Role of dynamic holography with photorefractive crystals in a multifunctional sensor for the detection of signature features in movable cultural heritage

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ABSTRACT

This paper is one of a series submitted by the Multi-Encode Project consortium and covers the development of holographic interferometry with dynamic photorefractive crystals. The aim of the first phase of the project is to assess the existing techniques for detection of signatures in various types of artworks. The trademark of our technique is a very high resolution in the fringe pattern. We will show the potentiality of our technique for the present application.

Keywords: Holographic interferometry, photorefractive crystals, cultural heritage

1. INTRODUCTION

The use of optical coherent techniques for artwork assessment is not new. A lot of work has been done in demonstration of several such techniques by some European groups. The first evidence was shown by Amadesi et al. [1] who used holographic interferometry to detect debondings in old paintings. Since then different groups have contributed significantly to this field of research. One can cite Paolelli and Spagnolo, whom review paper [2] is a significant summary of their work and work of others, the Oldenburg University [3-6] and finally the Institute of Electronic Structure and Laser of Heraklion [7-10]. The two first groups have considered portable ESPI systems for the diagnostics of artworks and historical monuments on site, while the Heraklion group considered classical holographic systems with higher resolution or different other techniques such as laser vibrometry. Often the aim is to detect cracks or debondings that are not visible to the eye but that give a significant signature to holographic techniques, say variations of a few tens of nanometers to a few microns when the artwork is solicited by thermal, mechanical loads or vibration (loudspeaker, shaker). Also these techniques are used to study the influence of external conditions on the deterioration the artwork.

The European project FP6 MULTIENCODE ("MULTIfunctional ENCODing system for assessment of movable cultural heritage", contract SSP 006427) aims at going a step further by establishing a new standard Impact Assessment Procedure (IAP) for monitoring of defects of movable artworks, either for conservation purpose (unstable defects) or for authenticity verification (stable defects).

The techniques used to encode the defect signatures are based on holographic techniques that produce unique interference pattern arising from a defect located in the artwork that undergoes a known and reproducible non-destructive load. The project focusses on two types of movable artworks: the wooden icons (provided by National Gallery of Athens) and textile canvas (provided by Tate of London). However the future application of the methodology and technique developed in the project will not be necessarily limited to these particular cases.

The project axes are the following:

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• investigation of holographic techniques for IAP: electronic speckle pattern interferometry, shearography and photorefractive dynamic holographic interferometry are considered
• develop a standardized procedure common for all techniques for optimized observation of defect signatures in interferograms
• develop an encode-decode tool for storage into and retrieval from a defect database related to the artwork
• design and manufacturing of an optimized sensor
• demonstration of sensor on movable artworks provided by end-user galleries.

The coordinator of the project is the Institute for Electronic Structure and Lasers of the FORTH, located at Heraklion (Crete, Greece). The other partners are the Institut für Technische Optik of the University of Stuttgart, the Centre Spatial de Liège of the University of Liège, the company OPTRION (Angleur, Belgium). The end-users are the National Gallery of Athens (Greece) and the Tate in London (UK).

Different papers are presented by other partners of the project at the same conference "O3A: Optics for Arts, Architecture, and Archaeology” and published in this proceedings (Vol 6618). They discuss in details the state-of-the-art of optical methods for artwork assessment and other techniques considered in the project (ESPI and shearography).

In this paper, we will present the results obtained with photorefractive dynamic holographic interferometry. Holographic Interferometry [11] (HI) is a non-contact full-field nondestructive technique that is used to measure optical path differences arising from displacements/deformations of solid objects or from refractive index changes in liquids or gases. It requires a laser beam that is divided in two parts: one will travel via the object (object beam), the other not (reference beam). Both beams are superimposed at the level of a recording medium where their interference (hologram) is recorded as local variations of the medium properties (refractive index, thickness or optical absorption). In our case, we use PhotoRefractive Crystals (PRCs) for recording holograms. Their interest is now well known since they are able to record hologram in situ, without any chemical or other assisted processing, contrarily to other types of recording media, such as holoplates or thermoplastics. This behaviour being dynamic, we often refer to "dynamic HI".

We already have presented the development of the photorefractive holographic camera [12-14], as well as some applications [15]. In section 2, we will review the principle of this instrument. Afterwards we will show the results of the first part of the project which consists in investigation the applicability of the technique and to find a suitable methodology for observation of specific signatures related to defects. In section 3 we will focus on wooden icons and representative samples with known defects provided by the National Gallery of Athens. In section 4 we will focus on paintings on textile canvas and representative samples provided by the Tate Britain. In section 5 we will present a standard protocol agreed between developers and in section 6 we will show some results obtained with our system and the new protocol.

2. PRINCIPLE OF PHOTOREFRACTIVE HOLOGRAPHIC INTERFEROMETRY

The holographic camera is shown in Figure. 1. The working principle is the following. Both recording beams (reference and object) are continuously incident on the crystal. The recording of the hologram takes place under the response time of the photorefractive effect. It is mainly driven by the reference beam intensity that can be tuned within some limits [13]. The response time to use depends mainly on the external conditions under which the holographic camera is utilized but generally its value ranges from 5 to 10 seconds if a moderately stable environment is considered (few external vibrations and air turbulence, no need of vibration compensated optical table). This response time being the same at the recording and the readout, it must not be too short in order to allow a proper use of the phase-shifting process during interferograms capture [13]. Once the readout is complete and the first hologram erased, the instrument is ready for a new measurement. The repetition rate of the measurement sequence obviously depends on the response time.
This system is adapted to quasi-static measurements (with application of phase-shifting) or to dynamic events (with single frame analysis, such as Fourier transform with fringe carrier addition) [13]. Numerous examples of applications have been shown in the detection of defects, impacts, delaminations. Also pure displacement metrology can be performed: CTE measurement, comparison with FEM, among others [15].

In all the applications presented in those previous papers, what is remarkable (and is the trademark of our technique) is the high quality of fringes and their resolvable density. Indeed since we do not resolve the speckle, we have no speckle noise in the interferogram. Additionnally, we make use of specific properties of the PRC (the so-called anisotropy of diffraction) which has the consequence that the constrast can be adjusted to values almost equal to the maximum of one.

This excellent fringe quality allows to have an extended range of measurement: we can easily resolve interferograms with 5 pixels/fringe. The smallest values measurable have been calibrated too: the accuracy is typically 10 to 15 nm, mainly limited by the external perturbations but not by the photorefractive erasure of the hologram during the readout [13]. The observable area depends on the illumination laser power. A good rule of thumb is that we reach this level quality on a 50x50 cm² white coated object illuminated with 400 mW.

3. INVESTIGATION OF PHOTOREFRACTIVE HOLOGRAPHIC INTERFEROMETRY ON WOODEN ICONS

The first type of artworks considered in the project is the wooden icons. The National Gallery of Athens (NGA) manufactured samples which are representative of the type of substrate (wood) with presence of various types of defects (cracks, nails, knots,...).

The general procedure we followed in previous NDT applications to observe defects is the following. First, we record a hologram of the sample at rest. Second we stress it one way or another and then, third, we observe simultaneously the stressed object together with its holographic unstressed image which is diffracted by the crystal. The interferogram shows the global deformation of the object and defects are located by a strong differential behaviour around their location.

Here we decided to investigate the same procedure with thermal stress of a few seconds followed by thermal relaxation prior to interferogram observation. CSL used a home-made object holder (Figure 2(a)) and 500 W halogen lamp (Figure 2(b)) as well as various illumination geometries (1 lamp on front, 1 lamp on back; 2 lamps on front,...)
The next figures show typical results obtained on one of the wooden icons. Figure 3(a) shows a schematic sketch of the icon with defects and their location represented. One can see a circular knot with a vertical crack in the middle of the icon. A small nail is present on the upper right corner. Figure 3(b) shows the phase interferogram (after application of phase-shifting) observed after a few seconds heating and relaxation time on the order of 2 minutes. The two main defects (surrounded by dashed lines) give rise to signatures in the fringe pattern. In particular, the crack is seen via a strong change of fringes direction. Figure 3(c) shows the phase map obtained after phase unwrapping of Figure 3(b). An interesting way of showing the defects is by differentiating the unwrapped phase image which allows to obtain a sheangraphic-like image as displayed here in Figure 3(d) (here a horizontal shear has been applied numerically). Another way to measure and locate precisely defects is to trace horizontal and vertical profiles in the unwrapped phase map, respectively Figure 3(e) and Figure 3(f).

Figure 3. Typical results obtained on wooden icons.

4. INVESTIGATION OF PHOTOREFRACTIVE HOLOGRAPHIC INTERFEROMETRY ON TEXTILE CANVAS

The other type of movable artworks considered in the project is that of representative paintings on textile canvas, provided and manufactured by the Tate and shown in Figure 4(a). Prior to painting, the museum conservator have introduced a series of defects of different types as can be seen on the picture taken prior to painting (Figure 4(b)). Additionally to these internal defects, a large circular crack (visible at the eye) is present in the centre of the paintings in Figure 4(a).
Besides the search for internal defects, what was of interest for the Tate conservators is the observation of crack propagation, or the prediction of further crack appearance prior to crack visibility at the eye. Because of the particular nature of the canvas and its mechanical behaviour, different types of stresses have been tested.

Before describing these different stimulations, we had to face the fact that such canvas are naturally vibrating due to the acoustic noise in the lab (noise of the equipments, air movement due to closing doors, etc). Since our holographic camera records the reference hologram during 5 to 10 seconds, such conditions of use on such difficult object often prevent us to have good recording and hence good interferograms.

Therefore our first investigations concerned the stabilization of the canvas. For that we considered first a stainless steel plate put in close contact to the back side of the canvas. This gave very good results but was not retained for its bad applicability in practice. Another solution is to use the backboard that comes with the painting during its travel in a special box. This backboard is a wooden plate on which is glued a styrofoam plate of typically 2 cm height and that is close to the back side of the canvas but not directly in contact with it (Figure 5). Experiments showed that the backboard presence was a good solution for stabilization of the painting during hologram recording and that point of the procedure was agreed by the conservators.

The first stimulation of the object is the natural excitation which is an undeterministic combination of temperature changes, Relative Humidity (RH) changes and acoustic noise vibrations. After a reference hologram is recorded, interferograms are observed sequentially at various instants ranging from minutes to tens of minutes. We have to note that between the readouts, the photorefractive crystal does not receive any light in order to not erase the reference hologram. This is possible by an internal shutter placed onboard the device.
Figure 6. Interferograms on canvas painting obtained by natural excitation.

Figure 6(a) shows the interferogram obtained 2 minutes after reference recording. We can see that the central crack yields a clearly circular pattern in the center. Figure 6(b) is taken 6 minutes after reference recording, the fringe pattern is denser but the overall fringe shape is similar. None of the artificial internal defect is clearly visible in the pattern. Natural excitation is an interesting mean to detect the defect signatures of the canvas, for instance the crack can be easily identified by changes in the fringe pattern. The latter is quite complex and if the measurements are repeatable and reproducible, it could be a good fingerprint of the canvas. The problem is precisely the repeatability and reproducibility of the measurement. Indeed, results obtained with a natural excitation are dependent on the environment. Thus if this excitation is to be used, the surrounding environment of the canvas has to be controlled.

After discussion with conservators of Tate, the problem of crack propagation can be addressed by the variation of RH which seems to be the more efficient because the tension of the canvas textile strongly depends on RH. In order to artificially induce and control the RH surrounding the canvas, Tate prepared cassettes that fit into wooden frame of the painting. Figure 7 (a) and (b) show, respectively, overall and detailed views of the cassette that incorporate silical gel balls that are kept in place by various surrounding sheets of plastics. The silica gel balls are not in direct contact with the canvas but they have an effect on the RH at the canvas level through micropores that exist in the plastic sheets. Figure 8(a) shows the sequence of operations for holographic interferometry with RH. Once the cassette is placed, the reference hologram is recorded after time T. The readout is performed at instant T+t. Figure 8(b) shows the result obtained when record occurred immediately after placement and readout 1 minute after. Figure 8(c) and (d) show results obtained when record takes place later (as indicated in the figure).
The interferograms in Figure 8 show that the fringe pattern is quite different from that obtained with natural excitation. One can see also very well localized spots in the interferograms, particularly in Figure 8(c) and which do no represent something known and present in the painting. We have attributed this strong local behaviour to the fact that some of the small silica gel balls are closer to the canvas than their neighbours, so that the RH has strong local differences in the transverse directions of the canvas. For this reason, we did not consider to carry on with this methodology.

For finding a more controllable way to stimulate the defects, we considered the more classical IR heating that was used for the wooden icons. Here a short heating of 1 s is applied with a 175 W IR lamp at 1 meter in front of the painting. Interferograms are observed some instants after heating has stopped. Figure 9(a), (b) and (c) respectively after 1s, 12s and 34s.
The fringe patterns have a shape that is more consistent with those found with natural excitation. Further experiment showed that the under the same circumstances and procedure, the interferograms are reproducible. Therefore this methodology is the one we will keep as a standard.

A more detailed analysis of the fringe pattern yields to conclusion that the higher density in the bottom of the images is due to overpainting (as can be seen in Figure 4(a)) and not to defects. None of the other holographic techniques compared allowed a good view of these defects.

5. STANDARDIZATION OF PROTOCOL

An important phase of the study was the establishment of a standardized protocol that includes the sample holder, the excitation type and related geometries. This is of interest if we want to insure consistent and comparative results between all developers in the project. Also a standard and reproducible procedure will allow better reproducing the boundary conditions on the artwork and, therefore, the signature of a given defect can be more consistently compared to itself during the life of the sample. From these different elements independently studied and developed by the 3 developers at the beginning, we selected the combination that worked the best. First a sample holder was developed that can be adapted to both the icons and the canvases (Figure 10(a)), second a 175 W lamp for IR heating was selected (Figure 10(b)) and finally 2 recording geometries can be considered (Figure 10(c) and (d)). The choice of the latter is conditioned by the fact that the experiments showed that some defects were best viewed by one geometry while other defects worked better with the second geometry.

The protocol also fixes the duration of heating to 10s for wooden icons, while it is of 2s for the canvases. The time one has to wait after the heating to start the interferogram readout depends on the technique used. With the photorefractive holographic camera, immediate readout is not possible if one wishes to apply phase-shifting, because the object deformation is rapidly evolving. While this was admitted to be possible with ESPI and shearography, this was not the case for our technique. Therefore we kept the usual procedure to perform readout after typically 1 minute, when the artwork is in a sufficiently stable state.

Figure 10. Standard protocol. (a) Adaptable sample holder, (b) 175 IR lamp, (c) and (d) 2 illumination geometries
6. RESULTS OBTAINED WITH STANDARD PROTOCOL

On the basis of this standard protocol, we have performed campaign of measurement with a large series of icons and canvases, before and after accelerated ageing procedures. It would be too long to present these results here and the investigations are not completely finished at the time of writing of this paper, therefore we have chosen to show results obtained on a true icon with known defects (Figure 11).

![Figure 11. Results obtained on a true icon with defects. (a) Picture of the icon with known visible defects located by rectangles, (b) basic interferogram obtained with the standard protocol, (c) phase interferogram corresponding to (b) and that shows the signature of known defects (dashed rectangles) and unvisible ones (ellipses).](image)

7. CONCLUSION

This project was important for us in order to check the applicability of our technique in such a difficult field, with objects that are not cooperative and that cannot be painted as one generally does with most type of objects. Also the paintings generally show strong differences in color and reflectivity, going from a dark brown scattering subject to a bright specularly reflective gold layer. Nevertheless the behaviour of our instrument was quite good with respect to these samples characteristics. Also most of the results shown here have been obtained with our instrument mounted on a theodolite tripod which constitutes another incremental improvement.

Through all the experiments described above, we have shown that our technique is capable of observing small signatures of defects. This was one of the most positive evaluation points given by end-users in an assessment phase. The weak point remains the sensitivity to perturbations in the case of the canvases which required to adapt the procedure by using a canvas stabilization mean, like the presence of the transport backboard, because other advanced techniques such as active phase control is not well adapted to the type of perturbations present. A more general conclusion at this step of the project is that other techniques such as ESPI and shearography provide complementary results.

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REFERENCES