Panel Paintings Inspection Analysis Using Active Thermography in the Mid-Wave and Long-Wave Infrared Region

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Abstract: Active thermography was used for characterisation of multi-layered paintings panel structures and analysis of defects caused by aging and environmental effects. Pulsed Thermography setup was applied to provide and inspect a dynamic thermal response, which was recorded by mid- and long wavelength infrared TELOPS cameras. Control, synchronization and data analyses were provided by Professional software (DisplayImg 7). Active thermography was demonstrated as being appropriate for characterization of various defects on painting layers and detection of under-drawings, pentimenti and canvas. Such multispectral approach provided simultaneous complementary information on the specimen under inspection.

Keywords: non-destructive tests using infrared cameras, active thermography

1. Introduction

Modern scientific instruments and methods are extensively applied for obtaining information on heritage cultural art objects and paintings, thus providing comprehensive in-depth investigations of various artworks.

For the studies on panel paintings and their heterogeneous multi-layer structures (concealed glues, gesso composed of glue and chalk or gypsum, paints and resin varnishes), analytical methods and procedures for their analyses allow one to study each individual layer to inspect the whole painting piece (wood frame, support, preparatory layers, paint and varnish levels) [1] and also to reveal unexpected underlying features (under-drawings, pentimenti, etc.). Analytical procedures are aimed to improve readability of artefacts undetectable by the naked eye. The obtained information may provide deeper insights for understanding the particular context behind the painting under inspection.

Indeed, paint media, such as wax, egg tempera, oils, and their combinations, can include materials of different thermo-mechanical properties [2]. External environmental effects (temperature, humidity, condensation-vaporization, air pollution, inappropriate light exposure, presence of bacteria, etc.) may cause mechanical deformations, like expansions and contractions of different zones on the layered structure. These deformations can be amplified by natural aging and may affect mechanical properties of each layer and, eventually, result in detachments, delamination, powdering and development of cracks [2, 3]. A non-invasive investigation of layer-by-layer of a painting may allow one to gain a better insight in defects formation and also to understand the specific modus operandi of the artist. Among numerous non-destructive diagnostics [4], active infrared (IR) thermography may be mentioned as a well-established technique [5, 6], which may provide a fast inspection of large surfaces.

Active thermography was used for characterisation of multi-layered paintings panel structures and analysis of defects caused by aging and environmental effects. Pulsed Thermography, was applied to provide and inspect a dynamic thermal response, which was recorded by mid- and long wavelength infrared TELOPS cameras. Control, synchronization and data analyses were done using a professional software (DisplayImg 7). Active thermography was demonstrated as being appropriate for characterization of various defects on painting layers and detection of under-drawings, pentimenti and canvas. Such multispectral approach provided simultaneous complementary information on the specimen under inspection.

Active IR thermography for Heritage Science studies can provide inspection of subsurface layers. Due to the sensitivity of this method to different pictorial materials, it is possible to probe down to the preparatory layer to inspect possible under-drawings, subsurface defects as described before and the presence of nails as well. During active infrared (IR) thermography application, the surface of the inspected painting panel is heated by an external source in order to produce a dynamic thermal response, which can be detected and recorded with an infrared camera. A mid- or long-wave Infrared (MWIR or LWIR) camera is used

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to measure a thermal flux emitted by the specimen as a response to the excitation. Temperature estimation is performed on IR radiation emitted from the surface. MWIR or LWIR camera displays and records the corresponding evolution of thermal contrast. However, LWIR measurements are usually less sensitive to ambient illumination, while MWIR band exhibits a lower optical diffraction and background radiation, which results in a sharper imaging with a higher contract. Also, using the spectral distribution of the emitted energy, it may be estimated that a blackbody at 293 K emits only 1.1 % of its energy in MWIR band, compared to about 42.4 % in LWIR band.

In this work, Pulsed Thermography (PT) was used for a non--simultaneous two-spectral band (LWIR and MWIR) inspection of two old oil compositions painted on canvas (Fig. 2a and Fig. 2b) provided by Centre de Recherche et de Restauration des Musées de Francethe (C2RMF) of Louvre Museum. PT method may be seen as one of the earliest one among those of active IR thermography [7]. The method is often referred to as "flash thermography" since in its classical configuration, a set of photographic flashes is used to heat the surface of the inspected object.

Advanced processing techniques are required to analyse the acquired data. In our study, we applied Pulsed Phase Thermography (PPT) [8–13]. The results of our study have demonstrated that active IR thermography in MWIR or LWIR may allow both characterization of internal defects and in-situ inspection of paintings for detection of under-drawings, pentimenti and analysis of preparatory layers and canvas, thus providing valuable insights into artwork history and useful pre-restoration information.

2. Materials and method

2.1. Active termography set up

In our studies, an active thermography setup was used (Fig. 1) for analysis. This systems series offer non-destructive testing solutions for the evaluation of components or assemblies and subsurface defect detection without damaging the materials. The active thermography solution combines a Telops high end thermal infrared camera with deferent external excitation sources solutions and a user-friendly post-processing software. Optical excitation sources such as flash and halogen lamps or lasers are available along with electromagnetic and mechanical sources (inductive coils, ultrasound generators). A wide range of solutions are available from basic systems to compact integrated systems with a variable level of automatization depending on the customer needs and constraints. Experiments shown in this paper comprised two flash-pulse excitation sources were used (two Hensel flash-lamps with a Hensel Tria 6000-S high-power flash-pulse generator), an infrared camera, and NDT software. The maximum output power of each excitation source was 6 kJ, and a flash-pulse length was about 3 ms. Thermal response of each specimen was measured by high-speed, high-sensitive cooled IR cameras (TELOPS), such as MWIR (FAST M350, 1.5–5 µm) and LWIR (FAST L200, 7.5–11.5 µm), having 640 × 512 pixels resolution and ~20 mK NETD at 25 °C. An optical lens (50 mm focal length) and the camera/specimen distance in the range of 0.8–3 m allowed one to obtain the spatial resolution between 200 and 900 µm/px. The camera frame rate was 100 Hz, and the acquisition duration was about 30 s.

2.2. Samples

In this work we analysed two panel paintings from C2RMF of Louvre Museum. The first painting shown on Fig. 2a is about 26 cm × 32 cm in size and was made in the XIX century. The painted scene represents a river with a bridge connecting two parts of a town. The top right part of the painting was peeled off for previous analysis (not discussed in this paper). The second painting depicted on Fig. 2b is about 46 cm × 55 cm in size and represent a replica (46 cm × 55 cm) of Frans Hals, La

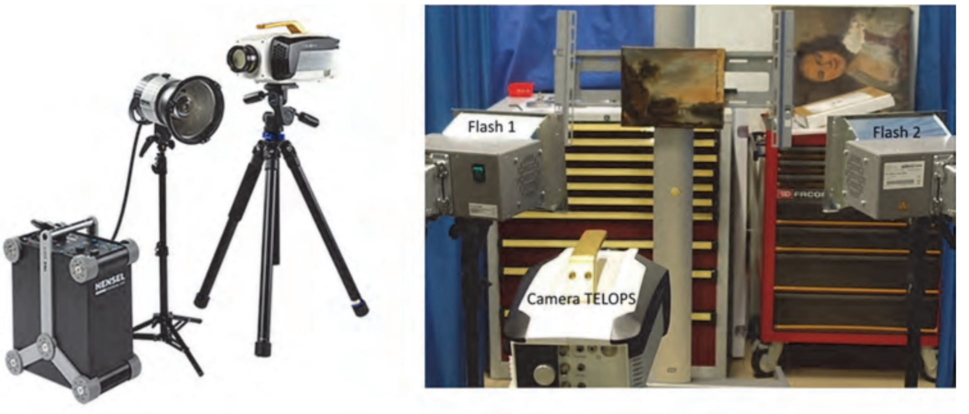

Fig. 1. Active thermography set up and experimental configuration including the paintings, Telops camera and two flash lamps
Rys. 1. Aktywny zestaw termograficzny i konfiguracja eksperymentalna obejmująca obrazy, kamerę Telops i dwie lampy błyskowe

Fig. 2. Photographs of the paintings analysed by active thermography;
a – XIX century small painting (26 cm × 32 cm), XIX century;
b – replica of Franz Frans Hals (46 cm × 55 cm88 cm × 88 cm)
Rys. 2. Fotografie obrazów analizowanych za pomocą aktywnej termografii;
a – XIX-wieczny mały obraz (26 cm × 32 cm), XIX wiek;
b – replika Franza Halsa (46 cm × 55 cm88 cm × 88 cm)

Bohémienne (1628–1630). This painting is a portrait of character of a smiling young lady from Caravaggism. Some parts on this painting were also intentionally peeled off for previous analysis (not discussed in this paper).

3. Results

3.1. Time dependent results

The Pulsed Thermography experiments were done in reflection mode. The panel painting sample was submitted to the thermal pulse generated by the flash lamp, this then induce non-stationary heat flow in the sample. In order to illustrate this, the thermal infrared radiation emitted by the replica La Bohémienne painting during the cooling process is measured by the IR camera as a function of time. The measurements obtained before, during and after the flash excitation and the temperature profiles of three regions of interest with different painting thickness depicted in Fig. 3 lower panel show continuous non-periodical signal decays after the temperature increase generated by the flash. One can notice that the cooling dynamic is different in the three regions, result of different heat propagation properties in those regions related to their different thermomechanical properties and thickness.

For analysis data are transformed from the time domain to the frequency spectra using the dimensional Discrete Fourier Transform (DFT). This analysis technique is referred to as Pulse-Phase-Thermography (PPT).

3.2. Phase and amplitude data

The active thermography data analysis software used in this work is DisplayImg Professional. This software provides an optimum workflow, while offering a wide range of powerful functions to analyse and post-process images and image sequences. Discrete Fourier Transform is used to compute the amplitude and the phase images. Figure 4 lower panel display an example of phase and amplitude obtained from measurements of the replica La Bohémienne. Phase data are particularly interesting for active thermography data analysis because they are less affected by environmental reflections, emissivity variations, non-uniform heating, surface geometry and orientation compared to raw thermal data. This is very important for instance for quantitative analysis.

To study different spatial resolutions and thermal behaviour of the painting surface during and after the thermal pulse excitation, the specimens were analysed at different distances from the IR camera. The obtained data were processed using DisplayImg Professional software. Signal and image must be specially processed in order to improve signal-to-noise ratio (SNR), to enhance defect contrast, to make adjustment correction for artefacts, and characterize the defects. Phase images were of a particularly interest since most of the detrimental thermal and

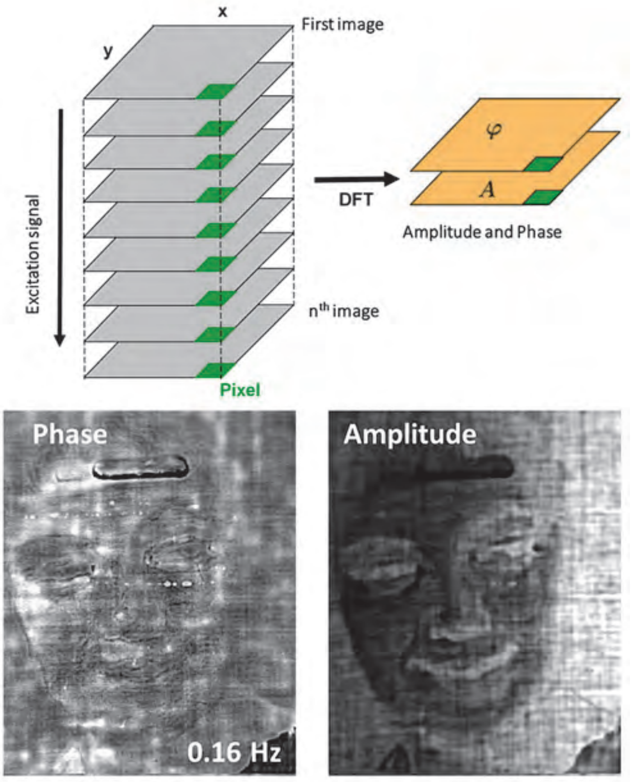

Fig. 4. Workflow of the Pulse-phase-thermography technique used by Reveal Lab software and example of amplitude and the phase images computed by the software
Rys. 4. Przebieg pracy techniki termografii impulsowo-fazowej wykorzystywanej przez oprogramowanie Reveal Lab oraz przykład obrazów amplitudy i fazy obliczonych przez oprogramowanie

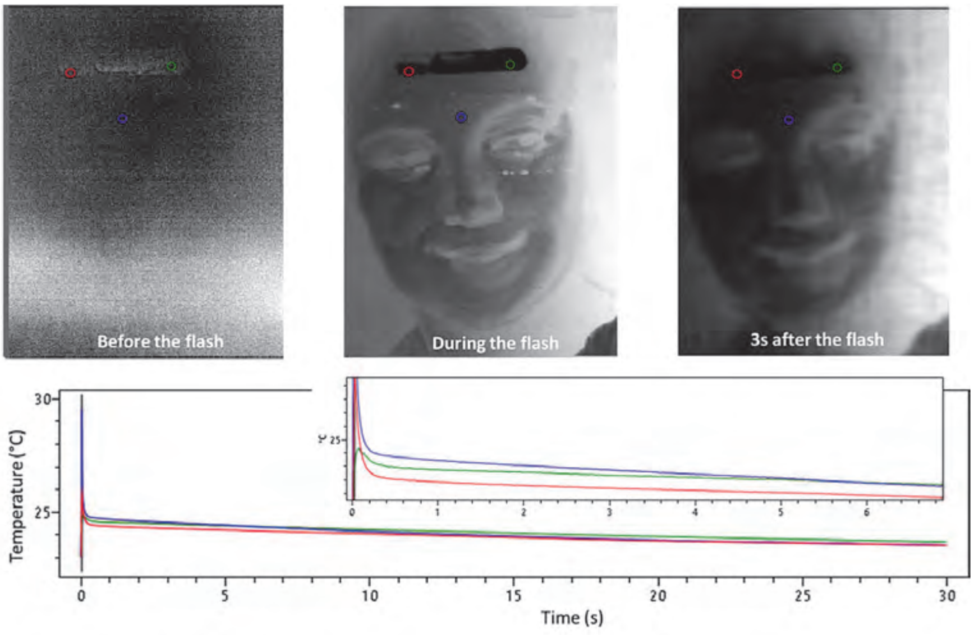

Fig. 3. Temperature map of the replica La Bohémienne recorded before, during and after the flash excitation (upper panel) and Transient temperature curve of three regions of interest with a zoom 0–7 s (lower panel)
Rys. 3. Termogram repliki La Bohémienne zarejestrowany przed, w trakcie i po wzbudzeniu lampy błyskowej (górny panel) oraz krzywa zmiany temperatury przejściowej trzech obszarów zainteresowania z powiększeniem 0–7 s (dolny panel)

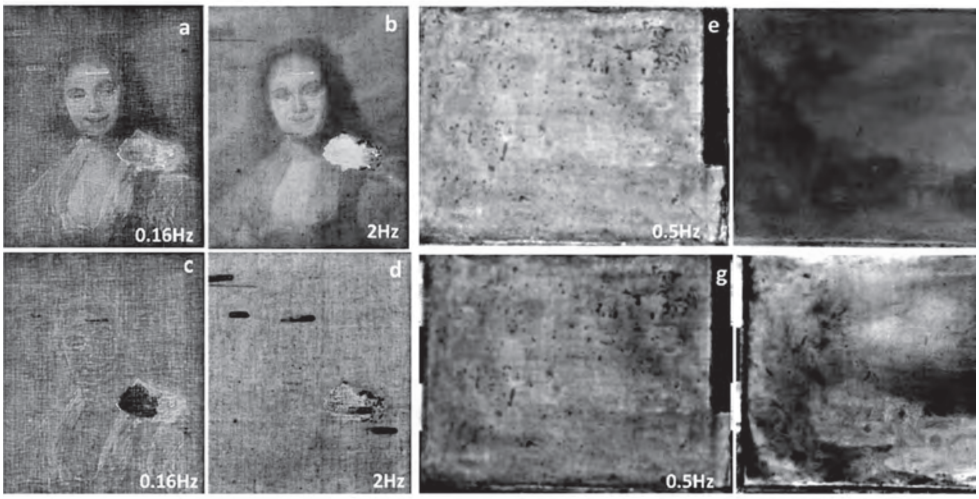

Fig. 5. Phase images of the Franz Hals replica (a, b, c and d) and small painting (e, f, g and h) in MWIR (a, b, e and f) and LWIR (c, d, g and h)
Rys. 5. Obrazy fazowe repliki Franza Halsa (a, b, c i d) i małego obrazu (e, f, g i h) w MWIR (a, b, e i f) i LWIR (c, d, g i h)

optical effects observed in PT could be considerably reduced. Figure 2 depicts some results of the Fourier transformation and phase analysis of the replica (Fig. 5a-d) and the small painting (Fig. 5e-f) in MWIR (Fig. 5a-b and Fig. 5e-f) and LWIR (Fig. 5c-d and Fig. 5g-h). In PPT, the deeper layers are seen at low frequencies, while shallow ones are seen at high frequencies. Figure 5a (MWIR) and 5b (LWIR) clearly show the textile support of the canvas. The canvas fibres are observed with the same resolution in both IR bands, thus demonstrating the potentiality of IR thermography to penetrate the paintings from the front side up to a decent depth for in situ measurements. It should be noted that the replica La Bohémienne was more clearly seen on MWIR phase images at all frequencies than in LWIR. The paint layers were intentionally removed in a limited area (see Fig. 5b) to analyse the preparation layer. Phase images exhibiting a stronger contrast were obtained in LWIR than in MWIR in this layer. Identical defects were also seen in MWIR and LWIR at 2 Hz (Fig. 5.b-d), but their contrast was higher in LWIR. The PT imaging of the small painting also allowed us to identify the canvas in two IR bands (not shown here) and many random dark spots (Fig. 5 e-g), which may be interpreted as a possible presence of glue droplets used to attach the old canvas on the new one. Indeed, previous investigations have shown that the original painting underwent a transposition in early 20th century, a common practice in restoration. The PT imaging has revealed that the painting pigments are seen more clearly in MWIR phase images (Fig. 2f, in the tree at the top left). In contrast, the painting pigments in LWIR phase images are practically not visible (see Fig. 5g for comparison). Our analysis revealed the presence of a pentimento (Fig. 5g, on the lower right part with a church steeple shape). The pentimento appears to be less detectable in MWIR images. Other features, such as underdrawings, pencil marks, were also detected during the analysis.

4. Conclusion

Infrared active thermography method appears as a promising and efficient technique for paintings inspection, appropriate for gathering valuable information on historical paintings, including their preparation and painting procedure, their history, preservation conditions, and defect analysis. All those data can be stored as Artwork unique finger print. The obtained results revealed that analysis in MWIR and LWIR may provide complementary information due to the differences between imaging in these spectral bands, the background ambient radiation and spectral response of painting constituents. It was demonstrated that active IR thermography in MWIR or LWIR may provide internal defects characterization, in situ inspection of paintings for detection of under-drawings, pentimenti and analysis of preparatory layers and canvas, thus providing valuable insights to heritage science and restoration community.

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Analiza inspekcji obrazów przy użyciu aktywnej termografii w zakresie średnich i długich fal podczerwieni

Streszczenie: Aktywna termografia została wykorzystana do charakteryzacji wielowarstwowych struktur paneli malarskich i analizy defektów spowodowanych starzeniem i wpływem środowiska. Termografia impulsowa została zastosowana w celu zapewnienia i kontroli dynamicznej odpowiedzi termicznej, która była rejestrowana przez kamery TELOPS o średniej i długiej długości fali. Kontrolę, synchronizację i analizę danych zapewniało profesjonalne oprogramowanie. Aktywna termografia okazała się odpowiednia do charakteryzowania różnych defektów na warstwach malarskich i wykrywania podrysowań, pentimenti i płótna. Takie wielospektralne podejście zapewniło jednoczesne uzupełniające się informacje na temat badanej próbki.

Słowa kluczowe: badania nieniszczące z wykorzystaniem kamer na podczerwień, termografia aktywna

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