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Characterization of hidden defects of an original XVI century painting on wood by Electronic Speckle Pattern Interferometry

G. Arena(*)

CNR Institute of Applied Sciences and Intelligent Systems "E. Caianiello"
via Campi Flegrei, 34, 80078, Pozzuoli (NA), Italy

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Summary. — Electronic Speckle Pattern Interferometry, a non-contact and non-destructive optical diagnostic technique, was employed for evaluating the conservation state of a XVI century painting on wood. The whole structure alterations, induced by the laboratory temperature and relative humidity variations, were evaluated. Long-term analysis, by sequential recording and subsequent off-line processing of the fringes progression, was carried out. Local flaws and hidden detachments of pictorial layers from the support, which could not be recognized by traditional art-restorer survey methods, were also easily revealed. In such a case, a simple measurement approach was utilized, with the aim to get a user-friendly method for art conservators. The results demonstrate that the interferometry method can largely improve the traditional art conservation survey techniques.

PACS 07.60.Ly – Interferometers.
PACS 06.30.Bp – Spatial dimensions.

1. – Introduction

In the history of artistic techniques, wood had been one of the most popular support materials for polychromies. The oldest artefacts come down to us, thanks to the favourable climatic conditions of preservation, date back to the Egypt age. Construction techniques evolved steadily in the painting history, driven by needs related to the style evolution, but also to improve the support stability and the mutual interaction between the paintings materials. Support shapes and sizes have changed through the centuries, adapting the painting social function, its utilization and meaning, in the cultural context. Although historical sources describe in detail the painting techniques, only in the Cennino Cennini's treaty, which dates back to the beginning of the 15th century, it is

(*) E-mail: giovanni.arena@cnr.it

possible to find detailed information on supports assembling procedures. Other important source are statutes and contracts of the guilds. Availability of local wood was one of the first instances influencing the support construction techniques. In Italy, poplar wood (*Populus alba*) and, in some cases, cypress (*Cupressus sempervirens*) were very common. Art schools in the Netherlands, Flanders, France and England employed oak, a hard wood that allowed for thin boards. In Germany, mainly silver fir, spruce, oak and lime were employed [1-3].

Wooden substrates are affected by deformations produced by continuous contractions or expansion due to the moisture exchange, that occurs prevalently on the back of the panel, as the preparation and painted layers protect the front of the board. The typical "craquelure" on the pictorial layers [4] is the major damage resulting from the cumulative effects of reiterated compressions and tractions cycles.

To prevent distortions of paintings, usually, ancient craftsmen had been using crossbars, applied on the rear of the painting by using metal nails.

Electronic Speckle Pattern Interferometry (ESPI) is a well-established, non-contact and non-destructive optical technique, increasingly employed as a diagnostic tool in the field of cultural heritage. ESPI is based on the traditional double-exposition holographic method [5, 6], formerly utilizing special photographic plates and later electronic equipment [7]. ESPI utilizes, in its basic implementation, a laser, a TV camera and a few optical components, providing non-contact, full-field, sub-micrometric capacities. The object under test is imaged onto the camera sensor, where a reference laser beam is also superimposed, in this way producing a hologram.

ESPI measurement procedure involves the recording of at least two, temporally spaced, holograms of the object in different states. Small displacements of the object under test are induced by applying a very slight thermal or vibrational load between the two recording holograms. The ESPI output consists of an interferogram —resulting from the numerical processing the two recorded holograms— overlaid onto the image of the object under examination. The object is simply illuminated by a low-intensity laser light; no object modifications —even less damages— occur. Whole-body structural behavior as well as local micro-displacements can be evaluated. A large number of numerical methods have been developed for PC-based automated processing of ESPI interferograms, providing high spatial resolution and accurate, quantitative measurements. However ESPI is, basically, an image-based diagnostic method. The visual analysis of the shape and the number of fringes can provide a quite simply interpretable evaluation of both global deformations, as well as of damages and hidden defects in restricted areas. This approach fully meets the requisite of qualitative estimation usually required in the artworks diagnostics. Descriptions on the ESPI basic principles and its applications for cultural heritage diagnostics can be found in refs. [8-24].

2. – Motivation

The behavior of a wooden painting, with respect to the thermo-hygrometric fluctuations, is quite complicated and exhibits low short-term repeatability, prevalently due to the random moisture content, inside the board, at the start time of each examination. Consequently each structural test merely shows the unique response of the artwork at the moment of the investigation. Therefore, many measurements are needed with the aim of collecting as much information on its behavior. An art conservator appropriately trained on the basic principles and rules for managing measurements, could accomplish such a task without the need for an onsite expert in optics. Typically an art conserva-

Fig. 1. – Pictures of the front side and back side of the painting.

tor is discouraged from utilizing instrumentations and methods outside of the realm of her/his field of knowledge. Therefore our main motivation was to provide a user-friendly tool, wished for familiarizing an art conservator with interferometric method, that can largely improve the traditional artwork survey methods. Unavoidably, a restorer needs to migrate a little into the physics world. Her/his previous artwork knowledge (technique of the construction, structure, materials, restoration history, etc.) is a crucial requirement for correctly understanding the ESPI results [25-27].

3. – Experimental section

The artwork on which we performed the analysis represents a Madonna with Child, by stylistic way dating back to the end of the sixteenth century. (Collection of "Suor Orsola Benincasa University", Naples.) The support is, unusually, a single wooden plank (72 cm in width, 87 cm in height, 1.5 cm in thickness). The fiber is regular, with no evident faults. The control system consists of two chestnut cross-bars ($72 \times 4.7 \times 2.5$ cm), applied to the panel by five metal nails. The preparation consists of a layer of white lead, about one millimeter in thickness (fig. 1).

We utilized a commercial ESPI system (K100/HOL by K. Stetson Associated). The light source was a DPSSL 532 nm, 0.75 W laser (Torus by Quantum Laser Ltd). The system is able to acquire, process and display up to 30 interferograms/s. With the aim to provide high stability of the artwork and for minimizing the frictions acting against displacements, we designed a custom highly stable holder, supporting the artwork simply by two rods that hold the upper rear cross-bar. The high stability we gained allowed us to record long-term, real-time sequences of interferograms, at a frame rate of 12 frames/s. Measurements were performed in optimal laboratory conditions, by utilizing an anti-vibration optical table and by minimizing air turbulences and acoustical noise. Temperature and relative humidity were monitored by a data logger (TESTO Mod. 175H1). In fig. 2 the laboratory set up is shown.

The study of the behavior of the overall structure can provide information for designing both an appropriate control device as well as adequate conservation microclimate.

A traditional method for measuring deformations of wooden supports employs displacement transducers [28]. Recently the effects of the relative humidity changes were measured on a wooden panel by using an array of fiber Bragg gratings glued to different critical points [29]. A further method uses the digital image correlation technique and finite-element modeling [30]. However ESPI, that allows for full-field measurements of out-of-plane displacements, can be utilized on large surfaces, once the long-term object stability is assured.

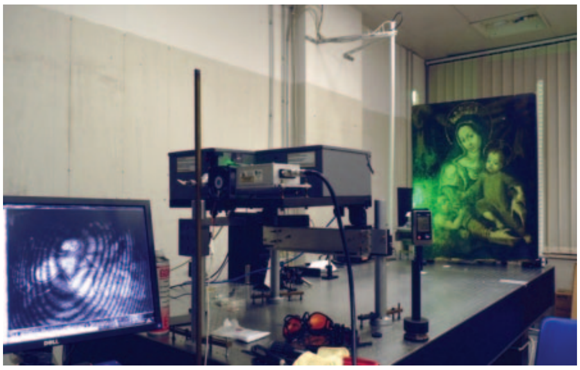

Fig. 2. – Laboratory set up.

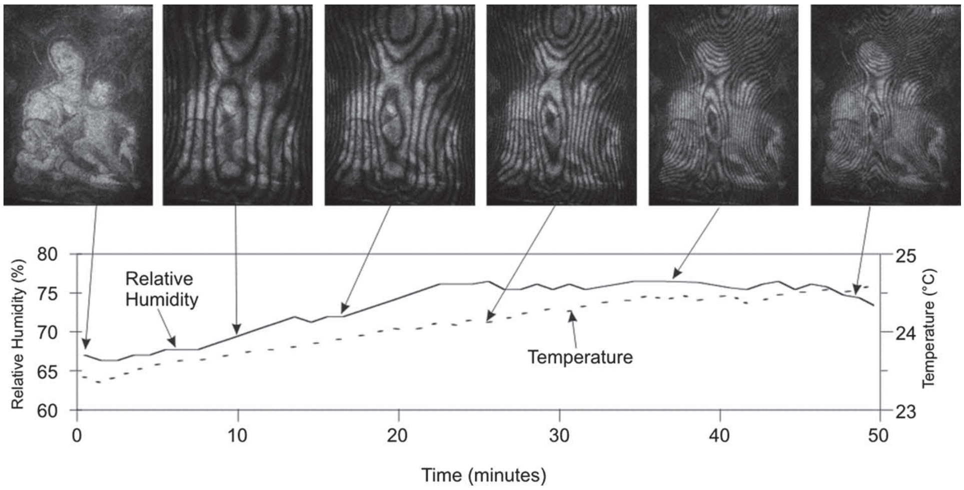

Fig. 3. – Fringes evolution following the room microclimate variations.

We performed long-term recordings of the fringes patterns progression, that revealed the dimensional response of the panel to the room microclimate variations. The provided "Video_1" [31] shows the evolution of fringes recorded during a 50 minutes time interval. In fig. 3, interferograms extracted from Video_1, show the evolution of fringes, whose number and profiles, represent the artwork structural deformation caused by the room microclimate variations, reported in the graph.

It appears evident that the painting distortions, revealed by the profiles of fringes, are strongly influenced by the rear cross-bars, that do not work properly in reinforcing the entire painting. On the contrary they appear to worsen the situation as they do not inhibit the curvature in the middle area of the painting, in this way generating stresses. Such a situation is demonstrated in fig. 4. In (a) the image of the painting back side. In (b) the yellow lines locate the position of the rear cross-bars, onto the interferogram, that reveals a lower deformation amount in the cross-bars areas, with respect to the middle area of the painting. In (c) the full-field relative displacements 3D-plot, showing the distortion of the whole painting.

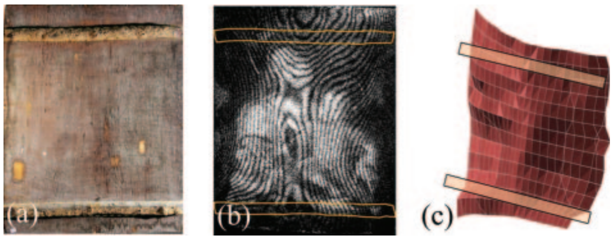

Fig. 4. – Whole-body displacements are strongly influenced by the rear cross-bars.

4. – Local damages evaluation

For restoration purposes, it is important the accurate localization of flaws and hidden defects, particularly of incipient detachments of pictorial layers from the support.

The whole surface interferograms, shown above, have insufficient resolution for revealing localized small damages, as micro-cracks or detachments of pictorial layers from the supports. However the ESPI system allows for testing restricted areas of any sizes, simply by imaging just the region of interest. A painting on wood is a multilayered structure, made of the wooden support and several preparation and painting layers. Aging effects, due to temperature and relative humidity fluctuations, involve, in the very first stage, the loss of adhesion of pictorial layers, that fatally evolves towards irreversible cracks, as schematically exemplified in fig. 5 [32].

A key feature of ESPI is its ability in revealing hidden detachments, allowing for restoration interventions, before their ultimate consequences.

We performed measurements for revealing localized damages in restricted areas, by irradiating the whole artwork back side. The painting temperature increased by a few degrees, completely safe for the artwork. A simple tungsten bulb was employed. In fig. 6 examples of results obtained by irradiating the painting back side by a 100 W tungsten bulb, at one meter distance from the painting, are reported. The artwork temperature increment was of 2.8 °C. Hidden defects, not detectable by traditional restorer survey methods, were revealed. In particular typical "bubble" detachments, on the face of the Virgin, were evidenced. In the fig. 7, outlined fringes (on the left) and arrows (on the right), identifies the position of the detachments onto a white-light image.

However this method has a very poor repeatability. In fact, the images shown in fig. 6 appear dissimilar, despite they were obtained by measurements performed in almost the same area, with the same measurable temperature and relative humidity values. The major cause influencing the different painting responses is the unpredictable moisture content, inside the wooden panel, that inhibit the full control of experimental

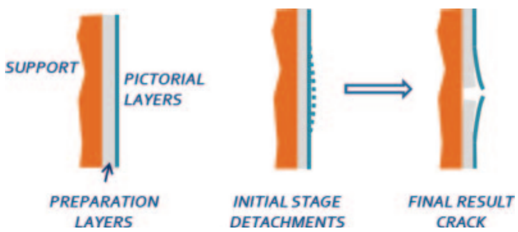

Fig. 5. – Simplified illustration of damages formation.

Fig. 6. – Local damages revealed by irradiating the painting by a simple tungsten bulb, that produced a minimal temperature increment.

Fig. 7. – The position of three hidden "bubble" identified, onto the white-light image, by outlined fringes (on the left) and arrows (on the right).

conditions [33]. As a consequence, usually, usable fringes patterns are unsystematically obtained, among a number of frustrating and time-consuming attempts. As mentioned above, each test merely shows the unique response of the artwork at the moment of the investigation.

5. – Speeding up measurements

5·1. *A practical approach as user-friendly tool for trained art restorers.* – To speed up measurements we adopted a procedure consisting of three steps. In the first step a controlled irradiation on the front surface of the area of interest, instead of overall painting, is performed. The second step consists of the real time video recording the fringes generated by the displacements of pictorial layers inside the area of interest. Finally, by replaying the recorded interferogram sequence, the deformations of fringes are traced onto the white light image of the area under examination, properly superimposed onto the fringes pattern. In general fringes have circular or elliptical shapes, discontinued by localized deformations generated by structural defects (see fig. 8). Well-established rules, that associate categorized fringes shapes with distinct defect types, allow recognizing different damages on the painting [34]. Non-destructive techniques, in cultural heritage applications, typically require a qualitative estimation of the artwork condition. The visual evaluation of the interference patterns fully meets such requirement. However a sub-micrometric accuracy can be achieved. To detect the surface hidden defects, the preferable choice consists on shortly irradiating the front surface of the painting, merely in the region of interest. By using this method, essentially only the pictorial layers are heated. The region under test was irradiated just for the length of time required to

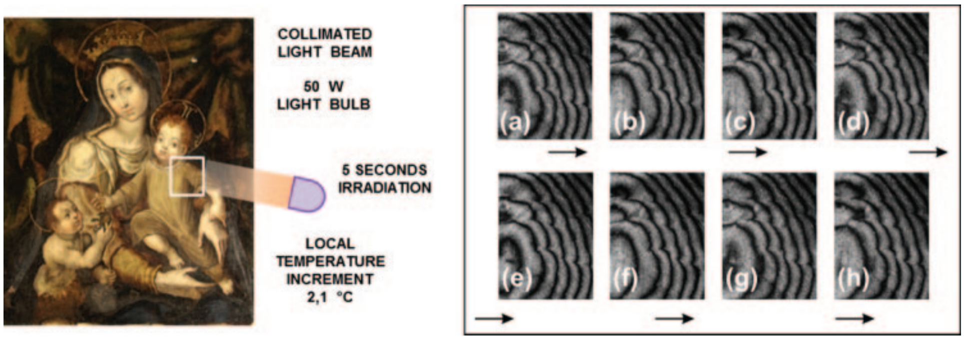

Fig. 8. – The white frame identifies the tested area. On the right, from (a) to (h) a selection of interferograms extracted from the Video_2.

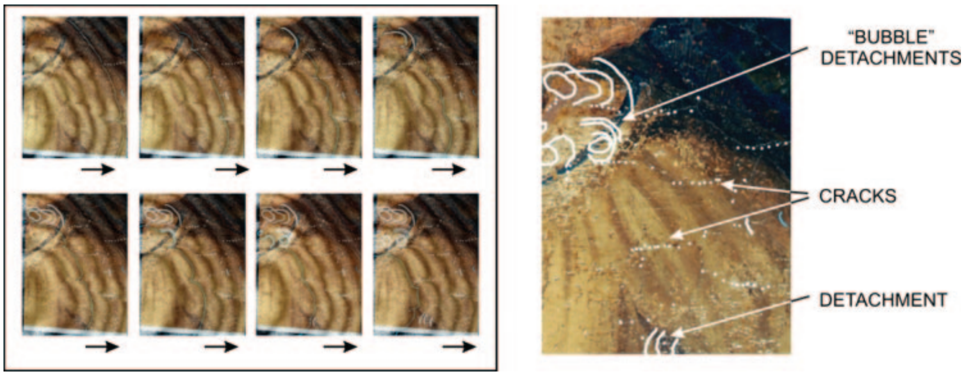

Fig. 9. – On the left, frames extracted from Video_3. For the sake of clarity fringes have been outlined by white lines. On the right, the revealed defects are shown by arrows.

obtain local deformations of fringes suitable for the easy detection of damages. However, by varying the thermal load, different defects can be revealed, depending on their "stiffness". For irradiating the painting we used a collimated spotlight with a 50 W halogen tungsten lamp, as light source. The surface temperature was measured by an I.R. thermometer (FLIR TG 165). In any case we were careful never to exceed a local temperature increment of 5 °C.

In our case we recorded the fringe patterns during the cooling step, after the spotlight was turned off. In the provided Video_2 [35] the fringes progression, in the area inside the white frame in fig. 8 (on the left), is shown. In the same fig. 8, on the right, frames extracted from the Video_2, are also shown. The Video_3 [36] shows the defects tracked on the white light image of the painting, onto which fringe patterns have been superimposed. In fig. 9, on the left, interferograms extracted from Video_3 are shown. Fringes have been outlined by white lines for evidencing their local distortions. Almost eight frames were sufficient to trace the defects. In the same fig. 9, on the right, the revealed hidden defects, among a number of widespread visible ones, are shown by arrows. External cracks are identified by dotted lines. Hidden detachments are identified by solid lines.

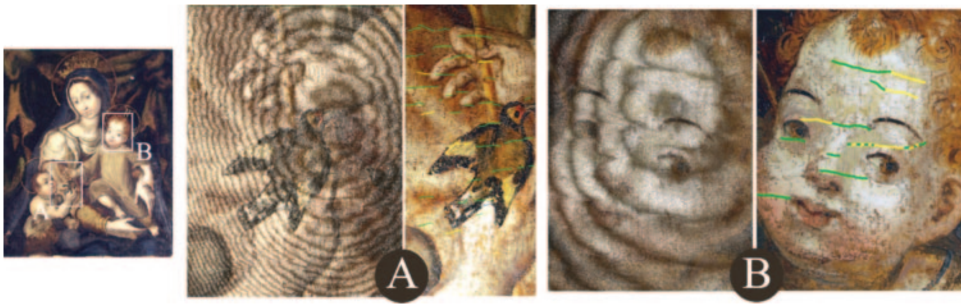

Fig. 10. – Damages revealed in the areas identified by white frames. Hidden defects (yellow lines), among a number of widespread visible ones (green lines), are shown.

In fig. 10 more results, obtained by the same method, on different areas are shown. In (A) yellow (light grey in the greyscale image) lines identify hidden flaws among a number of widespread visible ones, identified by green lines (grey in the greyscale image). In (B) a measurement on the face of Infant Jesus allowed to reveal detachments under three restored zones, where lost pictorial layers appear filled by plaster layers and repainted with colored lines emulating the original color ("rigatino" tecnique). Yellow lines (light grey in the greyscale image) identify non-visible or partially visible cracks while green lines (grey in the greyscale image) identify flaws detectable by visual inspection. This results demonstrate that the restorer was not able to recognize the hidden detachments and applied the plaster layer onto the "broken" preparation layers. Presently, damages are entirely or partially hidden under the plaster layers. It is highly probable that they will evolve towards visible cracks.

6. – Conclusions

We evaluated the overall deformations of a painting on wood, dated to about the sixteenth century. By analyzing previously recorded interferograms sequences, it was possible to monitor the evolution of fringes and thus to follow the overall progression of the painting deformation, assessing its unequal distortions, caused by two non-properly working cross-bars, applied on the back side. We showed that the two cross-bars are not adequate for reinforcing the entire painting.

In addition, by an extensive survey on restricted areas, we found several typical hidden detachments that are precursor of future cracks, as well as the evidence of inadequate restorations on the pictorial layer. We demonstrated the reliability of ESPI as a user-friendly tool for a trained art conservator, by utilizing a quick fringes analysis approach.

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