp. 87-95.

[3] I.Roselli, V.Fioriti, I.Bellagamba, M.Mongelli, A.Tatì, M.Barbera, M.Magnani Cianetti, G.De Canio, “Urban transport vibrations and cultural heritage sites in Rome: the cases of the temple of Minerva Medica and of the Catacomb of Priscilla”, WIT Transactions on Ecology and the Environment, 223, 2017, pp. 335-343.

[4] V.Fioriti, I.Roselli, G.De Canio, “Frequency Domain Analysis of the Minerva Medica Temple by means of the Motion Magnification Methodology”, 2018 IEEE International Conference of Metrology for Archaeology and cultural heritage (MetroArchaeo2018), Cassino 22-24 October, Italy, pp. 314-318.

[5] I.Roselli, M.Malena, M.Mongelli, N.Cavalagli, M.Gioffrè, G.De Canio, G.de Felice, “Structural health monitoring by ambient vibration testing of the Ponte delle Torri of Spoleto during the 2016-2017 Central Italy seismic sequence”, Int. J. of Civil Structural Health Monitoring, Vol.8, No.2, 2018, pp. 199–216.

[6] V.Fioriti, I.Roselli, A.Tatì, R.Romano, G.De Canio, “Motion Magnification Analysis for Structural Monitoring of Ancient Constructions”, Measurement, Vol. 129, 2018, pp. 375-380.

[7] S.Forliti, V.Fioriti, I.Roselli, A.Tatì, A. Colucci, “Motion Magnification Analysis city monitoring”, Measurement, Sustainable Development and Planning 2020, 22-24 October, Online.