Optical techniques for the characterization of surface-subsurface defects in painting layers

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ABSTRACT

3D optical techniques are proven to be useful for the study of the artwork's surface morphology because they allow non-contact and noninvasive measurements. Detailed topographic analysis of the surface including a quantitative evaluation of defects related to the painting layers can be performed by means of holographic conoscopy on a micron scale. Moreover, artwork surfaces can be examined with suitable 2D optical techniques in the IR range to investigate defects at a subsurface level. In particular, thermography in the Mid-IR band 3-5 micron allows the detection and spatial mapping at a suitable resolution of the delamination of painted layers. An integrated model of the surface-subsurface defect distribution can be obtained by superimposing the results of the two above techniques, for a more effective analysis and monitoring of the delamination decay typology according to the specific case study. The delamination of organic paint layers from inorganic support is a decay that affects many wall paintings based on both traditional (oil and tempera) and synthetic media (acrylic and vinyl copolymers). Defining the factors that cause delamination, finding out strategies to restore the adhesion between paint layers and support, and monitoring the restoration intervention are fundamental conservation objectives. This paper investigates the feasibility of a joint use of holographic conoscopy and IR thermography for exploring the delamination decay typology of ad hoc laboratory samples. Set up includes a scanning micro-profilometer, and a thermal PtSi camera with a controlled IR source to provide heating stimulation.

Keywords: thermography, optical micro-profilometry, paint layer delamination, wall paintings, artwork topography, 3D survey, data integration

1. INTRODUCTION

Structural decay of wall paintings is a complex problem involving a variety of materials, decay typologies, conservation, and environmental conditions[1]. One of the needs for properly studying and preserving wall paintings is finding out adequate non-invasive diagnostic methods that allow *in situ* detection and mapping of sub-surface defects, as well as their monitoring after consolidation treatments[2]. The delamination of organic paint layers from inorganic support is a decay that affects many wall paintings based on both traditional (oil and tempera) and synthetic media (acrylic and vinyl copolymers). Defining the factors that cause the delamination, finding out strategies to restore the adhesion between paint layers and support, and monitoring the restoration intervention is a fundamental conservation objective for such kind of artworks[3-4].

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3D optical techniques are proven to be useful for studying the surface morphology of artworks, allowing noninvasive and non-contact measurements. Surface maps at different scale and resolution are acquired according the specific case study, i.e. target object and purpose of investigation, to produce the effective 3D survey[5-6]. In particular, a detailed topographic analysis of the surface on a micron scale can be performed by means of holographic conoscopy[7-8]. Even if the problem of surface analysis and characterization is still open when dealing with an artwork, and there is lack of rules in this application field in metrology, it is clear that a quantitative surface analysis including waviness and roughness computation may have many potential applications[9]. 3D microprofilometry is rarely applied to the study of paintings, mainly because of the difficulty to produce a reliable model with field instrumentation, besides the non-immediate legibility of the result, which requires a careful numerical processing. The technique can be effectively used for a quantitative evaluation of defects and features related to the pictorial film, e.g. detaches, differences in the thickness of the painted layers, and cracquelure patterns, whereas traditional methods such as raking light photography do not provide a numerical model.

Optical techniques in the infrared (IR) range are being widely used to examine the features underneath the artwork surfaces, given the diffusion capabilities of the IR wavelengths and their noninvasive character. In particular, IR thermography is effective in detecting the presence of inhomogeneous materials, sub-surface or structural defects, which can be revealed because of the induced thermal anomalies on the surface[10]. Thermal maps are acquired, in passive/active mode, in order to obtain a suitable thermal sequence of the investigated surface, which can be put in relation with the deep structure of the object according to the heat diffusion theory. The effectiveness of the technique depends on many parameters, related to both target object and experimental set up, including the environment. IR thermography is mostly performed in the Far-IR range 7-15 μm with bolometer sensors, and it was successfully applied to the analysis of the support of paintings and frescoes[11-13]. Recently, thermography in the Mid-IR range 3-5 μm with PtSi or InSb sensors was applied to the investigation of mural painting superficial layers[14]. The problem of mapping delamination of painted layers is crucial and less explored[15-16].

This research investigates the feasibility of a joint use of holographic conoscopy and IR thermography for the diagnostics of delamination defects in painting layers, by exploring the decay typology of ad hoc laboratory samples and fresco models. Efforts are addressed at finally developing an effective nondestructive testing method for wall painting examination, based on portable devices, and able to provide quantitative dataset related to both surface and subsurface defects.

2. INTEGRATED METHODOLOGY

2.1 Holographic conoscopy for surface defects micro-profilometry

Surface analysis is performed with scanning micro-profilometer based on holographic conoscopy.

The working principle is sketched in Figure 1. The laser beam reflected by the sample interacts with the uniaxial birefringent crystal placed between two circular polarizers and an interference pattern is generated. Surface heights, i.e. optical path differences, are computed from the interference fringes recorded on the CCD camera. The micro-profilometry works on surfaces with almost any reflectivity, it is not sensitive to color gradients, and allows the survey of very small details, like holes of < 1 mm diameter and 25:1 ratio between quota and diameter[7-8].

The scanning micro-profilometer is a custom assembled device based on a commercial conoscopic probe mounted on two motorized high-precision linear stages (Figure 1). The probe is equipped with a 50 μm lens which sets a quota resolution of nearly 1 μm, and a dynamic range of 8 mm at 40 mm stand-off distance. The overall accuracy is better than 6 μm. The system allows measurement on a maximum area of about 300x300 mm^2. The instrument has a maximum transversal resolution of 20 μm, with an acquisition speed ranging from 100 to 400 point/s depending on the set spatial sampling frequency. The whole system is computer controlled. The final 3D maps are computed with a custom software.

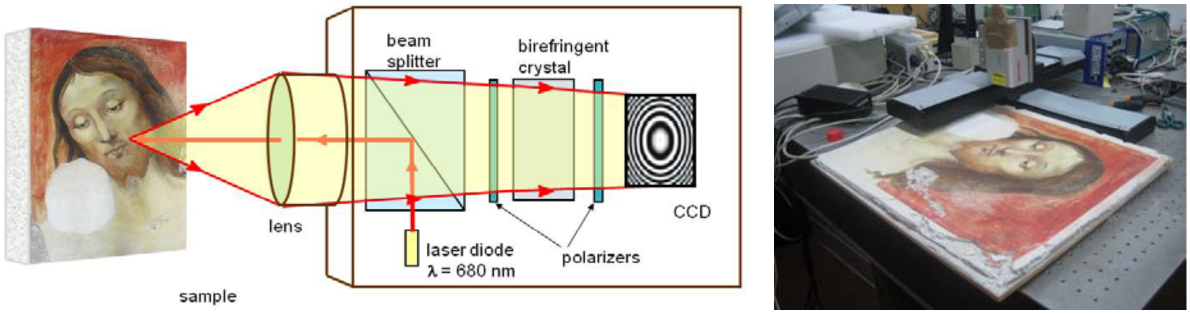

Figure 1. 3D holographic conoscopy. Sketch of the principle and micro-profilometer scanning device.

2.2 Pulse Mid-IR thermography for subsurface defects mapping

Subsurface analysis is performed with pulse thermography in the Mid-IR range 3-5 µm.

A pulse heating is applied on the target surface, and the thermal maps sequence of the heat decay, on the target surface, is acquired. The surface temperature value is affected by the reflection of thermal waves from subsurface features causing anomalies that allows the detection of material "defects", e.g. subsurface voids, such as the delaminated areas in painting layers[10].

The thermographic device is a Nikon LAIRD-S270 camera, based on a cooled PtSi detector (475x442 pixels) with spectral sensitivity in the Mid-IR 3-5 µm, -20°C÷250°C temperature range at resolution of 0.2°C. Initial heating or pulse heat stimulation is provided by a controlled IR lamp. The target surface was illuminated orthogonally with different IR sources (tungsten 500W lamp and low voltage halogen lamp), varying either the pulse length or the distance between source and samples. The thermal response decay is stacked in high spatial resolution maps for MATLAB computing. Figure 2 shows the measurement set up.

Testing of suitable measurement condition was done in order to find out the more effective short term heating, together with a safe (as minimum as possible) temperature gradient for the artwork, and an acceptable trade-off between smallest resolved feature and field of view[15]. The final sampled pixel at painting surface is less than 500 µm.

Figure 2. IR thermography. Measurement set-up.

2.3 Integrating the information

An integrated map of the surface-subsurface defect distribution can be obtained by superimposing the results of the two above techniques, for a more complete analysis and monitoring of the delamination decay typology according to the specific case study. 2D thermal map provided by Mid-IR thermography contains the thermal anomalies of the surfaces, which are related to subsurface defects but also to emissive materials, e.g. black pigments, in the superficial painted layer. 3D surface profilometry provides heights data related to surface topography, giving a quantitative model of the form, waviness, and roughness, thus mapping defects at a superficial level. Integration of the two dataset provides a documentation at both subsurface and surface level. On one hand, it solves some ambiguities regarding the thermal anomalies and confirms the interpretation of thermal map in some cases. On the other hand, the surface defects mapped quantitatively in the micro-profilometry can be evaluated, at some extent, also in their contribute at a subsurface level.

3. MEASUREMENTS AND RESULTS

3.1 Laboratory samples

The proposed integrated approach was first tested on laboratory samples, with the aim of analyzing 3D surface topography and thermal responses due to both different defects and different properties of the paint layers (chemical composition and thickness). In order to evaluate the feasibility of the method for the examination of genuine wall paintings a set of mock-ups, differing in paintings techniques and decay typologies, was tested.

Models of fresco, based on traditional techniques (tempera grassa on mortar support), were provided by the restoration centre Opificio delle Pietre Dure, Florence Italy. Such models have been exposed to different conditions and treatments for mural conservation, and are subject to a variegate decay, thus matching the case of a real ancient painting (concurrent use of different painting techniques, different decay typologies, and traces of past restoration treatments). The case study presented in this paper, as an example, is shown in Figure 3.

Further testing was carried out on samples resembling contemporary murals executed with synthetic binding media on cement lime mortar support[15]. This series of samples included: a mock-up presenting a partially detached paint layer (80±10 μm thick), cast with a commercial emulsion paint based on an acrylic copolymer; a mock-up set based on commercial emulsion paints, which differ in binders and pigments (Figure 3). Delamination of the paint layer from the support was induced by capillary absorption of water.

Figure 3. The fresco model, copy by Perugino, based on traditional techniques (left); the mock-up set for contemporary materials (right).

3.2 Thermography and micro-profilometry measurements

Active thermography performed on complex fresco models was able to detect a number of subsurface defects, such as detaches of the painting layers, cracks, and subsurface defects caused by interventions. In Figure 4, the raking light image and the thermal map are reported as result, showing that the latter improves the information regarding the delaminated area with the localization at subsurface level. The most emissive areas, such as the traces of drawing or the black pigment, can be differentiated with respect to the detached area by inspecting the decreasing temperature profile. The insulating properties of the void in the delamination cause the temperature to decrease more slowly than the not damaged, high emissive area.

Thermography in the Mid-IR was applied to the monitoring of consolidation treatments in the contemporary target samples, characterized by artificial controlled delamination defects induced in laboratory. By acquiring thermal maps before and after the intervention it is possible to understand the suitability and the effectiveness of the applied consolidation treatment (Figure 5).

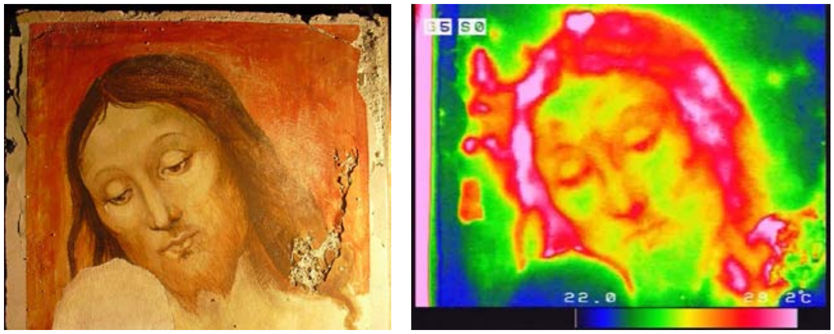

Figure 4. Fresco model. Raking light image (left); thermal map (right). The thermal map provides a map of delamination at a subsurface level.

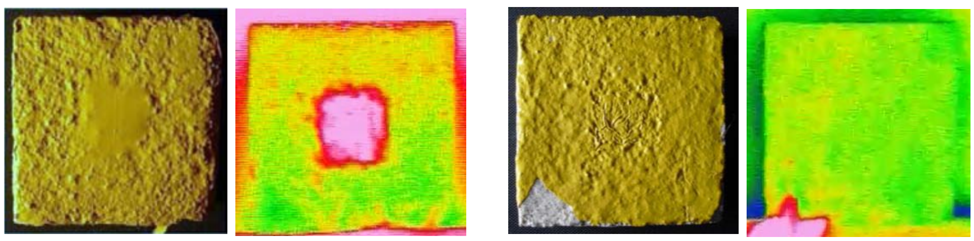

Figure 5. Contemporary target sample with a detached paint layer. Photo and thermal map before (left) and after (right) the consolidation treatment for monitoring its effectiveness.

Micro-profilometry was performed both on the fresco model, and on the contemporary target samples. For the fresco model, significative ROIs were chosen for the integration with the thermal data (Figure 7-8). Surface topography is described quantitatively in terms of heights data, at a micron scale, which can be analyzed using simple 3D visualization or profiling tools, or advanced processing for texture analysis, e.g. roughness computation. Figure 6 reports, as an example, the micro-profilometry of the target sample after the consolidation treatment, which can be used for numerical assessment of surface alterations in relation to the intervention.

The surface data map is integrated to the thermogram in order to obtain a more complete mapping of a specific defect at both surface and subsurface levels (Figure 9). Moreover, matching subsurface map to surface morphology allows, in general, a more comprehensive analysis of the defects typology, solving in some cases the ambiguities in the interpretation of the thermal results that are caused by the emissive contribute of materials (Figure 10).

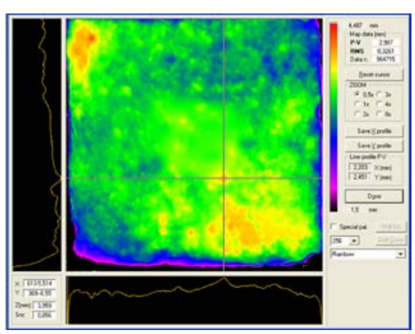

Figure 6. Microprofilometry of the target sample after consolidation: heights surface data map and depth profiles for quantitative estimation of surface alteration.

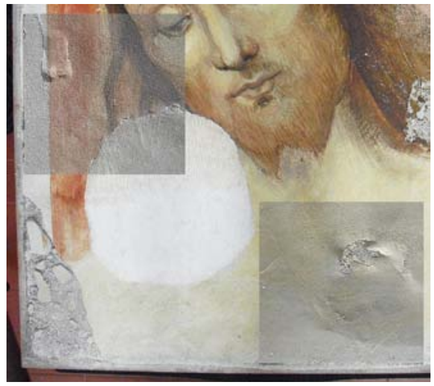

Figure 7. Fresco model. Microprofilometry (raking light model) superimposed to VIS image

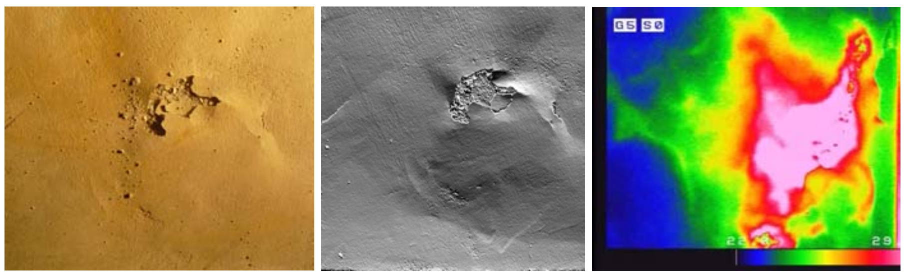

Figure 8. Fresco model. Raking photo; Microprofilometry (raking light model); thermal map

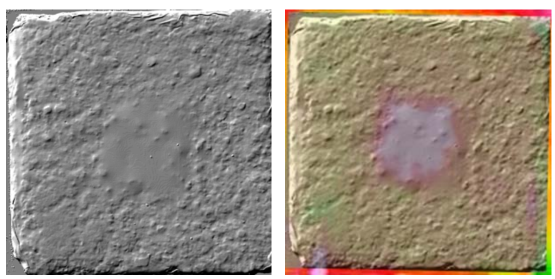

Figure 9. Raking light model from microprofilometry data (left); superimposion the raking model with the termal map for correlation of surface topography and defects to subsurface delamination before/after consolidated

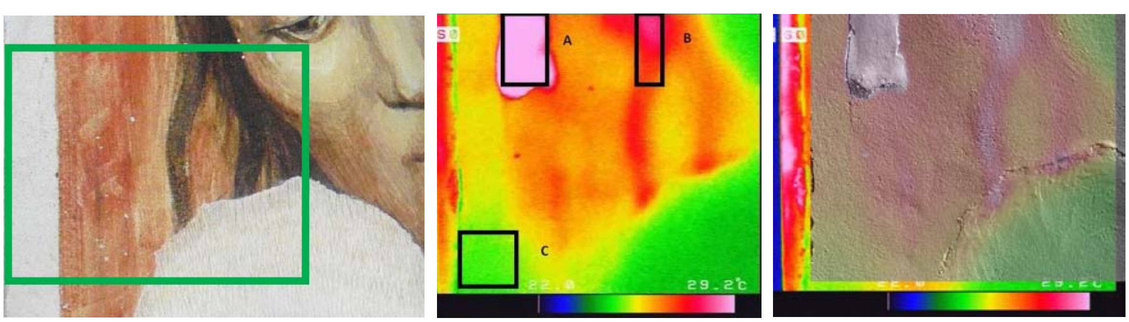

Figure 10. Fresco model: investigated ROI (left); thermal map (center); superimposition of microprofilometry and thermal map (right) for an integrated documentation of surface-subsurface defects. The detached area (A) and the emissive pigment (B) cause both thermal anomalies, but has different surface topography.

4. CONCLUSIONS

An integrated diagnostic approach based on Mid-IR thermography and micro-profilometry was proposed for a more effective analysis of delamination in wall paintings. Holography conoscopy provides 3D surface map at a micron scale allowing a quantitative evaluation of the defects related to the surface morphology of painting layers. Thermography in allows the detection and spatial mapping at a suitable resolution of the delaminations of painted layers, and of deep alteration of the support. The integrated map of the surface-subsurface defect distribution obtained by superimposing the dataset provides a multi-layered survey, which allows a more complete documentation of the different decay tipologies, as well as improve the interpretation of the single diagnostic results. Moreover it opens the way for a more quantitative analysis of the decay problem, including the effectiveness of the consolidation treatment. The feasibility of the method has been tested and demonstrated on models based on both traditional (oil and tempera) and synthetic media (acrylic and vinyl copolymers), and is going to be applied, in situ, to genuine fresco artworks in the next future.

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