Complimentarity of digital holographic speckle pattern interferometry and simulated infrared thermography for Cultural Heritage structural diagnostic research

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Abstract— *In the field of art conservation there is an increased demand for non destructive and non invasive techniques able to perform remote defect detection for structural evaluation of historical structures and works of art. The techniques must have some basic important characteristics as non destructivity, accuracy, repeatability and desired features as non contact, portability, resolution, broad range of applicability. The simulated infrared thermography (SIRT) and digital holographic speckle pattern interferometry (DHSPI) are systems discussed in detail elsewhere; in this paper have been used in combined testing on art related targets according to the above criteria. Results confirm the effectiveness of both techniques in the conservation field and examples are here in presented. Each system is thus described as individual method highlighting the advantages and limitations of each. The aim is to present the suitability and appropriateness for accurate defect mapping in structural documentation reports. This work is considered preliminary and is in progress for the future hybrid synthesis of systems and data.*

***Keywords*— *Artwork conservation, Cultural heritage, Holography, Interferometry, Infrared thermography*.**

I. INTRODUCTION

The structural diagnosis is an essential part of conservation research during the documentation of both mobile art works and immobile structures. Conservation strategy requires beforehand a detailed analysis of the condition of the art object. The condition report refers to the object as a whole and its constituent materials in terms of physicochemical deterioration and structural integrity.

Independent of the type of the object there are standard deterioration features which threaten cohesion of constituted materials and structural stability. These are two big categories of defects known in art conservation as cracks and detachments, which both are generated gradually or abruptly from natural or unusual stress related phenomena. These deterioration features depending on the age and maintenance of objects may at first be invisible under the surface but gradually elongate or expand and tend to affect the surrounding area. Through this process they become centers of structural instability and the affected areas become weaker compared to the unaffected areas. In this way parts of the structure change their mechanical properties compared to healthier parts. The magnitude of the deterioration manifests through the mechanical resistance of the object to any load. Tools that can visualise this anisotropy and detect characterise the defects and their impact on the structure become crucial if conservation and preservation plan is underway.

1.1 Implemented techniques

The two techniques captured our attention during a restoration campaign[1] carried out on-field at Saint-Savin sur-Cartempe[2] (FR) where we performed with two separate systems comparison of results [1]. The techniques have important common characteristics, being a) non destructive, b) full field and c) portable; while they provide crucial complimentary information for the structural condition of the object, being a) detailed structural micromorphology condition through quantitative risk

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[2] ***Results have been published see reference 1***

map; available by the use of the DHSPI system, and b) thermal gradient of the surface and diverse in-depth resolution; available through the use of system SIRT.

Digital Holographic Speckle Pattern Interferometry (DHSPI) is a technique based in Holographic interferometry (HI) and electronic speckle pattern interferometry (ESPI) [2, 3], which are well-known nondestructive techniques used primarily in industrial sector for quality control [4, 5]. The technique allows for full-field contactless visualisation of surface displacement revealing the subsurface discontinuities [6]. The measurement based on interference fringes number counting each fringe pair to correspond to 1/2 wavelength of the laser light used.

The Stimulated Infra-Red Thermography (SIRT) permits the detection of delamination of the wall layers. First, the analyzed sample is excited with a flux of photons that produce an increase of the temperature of the area. The variation of temperature leads to a variation of the infrared radiation that is visualized through an infrared thermography camera. The photo-thermal signal depends on parameters governing these physical phenomena: thermal conductivity, thermal emissivity, thermal diffusivity, temperature, specific heat, and density. In addition, theses parameters can be correlated with the following characteristics of the object: aspects of the surface, presence of delamination, presence of cracks, internal structure of the material, progress of a physical and chemical transformation, drying and sedimentation, etc. For the mapping, the hotter colors reveal warmer spots, which are linked to the presence of an active interface between materials or layers with different properties, for example a void beneath the surface or an interface between two different mortars. The air is a very good insulator that induces the accumulation of heat in the layer just above the void [12-13].

The interferometry techniques in various versions and infrared thermography (IRT) are often used in combination because they give complementary information, mainly in the field of defect detection. Nevertheless in all cases, they are implemented as separate devices with their own imaging systems which are used in post processed combinational analysis. The delivered data either the raw interferograms from which deformation map is constructed or the acquired thermal images require to be macroscopically or digitally redefined and resized for correlating or comparing both data in one.

The concept presented in this paper is based on the fact that interferometry and thermography acting on visible and infrared range of the spectrum can be synchronised at first level before data acquisition to obtain direct correlation of images. The concept is tested out gradually starting first with feasibility tests in the lab and then in a preliminary combinational level in the field as will be shown in methodology section. Experimental work in the lab has been elaborated with the DHSPI system and Infrared Thermography IRT and on-field with the DHSPI system and Stimulated Infrared thermography SIRT.

II. METHODS

Holographic Principle

The system used has its base on coherent interferometric technique which is based on the holographic principle to record phase variations of mutually coherent laser beams represented by beams carrying an object (O) and reference (R) field [2, 4]. The holographic process of wave superposition at recording plane may be represented mathematically by the intensity equation (Eq.1)

$$I \propto U_0 U_0^{\,*} + U_R U_R^{\,*} + U_0 U_R^* + U_0^* U_R \tag{1}$$

In optical holographic interferometry (HI) the superposition of holographic wave fields gives rise to visible interferometric fringes with the number of fringes multiplied by ½λ corresponding to the magnitude of surface displacement, expressed in μm or fractions of micrometers. The technique is directly quantitative while the measurement unit of half of the laser wavelength employed allows the recording of microscopic surface motion with high precision. More analytically, it implies that any object point P scatters laser light in all directions and to the recording plane and after the object point is displaced by L, the point moves from P to position P', which is accompanied by displaced light scattering, fig 1. In the two instances before and after displacement a recording plane representing positions P, P' interferes with the plane of the reference wave U_R. The holographically formed waves are recorded and then reconstructed simultaneously to visualise the phase difference (Δφ) between the displaced waves as an interference fringe pattern. Fringes are isotopic curves with constant values of Δφ with dark fringes being odd and bright fringes even multiples of π. If a lens is used to image a speckle pattern field for digitisation and numerical analysis [7] with a reference, the object beam intensity varies locally and is considered coherent only locally and not in the whole field area, as in the lensless optical processes. This is due to restrictions of the autocorrelation function in speckle fields determined by the intensity distribution and size of the speckle [8].

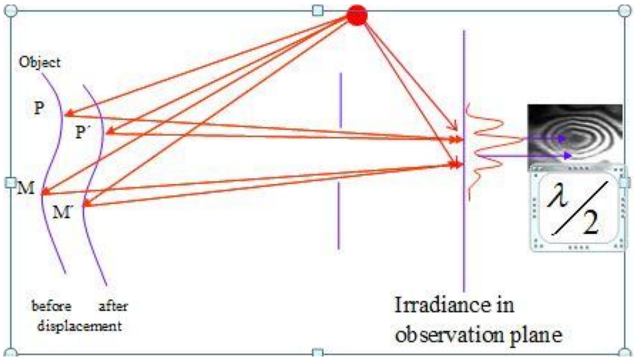


FIG 1. PRINCIPLE OF HI WAVE SUPERPOSITION

The isotopic contour lines of interference fringes describe the three dimensional way of the deformation taking place at the object's surface. The surface is deformed according to the content of the subsurface and internal condition in the bulk of the object As such the surface deformation topology witnessed interferometrically offer the information in regards to the internal structural condition. The areas of internal alterations are detected by the aberrations they cause to the homogeneity of the interference fringes, such as abrupt change of the fringes curvature, changes in fringes density, changes in fringe direction etc. The resulted fringe patterns are or numerically become visible and allow direct qualitative evaluation of the hidden defect causing the fringe aberration [6, 9].

2.1 Systems presentation

2.1.1 DHSPI Digital Holographic Speckle Pattern Interferometry

A custom-developed laboratory prototype system termed DHSPI is set up and is used to monitor the structural responses of the samples under test. The experimental set up uses a Nd:YAG Elforlight G4 laser as a light source with special characteristics: 250 mW at 532 nm, DPSS (Diode Pump Solid State), high spatial-temporal coherence with TEM:00 SLM (Single Longitudinal Mode) and a coherent length of 30 m for far access illumination to the target, and a CCD detector Basler A102f with resolution 1392H x 1040V and pixel size 6,45 μm x 6,45 μm as high resolution digital recording medium. The captured images are transferred to a PC using the Firewire 1394 protocol. The object's surface is recorded using the 5-frame algorithm, which uses two sets of five captured images separated at temporal windows of 10 sec at each set. The first set of images is captured using the $\pi/2$ phase difference in a relaxed state of the sample. The second set of images is captured again using the $\pi/2$ phase difference but in a deformed (or displaced) state following an induced surface displacement of the canvas, with unknown phase difference. Every set of 5-images is captured and is compared to the first initial set. The metrological data provided by DHSPI is of the order of 266nm ($\lambda/2$, where λ is the laser wavelength) for the out of plane surface deformation. The system is shown in photograph fig 2 during on field application.

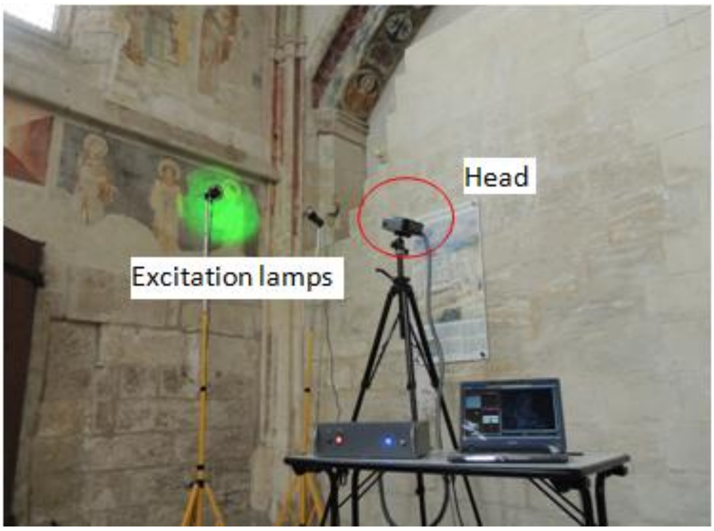


FIG. 2 CUSTOM DEVELOPED INTERFEROMETRIC SYSTEM FOR ON FIELD APPLICATIONS IN ACTION AT AVIGNON (FR)

DHSPI system is made in order to be able to record interferograms in sequential mode; for as long as the change on the surface is evident through the fringe patterns or the applied ΔT° C.

2.1.2 2.1.2 SIRT

Simulated Infrared Thermography (SIRT)

IR thermography has a broad range of applicability, as a non destructive and non contact diagnostic technology. It has been intensively used for structures or buildings diagnosis, mechanical inspections or cultural heritage in a passive way [12-14], and more recently in an active way [15-19].

The system used for the study comprises an excitation device, a detection device, and electronic and computing instrumentation for monitoring, fig 3. In order to obtain homogeneous energy deposition, the excitation source is a couple of halogen lamps. (Halogen I.R. Ceramic 500 W). This excitation source is modulated, in a pulse way, by means of electronics and of a computing of monitoring. The detection system is constituted of an infrared camera of thermography working in a synchronous way with the excitation system (20 °x 15° /0,3 m Field of view, 1,1 mRad Spatial resolution, 50 mK at 30°C Thermal sensivity, 7,5 to 13 µm Spectral range). Finally, an analysis module completes the system. The measurement can be done in the range of temperature -40°C to120 °C, with 2°c or 2% of accuracy. The incident flow of heat hits the surface of the material. The absorption of this heating will depend on the physical properties of the material. The emerging defects visible on the surface, such as cracks, might appear instantly due to the different optical properties. The sub-surface defects appear after some time depending on their respective depths. Such defects cause air pockets in otherwise uniform material, resulting in different distributions of the heat inside the materials. Different defects into a material exhibit different thermal responses to the same excitation.

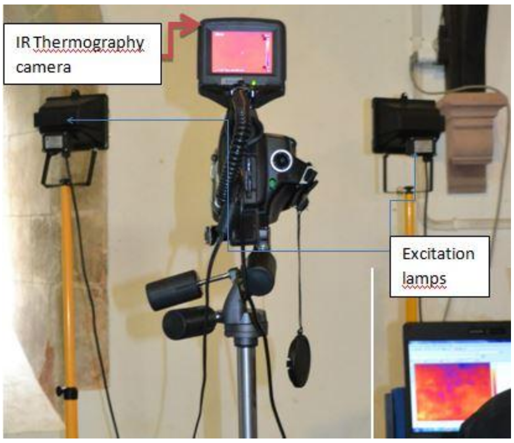


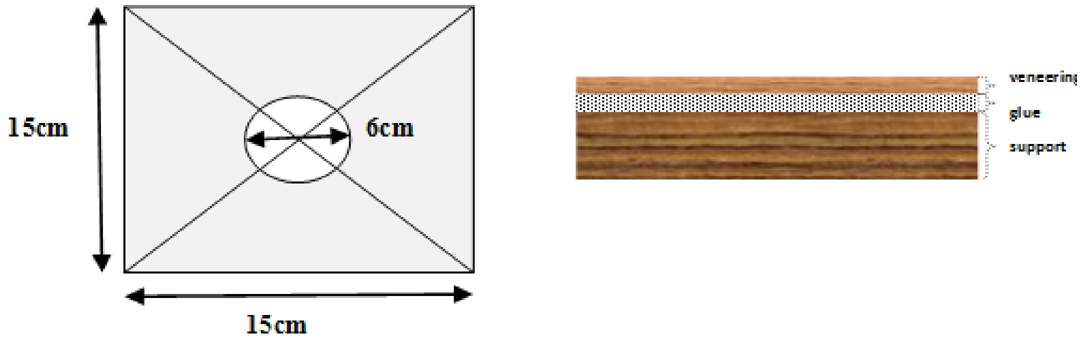
FIG. 3. ACTIVE INFRARED THERMOGRAPHY SYSTEM FOR ON FIELD APPLICATIONS IN ACTION AT MORVILLE (UK)

2.1.3 Samples construction

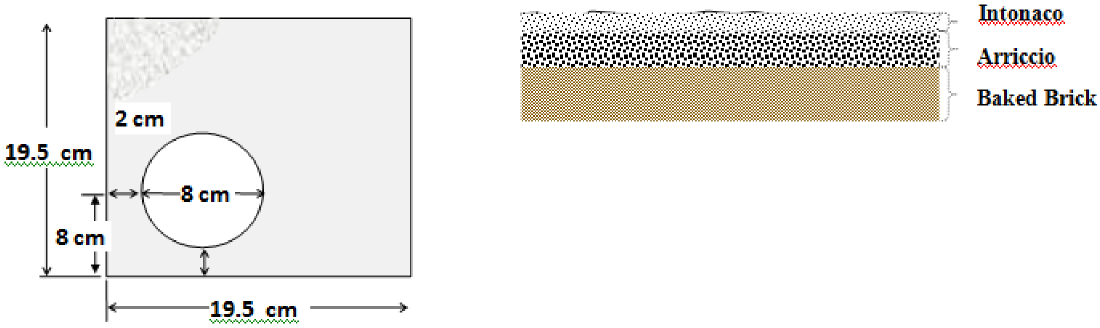
Two samples were used for the feasibility test in the laboratory. The samples were prepared at LRMH and were constructed to simulate marquetry and wallpainting type of artworks. Both are carrying circular detachments among surface and subsurface layers. Sizes and defect dimensions with the topography of the induced defects are shown in the schematics in fig 3. The marquetry is wooden furniture with extra wooden decorative coating. Due to the difficulty of wood as anisotropic material, various treatment methods applied. In specific example the method was chosen in which the wood coating is applied to animal glue, made of bones and sinews of cattle.

Fig 3a shows a section of a sample of three layers: a coarse wood based around 1,5cm, a layer of adhesive and a film of the surface wood paneling of about 1mm. The marquetery sample is made of 1.5 cm thick wood support with glue and 1 mm thin veneering layer with the detachment made by the insert of 1.5 mm thick Melinex® film placed directly on the wood support. The wallpainting, an art of wallpainting on which the painting takes place before drying the plaster of the wall so that the dyes be incorporated with it as it dries. Samples of wallpaintings created according to technical buon wallpainting, as the most classic and the most common types of detachments that appear in the murals. As shown in fig 3b the sample consist of three layers: a support, a coarse plaster and a fine plaster, which is painted. Baked brick is selected as support material, as it is lighter than stone and gives the desired conditions as a compact and durable material. Its dimensions are 19,7 X 19,7 x1.5

cm (industrial processing size). The coarse mortar (arriccio) has a maximum thickness of 1 cm and is composed of lime mixed with washed and sieved sand with 1-2 mm size (lime / sand ratio: 1/3). The fine mortar (intonaco) has a thickness of about 0,5 cm and also consists of lime is mixed with sand smaller (ratio lime / sand 1 / 2.5). The intonaco painted with earth colors in geometric patterns. The final thickness of the support with the two layers is 3cm. The detachment is made by applying a cyclic organic material, 8-10cm diameter, soluble in water. The material in contact water causes its almost complete disappearance, but even the retention part is quite small and is not a problem. The detachment position and size is shown in fig 3b. The sample at left corner is missing upper layer.



(A) MARQUETRY



(B) WALLPAINTING

FIG 4 A) MARQUETRY AND B) WALLPAINTING SAMPLES WITH DEFECT TOPOGRAPHY AND CROSS SECTION SCHEMATICS

2.2 Experimental procedure

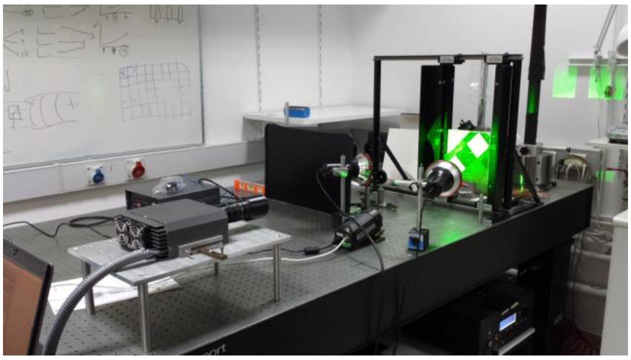
The two systems start recording simultaneously with the DHSPI getting the first exposure before excitation lamps are on and SIRT getting first exposure while the lamps are on. During the increase of surface temperature the DHSPI system is off while the SIRT system is recording. After the excitation lamps are switched off both systems follow the cooling down process. The procedure is shown in the interconnection diagram table 1.

TABLE 1

STEP 1	1. DHSPI measurement before any thermal loading 2. SIRT measurement starts simultaneously with (3) 3. Thermal increase to a pre-specified ΔT° 4. Thermal excitation stops
STEP 2	5. DHSPI measurement starts sequential recording during cooling down 6. DHSPI and SIRT record for as long as T° reaches initial surface value
STEP 3	4. Raw data monitoring and check while recording 5. DHSPI Numerical processing and Post-processing of deformation 6. DHSPI and SIRT images are compared

2.3 Lab feasibility testing

In order to start the investigation on the feasibility of the potential for thermostructural diagnosis data fusion of the two techniques experimental works were first carried out on laboratory based on the *assisted-knowledge* method which lies in using known-defect samples and follow the standard experimental procedure shown in table I. In fig 5a it is shown the experimental setup in the laboratory and in 5b during operation with the visualisation of the data in the pc. The excitation lamps are set up directing their radiation towards the surface of the target at an angle of 45° to 60° to the vertical and to a distance of 70 cm. Previous studies have given an average magnitude of temperature increase in these settings to achieve a slow gradual but transient increase of the surface temperature. The procedural parameter that influences most the temperature increase of the surface, apart surface properties as materials and aging condition is the duration of the excitation. Duration excitation is applied in gradual steps starting from zero excitation to few seconds and few tenths of seconds. The maximum requested surface temperature is kept within 0.2 - 2.0 ° C. The experimental works were carried on the two known-defected samples, the marquetry sample made of two wooden pieces and the wallpainting sample both carrying in their centre a purposefully induced detachment, as described in samples construction and fig 4a,b.



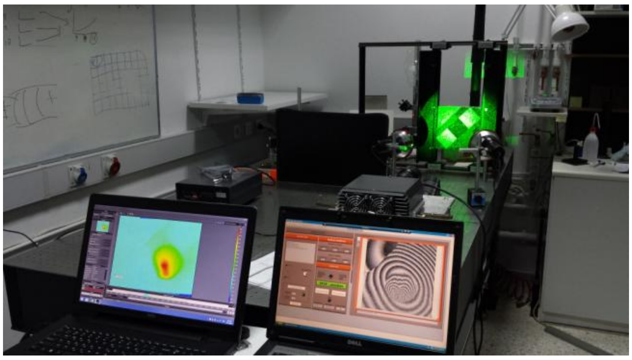


FIG 5. AT A) WITH RED LINES THE EXPERIMENTAL DHSPI AND WITH YELLOW THE -IRT SETUP, AND B) THE SYSTEM WHILE MONITORING THE COOLING DOWN PROCESS OF THE WALLPAINTING

III. RESULTS

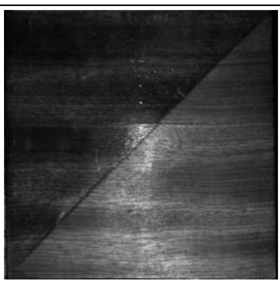
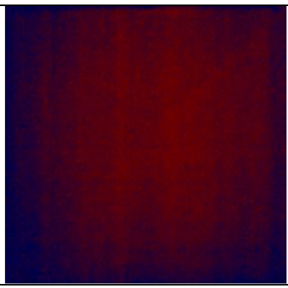
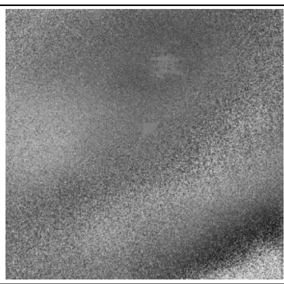
In this section are presented the preliminary sample results and the on field case examples. The collected data is dense and very rich in terms of structural information and cannot be shown here. Instead few characteristic exemplary images of data are shown to visualise the structural information and appropriatness of the systems for defect detection purposes in art diagnostic field.

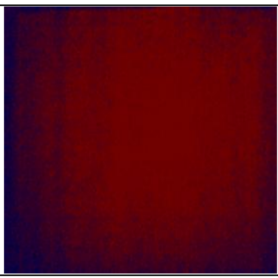
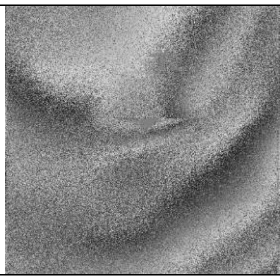
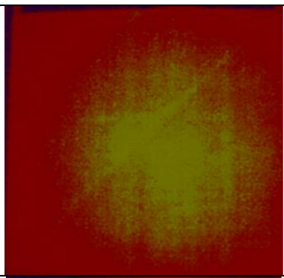
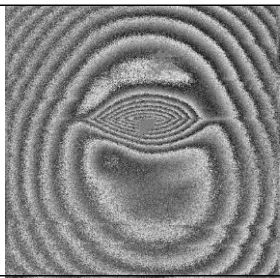
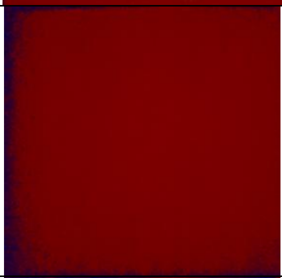
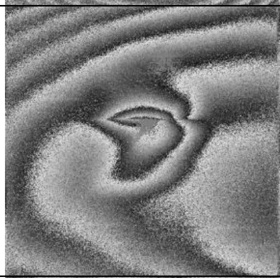
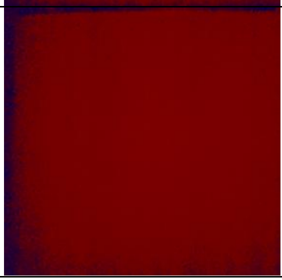
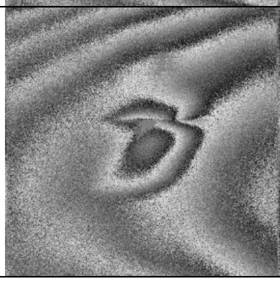
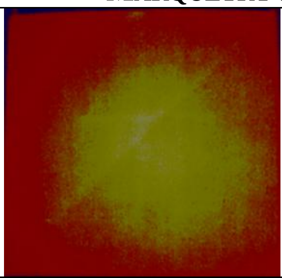
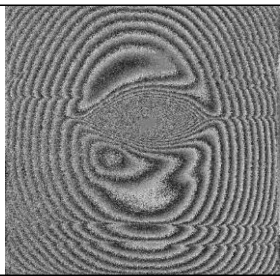
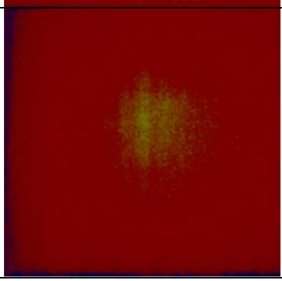
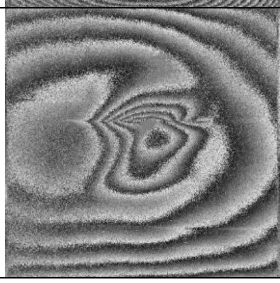
3.1 Example of Laboratory samples

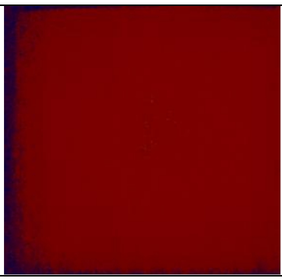
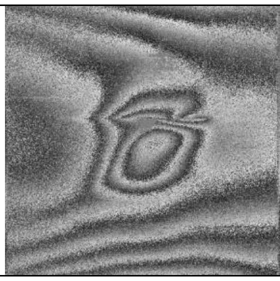
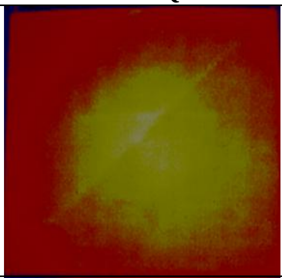
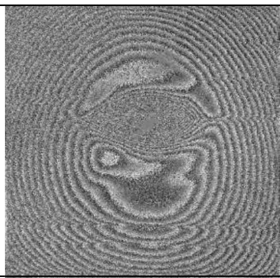
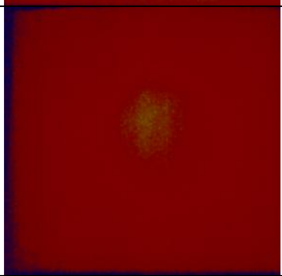
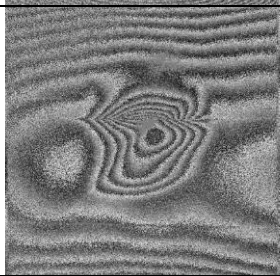
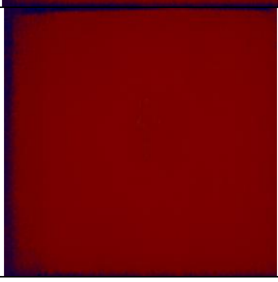
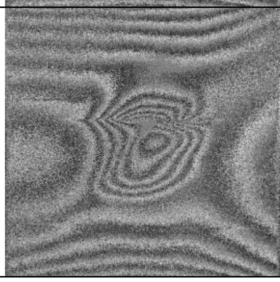
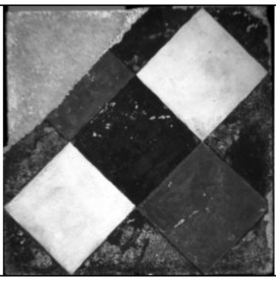
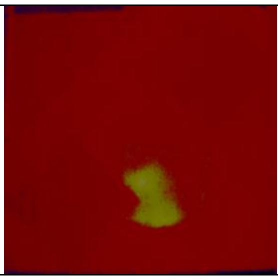
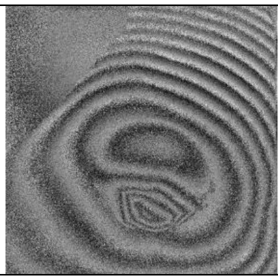
The feasibility investigation started in a lab using a FLIR IR camera as thermography monitoring system and the DHSPI. Both mounted on an optical anti-vibration table sharing same direction but having a different view point to the surface as it seen at fig. 5 with red line for DHSPI and yellow for IRT. The excitation started from zero excitation and to increase up to 10 sec excitation. The thermography images show the increase in color changes while the interferometry images show the increase in density of fringes within the fringe system that describes the defect. Fig 6 shows selected examples of reaction in increased excitation.

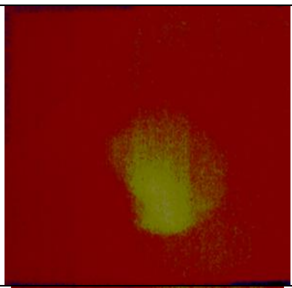
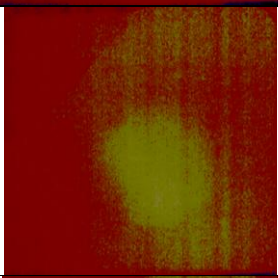
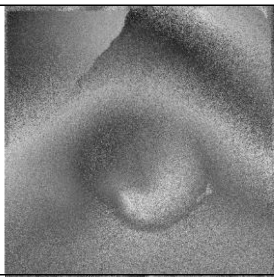
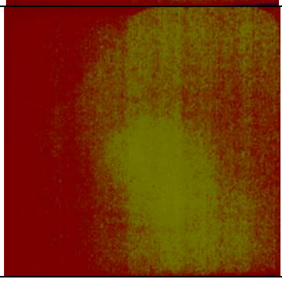
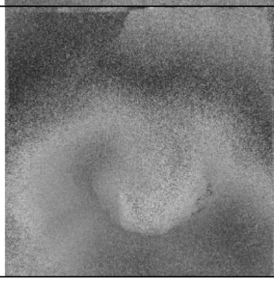
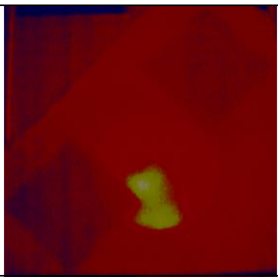
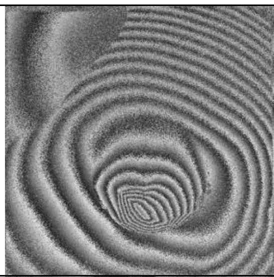
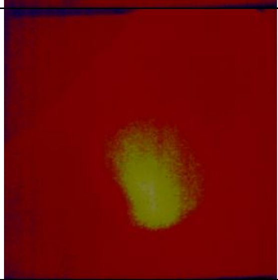
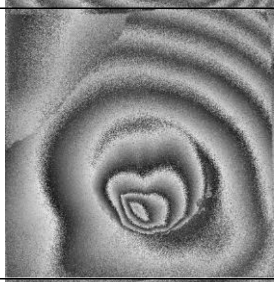
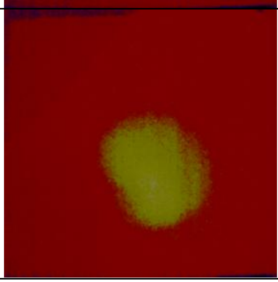
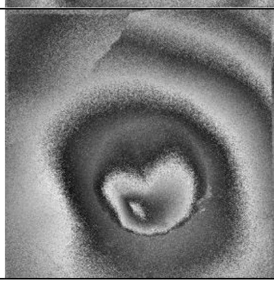
1a) Marquetry

excitation 0, every 30 seconds, DHSPI images every 30 sec

PART-A: MARQUETRY SAMPLE			
EXCITATION 0, EVERY 30 SECONDS, DHSPI IMAGES EVERY 30 SEC			
	IR IMAGES	DHSPI IMAGES	TIME
			At 30 Sec

			At 150 Sec
EXCITATION 3 SEC			
			At 15 Sec
			At 90 Sec
			At 135 Sec
MARQUETRY : EXCITATION 6 SEC			
			At 15 Sec
			At 90 Sec

			At 135 Sec
MARQUETRY : EXCITATION 10 SEC			
			At 15 Sec
			At 90 Sec
			At 130 Sec
PART B: WALLPAINTING SAMPLE			
	**EXCITATION 3 SEC**		
			At 15 Sec

			At 60 Sec
			At 90 Sec
			At 120 Sec
EXCITATION 6 SEC			
			At 15 Sec
			At 60 Sec
			At 90 Sec

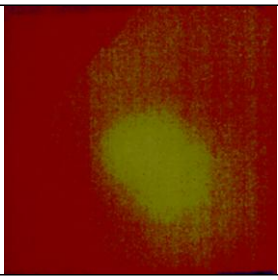
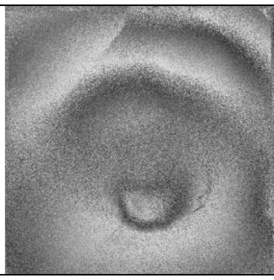
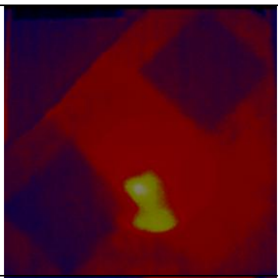
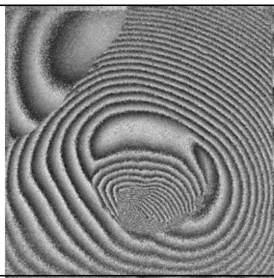
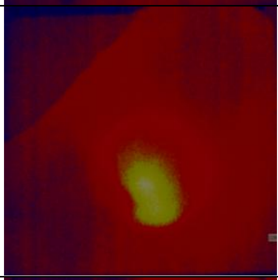
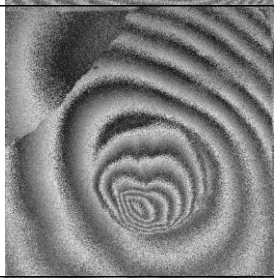
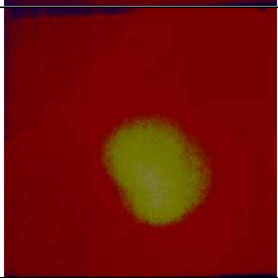
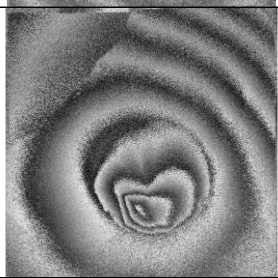
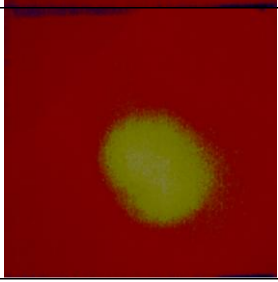
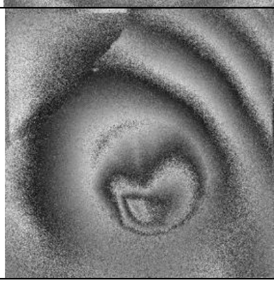
			At 135 Sec
EXCITATION 10 SEC			
			At 15 Sec
			At 60 Sec
			At 90 Sec
			At 130 Sec

FIG. 6 SELECTED EXAMPLES OF SAMPLES STRUCTURAL RESPONSES CAPTURED BY DHSPI AND IRT

The different reaction between marquetry and wallpainting is expressed directly in the visual representation of the images as they are captured during monitoring of the cooling process. The defects are becoming visible in both techniques one showing the thermal response and the other the deformation of the total surface and the microdeformation shape of the defect. A point by point correlation in the defected area among the thermal gradient and the deformation of fringes patterns is intriguing and possible for integrated data complimentarity. The analysis in many conservation cases has to be continued quantitatively and this is possible for each single DHSPI image by measuring the fringes and performing the 3 dimensional map and for SIRT images by analyse locally the thermal gradient. Both tools allow qualitative evaluation but if need can provide quantitative values.

3.2 Example from on-field application

As one of the important aims of the application described here is the potential synergy of the systems and their remote application on the field the next step is the transportation outside the laboratory with the objective to overlap the data to result one representation of surface reaction. The DHSPI II system and the SIRT system were implemented for synchronized monitoring of surface responses. The systems were set aside one on top of the other facing the plastered wall inside the Cathedral, as shown in fig 7.

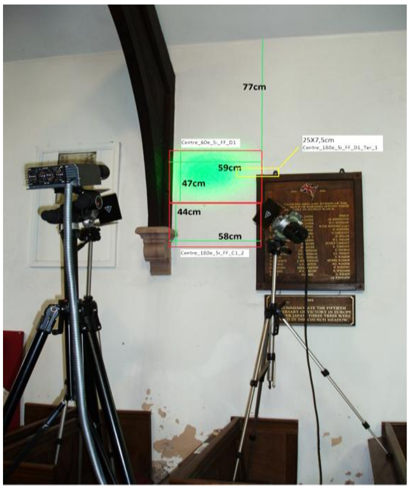


FIG 7. PORTABLE SYSTEMS SETUP FOR ON FIELD TESTING

The SIRT images are temporally integrated over cooling down period while DHSPI images are spatially integrated over every 3 sec minimum with the t=01 represents selection of the first record of the sequence. The following examples showed examined area with unknown realistic defects.

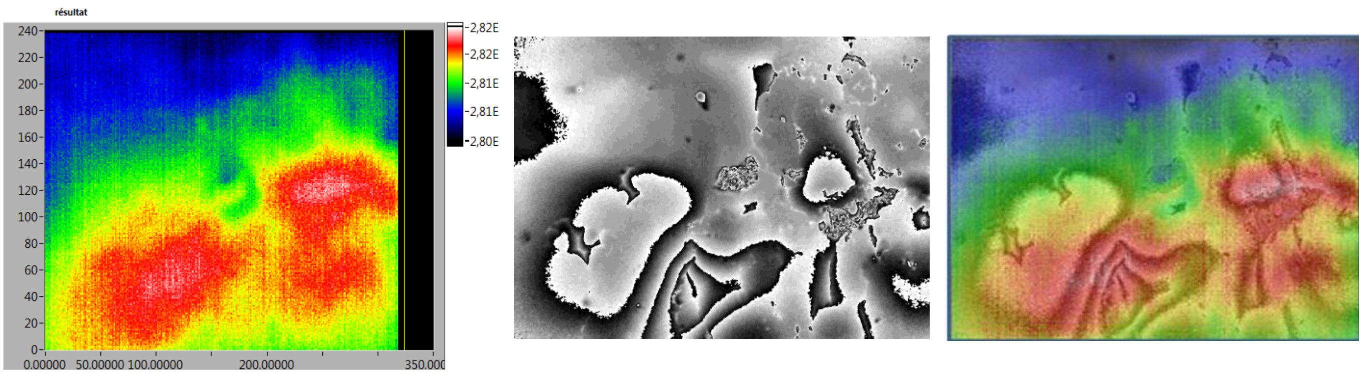


FIG. 8 EXAMPLE FROM WALL AREA WITH DETERIORATED PLASTER LAYERS, FROM LEFT THE SIRT IMAGE, CENTER THE RAW INTERFEROGRAM AND ON THE RIGHT THE OVERLAPPING.

The defects in resulted data interrupt the continuation of the main signal either in the case of SIRT or DHSPI. Interference fringes detect and they can trace the defect structure so as to highlight the microdeformations occured in a defect with high accuracy. Since the shaping of fringes indicates the morphology of the subsurface can be studied by conservators to decide their defect consolidation strategy. SIRT detected defects coincide with defects traced by DHSPI and thermal gradients are provided. The beam divergence give a large field of view in both techniques, as in the Cathedral case ≈ 80 cm^2 . Such high field of view is important in large scale objects as the eg walls of historical buildings and wallpaintings. In example in fig 8 the large divergence of laser beam for DHSPI was depended on the initial scanning of SIRT so when SIRT visualised a wall empty of defects the use of DHSPI could be applied on the same wall with large beam ≥1 $m^{2.}$ divergence and vice versa. In fig 8 the region was scanned with SIRT and due to defect existence the beam divergence was kept to 60-80 $cm^{2.}$. The image correlation is another problem since although the field of view is kept the same for both techniques the change in the angle among the detectors introduces errors in the overlapping diminishing the accuracy of it. Hence hw/sw corrections in acquiring the exact field of view are necessary.

IV. CONCLUSION

We have test and confirm that the combination of the active infrared thermography and the digital holographic speckle pattern interferometry contain highly complimentarity in the provided information in regards to the structural understanding of an artwork from surface responses. The techniques offer insight in the bulk of the materials and objects by plain and safe surface illumination. The techniques offer the important characteristics of non destructivity, accuracy, repeatability and the desired features of being remotely operated, non contact, portable, having high resolution for defect detection and structural investigation as well as broad range of applicability in different materials and constructions. The combination of the thermal distribution with the expressed reaction in terms of deformation of the surface holds high potential not only for the best description of defects and the assessment of condition reports required in art conservation and preservation of Cultural Heritage but also for the understanding of structural reactions that describe mechanisms of deterioration in general. Natural sources of deterioration and aging due to high humidity and moisture in microclimates is planned to be investigated further. The examples shown here are just some of series of original experimental data taken in the lab and on-field. The current state of research is focused on the development of workstation for providing to the data common field of view and stability conditions with next step also focused on correlation of data points and developments of exclusive algorithms for data handling.

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REFERENCES

[1] V. Tornari, E. Bernikola, E. Tsiranidou, K. Hatzigiannakis, M.Andrianakis, V. Detalle, J.L. Bodnar, “Micro-mapping of defect structural micro-morphology in the documentation of wallpainting wallpaintings”, International journal of heritage in the digital era, **1 (2)** (2013)

[2] V. Tornari, “Laser Interference-Based Techniques and Applications in Structural Inspection of Works of Art”, *Analytical and Bioanalytical Chemistry*; **387,** pp 761-80 (2007).

[3] Kostas Hatzigiannakis, Eirini Bernikola, Vivi Tornari, “A new portable Digital Holographic Speckle Pattern Interferometry system for artworks structural documentation”, Lasers in the Conservation of Artworks - Archetype publications Ltd, London, pp 210-212 (2013)

[4] C.M. Vest, *Holographic interferometry*, John Wiley & Sons, 1979

[5] W. Juptner, *Non destructive testing with interferometry*, Physical Research, Fringe 03, Academie Verl., pp 315-324, (1993)

[6] V Tornari, E. Tsiranidou, E. Bernikola, “Interference fringe-patterns association to defect-types in artwork conservation: an experiment and research validation review”, Applied Physics A **106(2),** 397–410 (2012).

[7] Jones, R. and Wykes, C., [Holographic and Speckle Interferometry], 2nd edition, Cambridge University Press (1989)

[8] Dainty, J. C., [Laser Speckle and Related Phenomena], Springer-Verlag, Berlin (1975)

[9] Osten, W., Werner, P. O. J. and Mieth, U., "Knowledge-assisted evaluation of fringe patterns for automatic fault detection," Proc. SPIE 2004, 256 (1994)

[10] Orphanos, Y., Tornari, V., Dabu, R., Blanaru, C., Stratan, A., Pacala, O., Ursu D., "Non-destructive speckle interferometry diagnosis method for art conservation," Proc. SPIE 6606, (2006)

[11] Mieth, U., Osten, W., Juptner, W., “Investigations on the appearance of material faults in holographic interferograms,” Proc. Fringe 2001, Elsevier, 163 (2001)

[12] D. J. Titman, “Applications of thermography in non-destructive testing of structures,” NDT & E International, vol. 34, no. 2, pp. 149–154, 2001.

[13] C. A. Balaras and A. A. Argiriou, “Infrared thermography for building diagnostics,” Energy and buildings, vol. 34, no. 2, pp. 171–183, 2002.

[14] E. Grinzato, C. Bressan, S. Marinetti, P. G. Bison, and C. Bonacina, “Monitoring of the Scrovegni Chapel by IR thermography: Giotto at infrared,” Infrared Physics & Technology, vol. 43, no. 3, pp. 165–169, 2002.

[15] E. Grinzato, P. G. Bison, and S. Marinetti, “Monitoring of ancient buildings by the thermal method,” Journal of Cultural Heritage, vol. 3, no. 1, pp. 21–29, 2002.

[16] H. Wiggenhauser, “Active IR-applications in civil engineering,” Infrared Physics & Technology, vol. 43, no. 3, pp. 233–238, 2002.

[17] J. L. Bodnar, K. Mouhoubi, G. Szatanik-Perrier, J. M. Vallet, and V. Detalle, “Photothermal Thermography Applied to the Non-destructive Testing of Different Types of Works of Art,” International Journal of Thermophysics, vol. 33, no. 10–11, pp. 1996–2000, Nov. 2012.

[18] J. L. Bodnar, J. L. Nicolas, J. C. Candoré, and V. Detalle, “Non-destructive Testing by Infrared Thermography Under Random Excitation and ARMA Analysis,” International Journal of Thermophysics, vol. 33, no. 10–11, pp. 2011–2015, Nov. 2012.

[19] D. Giovannacci ; V. Detalle ; D. Martos-Levif ; J. Ogien ; V. Tornari, E. Bernikola,"Case study of Sainte-Marie Chapel, Fontaine Chaalis (France): complementarity of different optical techniques ", Proc. SPIE 9527, Optics for Arts, Architecture, and Archaeology V, 95270L (July 7, 2015); doi:10.1117/12.2184600; http://dx.doi.org/10.1117/12.2184600

[20] J.C. Candoré, J.L. Bodnar, V. Detalle and P. Grossel, "Characterization of defects situated in a fresco by stimulated infrared thermography, Données textuelles et iconographiques , The European physical journal. Applied physics, vol. 57, n° 1, January 2012, p. 11002-p1-11002-p8.

[21] J.L. Bodnar, J.C. Candoré, J.L. Nicolas, G. Szatanik, V. Detalle, J.M. Vallet , "Stimulated infrared thermography applied to help restoring mural paintings", NDT&E International, vol. 49, 2012, p. 40-46.