MOTION MAGNIFICATION ANALYSIS FOR CITY MONITORING

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ABSTRACT

Motion Magnification Analysis is an image-based monitoring methodology. It is based on installation of smart objects (camera, smartphone, tablet). Thus, small movements of buildings recognizable in common digital videos are magnified throw algorithm called Moto Magnification. The case studies collected focuses on outdoor experiments carried out by researchers on Cultural Heritage sites: the so-called Temple of Minerva Medica in Rome, the Ponte delle Torri of Spoleto and the Archaeological complex of the Crypta Balbi, in Rome. Therefore, analysing the building vibrations is possible to understand the structural behaviour of the monitored elements by modal analysis; analysing frequency variations is possible to detect the elements state of decay. The methodology makes possible constant, rapid, intuitive visual analysis. It is a low-cost and low-environmental impact strategy and has the possibility to be widespread on the territory.

Keywords: Motion Magnification, monitoring, preservation, cultural heritage, non destructive analysis.

1 INTRODUCTION

Monitoring leads to a safe, efficient city, protecting new buildings and the cultural heritage and safeguarding inhabitants. To support engineers, a variety of devices has been developed: capacitive sensors, contact accelerometers, optical sensors, but there are disadvantages to be faced: costs, dimensions, energy requirements, specialized operators, installation settings, numbers of devices. Then, monitoring becomes fundamental in the disaster scene but often is too dangerous or totally impracticable install monitoring devices. We are going to consider an innovative, smart technology called the Motion Magnification Analysis.

This innovative technology is an image-based method which consists in the amplification of small displacements recognizable in common digital videos. Videos are processed through algorithms recently implemented by MIT [1]; Motion Magnification. Our purpose is only to give a general idea of the potentiality of the MM in the protection of Cultural Heritage Building and Archaeological Sites, with particular regard to applications for urban safeguard. The experiments show Motion Magnification Analysis (MMA) applied to the analysis of vibrations in the structural field. Therefore, analysing the vibrations induced by natural micro tremors such as wind, traffic, amplifying the displacements, it is possible to understand structural behaviour of element monitored and making modal analysis and analysing frequency of buildings. The text shows three case studies, outdoor experiment.

2 BACKGROUND

The analysis of image sequences in the field of civil engineering is not new. For many years attempts to produce qualitative (visual) and even quantitative analysis using high quality videos of large structures have been conducted, but with poor results. This was because of some limitations, such as pixel resolution, signal noise, low camera frame rate, computation time needed and, finally, a lack of appropriate algorithms able to deal with the extremely small motions related to building displacements. These and other limitations have restricted the applications of digital vision methodologies to few practical cases.

Nevertheless, recently important advances have been obtained by Freeman and collaborators of the Massachusetts Institute of Technology (MIT). Their algorithms, named

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Motion Magnification (MM), seems able to act like a microscope for motion and, more importantly, in a reasonably short computer time. The latter point is crucial, as it is well known that video processing takes a lot of time and resources. Therefore, any viable approach must consider the reduction of the calculation time as an absolute priority. The basic MM version looks at intensity variations of each pixel and amplifies them, revealing small motions which are linearly related to intensity changes through a first order Taylor series for small pixel motions. Motion Magnification Analysis development can be summarized as in Fig. 1.

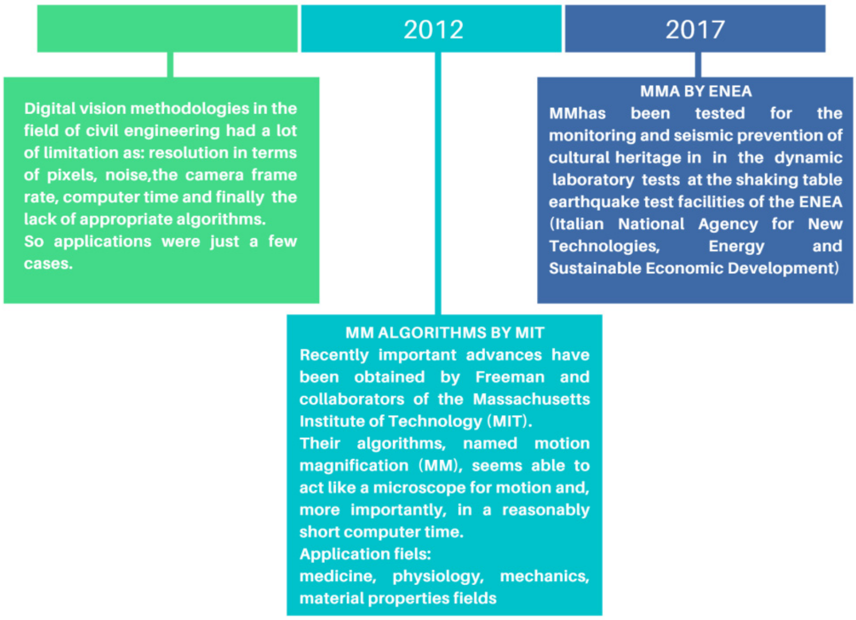

Figure 1: Motion Magnification Analysis development.

3 GENERAL METHODOLOGY

The MMA methodology aim is to map the surfaces shot by the video camera as an array of contactless "virtual sensors". Thus, each pixel is interpreted as a sensor, therefore a measuring point that acquires and records a physical quantity for the duration of the video, frame after frame. The signal is given by the variation of the pixel which can then be treated using traditional frequency analysis techniques. The quality of the video recording is decisive for the accuracy of the analyses. The researchers have experienced that also video taken by ordinary cell phones can provide interesting indications if the object vibrates at frequencies of a few tens of Hz as it usually happens in many structures. For the optimal use of MM in vibrational monitoring, it is necessary to pay attention to some critical issues that are much critical in outdoor experiments. The first aspect to pay attention is noises, so avoid large motions for example people passing by in front of the camera, non-fixed mechanical, dust, vibrations of camera or people talking near the camera, in general anything that can interfere with shooting. Pay attention to wind, temperature, humidity.

Camera positioning is very important, is better use tripod in order to eliminate vibrations. Pay attention to distance, recording degree (90° if possible). Camera frequencies of interest are below 50 Hz, so a frame-rate of 120 fps is optimal. The recording surface needs to have presence of edges or texture, helpful for the MMA. These circumstances produce a certain amount of noise, to be added to other disturbances. Signals from the magnified motion technique do not directly provide the displacements, although they could be recovered by means of the constant contours method. On the other hand, they may be used to calculate the power spectral density (PSD) or the FFT, allowing the modal analysis and the calculation of the frequency response function (FRF). There are other physical limitations, such as illumination, shadows, camera unwanted vibrations, poor pixel resolution, low frame rate, presence of large motion, distance from the object, that decrease severely the quality of the MM and should be taken into account in order to achieve high-quality results.

4 THE MAGNIFIED MOTION

The Motion Magnification theory is based on the simple observation that videos can be seen as a temporal sequence of frames, which from a mathematical point of view are simply matrices of light intensity or colour signals contained in each pixel. Such signals can be written as $I(x, t)$, where I is the light intensity, x is the image-position of the pixel and t is the time in the sequence or video-time. According to the Eulerian description of the magnification algorithm by Wadhwa et al. [2], and considering for simplicity the mono-dimensional displacement δ (t) recorded in the image, the expression for the magnified signal is as follows:

$$\Delta I = f(x - (1 + \alpha)\, \delta\,(t)), \tag{1}$$

where α is the amplification coefficient.

Under the assumption that the recorded displacement is very small, a Taylor's first order series can be suitable to describe the intensity I, accepting a relatively small error ε due to the Taylor's approximation:

$$I(x, t) = f(x) - \delta(t)\, (\partial f / \partial x) + \varepsilon. \tag{2}$$

After several mathematical passages, as described in Wadhwa et al. [2], the magnified intensity I_{magn} can be written as follows:

$$I_{magn}\,(x, t) \approx f(x) - (1 + \alpha)\, \delta(t)\, (\partial f / \partial x). \tag{3}$$

The overall process can be visualized as in Fig. 2, where the motion displacement is magnified just adding the term $\alpha\Delta(x, t)$ to the signal intensity $I(x, t)$. The assumptions made maintain their validity as far as the recorded motion can be well described as a linear process, which substantially means that the theory is valid for slowly moving objects with small amplifications.

Further considerations can be made on the noise of variance σ^2 to be added to the signal intensity, that is also amplified along with the real signal.

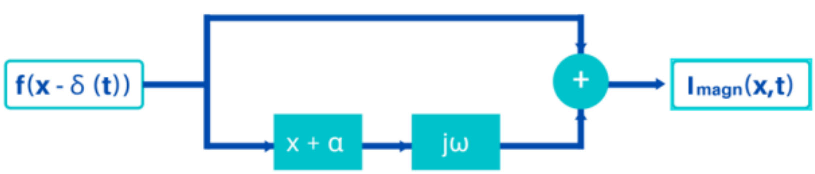

Figure 2: Temporal filtering applied to each pixel time history. Cut-off frequencies have to be chosen carefully in order to enclose the spectral band of the studied phenomenon, while excluding other frequencies.

Obviously, the required computer time depends on the video duration. Thus, it may become a major issue for long videos processing. To limit this issue the video can be cut both in terms of duration and frame dimension, e.g. zooming to the moving object within the view.

In addition, unstable lighting conditions, presence of shadows on the moving object, camera vibrations, etc. all constitute other possible physical source of error and should be removed.

The quality of the final result is higher if the used camera is provided with good pixel resolution and high frame rate. Also important to obtain good quality results is the camera positioning. The camera should be positioned at the smallest distance from the moving object and its view point should be as orthogonal to the studied motion as possible.

Moreover, it should be taken into account that, according to Shannon-Nyquist Theorem, a signal is correctly reproduced under the following condition:

$$f_{sampling} \geqslant 2f_{max}, \tag{4}$$

where f_{max} is the highest frequency of the recorded motion signal and $f_{sampling}$ is the sampling frequency, which coincides with the acquired video frame rate f_{fps}.

5 CASE STUDIES

The experimentation in the outdoor environment concerned the study of three Cultural Heritage sites: the so-called temple of Minerva Medica, which is located very close to a tramway [3], the Ponte delle Torri of Spoleto [4] and the Archaeological complex of the Crypta Balbi [5]. Different vibration sources may be present and excite historic buildings. In the case of the temple of Minerva Medica the main vibration source is given by trams passing by very close to the studied building (Fig. 3), while in the case of the Ponte delle Torri it is the wind. The trams passages induce very stronger vibrations to the so-called temple of Minerva Medica [6].

Figure 3: View from the west of the so-called temple Minerva Medica, Rome. A tram passing by (bottom left).

Fig. 4 shows the first frame of the magnified video recorded after a tram passage close to the temple of Minerva Medica. The red boxes, enhance the parts of the monuments indicate by the MM analysis as more prone to vibrate, the areas that showed ampler motions. Modal analysis by MM of the experimental field videos was performed and compared to analogous results obtained through conventional vibration instrumentation acquisitions, namely velocimeters, whose data were processed by different Operational Modal Analysis (OMA) techniques to extract modal parameters. The comparison showed that MMA identified the first modal frequency at 1.95 Hz with an accuracy of less than 1%.

Figure 4: A frame from the video "MMIII_magnified_115959" (Minerva Medica temple magnified motion). Red boxes indicate the points with highest vibrations amplification).

Figure 5: View from North of the Ponte delle Torri of Spoleto.

In the case of the Ponte delle Torri of Spoleto (Fig. 5) videos and velocimeters data were recorded at the same time [7]. The velocimeters data were processed and analysed to identify the first four modes in terms of shapes and frequencies.

Table 1 shows the identified four modal frequencies. They are in the range 0.6–1.5 Hz, hence the algorithm was designed to enhance mainly the motions of this frequency range. Table 2 shows the four modal frequencies identified by quantitative analysis in the frequency domain using the MM methodology. The second mode is recovered with a quite large error (6.79%), while the other modes were obtained with a satisfactory precision (around 1%–2%). In this case study it must be taken into account that positioning the camera in order to take the video from an optimal recording angle of view was not easy for the remarkable distance from the target and the absence of suitable image edges on the monument. MMA was also used for the assessment of the structural vulnerability of the structures in the archaeological site of the Crypta Balbi complex (Fig. 6). In particular, MMA was applied to monitor some walls and facades along a possible visitors' tour. In this circumstance, MMA proved to be a useful method to improve visitors' safety. The main wall along the proposed visitors tour is subject to verification of the projecting elements.

Table 1: Natural frequencies of the first four modes by different OMA techniques (FDD, EFDD, SSI) and average (Avg) values.

Mode	OMA technique			Avg f (Hz)
	FDD f (Hz)	EFDD f (Hz)	SSI f (Hz)	
1	0.632	0.631	0.632	0.632
2	1.006	1.014	1.014	1.011
3	1.497	1.496	1.494	1.496
4	1.976	1.976	1.973	1.975

Table 2: Frequencies of the first four modes by MM and percentage error with respect to average OMA frequencies of Table1.

Mode	MM technique f (Hz)	% error
1	0.638	1.00
2	1.080	6.79
3	1.522	1.76
4	2.013	1.92

Figure 6: Aerial view of the Crypta Balbi complex, Rome.

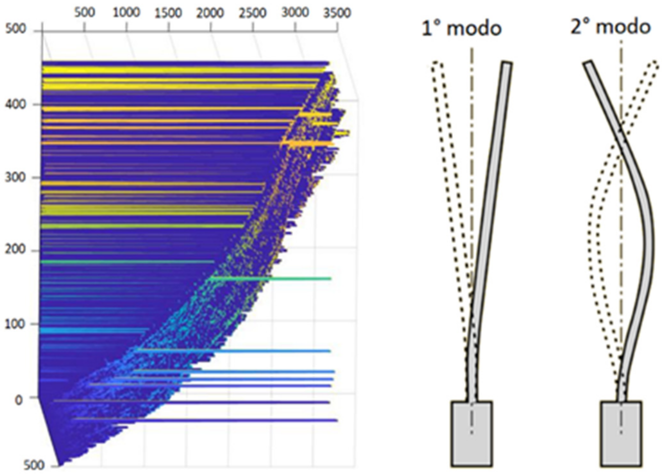

Figure 7: (a) Map of the maximum displacements in the wall vibration in the frequency range 0.5–1.5 Hz can be compared to (b) Theoretical modal shapes.

The colour scale in Fig. 7 shows the normalized displacements from a minimum (dark red) to the maximum values (white). Normalization values are in a scale from 0 to 1. This particular kind of representations display the points of the wall with larger displacements. It might be used to have indications on the most instable portions of the wall.

In the case of the studied archaeological site of the Crypta Balbi, complex evident situations of instability of roof tiles and of some wall portions were identified. A further advanced representation can be performed to map the maximum displacements in the wall vibration. This technique can 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 identify. An example is shown in Fig. 8 comparing the wall maximum displacements in the range 0.5–1.5 Hz with the theoretical modal shapes of 1st and 2nd modal shapes.

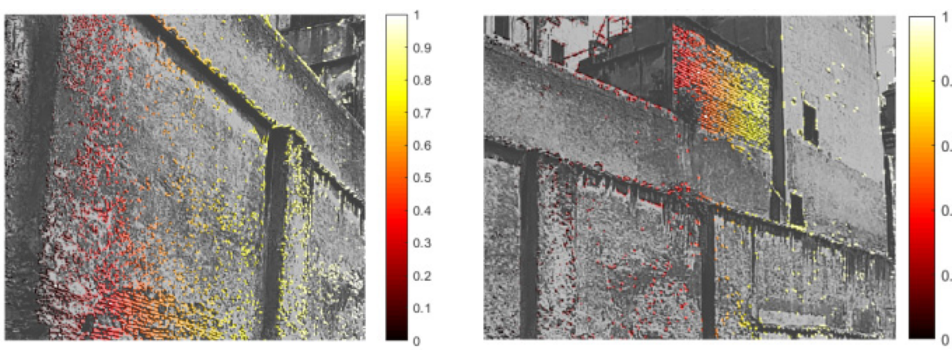

Figure 8: Digital video analysis of the relative normalized displacement patterns of the main wall along the proposed visitors tour.

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6 CONCLUSIONS

The illustrated case studies demonstrate that the acquired MMA data, compared with conventional methods for ambient vibration testing, such as accelerometers and velocimeters, provided satisfactory, even if less accurate, indications on the dynamic behaviour of structural members.

Though the proposed method is less accurate than conventional methods for ambient vibration testing, such as accelerometers and velocimeters, the MMA provided satisfactory results. In particular, the obtained modal frequencies resulted very close to the ones calculated by consolidated methods based on OMA approach of conventional velocimeters data, with errors limited to just a few percentage points. MMA has a great potential: the methodology is going to makes possible rapid, intuitive and low-cost visual analysis. It's a sustainable process and advantages are many: it is low cost technology because of monitoring cheap smart object installed (camera, smartphone, tablet); is user friendly and do not need cable or specialized operators, it could give approximate instant results.

Moreover, this method gives possibility to have a lot of measurement point because every pixel it's a virtual sensor. The monitoring element can be studied remotely by camera and we can obtain instant visual values. We obtained satisfactory results in laboratory and also in the urban environment, even using low frame-rate video cameras. Currently, the issues are noise in video, but they are going to improve with the develop of technologies.

The recent advances in the digital image and video processing have opened the door to applications to the analysis of vibrations, in particular by Motion Magnification in the videos, this technology will allow constant monitoring of many structures of the public cultural heritage, so recognize presence of danger for example imminent collapses. Innovative cameras are available today, which can record and elaborate the MM in the meantime. Concluding, MMA is a valuable method for the management of the cultural heritage and a precious tool for making decisions about recovery or securing interventions before and after seismic event or disasters strategies.

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