



Interference Fringe Patterns in Documentation on Works of Art: Application on Structural Diagnosis of a Fresco Painting

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Abstract: In an interferometry process the successful recording of interference fringes is the primary purpose. A successful interference fringe pattern is formed under strict boundary experimental conditions to provide a high contrast light distribution record. The physical significance of interference fringe patterns is highly evaluated for its high spatial information content and therefore it is explored in many fields of applied science and engineering. Among the most recently explored application domains is the field of Cultural Heritage. The fringe pattern significance is examined as to provide an accurate qualitative and quantitative measuring method to investigate, interpret, document and diagnose existing structural condition and influencing effects on the structure's integrity especially in concern of artworks. These are irreplaceable treasures of human creativity and as such are treated under ethical perspectives of humanities regardless the commercial value they represent; as such in order to evaluate the structural condition maximum image recording resolution and spatial reactions' sensitivity are key factors for diagnostic analysis and documentation. In interference application for art conservation the fringe pattern formation provides a unique information source and measurement capabilities far beyond current practices. In this context a laser based interferometry system is considered most suited to documenting the structural condition of movable/immovable artworks and in the presented application the provided properties are explored to understand and evaluate on the structural documentation of artworks.

Keywords: Laser Applications, Holographic Interferometry, Structural Diagnosis, Cultural Heritage, Artwork Conservation, DHSPI

1. Introduction

Cultural heritage is exposed to many different conditions and situations thus is influenced by several factors, naturally or anthropogenically imposed, leading to the gradual wear and subsequent deterioration of the aesthetic quality and material characteristics. Deterioration of artwork and monuments due to materials' degradation, strength loss and elasticity failure severely threatens the irreplaceable cultural heritage if preventive measures are not taken timely. The

visible deterioration signs such as cracking, detachment, bending, painting flaking etc., are visible indications of irreversible structural deterioration. The aim remains to develop and use tools to prevent the deterioration prior to irreversibility stage. The use of interference-fringe patterns in artwork structural condition assessment due to the high spatial resolution offered, able to detect inborn defects such as displacements with displacement resolution ranging in the order of half a wavelength of incident light to some multiples of it could be employed as an early warning system.

Art conservation researchers examine several factors when

studying an object in order to determine what the structural faults are, how much they threaten the artwork, whether the environment the artwork is housed in is safe, what effect the change of environmental conditions will have on a material, etc. The use of various tools is necessary employed to scientifically answer these questions. Interferometry has been used in various scientific areas (astronomy, physics, engineering, medicine) [1-3] and has provided solutions to complicated questions with great success. As such, has been also successfully exploited in Cultural Heritage and applied primarily to detect and evaluate subsurface damage [4, 5] and therefore to provide useful information on the structural characteristics of artworks. The technique's capabilities may convert it to a strong candidate to become a necessary tool for the conservation community [6, 7]. Interferometry has been applied on a wide variety of artworks and monuments [8-12] providing two basic advantages: a) submicrometric-scale measuring and b) non-destructivity [12-15]. In this work, holographic interferometry was used in order to determine the structural defects and possible mechanical discontinuities of a fresco painting from a private collection. For the application we employed a new portable system termed Digital Holographic Speckle Pattern Interferometry, or short DHSPI, based on optical geometry of hologram interferometry [16]. The importance of the structural diagnosis is based on the fact that the holographic interferometry method is a repeatable non destructive, non contacting, non invasive and accurate investigation method that allows the researcher to identify a variety of structural problems and to prognose the state of their condition in order to provide the restorer with a a) detailed defect micromorphology map and b) a quantified risk-priority map for the restoration strategy. In this paper focus is on direct qualitative assessment on the examination floor.

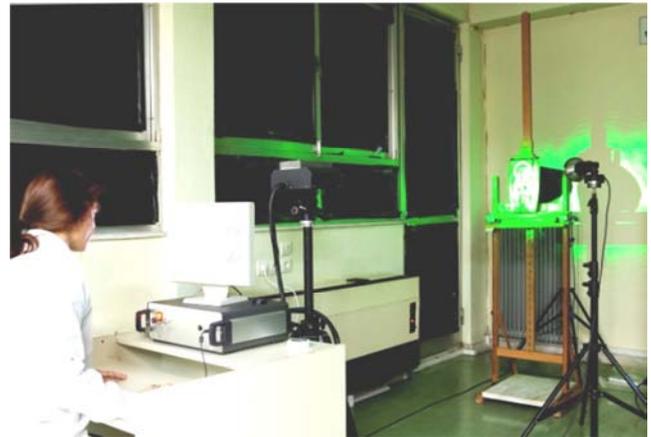
2. Experimental Methodology

2.1. System View

DHSPI (Figure 1) is the result of many years of optical holographic interferometry and speckle interferometry research of the author Dr Vivi Tornari from the Holographic Applications Laboratory of the Institute of Electronic Structure and Laser at the Foundation for Research and Technology Hellas (IESL-FORTH) and the capitalisation of several European funded projects to name some LASERART and MULTIENCODE of the same research group under her supervision. The system was custom developed aiming to face everyday art conservation investigation needs. Since explicit presentation of the technique and system is not the aim of this article, the interested reader is advised to seek literature-references [16-24].

In DHSPI the interferometric comparison is achieved by two beams of the same laser after amplitude modulated beam splitting providing the two arms of an interferometer from which one is mirror-driven and collimator-expanded to illuminate by a controlled divergence beam the surface and

be scattered by it. The beam illuminating the object is termed OB (Object Beam) and the other, spatially filtered and collimated, that is used to serve as a reference for the interference phenomenon to take place is termed RB (Reference Beam). As a result, an interference is produced and is collected on a CCD plane to be acquired by a frame grabber and further analyzed by numerical processes via specially developed software. Schematic representation of the DHSPI optical geometry satisfying fundamental holographic interferometry operation principle is shown in Figure 2 [23].



(a)



(b)

Figure 1. (a) The complete DHSPI II system in laboratory operation, with computer, electronics and peripherals and (b) the laser head on tripod.

DHSPI offers some crucial advantages in the artwork field such as: a) the laser beam depending on the laser power can be expanded up to 1 meter in diameter to cover large surface areas accelerating the documentation process, compared to lengthy point by point practices, b) it allows remote access in seeing the subsurface condition and locating subsurface discontinuities without contact, saving in many cases the need for heavy installation facilities, c) the result is visual and an operator with proper training can see the defects and assess them directly at the time that they appear on the monitor screen, allowing for working on-field hand by hand with the conservator and direct proper preventive actions, d)

it is directly quantitative allowing for further processing and post processing routines in problems that further analysis and elaboration of data is desirable, and e) the development of specialized software routines allow for real time data acquisition and evaluation minimizing the need for keeping scaffolds for long periods of time disrupting the normal use of a site.

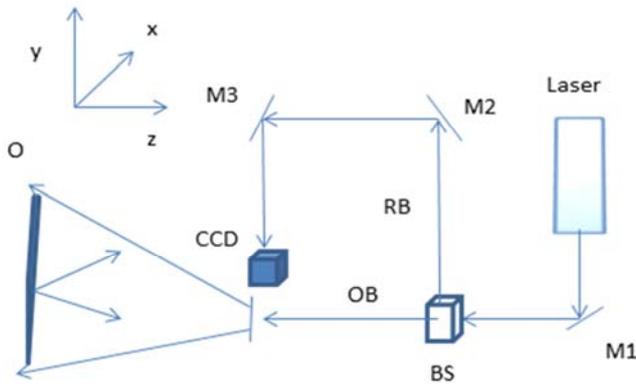


Figure 2. Schematic geometry of DHSP I where M: Mirror, OB: Objective Beam, RB: Reference Beam, BS: Beam Splitter and O: Object.

2.2. Fundamental Principle of DHSP I Based on Holographic Interferometry Methodology

Optically coherent is the term used to denote interferometry performed under strict boundary conditions by a spatiotemporally coherent illumination source usually termed laser. The laser source can be used to provide two beams that are mutually coherent in time and space and as such are capable of generating the coherent physical phenomena of interference and diffraction. Holography is the combined result of a two-step process: in the recording process it is the capability of the incident optical waves to get superimposed to produce an interference grating and in the reconstructing process it is the capability of the incident wave to get diffracted by the produced interference grating [22]. The result is a wave reconstruction identical to the one used to produce the grating. This is the only known process to reconstruct light waves [1].

Holographic interferometry is the comparison of two temporally separated holograms of the same object to output a signal of optical path alterations constituted of constructive and destructive interference in the form of interference fringe patterns. Therefore, it enables static or dynamic displacements of rough surfaces to be studied with interferometric precision. Fringe patterns indicate the surface displacement after it has been subjected to specific loading [23]. By the hologram interference, any phase difference occurrence can be measured [17].

According to the fundamental equation of holographic interferometry,

$$\Delta(x, y) = 2\pi/\lambda K(x, y) \cdot L(x, y) \tag{1}$$

the phase difference δ is given as a scalar product of sensitivity vector K and the displacement vector L multiplied

by $2\pi/\lambda$ containing the information of this alteration. For a phase difference to be visualized in terms of a fringe pattern, there should be a phase change among the two object holograms in the object wave field given by

$$U_0(x, y) = a_0(x, y) \exp[-i\phi_0(x, y)] \tag{2}$$

in a way that the final object wave becomes

$$U_0(x, y) = a(x, y) \exp[-i[\phi(x, y) + \Delta\phi(x, y)]] \tag{3}$$

where $\phi(x, y)$ is the phase information related to object shape, features, depth, etc. and $\Delta\phi(x, y)$ in the second term of object wave equation, any known or unknown load induced in the object is coded. In double exposure, the same object recorded at different times gives two signals that are made to superimpose. The interest is purposefully on the scattered wave fronts as records of optical path changes due to an arbitrary displacement that affect the phase (ϕ) between two exposures, so that

$$\Delta\phi(x, y) = \phi_2 - \phi_1 \tag{4}$$

The optical phase shift between the two identical temporally separated wave fronts reveals the displacement in the form of the interference fringes cosine intensity distribution:

$$I = (1 + \cos \delta) \tag{5}$$

with bright and dark fringes of constructive and destructive interference forming contour of neighboring surface points of equal displacement values. For the purpose of computation of fringe patterns to count the fringes to a given location from 0th order fringe and deduct the phase change from $\phi_2 - \phi_1$, only the change in optical path length of light scattered by corresponding points are needed; hence, in the experiments to follow, a N_{th} order bright fringe to correspond to a phase change [17]

$$\Delta\phi = N_{th} \lambda / 2 \tag{6}$$

which is always experimentally secured and is used to calculate the value of displacement to a specific direction. The measurement procedure and optical arrangement to acquire the optical path change depend on the application aim [22].

2.3. Experimental Procedure

The artwork plays a crucial role in the settings of the system and measuring procedure. The examination of artworks was performed under the experimental procedure shown in Table 1, taking into consideration the different settings required depending on the nature of the artwork.

Table 1. Experimental procedure.

Step	Action
Step 1	Artwork, system and peripherals settings, calibration and positioning
Step 2	10-20 min settling time for low vibration cease
Step 3	OB initial position, recording t=0
Step 4	Induce thermal excitation on artwork surface
Step 5	Recording start time every pre-specified time interval

Table 1 describes the stepwise experimental procedure followed to generate records of interferograms visualizing the interference fringe patterns carrying the information about the structural reaction. At step 4 the differential process for interference dominates the fringe formation and can be repeated without any change in steps 1-3. After completion of step 5 the digital processing of interference fringe patterns provides the data for post-processing analysis.

In regards to the thermal excitation of step 4 the DHSPI system is used to perform measurement of surfaces during displacement and in order to provoke displacement it is equipped with two thermal lamps. The thermal excitation of the surface is achieved by a thermal loading directed to the surface. In this case the induced transient thermal excitation, due to the nature of the physical processes involved, excites the surface, subsurface and bulk provoking a most effective visualization of the overall condition. This type of excitation is safe as long as the surface deformation does not exceed the resolution range of N counting up to few tenths of microns. The typical thermal loading regime necessary for the required displacement is the increase of the surface temperature within the range of a minimum of 0.5-1°C to a maximum of 3°C, an alteration acceptable considering that it lies in a much lower range than the uncontrolled seasonal or daily fluctuations in museums and galleries on the level of $\Delta T \approx 5-8^\circ\text{C}$ [11]. After the thermal excitation is terminated, the natural cooling process of the object takes place and sequential or single recording begins. The recorded data are interferograms visualizing in intensity variations the surface displacement at specifically determined time intervals (Figure 3).

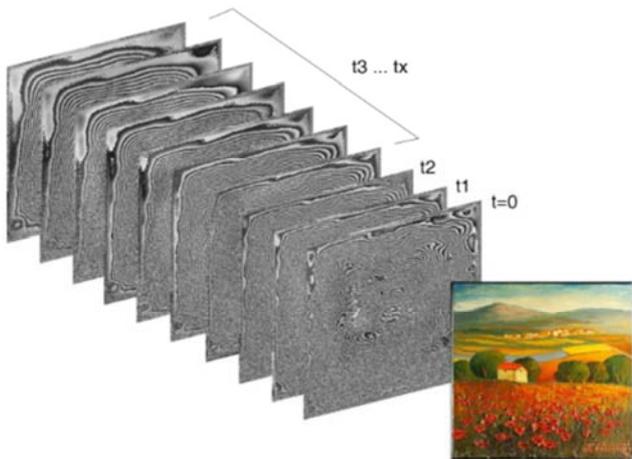


Figure 3. Schematic of the recording procedure where time interval is the time between two recordings: $t_i = t_i - t_{i-1}$.

The interferometric data visualises the peaks and lows of displacement localising the defected areas of interest with specific pattern formations. In case of sequential data recording the effect of thermal or other loading is also visualised as changes in fringe density.

The displacement effect of thermal loading is added on the diagram in Figure 4 especially for the case of fresco fragment attached on framed canvas support. Canvas consists a high-

hygroscopic and vibration-responsive object, consequently thermal excitation contributes to a great number of interrelated fringe systems. In Figure 4 an exemplary result of the cooling process of the attached fresco-canvas combination is shown. The dense fringes representing the dimensional reaction of the surface during cooling down at variant experimental times suggest that the reaction of the surface is very intense. The observation is confirmed throughout the cooling down process. The dense fringes signify a strong displacement. The reaction corresponds to the unstable canvases behavior [15].

The interferograms (Figure 4) highlight the reaction of the surface in interaction to inner layers and canvas during time; starting with the surface visualization towards inner layers and the bulk. Areas with localized fringe patterns are observed throughout the process. These carry information on structural anomalies, as cracks and detachments, displaced in different density from the rest. The qualitative processing implies collection of the coordinates of the repeatable localized reactions to locate the centers of anomalous displacement generation corresponding to existing structural defects. The fringe density remains strong and longer cooling down time is required for the strong reaction to cease.

Respectively, stiffer materials, e.g. of a wooden surface such as icons, require greater excitation periods to provide successful fringe pattern formation. The longer thermal excitation is performed stepwise in small increasing steps.

Thus, investigation protocols differ and the most deteriorated artworks essentially require preliminary investigation to determine the optimum thermal excitation to achieve the required displacement and accepted ΔT as well as to set the rest of measuring parameters. Figure 5 shows the cooling process of the fresco with a maximum 1.9°C increase of the temperature applied from different directions (front, front back and back directions). The transient alteration of the artworks' dimensions due to the cooling process allows interferogram formations to reveal. The temperature and humidity conditions of the room were steady throughout.

The time interval (t_i) chosen refers to the time between two consecutive recordings; defect detection and structural documentation maps are considered short-period procedures (investigation protocols) and a time interval of 1 to 5s is chosen to follow process no longer than 5min (short-period process). Long-periods procedures refer to other type of research requiring long intervals as minutes in longer monitoring times from hours to weeks e.g. research on environmental impact [24]. In the investigation protocol for defect detection diagnosis, a time interval of the order of few sec is thus employed for each interferogram allowing to closely monitor the configuration of fringe systems and trends that prevail on the surface of the object throughout the process until the object reaches its initial temperature. The time interval plays a key role since the misuse of this parameter can lead to incomplete data, loss of the general picture prevailing to the surface and hence it can mislead the researcher to incomplete conclusions. In routine documentation according to the investigation protocol the ΔT

is set directly to reach a maximum of 0.5-0.9°C and interval between records is set directly to 5s.

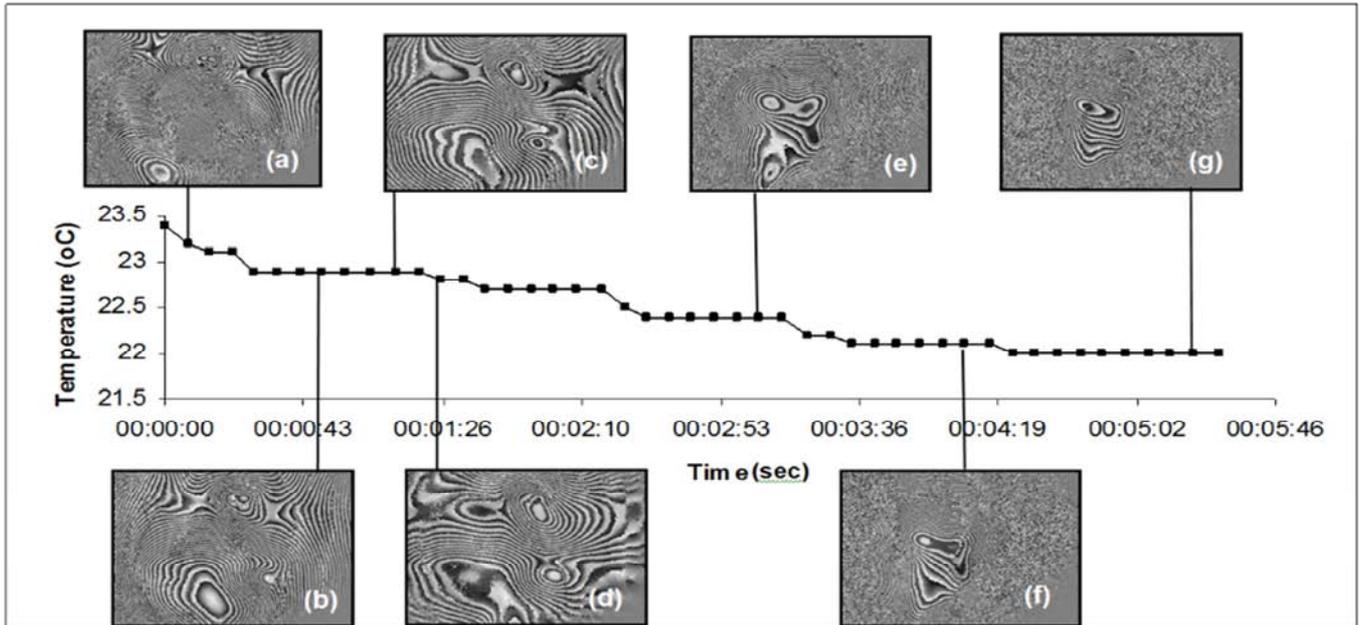


Figure 4. The cooling down process after thermal excitation of the surface. (a-g) interferograms recorded on specific intervals.

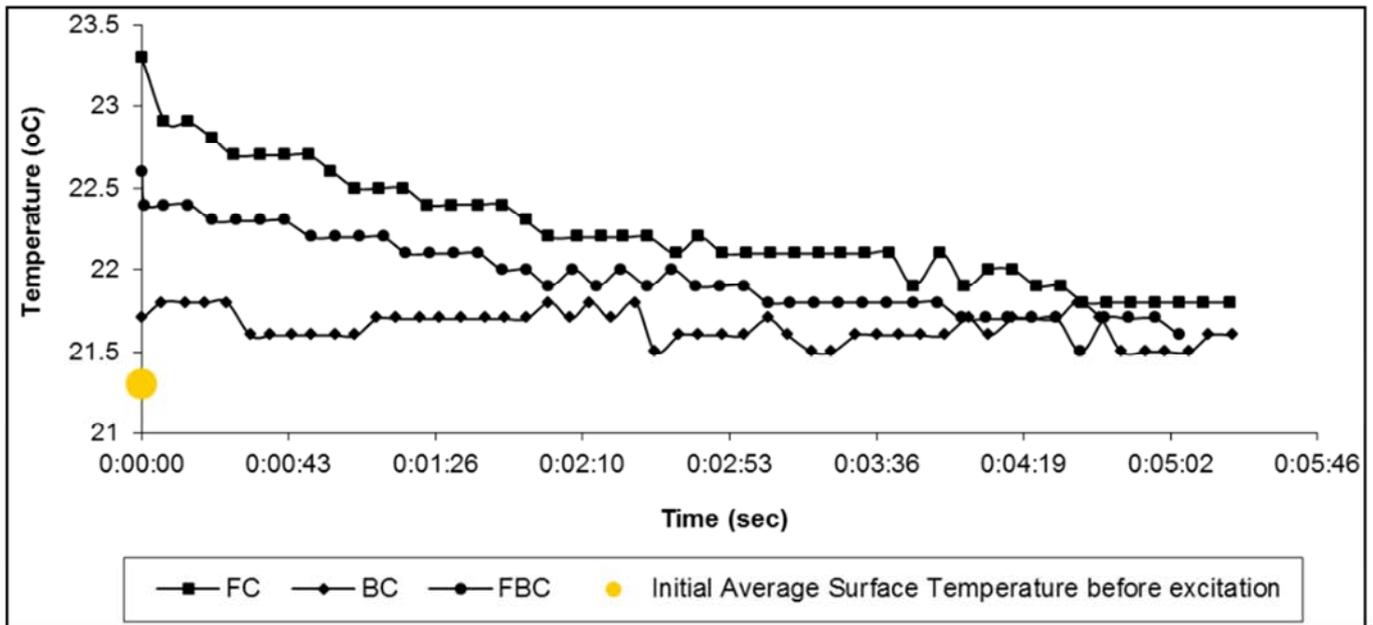


Figure 5. Exemplary cooling process of the fresco for FC, BC and FBC.

The necessary alteration of the investigated object is given by two IR lamps equipped as peripheral instrumentation the DHSPI system. The IR lamps are placed according to the configuration chosen. In this study three configurations were applied: Front (FC), Back (BC) and Front-back configuration (FBC). In the first two configurations the investigated object is thermally altered only on one side either front (surface, front view) or back (rare view). In the FBC the object is overall illuminated, both front and back (Figure 6). In any case in order to achieve uniform excitation the IR lamps should be placed in smoothly overlapped beam position.

2.4. Classification Table for Fringe Patterns to Defect Localisation

As long as Holography and holographic interferometry are spatially sensitive techniques and their use as metrology techniques is based on interference laws the fringe patterns are visible representations which can be qualitatively and quantitatively analyzed [16-20]. However, the holography image is reconstructed after the formation of invisible primary fringes which do not allow any visible observation of fringes to be obtained. If there are visible fringes on an

optical hologram they are termed "rigid body" fringes and an undesired motion during the recording process is signified. However there is a class of secondary fringes that are visible and processable and these are the aim and result of holographic interferometry presented here. The secondary class of fringes is visible and quantifiable allowing detection of the surface displacement and assessment of the magnitude of deformation. Also, by qualitative studying of the visual interference fringe patterns a variety of subsets of fringe patterns may be exported to serve as local indicators of structural defects [21-23, 25-26].

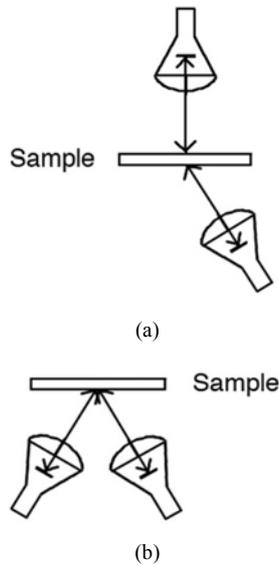


Figure 6. Configuration set up: (a) Front-Back, overall excitation and (b) Front or Back.

The fringe patterns provide a visual aid to identify local areas of structural discontinuity in regards to the overall surface displacement from its initial position. The reacting surface points generate at each recording instance fringes half-wavelength apart on the total field-of-view. The qualities of measurement compared to any known point-wise, scanning, microscopic, stereoscopic or trigonometric method are of unsurpassed resolution in microscopic scale and deformation level [12-14]. There is not any sensor yet that could record spatial frequencies as high as in the range of 10^{14} Hz, which is a usual range of phase modulation in interference pattern formation giving rise to intensity variations. The invisible structural condition is revealed, since any finite point of examined mass if displaced contributes to interference formation. The invisible becomes visible in coded pattern form and displacements studied by this effective tool allow applications in the majority of art structural diagnosis conservation problems.

In short, these patterns are due to generation and evolution of deformation processes of physical objects and can be studied and highlight natural mechanisms of physical deterioration. They are defined as spatially sensitive because they are dependent on the acquisition of optical path distances caused by surface displacements of the order of $\lambda/2$. Displacement in optical path refers to any spatial change of natural or artificial origin detected in the coordinate's matrix of the surface affecting the optical-path of the interferometer. Deformation occurs as a result of instantaneous or continuous or gradual displacement processes that influence the physicochemical integrity or physicochemical composition of materials deteriorating the constitution and construction of objects.

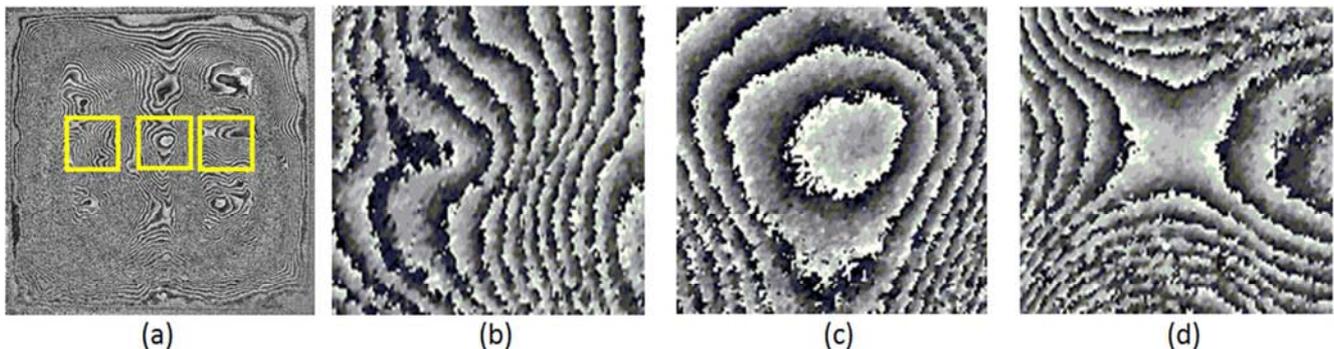
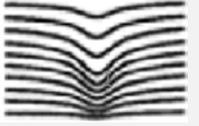
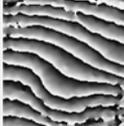
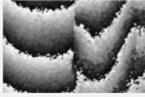
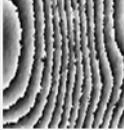
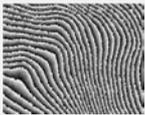


Figure 7. Fringe patterns of holographic interferometry manifest in symmetrical scale-less forms, in a) whole body displacement and in b-d) zooming in local defects as manifest in b) for hidden propagation, in c) detachment and in d) for crack.

The fringe pattern classification to defect identification is verified through experiments and mathematically and is validated through "known-defect" applications which is the term used for purposefully induced defects in technical samples [10]. Alternatively, it is used for existing defects extracted from conventional conservation maps provided in real artwork applications. The "whole-body" or "overall" general patterns are terms indicating the patterns that correspond to the total field of view of the recorded surface geometry as opposed to the term "local pattern" which corresponds to defect localisation in a part of the "overall"

general or whole body pattern of the surface system. The "local vs. overall" ratio shows percentage of anomalies used in priority maps and for the evaluation of deterioration [15]. In order to correlate the fringe pattern to type of defect a classification table is used. The most common patterns that are formed because of a construction fault are shown in Table 2 [15, 27]. The column "Real Example" in Table 2 illustrates details of interferogram results of previous studies on variant objects in our lab with the same technique and will be used further in this study.

Table 2. Fringe pattern Classification.

Graphical Representation	Name	Real Example	Observed Features	Possible Cause
	Circular Fringes		<ul style="list-style-type: none"> • Closed and Open curves • Smooth direction change • Continuous curves 	Internal detachment or void
	Curved Fringes		<ul style="list-style-type: none"> • Open curves • Smooth direction change • Continuous curves 	Internal crack or detachment, propagation
	Dead-end Fringes		<ul style="list-style-type: none"> • Preservation of fringe direction • Non continuous curves 	Surface crack
	Density changed Fringes		<ul style="list-style-type: none"> • Usually combined with other patterns • Variable fringe curves 	Trends
	Direction Changed Fringes		<ul style="list-style-type: none"> • Abrupt direction change from one direction to another • Continuous curves 	Material change or surface bending

Uniform symmetrical arrangement of fringes manifests in whole body displacement [10], while breaks in symmetry of fringes manifest in local displacement due to defect presence with each defect manifesting in characteristic form of loosing symmetry and topology. As expected, the number of artworks presenting a homogeneous state is limited as most of the artworks are multilayered and consist of numerous mixtures of materials. Examples of secondary interference patterns are shown in Figure 7. These are common fringe patterns though generated by mostly organic materials which carry defects of known or unknown origin [28].

Although each work of art presents unique structural profile the interpretation of the structural characteristics and imperfections in the form of fringe pattern reveals similar behavior and does not depend on artwork type. Objects consisting of different materials exhibit similar geometry on the resulted interferograms [24, 29-32]. Thus a mural or a canvas can exhibit similar anomalies of the fringe patterns corresponding to same types of defects.

3. Considerations on Interference Patterns for Artwork Analysis

In order to use interference products as a means to diagnose complex structural condition the protocol of *fringe pattern formation* and *fringe pattern identification* is established. Interference fringe pattern formation is optically ensured by use of the strict boundary conditions of optical geometries and physical principles. The fringe pattern identification in regards to the fringe pattern expressed variability in complex structural conditions is

still under development. Fringe patterns are used for quality control. The quality control accepts standards in fringe pattern formation with fringe deviations being defined as deviations from normal fringe distribution in terms of spatial frequency and angle of inclination indicating respectively the amplitude and direction of force. In industrial applications the principle of fringe deviation finds optimum applicability. Tested components in industry present standard fringe patterns with fringe distribution and fringe deviations indicating faulty components in order to be dismissed from the production line. Deviations are considered both at fringe number density, orientation and fringe pattern shape, e.g. in water pipe construction testing fringe number indicates the reaction to pressure while fringe shape and orientation identifies the defective pipes. Same standards stand in optical and microcomponents testing industries [10].

In order to use the interference fringe in art conservation structural analysis and diagnosis the above definition of fringe pattern indicative deviations is expanded to advanced complexity forms. In regards to the fact that artworks are unique objects of irreplaceable value to be preserved and maintained the fringe pattern complexity cannot be overlooked and must be solved. Artworks and cultural heritage objects present a plethora of interrelated defects due to aging of material and structural physicochemical degradation. The task to assess structural condition becomes more complicated according to the artwork construction and age and equally the assessment of degradation to a diagnostic conclusion becomes more challenging.

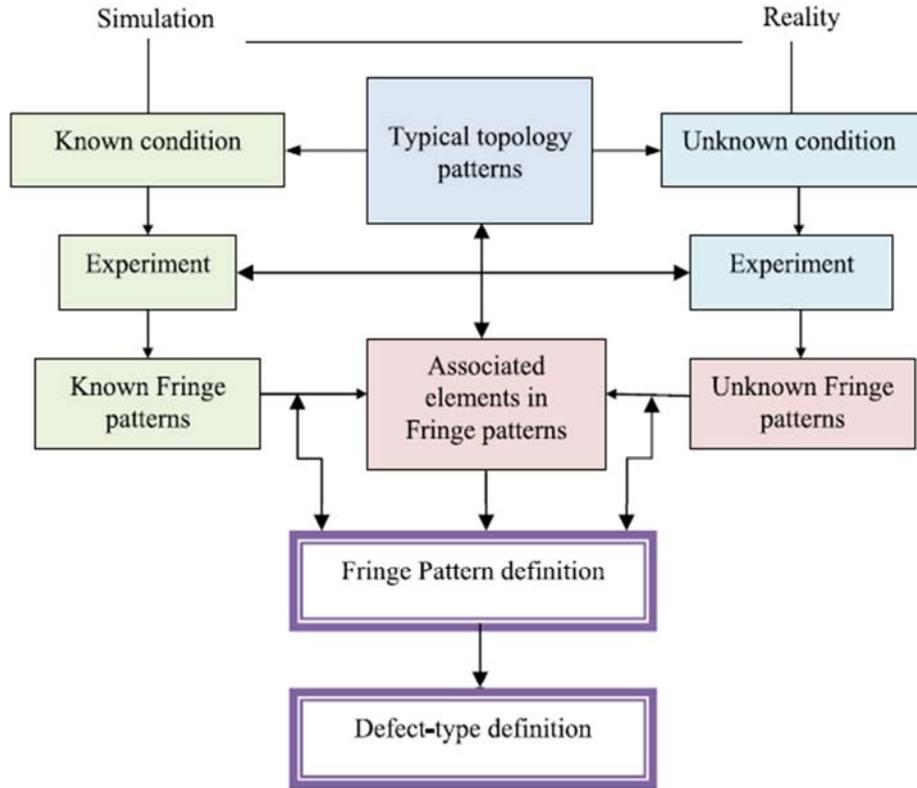


Figure 8. Interconnection Scheme of stepwise procedure to validate defects through unknown fringe patterns in artwork documentation.

According to the various defects which commonly occur in aged artworks, various morphologies of fringe pattern shapes are generated. In direct visual qualitative documentation using fringe pattern maps the task is to successfully locate and isolate the various local morphologies of fringe patterns. The next step of diagnosis is to correlate the local morphology to the type of defect that it represents and suggest the reason of the subsurface problem. This is to signify from its effect on the surface the fringe distribution captured from the surface reaction and defines the subsurface problem. This is the step in which it is important to apply the maximum amount of prior knowledge or predictions about the physical quantities to be determined and get the data that can define the unknown defect. In the case of artworks this means to study the method of construction and materials from which the defect generation is dependent e.g. detachments are generated only in between two-layered or multilayered constructions. The lack of studies on fringe pattern morphologies in association to defect-type in artworks required a long-term validation study on samples simulating various artworks and their defects. Therefore the anticipated method to validate defect type relies on the experimental verification between the fringe-patterns generated by controlled known defects to fringe-patterns generated by unknown defects. The schematic operational diagram in Figure 8 [10] is followed to associate simulation with real case. Hence fringe patterns not only show a defect location but define the defect type. It is important to use the diagnostic strength

that fringe patterns hold, otherwise it is not possible to define the defect type without the visual appearance of a fringe-pattern by relying only at the fringe density as a source of information.

4. Results and Discussion

4.1. Fresco

The investigated subject is a fresco and belongs to a private collection (Figure 9). Although there is insufficient evidence for the origin of the object it is likely to have been a ceiling painting i.e. part of the decoration of a ceiling. The last layers of mortar have been detached from the ceiling and fastened onto a linen cloth and a wooden frame.

4.2. Localization of defects by Fringe Patterns

The object is examined by all three configuration types suggested in this study (FC, BC and FBC) and the resulting interferograms are analyzed for structural information of the subsurface. In order to investigate the structural mechanical condition and to detect defects on the fresco an analysis of three stages is performed. Initially, each interferogram is analyzed in individual areas of interest. Each area of interest is recognizable as it forms a local discrete appearance consisting of one or more distinguishable fringe patterns and it can be confirmed by 2d and 3d maps constructed by the system's software (Figure 10).

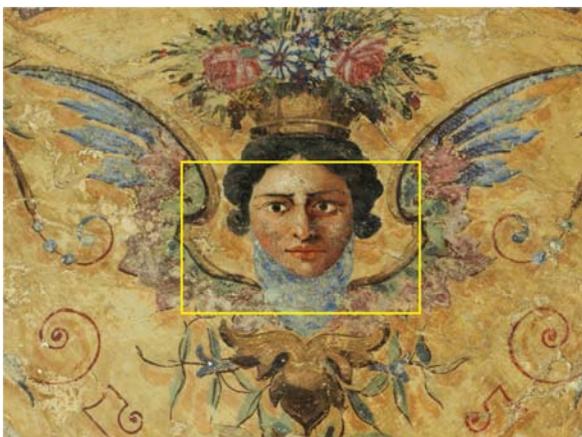


(a)

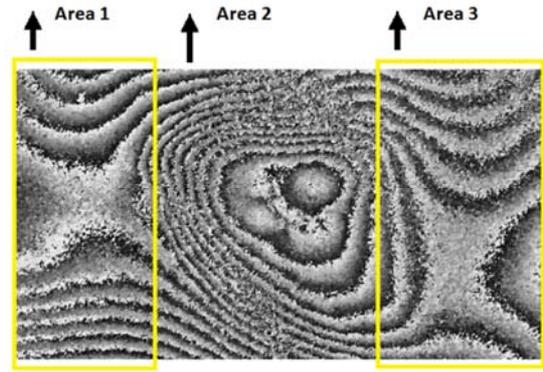


(b)

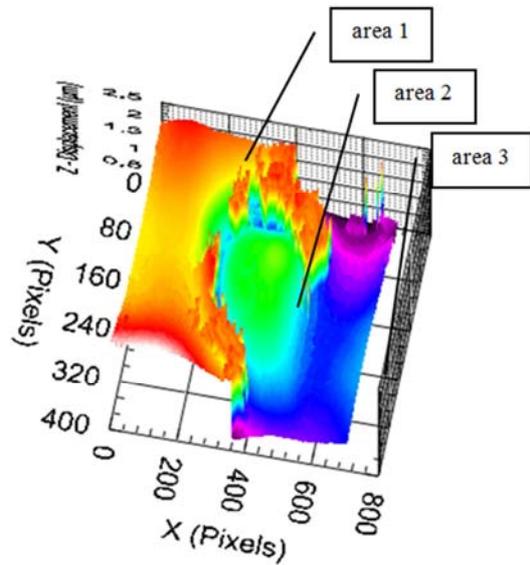
Figure 9. Object of study: (a) front view, (b) rear view.



(a)



(b)



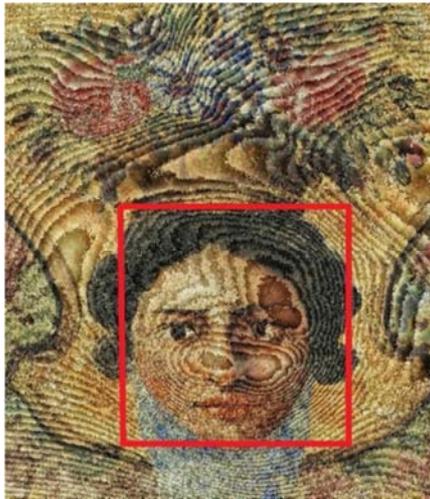
(c)

Figure 10. Exemplary of how structural information is assessed: (a) investigated area in the yellow box, (b) interferogram view and in (c) 3d view.

Then, each region is isolated and the fringe patterns are located. An example of the first two stages of fringe classification is given in Figure 11. The classified fringe patterns presented on Table 2 are used.



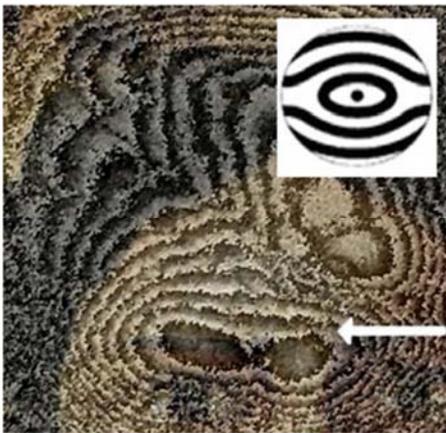
(a)



(b)



(c)



(d)

Figure 11. In (a) The investigated area of the fresco, in (b) an exemplary interferogram of the fresco and selecting the area of interest in red box, in (c, d) a characteristic detail of local curved fringes discontinuity and a detail of local discontinuity identified as circular fringes. The formation represents crack with lateral multiple detachment growth.

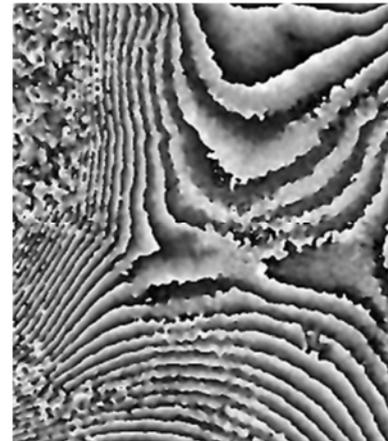
Carrying this procedure for each area and pattern formation a detail defect detection map is achieved.

Finally, the interferograms with the detected fringe patterns are examined temporally. Priority is given on

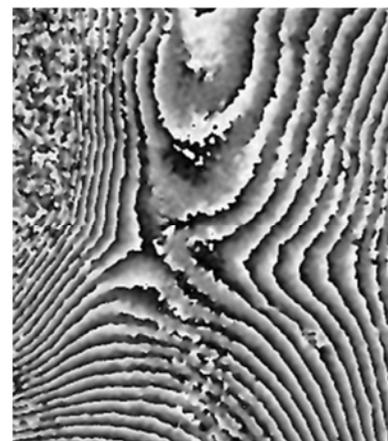
formations with strong presence and persistence in time. Figure 12 shows an example of a saddle formation appearing first time at $t=6s$. It remains present in a stable form and unaffected by the adjacent formations until $t=77s$. The specific formation persists over time suggesting a laterally stressed area of high defect interest for conservators. It took ≈ 70 seconds for a saddle shaped deformation to appear and disappear visualising and indicating the deformed shape of displacement for the areas 1 and 3 of fig10b.



(a)



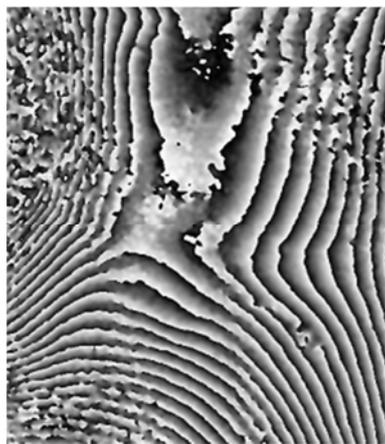
(b)



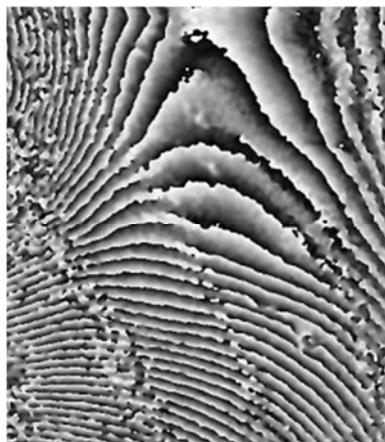
(c)



(d)



(e)



(f)

Figure 1. Saddle formation of the investigated area shown in the yellow box (a) over time for (b) $t=13s$, (c) $t=24s$, (d) $t=48s$, (e) $t=70s$ and (f) $t=141s$.

4.3. Structural Diagnosis by Synthesis of Data

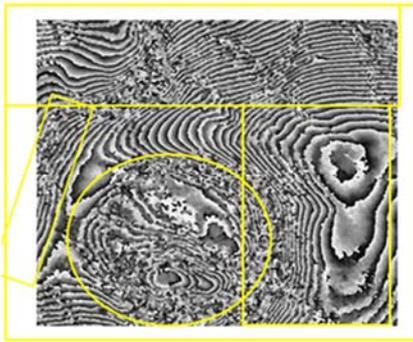
Depending on the excitation arrangement used and the duration of data visualisation is synthesized the information about the structural condition of the investigated object.

a) Back excitation: A back configuration is applied on the fresco (Figure 14a) in order to determine whether the object is safely well glued to the grid canvases. The results show

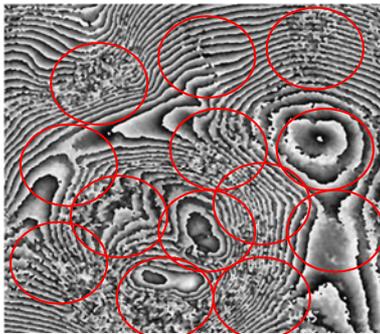
that the support effect on the surface indicates impact within safe limits. This information is found in the immediate response of the monitored front surface which in the back configuration is getting excited only by the thermal diffusion from the back surface forward to the front surface. It is revealed by the fast presence of fringe patterns on the monitored surface from the start of the recording time that indicates the direct influence of the substrate to the monitored surface. If it was not well fixed the fringe formation would require longer time. This observation, which is repeated with the immediate presence of fringe pattern in all tests during the back protocol examination confirms that the surface is well adhered to the mesh canvases. Hence the painting has good adhesion and re-framing is not needed.

b) Front excitation: The examination of data from the front surface examination revealed three scales of defect interconnection. There are a) largely expanded deterioration centers covering the painting all across surface, within which exist b) smaller scale multiple localised defects and in many of them include c) locally intense microdeformation structures. These deformation centers propagate and interact enhancing in locally strict defined areas the degradation of materials and promoting the overall surface degradation. As such the image of the front surface manifests high magnitude of local defects indicating strong front surface deterioration. In addition it is important for restoration strategy that the painting surface is divided in centers starting of those of large regions as in yellow boxes in fig 13a, in which deformation covers significant surface area as seen with sparse and dense spatial distribution range of fringe patterns that generates clear divisions in the interferogram image. Hence, larger but sizeable areas of the valuable surface exhibit diverse reaction to thermal impact. These areas are expected in future times to be exacerbated if the cause of the trends not addressed by experienced conservator. Emphasis of the analysis is given to the central theme of the painting (the depicted face) which proves to be a separate, with clear limits, area of intense defect overlapping where cracks generate detachments and detachments generate cracks (Figure 13 a-c). Expanded fringe systems are easily distinguished in fig 13a and correlated to the painting areas, then local defects fig 13b including microdeformation systems fig 13c are extracted, as it is shown by yellow and red circles in Figure 13a-c. In the figure 13d-f, after the wide regions including smaller interconnecting defects are extracted, further temporal elaboration to distinguish microdeformation shapes as rise with time within the previous areas can be performed. The color 3D map can be overlapped to the painting to highlight the final diagnosis result (fig. 14c). The revealed complex defect system is assigned to past restorations and the intense deformation suggests a condition that new defects are or would soon be formed. This conclusion is synthesised by the evaluation of the temporally consistent fringe patterns which are considered existent defects as compared to trends of fringe patterns as they propagate with time which are considered as inborn defects. It is common to observe long term

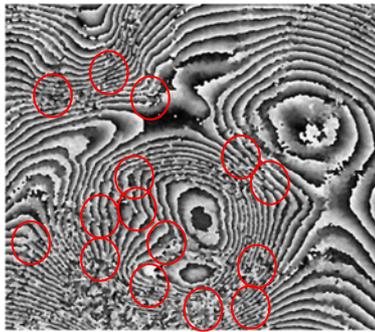
appearance of interference patterns with fringe patterns that appear inconsistently in shorter time periods. The temporal evaluation is used to reveal depth positioning as well as foresee new defects.



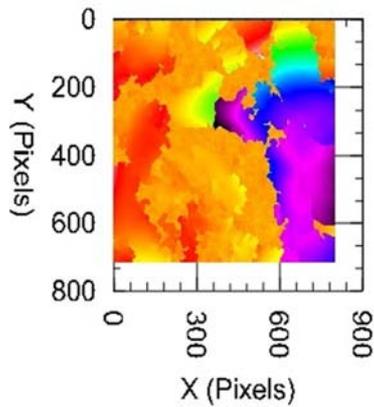
(a)



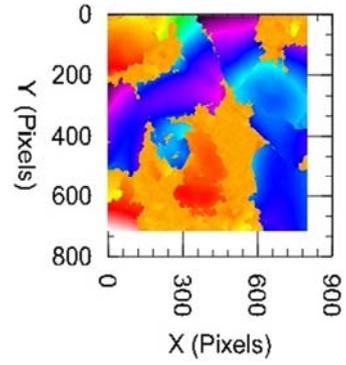
(b)



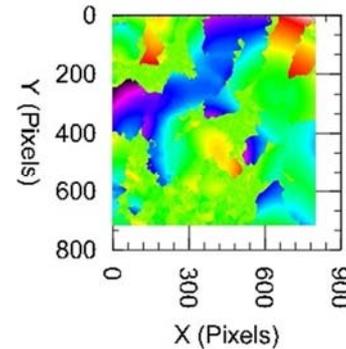
(c)



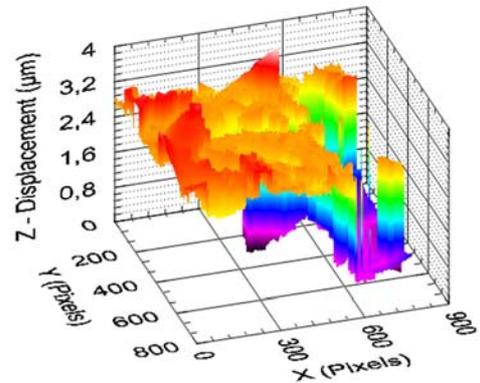
(d)



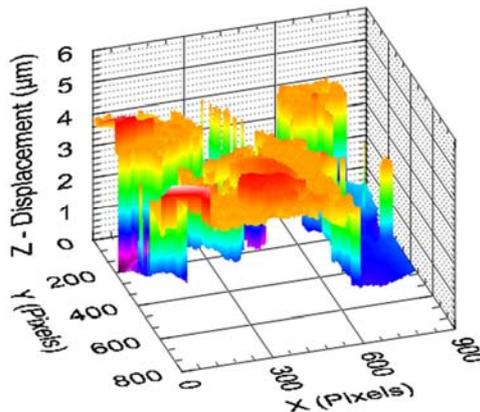
(e)



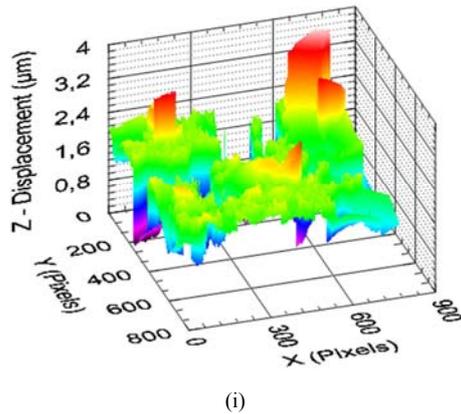
(f)



(g)



(h)



(i)

Figure 13. In (a-c) exemplary interferograms for $t_1=41s$, $t_2=106s$ and $t_3=156s$, in (d-f) the 2d surface for t_1 , t_2 and t_3 respectively and in (g-i) the 3d images with the z-displacement for t_1 , t_2 and t_3 respectively.

Finally, the painting is examined by overall excitation (Front-Back configuration). The FBC revealed and confirmed the previous observations. The wide areas include also within their abstract boundaries localised fringe patterns with further locally defined microdeformations without changing the overall estimation of the structural condition or the understanding about the response of the surface and the locally limited and locally stretched areas. Also the previous remark of immediate priority on restoration of the main theme, the depicted face, is confirmed as of major priority.

Finally a risk priority defect map is synthesised and is shown in Figure 14, as has been traced from examination of area 2 figure 10b the central theme of the painting, indicating the positions, shape and size of the existent defects with the colors indicating the type of defect. Priority is given to the deteriorations that persist during examination because it concerns the full thickness and represent defects that affect most the surface. These require immediate care. These are areas that once fixed can stabilise the overall tendency for deformation of the painting. In this context the map is termed risk priority map and can be used as an accurate guide by the conservator to locate the major points of interest during restoration process.



(a)



(b)



detachment internal crack surface crack trends

(c)

Figure 14. In (a) the central theme of the fresco, in (b) an overlapped exemplary interferogram and in (c) the Risk Assessment Map.

5. Conclusions

The use of interference fringe patterns in investigating the structural condition proved to be a procedure revealing rich information content for structural diagnosis far beyond conventional and other widely used methods; but requires skilled personnel with advanced training and prior knowledge about the artwork and the ability to synthesize complex data. The knowledge one should combine and make a synthesis of procedures and information is tedious but unique. In this article it has been chosen to be shown the manipulation of data over the developed automation routines and software tools due to the high educational and research potential that the synthetic ability offers to a scholar. The classification of interference fringe patterns as indicators of structural condition and the synthesis of data as indicators of risk is used to define the position, size, type of defects and to assess overall structural condition and immediate structural risk of deterioration in artworks. This

information properly addressed can be an aid to solve many ambiguities in restoration processes. The development of a portable system based on remote digital acquisition of consecutive holographically generated speckle patterns (DHSPI) provides a recording system of the highest information content to assess a vast range of art conservation problems on-field.

The investigation of a fresco attached on canvas based on interference fringe patterns and the fringe pattern evaluation methodology showed that although the painted artwork has immediate maintenance needs as illustrated by the priority maps its mechanical integrity is safe and canvas and frame change are need not be of immediate conservation actions. However, the overall consideration and overall assessment of the structural condition of the fresco related to the maintenance status of the fresco to date indicate that for the optimal management of the conservation problems it is recommended to fix thoroughly the indicated faults and imperfections. The examination of the substrate indicates that the time the painted surface was glued to the canvas's grid is relatively recent. The presented application demonstrates only a small fragment of interferometry's capabilities in the qualitative diagnosis in cultural heritage field but this technique has far more uses as for example could also be used to compare fastening methods or the state of the artwork before and after conservation or before and after transportation, assess environmental impact, compare holding and display methods, as well as to examine the effects of conventional conservation techniques to their optimization and numerous other applications for which methodologies are defined according to the problem [8, 9, 24, 30, 33-35].

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