TV-Holography in Artwork Diagnostics

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TV-holography can hold a great potential in non-destructive diagnostics of the state of conservation and preservation of artworks. Its use in revealing debonds, cracks, voids, delaminations or residual stress in both ancient paintings on wooden panels, staturaries and mural supports has been proven. The method is easy to apply and very functional for the basic objectives of conservation; its compactness enables detection of microdisplacements even in non-laboratory environments. Measurements in field of microcracks and subsurface detachments on ancient frescoes and panel paintings are reported.

**Key words:** non-destructive testing, interferometry, electronic speckle pattern interferometry, TV-holography, artwork diagnostics

1. Introduction

One of the most important technical problems in ensuring the long-term conservation of cultural heritage is checking of its condition. Natural ageing, the cumulative effects of fatigue, excess loading, modification of the environment, atmospheric pollution and human errors are the factors which lead to artwork deterioration of varying degrees of severity; the study of the various types of damage is very complex and generally requires an evaluation case by case.

Wooden panels and frescoes are artifacts particularly able to optical techniques testing. In fact a painting on wood or on a wall can be considered as a layered structure with a support. The Fig. 1 shows a typical layered structure on a wooden panel in use in the paintings since XIII century. The wooden or mural support is coated with some priming layers which constitute the basis for the painting. Being less thick the layers, normally made of mixture of gesso and glue, are more fragile than support, which, if unstable, places a strain on them. With time, coatings lose their elasticity and their ability to follow the movement of the support causing the panel or the fresco to crack. Furthermore abrupt changes of environmental temperature and humidity, traffic induced vibrations, and heat exposure may produce unpredictable stress distribution in the heterogeneous materials of the support with consequent damage of the painted surface. Comprehensive measures are taken to protect and conserve the artworks and to restore them as necessary, but they give positive results only if experimental methods are available for detecting the state of preservation, locating the flaws and determining its characteristics. Since 1972 holographic techniques have been proposed to solve specific problems regarding the location and size of incipient hidden defects, voids, dishomogenities in wooden panel paintings, carvings and frescoes\(^1\)–\(^4\) and to prove the effectiveness of the repair work after restoration. Generally the visual observation of the fringe pattern, covering the three-dimensional holographic image of the specimen, furnishes a qualitative information about the overall deformation of the complex structure as well as the location of strain or stress concentration (defects). However the artists have seldom applied these techniques for routine inspections. The reasons for this are the following: the mechanical stability necessary for holographic measurements is not readily compatible with in-field conditions unless pulsed lasers are used; furthermore the optical alignment of holographic set up, the development and reconstruction of holograms are time consuming process requiring skilled operators.\(^5\) However in the last years the use of holographic interferometry as a diagnostics tool in artwork conservation has grown from a position of speculative research into one of more general practical applications with the advent of electronic or digital holographic techniques combined with the use of optical fibers and modern methods of image processing.

Portable measuring instruments based on electronic speckle pattern interferometry (TV holography) have been proposed recently\(^6\)–\(^7\) and might become very popular among artwork restorers, allowing a rapid and real-time diagnosis of several types of defects with the same sensitivity of holographic techniques also in nonlaboratory conditions. The aim of this paper is to give a survey of the several practical applications of an electronic speckle pattern interferometer in artwork preservation field. By starting from a rapid analysis of the experimental apparatus, we report the results of investigations effected on some ancient artworks with a particular emphasis for the possibility to operate in situ during a restoration process.

2. TV-Holography Interferometer

The TV-holography, often referred to as ESP (Electronic Speckle Pattern Interferometry) was developed in the early 1970s as a method of producing interferometric data electronically without using the traditional holographic recording techniques.\(^8\)–\(^10\) In this method correlation fringes are displayed in real-time as the object deforms; each fringe represents a line of constant displacement.

We give only a brief practical description of the particular system used in the studies presented in this work and
refer to elsewhere\textsuperscript{11-13} for more details. As it is shown in Fig. 2, the two beam speckle interferometer consists of an optical head and a PC based image processing. Coherent light coming from a laser diode (10 mW), is coupled by a gradient index (GRIN) rod microlens to a single mode fibre and then split by bidirectional coupler light (50/50) into reference and object illuminating beams. The light scattered from the object is focused onto the sensitive area (plane $x,y$) of a CCD camera by an imaging lens. The fiber, which illuminates the object, is mounted upon a $x$, $z$ translation stage, adjustable by a piezoelectric device.

With a PC based image processing the video signal with the object in its unaltered position can be digitised, processed and stored in a reference frame. During the experiments the incoming patterns can be taken continuously, digitised and subtracted from the reference state. The resulting function is given by\textsuperscript{10}:

$$B_0=\left|I(x, y)-I'(x, y)\right|^2=N(x, y)E(x, y)$$

where $N(x, y)$ represents the speckle noise and $E(x, y)$ contains the required information. More explicitly, we have:

$$N(x, y)=8I_0(x, y)I_0(x, y)\left[\sin^2\left(\theta(x, y)\right)+\frac{\lambda x}{2}\right]$$

$$E(x, y)=1-\cos\lambda \psi(x, y).$$

Here, $I_0$ is the intensity scattered by the object, $I_0$ is the reference beam intensity, $\theta$ the phase difference between the object speckled field and reference beam, while $\lambda \psi$ carries the information about the object deformation.

As in ordinary hologram interferometry, the image is interferometrically sensitive to in-plane or out-of-plane displacement. By illuminating the object with two beams at equal angle $\phi$ to the surface normal, the interferometer is sensitive, for collimated illumination, to in plane displacements (Fig. 2a). In this case, the fringe sensitivity is given by:

$$d=\frac{\lambda}{2 \sin \phi}$$

where $d$ is the object displacement in the sensitivity direction between adjacent fringes. For out-of-plane displacement measurement the specimen surface is illuminated only by a laser beam while the other one is converged directly through a fiber into a splitter cube located between the imaging lens and the CCD plate (Fig. 2b). The fringe sensitivity in this case, for collimated illumination, is given by:

$$d=\frac{\lambda}{1+\cos \phi}$$

For small values of the angle $\cos \phi \approx 1$, $d$ is the object out-of-plane displacement. The optical head is contained in a closed, dust-free, mechanically and thermally stable portable box.

The resulting fringes are similar in appearance to conventional holographic fringes, but they appear very noisy, due to the larger speckle size; for this reason they are electronically treated for noise removal and contrast enhancement with some filtering procedures.\textsuperscript{15-16} For most applications only a qualitative interpretation of the correlation fringes is required. However, for some particular studies (for example: the choice of stress method, calibration experiments, etc.) a quantitative interpretation of the fringe pattern may be necessary. For this reason this ESPI set up includes the possibility to introduce spatial-carrier fringes.

A phase variation between the image and a reference one is introduced with the rotation of the object beam; this rotation causes a carrier spatial frequency modulation to appear added to the phase difference due to the deformation.

The resulting intensity distribution, $B_0(x, y)$, of a two-dimensional fringe pattern can be rewritten as follows:

$$B_0(x, y)=N(x, y)\left[1-\frac{1}{2}\exp[i\lambda \psi(x, y)]\right]$$

$$\cdot \exp[i2\pi(f_x x+f_y y)]$$

$$-\frac{1}{2}\exp[-i\lambda \psi(x, y)]\exp[-i2\pi(f_x x+f_y y)]$$

where $f_x$ and $f_y$ are the linear components of the imposed rotation and $\lambda \psi(x, y)$ the phase variation.

A Fourier transform algorithm can be used for retrieving the phase function in the spatial frequency plane. For details about this technique see Ref. 19-21.

On the other hand for the particular field of application it is also important for the restorers during the restoration process, to know the exact location of the defective area on the fresco as indicated by fringe irregularities. For this reason in our system the image of the illuminated region is captured by TV camera and stored; subsequently it is modulated by relative ESPI fringes, so obtaining superimposition on the video monitor.

3. Experimental Results

As it is well known, conventional holographic interferometry as well as TV-holographic techniques can be used as non destructive testing wherein the parameter of interest (crack, void, detachment) can be made manifest as
discontinuity in surface deformation; the discontinuities appear as an anomaly in an otherwise regular interferometric fringe pattern and hence enable the region of fault to be identified.

For opaque objects, TV-holography provides information about the displacement of the object's surface only. However, to detect delaminations or weak areas in the object's interior, we must find excitation mechanisms which transform interior inhomogeneities into interpretable surface movements. The excitation must provide a response from a defect which is readily differentiated from the response of a perfectly good structure.
Usually the stressing method (a temperature gradient obtained by heating the surface by a infrared lamp or a stream of moderately warm air) is chosen empirically with guidance provided by an analysis of previous results obtained from programmed models.

Finding the best stressing method is generally a function of the component and the expected nature of the fault.

Generally artworks are analysed in thermal drift (with a brief thermal irradiation which raises the surface temperature of some degrees) or in ambient drift (under ambient parameter variations).

It seems that the thermal-drift method is considerably better in detecting detached regions than the ambient-drift method: many more detachments are pointed up and they are much more defined.

The interpretation of ESPI correlation fringes is made on the basis of experiments effected on models simulating panel paintings and frescoes with the most common defects. As a rule, ancient paintings were made on poplar boards consisting of several separate pieces glued together, coated with some priming layers which constitute the basis for the painting. In the majority of the cases, detached regions due to poor cohesion between the priming and wooden panel, and the priming and paintings occur under ambient parameters variations (temperature and humidity), while irregular wood grain or structural anomalies of the support can cause the formation of subsurface cracks or fissures. The frescoes in ancient churches or in open environments present the same problems of wooden paintings; the strain and stress of the wall can cause detachments between the layers or cracks in the painted surface, finally resulting in complete disintegration of the artwork.

By comparing the known construction of the test samples with the results, the feasibility of the technique is established for known conditions.

In fact from the studies effected on models it is reasonable to assume that where there is a high spatial density or islands of fringes, strain concentrations or defects are present; while discontinuities along the trend of some fringes indicate the presence of cracks. In the following we report some applications of the TV-holographic interferometer on test models and on ancient artifacts.

The Fig. 3 shows the fringes on a model with simulated defects recorded with the system in out-of-plane configuration. The test model consists of wood poplar support (16

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Fig. 3. TV interferogram of a wooden model with a subsurface detachment.

Fig. 4. Speckle interferogram relative to the same specimen of Fig. 3 with carrier fringes.

Fig. 5. 3D plot of the defect.

Fig. 6. Correlation fringes showing the presence of a crack on a model.
Fig. 7. *Madonna in trono con Bambino* by Giotto under restoration at Opificio delle Pietre Dure e Laboratorio di Restauro of Florence.

Fig. 8. Fringes showing a detached area in the wooden painting.

Fig. 9. Schematic drawing of a fresco with the map of blind cleavages between priming layers and support.

Fig. 10. ESPI fringes revealing the presence of a debond area in a fresco, relative at the square zone indicated in Fig. 9.

Fig. 11. Fringes in the same area after the restoration process.

... cm × 13 cm × 2 cm), coated with some superposed priming layers. Inside the layered structure a detached region of known form and extension was provoked by the insertion of suitable plastic sheets to simulate the presence of defect. A subsurface detachment due to the loss of bond between the layers, difficult to detect with traditional techniques, is revealed by closed fringes. Figure 4 shows a specklegram on the same model obtained by adding carrier fringes, while a 3D plot of the defect is reported in Fig. 5.

Figure 6 shows correlation fringes relative to a typical crack on a wooden panel, recorded with the system in in-plane configuration.

Investigations of the possibility of using the system in...
cm × 97 cm, XIII—Church of St. George in Florence under restoration at Opificio delle Pietre Dure e Laboratorio di Restauro di Florence).

The presence of a detached area between the support and the priming layers of the painting is pointed by islands of fringes in the interferogram (Fig. 8), as compared with the model with simulated defects.

An application of the versatility of the instrument during a restoration process in determining whether or not repair work has been effective was effected on a fresco in the church of St. Maria della Croce of Roio-L’Aquila (Adorazione dei Magi by Farrelli 1667); the map of some blind cleavages between priming layers and the support is reported in Fig. 9. Some specklegrams have been taken both before and after the fresco was restored. Figure 10 shows a particular zone of the fresco with the presence of a detachment surrounding a cracking area. Figure 11 shows how the crack and the surrounding area is repaired and a proper bond between the primer ground and the painting was reinstated for the detached region.

4. Conclusion

The validity of a portable digital speckle pattern interferometer in artwork diagnostics has been demonstrated with the detection of some typical defects in ancient wooden panel paintings and frescoes; the system is compact, cheap, easy to use and gives interferograms of good quality also in difficult environments. It could be in future a valid alternative to holographic interferometry as non-destructive testing of ancient artworks of all sizes under difficult conditions. Objects that are placed at considerable distances from the optical head can be inspected; the speed and stability of the system allows us to tackle experimental difficulties that would have called for a pulsed laser.

The versatility of the system allows to control in real time the state of an artwork during a restoration process in order to permit to the restorer to take the best decisions. Up to now, the restorer was guided in such matters by its judgment and experience rather than by precise rules.

The limits consist in the speckle noise, the pixel dimensions, the effects of speckle decorrelation, that affect the maximum displacement that the system can measure with respect to holography.

The size of an artifact that can be inspected depends how much light is reflected back to the instrument from the object and how small details we want to observe. With a 10 mW laser and a CCD camera with sensitivity 0.02 lx the observed area is about 400 cm².

The results presented give an idea of the potential application of a technology, mainly developed for industrial diagnostics, to the art patrimony restoration with a low cost working system.

References