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Ancient Monuments Analysis by Motion Magnification

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***Abstract* – A new methodology for digital image processing, namely the Motion Magnification, allows to magnify small displacements of large structures. Motion magnification acts like a microscope for motion in video sequences, but affecting only some groups of pixels. The processed videos unveil motions hardly visible with the naked eye. We apply the motion magnification to a scale mockup of the Hagia Irene church stressed by a shaking table, to the so-called Temple of Minerva Medica in Rome and to the Ponte delle Torri of Spoleto. Results are surprising, offering a low-cost, viable support to the standard equipment such as contact accelerometers, laser vibrometers, linear variable differential transformers.**

I. INTRODUCTION

Vibration monitoring of historic monuments in the urban environment is a relevant issue for health survey and damaging detection. Today, a new digital image processing method, namely the Motion Magnification Analysis (MMA), allows to magnify small displacements in video motions. Motion magnification acts like a microscope for motion in video sequences, but affecting only some groups of pixels, unveiling motions hardly visible with the naked eye. The motion magnification uses the spatial resolution of the video-camera to extract physical properties from images to make inferences about the dynamical behavior of the object. Researchers are very interested in assessing the method's feasibility, since conventional devices are surely more precise, but expensive and much less practical. Recently, a number of experiments conducted on simple geometries like rods and other small objects as well as on bridges, have demonstrated the reliability of this methodology compared to contact accelerometers and laser vibrometers. In this paper, we extend the MMA to the analysis of a 1:10 scale mockup of the church of Hagia Irene of Constantinople tested on a shaking table, to the so-called Temple of Minerva Medica in Rome and to the Ponte delle Torri of Spoleto. Results show that MMA allows a visual identification of vibration mode shapes and of the most vulnerable elements of the structures. Though our equipment was of low quality in order to test the methodology in an adverse environment, results were very good. Evaluating the health of large structures such as a historical monument in a short time span and possibly by simple devices that do not require expert operators, may be a pivotal issue in civil engineering. Thus, the availability of intuitive methodologies such as those based on a digital acquisition of images may result in a major breakthrough. However, 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 the resolution in terms of pixels, of the noise, of the camera frame rate, computer time and finally because of the lack of appropriate algorithms able to deal with the extremely small motions related to a building displacement. These and others limitations have restricted in the past the applications of digital vision methodologies to just a few cases. Nevertheless, recently important advances have been obtained by Freeman and collaborators at the Massachusetts Institute of Technology [1]. Their algorithm, named motion magnification, seems able to act like a microscope for motion and, more importantly, in a reasonably short elaboration time. The latter point is crucial, as it is well known that image 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 MMA version looks at intensity variations of each pixel, revealing small motions linearly related to intensity changes through a first order Taylor series, for small variations. Since our intention is only to give a general idea of the potentiality of the motion magnification, we will not enter into the formal description of the algorithm. Rather we will propose some practical implementation examples: a laboratory case-study and more importantly, two monuments such as the so-called Temple of Minerva Medica in Rome and the Ponte delle Torri of Spoleto.

The original video files were named:

- "Video Hagia Irene.ppt";
- "MMIII_ORIGINAL_115959";
- "SPOLETO_ORIGINAL_2578_crop".

While the motion magnified video files were named:

- “Video Hagia Irene.ppt”;
- “MMIII_magnified_115959”;
- “SPOLETO_magnified_2578_crop_alph140”.

All above files are downloadable at the following link:

https://drive.google.com/drive/folders/0Bz540aXsdKTnbjdsQVl6TzBYbVU?usp=sharing

II. THE ALGORITHM

Here we will describe the eulerian version of MM [1], although actually we have used the phase based version [2] to process the videos. Videos are made up of a temporal sequence of 2D images, whose pixel intensity is *I(x, t)*. The 2D array of color intensity is the spatial domain, while the time do-main corresponds to the temporal sequence. We consider a 1-D translating image with displacement $\delta(t)$. $I(x, 0) = f(x)$ at the image-position x and video-time $t = 0$ (for the treatment of the general problem, see [2]). We have:

$$I(x, t) = f(x - \delta(t)) \qquad (1)$$

The final expression of its motion magnified by constant α is defined as:

$$\Delta I = f(x - (1 + \alpha)\, \delta(t)) \qquad (2)$$

Now, if the displacement $\delta(t)$ is small enough, it is possible to expand the relation (1) as Taylor’s first order series around x, at time t:

$$I(x, t) = f(x) - \delta(t)\, (\partial f / \partial x) + \varepsilon \qquad (3)$$

where ε is the error due to the Taylor’s approximation and to δ being non-zero. The intensity change at each pixel can be expressed as:

$$\Delta(x, t) = I(x, t) - I(x, 0) \qquad (4)$$

Which, taking into account eq. (3), becomes:

$$\Delta(x, t) = f(x) - \delta(t)\, (\partial f / \partial x) + \varepsilon - f(x) \qquad (5)$$

and finally:

$$\Delta(x, t) \approx - \delta(t)\, (\partial f / \partial x) \qquad (6)$$

disregarding the error ε, meaning that the absolute pixel intensity variation Δ is proportional to the displacement and to the spatial gradient. Therefore, pixel intensity can be written as follows:

$$I(x, t) \approx I(x, 0) + \Delta(x, t) \qquad (7)$$

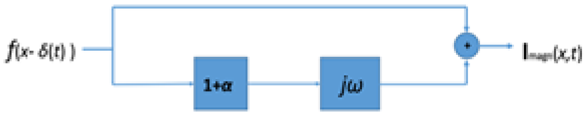

Fig. 1. Temporal filtering applied to each pixel time history. Cut-off frequencies have to be chosen carefully in order to enclose the band of the phenomenon to be analyzed and exclude other frequencies.

Magnifying motion by a given constant α, using equations (3) and (4), simply means that pixel intensity *I(x, t)* is replaced by magnified pixel intensity $I_{magn}(x, t)$ according to the following:

$$Imagn\,(x, t) \approx I(x, 0) + \alpha\, \Delta(x, t) \approx f(x) - \delta(t)\, (\partial f / \partial x) - \alpha\, \delta(t)\, (\partial f / \partial x) + O(\varepsilon, \delta) \qquad (8)$$

where $O(\varepsilon, \delta)$ is the remainder of the Taylor series. Finally, magnified intensity can be calculated as:

$$Imagn\,(x, t) \approx f(x) - (1 + \alpha)\, \delta(t)\, (\partial f / \partial x) \qquad (9)$$

but eq. (9) is immediately derived from the first order Taylor’s expansion of the magnified motion of the following:

$$\Delta I = f(x - (1 + \alpha)\, \delta(t)) \qquad (10)$$

It is important to observe that (6) is obtained by a band-pass derivation, thus the process can be basically summarized as in Figure 1. Therefore, we can say that to magnify the motion displacement it suffices to add $\alpha\Delta(x, t)$ to $I(x, t)$, as long as the Taylor’s expansion (9) is valid, that is until its remainder $O(\varepsilon, \alpha)$ is small. This limitation depends on the linear approach entailed in the Taylor’s expansion, either if the initial expansion (3) or the amplification α are too large. In practice, to remain into the linearity bound, we need slowly changing images and small amplifications.
Moreover, here we do not consider the noise of variance σ^2 to be added to the intensity, that is amplified too, resulting in an amplified noise variance $2\sigma^2\alpha^2$, thus the error to be evaluated should be $O(\varepsilon, \alpha, 2\sigma^2\alpha^2)$. Also, it should be noted that the calculation of $\Delta(x, t)$ implies the whole time span from frame 0 to the current frame at the time t.

If the video is long-lasting, the required computer time may be a major problem. Other physical limitations, such as the ones regarding illumination, shadows, camera unwanted vibrations, poor pixel resolution, low frame rate, presence of large motion, distance from the object, decrease severely the quality of the motion magnification, should also be taken into account in order to achieve good-quality results. In particular, the scene illumination should remain constant, as changing the background light could produce apparent motions.

Finally, we note that the Shannon-Nyquist Theorem has to be respected. In fact, to reproduce correctly a signal it is necessary the condition:

$$f_{sampling} \geqslant 2f_{max} \tag{11}$$

where f_{max} is the maximum frequency of the signal in the temporal domain, $f_{sampling}$ is the sampling frequency. Here (11) becomes:

$$f_{fps} \geqslant 2f_{max} \tag{12}$$

where f_{fps} acts as a sampling frequency. Therefore, using a 28 fps video-camera, the maximum frequency allowed is 14Hz, frequencies above this threshold will introduce spurious peaks because of the aliasing.

III. RESULTS

Videos have been recorded by means of low resolution, low frame-rate video-cameras, in laboratory and outdoor in the urban environment. The laboratory tests have been carried out at the ENEA shaking tables facility of the Casaccia research center, located near Rome, on a mockup of an ancient church [3]. The indoor experiments have assessed the effects of noise and consequently an image noise reduction procedure (the image skeletonization, see Figure 2 and the video Hagia_Irene.ppt) has been devised. The experimentation in the outdoor environment concerned the so-called temple of Minerva Medica, which is located very close to a tramway (Figure 3), and the Ponte delle Torri of Spoleto (Figure 4).

Of course, in the outdoor environment it is not possible to control recording parameters accurately [4], therefore it was necessary to test the MMA in a variety of weather conditions and different recording devices to ensure its reliability. 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 (see Figure 5).

Compared to the Ponte delle Torri, the Minerva Medica temple magnified motion analysis is surely more interesting. This is due to the different strains: in the first case the wind, in the second trams passing by closely.

Of course, the tramway produces much stronger vibrations and the effects are clearly evident in the video MMIII_magnified_115959. A simple analysis is performed in Figure 6, where is showed the first frame of the magnified motion of the video recorded close to the tramway that runs along the Minerva Medica temple.

The boxes contain the parts of the monuments more prone to vibrate, as indicate by the MM videos.

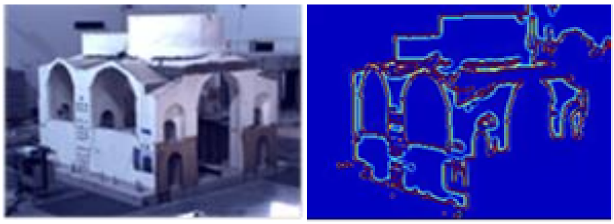

Fig. 2. The scaled model of Hagia Irene church (left) and the skeletonization image of the church (right).

Fig. 3. The Minerva Medica temple, Rome.

Fig. 4. The Ponte delle Torri of Spoleto.

Modal analysis by different numerical codes was performed for the whole bridge in order to reproduce the first modes in terms of shapes and frequencies and to identify the most interesting locations for in situ measurements [5].

In Figure 6 the first frame of the MM video of the Ponte delle Torri; it does not show strong motions, because of the small strain applied from the wind. However, it is noticeable the first modal shape, as confirmed by results of Operational Modal Analysis (OMA) techniques (Figure 7). The identification of the modal frequencies in the first modes, obtained applying several OMA techniques, is resumed in Table 1.

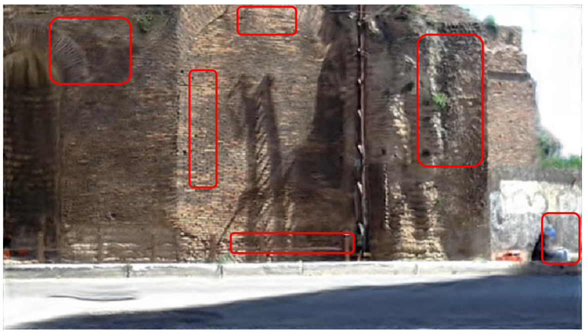

Fig. 5. A frame from the video “MMIII_magnified_115959” (Minerva Medica temple magnified motion). Red boxes indicate the points with highest vibrations amplification.

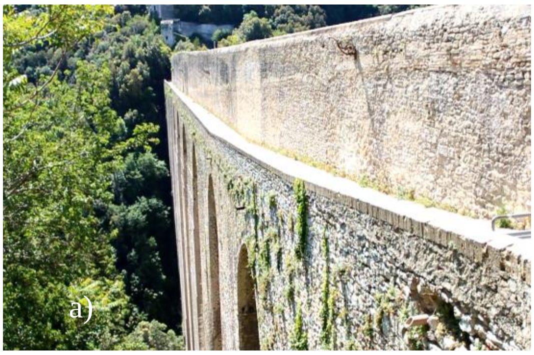

Fig. 6. Original frame of Ponte delle Torri a) and related magnified frame with parameters: amplification 140, frequency range 0.5-2Hz, video “SPOLETO_magnified_2578_crop_alpha140”, b).

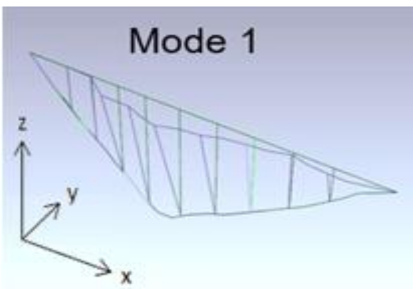

Fig. 7. First modal shapes of the Ponte delle Torri of Spoleto by Operational Modal Analysis (OMA) .

Table 1. Natural frequencies of the first three modes by different OMA techniques.

OMA technique	FDD f (Hz)	EFDD f (Hz)	SSI f (Hz)
Mode 1	0.635	0.634	0.635
Mode 2	1.021	0.956	1.018
Mode 3	1.509	1.360	1.504

Since phenomena in the original videos occur at different frequencies but usually we are interested only in some of them, the *a-priori* knowledge of those frequencies is useful to set the MM algorithm at its best, reducing noise. In this particular case, Table 1 indicates that modes belong to the range 0.6 – 1.5 Hz, hence the algorithm will be designed to enhance mainly the motions of this frequency range.
Experiments were performed within the COBRA project, funded by Regione Lazio, a program to support the study of monuments in Lazio; the main objective is to develop and disseminate methods, technologies and advanced tools for the conservation of the cultural heritage. The Italian National Agency for New Technologies, Energy and Sustainable Economic Development (ENEA) leads the project with its laboratories and several working groups.

IV. CONCLUSIONS

The estimation of the structural health of ancient buildings is a key issue for the cultural heritage protection, but it is mandatory to have quickly available appropriate, easy-to-use tools. To support engineers, a variety of devices has been developed: capacitive sensors, contact accelerometers, optical sensors, lasers, global positioning systems, linear variable differential transformers. Unfortunately, costs, dimensions, complexity of the associated electronics, energy requirements, specialized operators, are all disadvantages to be faced during measurement campaigns. In such a context, the continuous developments of digital vision technologies are very promising. Though till a few years ago such kind of methodologies were not viable, recent advances in the digital video processing have opened the door to applications to the analysis of vibrations, in particular by motion magnification strategies.
Actually, in our tests MM was effective in amplifying subtle motions in videos, recorded by commercial devices, making distinguishable the tiny displacements of structures exposed to mechanical disturbances and facilitating the evaluation of the building stability within a reasonable time. Advantages are many: no wires, no data storage, no physical contact, simplicity, low costs.

For a number of reasons, noise is a pervasive obstacle to MM, especially outdoor, nevertheless we obtained satisfactory results also in the outdoor environment using low resolution video cameras. Future experiments will assess a quantitative approach to the motion magnification and noise reduction.

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